

DATA-DRIVEN SEARCH FOR LONG-LIVED PARTICLES VIA DISPLACED VERTICES AT CMS

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

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May 2025

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Cornell University 2025

We report on a search for pairs of displaced vertices that is sensitive to long-lived particles (LLPs) in a low-background environment. This search uses 140 fb⁻¹ of $\sqrt{s} = 13$ TeV data collected by the CMS experiment and targets LLPs with mean proper decay lengths between 0.1 and 100 mm. Benchmark models are extended from the previous iteration to include exotic decays of the 125-GeV Higgs boson to a pair of LLPs, which decay hadronically to jets. The previous trigger targeted mass points of LLPs above 800 GeV and was unable to capture the sensitivity of this model. In this search, the same RPV SUSY models are probed as low as 200 GeV. By using a data-driven approach, analysis techniques from displaced-vertex reconstruction and selection, along with their systematic uncertainties, have been improved. To study vertexing efficiency, we employ a novel technique called "TrackMover", in which tracks are artificially displaced in data and simulated SM events to mimic the kinematics and topology of LLP decays. Low-mass LLPs decay to a pair of two soft quarks, posing an issue of no associated jets. Despite the challenge in certain models, this technique has been generalized for all our benchmark models. It could also be adapted to other CMS searches for displaced vertices. We report on vertexing uncertainties associated with the exotic-Higgs models. While the exclusion limit remains blinded, the displaced-vertex search is expected to continue providing complementary exclusion limits across models to other searches for LLPs with longer lifetimes.

BIOGRAPHICAL SKETCH

Peace Kotamnives was born and raised in Surat Thani, Thailand. After spending almost her entire life in the town of thousand rivers and connecting canals, she moved to Eugene, Oregon, where she earned a degree in physics and mathematics in Spring 2018 from the University of Oregon (UO). In fact, the plan to study abroad was not on her mind until her father serendipitously ran into his old friend, whose son studied physics in the UO PhD program, just a few months before her journey. Although she wanted to pursue a physics career and had a great support from her family to take on this opportunity, it came with unforeseen challenges from language barriers to cultural differences.

Despite the challenges of adjusting to a new culture, she adapted to life in a new country and was fortunate to be advised by Prof. Eric Torrence in various research projects. In Summer 2017, she was awarded the summer fellowship to work on the search for the resonance of di-Higgs boson at the ATLAS experiment. This opportunity has shaped her interest and continuation in a research career. After graduation, she moved to Ithaca, NY and attended Cornell University in Fall 2018 for the physics PhD program.

During the first two years, she faced unclear motivation and research direction, juggling between a number of physics courses, spoken English courses required for a teaching position, as well as trial research projects from laser-plasma simulation to numerical analysis. Amid the pressure of uncertainty and the arrival of COVID-19, she realized how particle physics research can help her recover a sense of joy, purpose and belonging. A few months after such a turning point was when her then-advisor, Prof. Ritchie Patterson, accepted her to join the CMS experiment and the search effort for long-lived particles. With a guided direction and a supportive environment from her advisor and

colleagues, she was able to soon find joy in her PhD journey. She balanced her PhD research with hobbies like watercolor painting, baking, running, and martial arts, integrating them into three pillars: work, health, and joy.

In addition to the search effort for LLPs, she also later contributed to firmware development for the HL-LHC track trigger hardware, advised by Prof. Peter Wittich. While most of her time for the CMS collaboration was based at Cornell, she had an opportunity to work in the CMS control room at Cessy, France for the Data Quality Monitoring (DQM) central shifts in 2022 for two short periods.

After completing her PhD, she plans to move to Boston, and work as a post-doctoral fellow in the field of proton therapy. She is passionate about using her particle physics skills to make proton therapy systems more accessible for cancer treatments worldwide. After this post-doc, she will return to Thailand to work as a senior researcher at the Faculty of Medicine Ramathibodi Hospital, Mahidol University, aiming to contribute and expand expertise in particle and medical physics needed in the country.

To protons, from fundamental physics to cancer treatment.

ACKNOWLEDGEMENTS

My journey up to this conclusion chapter of the PhD degree started on the day that my dad told me he could fulfill my dream of becoming a physicist...

I am grateful for his bravery and selflessness, even when we were unprepared for my financial support and English competency to study abroad. With unconditional support from my dad and my family, many obstacles were overcome. From constant Skype calls discussing my mental-health issues to a few now, I am able to proudly take every next step in my life with confidence and passion for good. Another key person who paved this journey for me was Chaowaroj Wanotayaroj (or P'Max). I am thankful for his guidance to life in the US, in the UofO, to a half-marathon running club, and to the field of particle physics. Within the UO community, I would like to extend my gratitude to Prof. Eric Torrence for mentoring my undergraduate research. I am also grateful to Kathleen Walls for sharing friendship and adventurous spirit in the early part of this journey.

In the Cornell community, where my PhD life began, I was welcomed by Prof. Ritchie Patterson to be part of her team in my time of uncertainty and confusion. Her relentless support and guidance on research and life have been invaluable. Ritchie has never made me feel behind. She always encouraged me to think critically on my results and ask simplified questions to make progress confidently. Although I came to Cornell with insufficient communication skills, Ritchie was patient and understanding of unrefined presentations and broken English. Rather than criticizing or ignoring, she always gave constructive and gentle feedback. She has absolutely catalyzed a turning point in my life to hope and joy in physics research.

Without my colleagues in the search for displaced-vertex and other CMS

collaborators, my daily routine and interaction would not be meaningful and inspiring. Firstly, I would like to say a big thank you to Joey Reichert and Shaun Hogan. They can go above and beyond in advising and mentoring in many technical components of the search. They are always available in the time of need for discussion and debugging. Other members in the group that I would like to extend the gratitude to are Abby Warden, Alec Duquette, Hannsjörg Weber, Ang Li, Yuqing Wu and other members as part of the displaced-vertex team at large. At my home institution, I am fortunate to be advised by Prof. Peter Wittich, my PhD committee member, who has been supportive and resourceful in my firmware development project and this manuscript. I also appreciate the dynamics and support in the academic environment at the CMS group at Cornell. There, I have been able to learn and grow in the field of particle physics from LEPP journal clubs, seminars, and (some) group meetings. The current and former members of the group apart from those mentioned that I appreciate our interactions are Prof. Julia Thom-Levy, Prof. Jim Alexander, Prof. Anders Ryd, Prof. Jennet Dickinson, Charlie Strohman, Rui Zou, Jose Monroy, Xuan Chen, Michael Oshiro, Divya Gadkari, Tres Reid, Derek Cranshaw, Xingchen Fan, Jason Fan, Sam Bright-Thonney, Joseph Grassi and Kasia Krzyzanska. It has been my pleasure to work with all the Cornell talented and exemplary researchers. I am grateful for listening to their talks, ideas and discussions, as well as joining lunches and taking trips together to various physics conferences.

Despite a happy ending in my PhD journey with Ritchie and the CMS group, I would like to express my gratitude to another PhD committee member, Prof. Yuval Grossmass. He welcomed me to Cornell and supported me in the early stage of my PhD along the way to this end. I also appreciate the support from Prof. Maxim Perelstein, who was a former director of graduate studies in the

physics department, for his patience and help in my time of uncertainty to find a research direction.

Moreover, it is the community of Ithaca that I have embraced to call home. I thank Susan Alferieff and her family for hosting me under their roof and for being my comfort zone in Fall Creek over the course of four years. I am much appreciated her warmth, gracefulness and friendship that have made me feel like an extended family member. I also have become friends and roommates with Namitha Suresh, Nidia Cristina Reyes Gil, and Andreia Fenley, learning from different perspectives and cultures and being inspired by these wonderful female PhD researchers. Additionally, my time in Ithaca could have been colder without the friendship that I have with the Thai Cornellians; Ornwara Tritrakarn, Sireemas Maspong, Tinakrit Sireerat and Sirithorn Siriwan, who we shared home-cooked meals and cared for each other in the time of need, and PhD friends; Kento Okada, Yi Xue Chong, Wee Hao, Vaibhav Sharma, Jingyi Wu, Jihoon Dean Kim, Chad Pennington, Charles Zhang, Aditya Mahalanabish, Shi-Yuan Ma and Avinash Mandaiya, with whom we shared hobbies and laughter in times of joy.

Lastly, I would like to thank my family, especially my dad, for always being by my side, not only as a father but as a mentor and a friend. I am grateful for the love and support that my mom, my brother, and my dad have been continuously sending across the Pacific Ocean and cheering me up to this finish line.

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CHAPTER 1

INTRODUCTION

It is a strange idea that we, as humans, who are larger than atoms by 10 orders of magnitude, want to see what is inside them. This may remind many of us of a scene in a movie like *Alice in Wonderland*, where Alice is falling down the rabbit hole because of her curiosity. Analogously, the rabbit hole is the world of particle physics, where the fundamental particles and their interactions are studied by curious humans. That is even stranger! How can we study something that is unbelievably small beyond our vision and imagination?

Back to when it all started, the idea of the existence of atoms was first proposed by the Greek philosopher Democritus in 400 BC. He called it atom for its *indivisibility*. His idea was then challenged by other believers, as well as scientists. Until today, the most accurate picture of the atom (Figure 1.1) has diverged from its initial theory greatly, not to mention the particles and their interactions deep down inside the atom that are not yet well-understood. While the triumph of the atomic model makes a great achievement in human history, it takes decades of learning, unlearning, and relearning new theories and experiments for the advent of *quantum mechanics*. Quantum mechanics is a primary tool to study subatomic particles and assign them with probabilities for their existence, suggesting the atomic model, as shown, dominantly attributed by the fast electron cloud with undetermined locations. Such intrinsic uncertainty is a concept in quantum mechanics, called the *Heisenberg uncertainty principle*.

Together with other concepts in quantum mechanics, by the mid 1900s new particles such as pions were discovered. Protons and neutrons were no longer proved as fundamental particles as previously thought. From there, the leap to

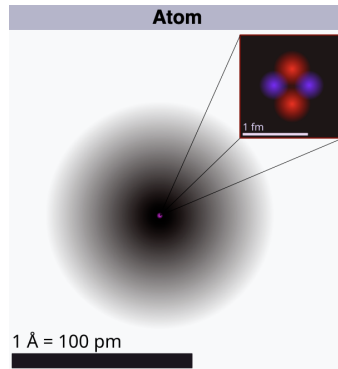


Figure 1.1: The most accurate depiction of a helium atom. The nucleus (pink) is distributed by the electron cloud (black). Zoomed in by five orders of magnitude (upper right), the helium-4 nuclei is composed of protons and neutrons. The black bar is one angstrom or 10^{-10} m[81]

new knowledge of nature was made. Particles as *matters* or *force-carriers* are organized and governed by *symmetry* into the *Standard Model* of particle physics. The Standard Model (SM), unlike a claim made by a single person, is an agreement of the scientific community from both experimentalists and theorists to construct the most succinct and self-consistent model to explain the observable universe. Over fifty years of its existence, the Standard Model has been tested and verified by countless experiments, and has been successful in predicting properties of particles and their interactions. Indeed, these fundamental interactions are experienced on a daily basis. For example, we stand on the ground via electromagnetic force, and we have come to being via strong nuclear force. Even how we smell a rotten banana is due to weak nuclear force. One infamous force that is not included in the Standard Model is gravitational force. As of today's understanding, gravity is a result of the curvature of space-time by mass and energy. It is not yet understood at the quantum level.

Therefore, the Standard Model is not the end of the story¹. As a matter of

¹if we were to aspire for a comprehensive *theory of everything*

fact, the Standard Model has its limitations beyond the unification of all forces. It is not able to explain some phenomena such as the existence of *dark matter*, the *matter-antimatter asymmetry*, and the *neutrino masses*. These limitations lead to an explosion of theoretical ideas and experimental searches for new physics beyond the Standard Model (BSM). To justify these theories, the *Large Hadron Collider* (LHC) was built to collide hadrons such as protons, and to investigate their byproducts at the energy frontier. Its major milestone is not only to discover the Higgs boson as predicted by the Standard Model, but also to search for new particles and their interactions that could explain these limitations. The former motivation is to prove the mechanism of mass generation. The Higgs mechanism is the only source of mass in the Standard Model. Furthermore, if the Higgs boson is discovered, studying its properties can be a tool to provide critical clues to the parameter space of new physics. In fact, the maximum energy scale of 14 TeV set at the LHC is high enough to produce new particles that are heavier than the SM Higgs boson mass of about 125 GeV, but low enough to be sensitive to the electroweak scale, where new physics particles interacting with the SM Higgs boson are expected to be produced.

Among a corpus of theoretical motivations guiding *ATLAS* and *CMS* experiments for signatures of the new particles in the LHC data, the most compelling and simplest extension of the Standard Model is the *Supersymmetry* (SUSY). SUSY introduces a new symmetry between *fermions* and *bosons*. It also proposes that there are more than one Higgs boson. A new counterpart particle for each particle in the Standard Model is called a *superpartner* with opposite spins (i.e. fermion – boson). For instance, a top quark has a superpartner called a *stop* quark. A *gluino* is a superpartner of gluon, which is a force carrier for strong interaction. A *neutralino* is a mixture of superpartners of the electroweak gauge

bosons and the Higgs bosons. The *lightest supersymmetric particle* (LSP) such as neutralino is a candidate for dark matter, as it is elusive to particle detectors either by its weak interaction with SM particles or its stable lifetime.

Over the past decade, no evidence of SUSY has been found since the SM Higgs boson was discovered in 2012 by the ATLAS and CMS experiments. The *exclusion limit* of SUSY particles at the LHC has been pushed to the TeV scale and beyond. The absence of SUSY particles conserving a quantum number called *R-parity* at the LHC has led to the development of new theoretical models that are more complex due to R-parity violation, but are still consistent with the SM and the experimental data. One of the most interesting models for many searches at the LHC, including this work, is the R-parity violating SUSY, which allows the LSP to decay to SM particles, detected by particle detectors. Generally speaking, the LSP is unstable and possesses a long *proper lifetime* ($c\tau$). Such LSPs, interchangeably called long-lived particles (LLPs), are predicted to have a proper lifetime between 10^{-3} and 10^6 mm in a number of models, including minimal flavor violation (MFV) SUSY [50], split SUSY [6], and stealth SUSY [44]. With this range of LLPs' proper decay lengths, they can travel a measurable distance before decaying and interacting with the detector material. More importantly, it appears as a physical object *displaced* from the primary interaction point, which is a unique signature not found in the most dominant SM process such as Quantum Chromodynamics (QCD) processes from proton-proton collisions.

In addition to LLPs based on the supersymmetric theories, the extension of the SM by the *dark sector* is another motivation to search for new physics. Notably, the dark sector does not interact with the SM sector directly, like SM particles, but it indirectly interacts with the SM sector through the SM Higgs

boson. Dark sector theories that predict a new scalar boson with a long proper lifetime due to a small coupling to the SM Higgs boson are called *Higgs portal* models such as hidden valley models [75] [76] [51], Folded SUSY [18], and Twin Higgs models [14] [34]. It is worth mentioning that these Higgs-portal models can resolve not just the dark matter problem, but also the *hierarchy problem*, which is the discrepancy between the electroweak scale and the Planck scale. With the many orders of magnitude of the SM Higgs-boson events expected in the *HL-LHC* (or LHC Run-4) data from the discovery era in the LHC Run-1, the search for LLPs from an *exotic decay of the SM Higgs boson* to LLPs [39] is the most promising way to make a leap in progress in our understanding of the dark sector and the hierarchy problem.

Despite a diverse set of theoretical ideas for new LLPs, the experimental signature of LLPs is unique. This uniqueness is based primarily on a hypothesis of their lifetimes. The unique signature of LLPs in this work, independent of new physics models, is the *displaced vertex* (DV) with proper lifetimes ranging from 100 μm to 30 mm. In this search, a displaced vertex is a secondary vertex that appears in the detector after reconstruction by *tracks* of charged particles at a distance significantly larger than the detector's resolution. With the sensitivity implied by LLPs' proper lifetimes, the search for displaced vertices takes advantage of a background-free environment within the LHC beampipe. This allows for the detection of an LLP decay point reconstructed far from the primary vertex, between 100 μm to 2 cm, before decaying hadronically to SM quarks. The hadronisation process of quarks resulting from the LLP decay interacts with the detector and manifests as *jets*. In other words, the simplified models of RPV SUSY can produce a pair of jets (called 'dijet') or multiple jets (called 'multijet') associated with an LLP decay. Each jet is pair-produced from the proton colli-

sions. On the other hands, the simplified model of the Higgs-portal models is the exotic decay of the SM Higgs boson produced and recoiled against proton-interaction jets to a pair of LLPs, which then individually decay to a pair of jets. As a result, the signal event of this search must be accompanied by *at least two displaced vertices*, all reconstructed by tracks in jets with a good resolution of vertex positions.

To design a model-independent search for displaced vertices, the DV analysis is guided by a data-driven principle. This involves reconstructing displaced vertices, determining the uncertainty between data and simulation, and estimating background yields in the search region. This work is structured as follows: **Chapter 2** discusses the Standard Model and theories beyond it, focusing on the search for LLPs. **Chapter 3** describes the LHC apparatus and the CMS detector for the Run-2 data-taking conditions. **Chapter 4** delves into the reconstruction and signature of SM particles by the CMS detector for event reconstruction, and briefly discusses the reconstruction of displaced vertices. **Chapter 5** describes the simulated samples used in the search and analysis techniques. This includes a trigger scheme, customized displaced-vertex reconstruction, a study on systematic uncertainties, background estimation, and the results on expected exclusion limits. **Chapter 6** presents ongoing efforts in other displaced-vertex searches and other displaced-object searches. It also discusses future prospects for the search for LLPs at the HL-LHC. Finally, **Chapter 7** concludes the work and discusses the potential impact of the search for LLPs with displaced vertices on our current understanding of the universe.

CHAPTER 2

THEORY

The focus of this chapter is to review the subject of particle physics, which is the study of the fundamental constituents of matter and their interactions, from the Standard Model (Sec. 2.1) that has countless evidence of its success to an extension (Sec. 2.4) that attempts to address its limitations (Sec. 2.3).

2.1 The Standard Model

2.1.1 Particles and forces

The Standard Model of particle physics or SM is a theory that describes the fundamental particles and their interactions. These fundamental particles include the smallest constituents of matter, and are responsible for the structure of the universe. Their interactions drive all natural-occurring phenomena. Of all the particles, the matter particles are divided into two categories, namely *quarks* and *leptons*. Quarks are particles that interact through the *strong nuclear force*, and are confined inside hadrons such as protons and neutrons. Leptons are particles that do not interact through the strong nuclear force, but are responsible for the *electroweak nuclear force*, which is a combined force of electromagnetic and weak nuclear forces. Matter particles are interacting through the exchange of force-carrying particles. These particles are responsible for the aforementioned forces. These particle contents are shown in Figure 2.1. The matter particles are in the outer ring, and the force-carrying particles are surrounded by them. From this point of view, the Standard Model is seemingly complete, and is beautifully

structured in a symmetrical way. However, of all forces in nature, the gravitational force is not included in the Standard Model, and is not yet understood at the quantum level. Another aspect that breaks its symmetry arises from an intrinsic angular momentum, called *spin*. Matter particles have half-integer spin, called *fermions* while force-carrying particles have integer spin, called *bosons*. Quarks and leptons can spin up or down relative to their directions of motion. These two states of matter particles are called *right-handed* and *left-handed* states. The weak nuclear force is the only force that violates the symmetry between the two states because there is no observation of right-handed states interacting with right-handed states in nature. In addition to this exception that the Standard Model is a chiral theory, the Standard Model also has no explanation for the asymmetric amount of anti-matter particles, compared to the abundance of matter particles, when the matter and anti-matter particles are identical up to the sign of their electrical charges. This is the violation of time symmetry by an assumption of the CPT symmetry. In other words, this also violates other symmetries, so-called *charge-parity violation*, which is responsible by the weak nuclear force. More discussion on the weak nuclear force is in Sec. 2.1.4 and on strong nuclear force is in Sec. 2.1.3.

At the center of Figure 2.1, the Higgs boson distinguishes itself from other bosons because it is not particle that is responsible for a force, but it gives mass to force-carrying particles as well as some other matter particles. The mechanism of how the Higgs boson gives mass to other particles is called the *Higgs mechanism*, and is discussed in Sec. 2.1.5. With regard to particle mass, the Standard Model is successful in predicting the mass of all particles, except the mass of the neutrinos, which are the lightest particles belonging to the lepton section of the Standard Model. The origin of neutrino mass is unknown. Non-zero mass

of neutrinos is required for the *neutrino oscillation*, which is the phenomenon of neutrinos changing flavors as they propagate through space. The discovery of neutrino oscillation implies that neutrinos have mass, and the masses are ones the 19 free parameters in the Standard Model [38]. The mass of neutrinos is not yet measured accurately, but it can be a clue to the existence of *dark matter*, which only interacts through the gravitational force, and is not explained by the Standard Model. More discussion on other shortcomings of the Standard Model is in Sec. 2.3.

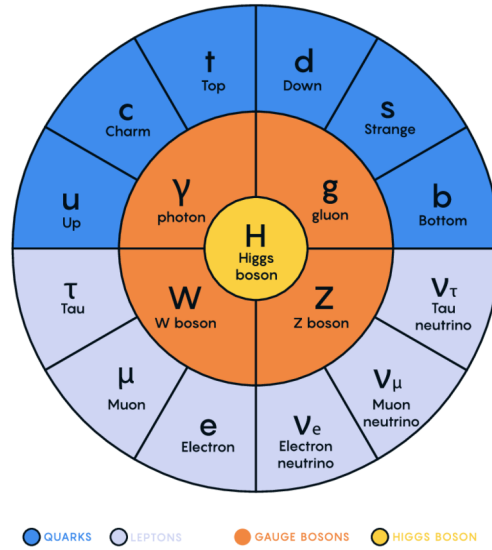


Figure 2.1: The Standard Model of Particle Physics. The outer ring includes fermions, which are divided into quarks at the top and leptons at the bottom. The inner circle includes bosons, which are divided into gauge bosons and the Higgs boson [63].

2.1.2 Quantum field theory

The theoretical framework that is the corner stone of the Standard Model is *Quantum Field Theory* or *QFT*. QFT is a theory that combines quantum mechan-

ics with special relativity in order to describe the interactions of particles. The theory is based on the principle of *local gauge* invariance, which is the requirement of the theory to be invariant under a transformation, including translation, rotation, and boost, of the fields at each point in space-time. These symmetric requirements lead to conservative laws of nature such as the conservation of energy, momentum, and angular momentum. The local gauge invariance as a group symmetry leads to the prediction of the force carriers, which are the *gauge bosons* in the Standard Model as mentioned in Sec. 2.1.1. The gauge bosons are *photon* for the electromagnetic force, *W* and *Z* bosons for the weak nuclear force, and *gluon* for the strong nuclear force. There are three main gauge symmetries in the Standard Model, which are $SU(3)$ for the strong nuclear force, $SU(2)$ for the weak nuclear force, and $U(1)$ for the electromagnetic force. Hence, the Standard Model can be expressed succinctly as

$$\begin{array}{ccc}
SU_C(3) & SU_L(2) & U_Y(1) \\
8G & 3W^a & B \\
= 1 & 8 & a = 1 \ 2 \ 3
\end{array} \tag{2.1}$$

where the subscripts C and L denote the *color* and *left-handed* chiral symmetries, respectively. The gauge bosons are represented by G , W^a , and B for the strong, weak, and electromagnetic forces, respectively. Another subscript Y is the *hypercharge* of the weak nuclear force, which is a combination of the weak isospin and the weak hypercharge [10]. The dynamics that is not captured by this expression is the *Spontaneous Symmetry Breaking* of the electroweak force, which is the unification of the electromagnetic and weak nuclear forces. The unification is achieved by the Higgs mechanism, which is discussed in Sec. 2.1.5. The

Higgs field is missing from the expression because it permeates in all space, and gives mass to the gauge bosons of the weak nuclear force as a consequence of the dynamics.

2.1.3 The quark model, QCD and hadronisation

The quark model was first proposed by Gell-Mann and Zweig in 1964, but had not been accepted widely until a decade later. The model was based on experimental observations of hadrons decaying into other hadrons, with similar masses, and the organization of them into the *Eightfold Way* as a result of SU(3) representations. This discovery began with the prediction of Yukawa particles of mass around 200 MeV [61], which were later discovered as pions. Pions are the lightest mesons, made of up and down quarks, and are responsible for the strong nuclear force. Other hadrons of higher mass were discovered later, and were classified into baryons and mesons. The relationship among hadrons led to the discovery of SU(2) symmetry, which was later extended to SU(3) symmetry. For instance, proton and neutron, which are the two states of a nucleon, and are related by the exchange of two different types of *quarks*. They transform under an approximate *isospin symmetry* as a two-dimensional representation of SU(2), called an *isospin doublet*. The explanation of three pions with different charges follows from the SU(2) symmetry by

$$2 \otimes 2 = 3 \oplus 1 \quad (2.2)$$

where the left-hand side represents the tensor product of two isospin doublets, and the right-hand side represents the decomposition of the tensor product into

a *triplet* and a *singlet*. The existence of three pions suggest that they form a triplet, but the mass of pions is smaller than the mass of nucleons, which implies that they consist of constituents that are more fundamental than protons and neutrons. Furthermore, the observation that a neutral pion decays to a pair of photons, suggests that the pion is a bound state of a *quark* and an *anti-quark*. Particularly, all the lightest-mass mesons have the J^P quantum number of either 0^- or 1^- , giving a strong evidence that (anti)quarks are fermions with spin $1/2$.

The quark model was further developed by incorporating the conservation of *strangeness*, which was discovered in the decay of *kaons*. This experimental evidence was in favor of the interpretation that a meson is a bound state of a quark and an anti-quark, which exists in three flavours called *up*, *down*, and *strange* quarks. Analogous to light mesons, heavy mesons were observed with mass of a few GeV. *D-mesons* and *B-mesons* are examples of heavy mesons, which are bound states of a *charm* and a *bottom* quark, respectively, with a light quark. Particularly, they have a long lifetime, in contrast to a *top* quark which decays before hadronisation. Another bound state of quarks is a baryon, which is a three-quark system. The proton and the neutron are examples of baryons, which are bound states of three quarks with different flavors. Before this came to realization, the Eightfold Way or the *baryon octet*, purposed by Gell-mann and Ne'eman [38], is a consequence of the transformation of three quarks as a three-dimensional representation of SU(3).

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \quad (2.3)$$

where the left-hand side represents the tensor product of three quarks, and the right-hand side represents the decomposition of the tensor product into a sin-

plet, an octet, an octet, and a decuplet.

In total, there are six flavors of quarks, and they are classified into three generations. Each generation consists of two quarks with different electric charges.

Although the quark model is successful in explaining families of new hadrons, it doesn't explain experimental data from *deep inelastic scattering* such as the scaling behavior of the proton structure function, and how quarks are confined inside hadrons [54], as well as the violation of *Pauli principle* from Σ^{++} [59]. Quantum chromodynamics (QCD) was proposed to address these issues. Its feature predicts a new charged boson, called *gluons*, and a new quantum number associated with a (anti-)quark through one of the three *color* charges, namely *(anti-)red*, *(anti-)green*, and *(anti-)blue*. More importantly, this speculation sheds light on the former questions as well as supporting the enhancement of the cross-section for $e^+e^- \rightarrow \text{hadrons}$ present in data, and an unexpectedly long lifetime of the J/ψ and ψ' mesons. Another feature, which is a *running coupling* α_s in the strong interaction, also attributes to *asymptotic freedom* of quarks and gluons at high energy, and *confinement* of quarks and gluons at low energy. These concepts are crucial for understanding the structure of hadrons and the formation of *jets* in high-energy collisions.

2.1.4 The electroweak interaction

In the previous section (Sec. 2.1.3), the strong force was discussed. Analogous to the strong force that is responsible by force-carrying particles like gluons, the electroweak force is responsible by photon, W and Z bosons. These force carriers are the gauge bosons of the QCD and electroweak (EW) sectors of the

Standard Model as shown in Eq. 2.1. In fact, the Standard Model theory before undergoing *electroweak symmetry breaking (EWSB)* (to be discussed more in Sec. 2.1.5) can be described by the following lagrangian terms:

$$\mathcal{L}_{\text{SM}}^{\text{classical}} = \mathcal{L}_{\text{Yang-Mills}} + \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{Higgs}} \quad (2.4)$$

where $\mathcal{L}_{\text{Yang-Mills}}$ explains the kinematics of gauge bosons and interactions among them within the same sector, $\mathcal{L}_{\text{Dirac}}$ explains the kinematics and interactions of fermions with gauge bosons, $\mathcal{L}_{\text{Yukawa}}$ explains the interactions of fermions with the Higgs boson, and $\mathcal{L}_{\text{Higgs}}$ explains the dynamics of the Higgs boson (Sec. 2.1.5). The Higgs mechanism that is attributed by the Higgs potential included in the $\mathcal{L}_{\text{Higgs}}$ term impacts the electroweak sector of the Standard Model to be broken to the electromagnetic $U(1)$ symmetry. Particularly, it is responsible for masses of the W and Z bosons, and the fermions, while gluons remain massless because the QCD gauge symmetry represented by $SU_c(3)$ is unbroken after the EWSB.

To be more specific, the electroweak sector before EWSB is represented by $SU_L(2) \times U_Y(1)$ and is involved in all terms of the lagrangian above (Eq. 2.1.4). Its kinematic contribution to the first term can be expressed as:

$$\mathcal{L}_{\text{Yang-Mills}}^{EW} = \frac{1}{4} W^a W_a + \frac{1}{4} B B \quad (2.5)$$

where the

$$W^a = W^a + g^{abc} W^b W^c$$

and

$$B = B \quad B$$

are the field strength tensors of the W^a and B gauge bosons, respectively. The SU(2) gauge group has a structure constant of f^{abc} and a gauge coupling of g is its coupling, but the U(1) gauge group has no structure constant with a gauge coupling of g .

The second term of the lagrangian in Eq. 2.1.4 is the Dirac term, which is the kinetic term of fermions interacting with the gauge bosons. The term is expressed as:

$$\mathcal{L}_{\text{Dirac}}^{EW} = \bar{\psi}_L i \not{D} \psi_L + \bar{\psi}_R i \not{D} \psi_R \quad (2.6)$$

where ψ_L and ψ_R are the left-handed and right-handed chiral fermions, respectively. D is the covariant derivative that includes the gauge bosons. The left-handed fermions are in a doublet representation of SU(2), and the right-handed fermions are in a singlet representation of SU(2).

The third term of the lagrangian in Eq. 2.1.4 is the Yukawa term, which is the interaction term of fermions with the Higgs boson after the spontaneous symmetry breaking (or EWSB), in which the Higgs field acquires the *vacuum expectation value* or (VEV). It is expressed as:

$$\mathcal{L}_{\text{Yukawa}}^{EW} = y_f \bar{\psi}_L \phi \psi_R + y_f \bar{\psi}_R \phi^\dagger \psi_L \quad (2.7)$$

where y_f is the Yukawa coupling of the fermion, ϕ is the Higgs field, and $\phi^\dagger$ is the complex conjugate of the Higgs field. The term is responsible for the mass

of the fermions, and the interaction of the fermions (m_f) with the Higgs boson, which is determined by the coupling strength of $m_f v$.

Lastly, the fourth term of the lagrangian in Eq. 2.1.4 is the Higgs term, and can be described by the following equation:

$$\mathcal{L}_{\text{Higgs}}^{EW} = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (2.8)$$

where the last term of this equation is the Higgs potential. It is the primary source of spontaneous symmetry breaking. The Higgs potential is expressed as:

$$V(\phi) = \frac{1}{2} m_H^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4 \quad (2.9)$$

where m_H^2 is the mass parameter of the Higgs boson, and λ is the self-coupling of the Higgs boson. Note that the Higgs field (ϕ) is a complex scalar field, written as $\phi = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$ or $\begin{pmatrix} \frac{1}{\sqrt{2}} (\phi_1 + i \phi_2) \\ \frac{1}{\sqrt{2}} (\phi_3 + i \phi_4) \end{pmatrix}$

The gauge bosons of the electroweak sector in the aforementioned lagrangian terms were described in terms of the vector fields, but they can be expressed in terms of the mass eigenstates by linear transformations to the mass eigenstates. These mass eigenstates A , W , and Z are commonly known as photon, W boson, and Z boson, respectively. The transformation is given by the following equations:

$$\begin{aligned}
A &= -\frac{1}{q^2 + g'^2} B (g W^3 + g' B) \\
W &= \frac{1}{2} (W^1 - i W^2) \\
Z &= -\frac{1}{g^2 + g'^2} (g W^3 - g' B)
\end{aligned} \tag{2.10}$$

where g and g' are the gauge couplings of SU(2) and U(1) as mentioned previously.

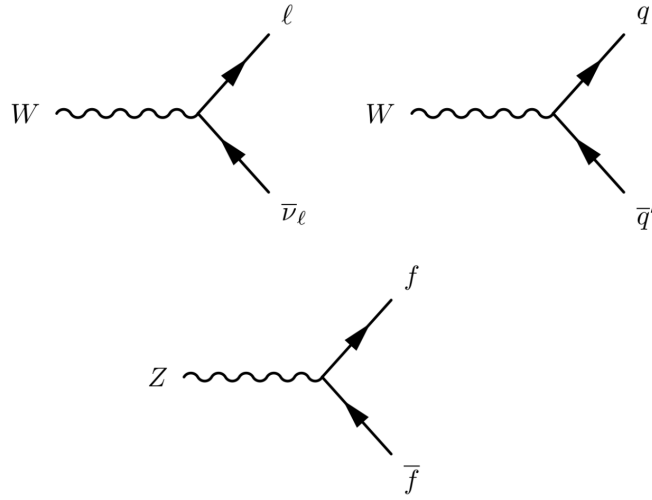


Figure 2.2: (Top) the decay of W boson to fermions (right) and to lepton, plus its neutrino, as a *semi-leptonic* decay (left). (Bottom) the decay of Z boson to a pair of fermions.

Since the W bosons are charged, they can interact with any fermions, but the particle product of the interaction must conserve the total charge of the final-state particles to be either +1 or -1. In contrast, the Z boson and photon are neutral, the total charge of their initial state or final state must be zero. Unlike photon, W and Z bosons are massive and exhibits force range in an order of the *Compton wavelength* of the bosons, which is the inverse of the bosonic masses. Hence, the electromagnetism is a long-range force, while the weak nuclear force is a short-range force. The decay mode of the W bosons can be either a pair of

quarks of the same generation or a lepton and a neutrino, shown in Figure 2.2 (top). A typical decay mode of the Z boson is the decay to a pair of fermions, which can be a pair of quarks, leptons, or neutrinos, shown in Figure 2.2 (bottom). It is important to note that the W bosons are not allowed to decay to a pair of the third generation of quarks (e.g. $t\bar{b}$) due to the violation of energy conservation in the decay process. Indeed, the W mass (m_W) is 80 GeV, which is smaller than the top quark mass (m_t) of 173 GeV. Nevertheless, the decay modes of the W bosons can involve quarks across generations through the *CKM matrix* that features the mixing of quarks. The CKM matrix is a unitary matrix embedded the strength of the flavor-changing weak interactions of quark pairs. The matrix is expressed as:

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 0.97 & 0.23 & 0.003 \\ 0.23 & 0.97 & 0.04 \\ 0.009 & 0.04 & 1.00 \end{bmatrix} \quad (2.11)$$

where these matrix elements are corresponding to the coupling constants of quarks in the weak interaction by the Lagrangian term $\mathcal{L}_{\text{Dirac}}^{EW}$. The CKM matrix is also a result of the diagonalization of the mass matrix of quarks, and determines the amount of *CP violation* in the Standard Model.

2.1.5 The Higgs mechanism

The Higgs mechanism was mentioned in Sec. 2.1.4 as the only source of the Standard Model particle masses through the spontaneous symmetry breaking of the electroweak sector. The lagrangian term of the Higgs field ($\mathcal{L}_{\text{Higgs}}^{EW}$), owing

to its potential term specifically, is responsible for this Higgs mechanism.

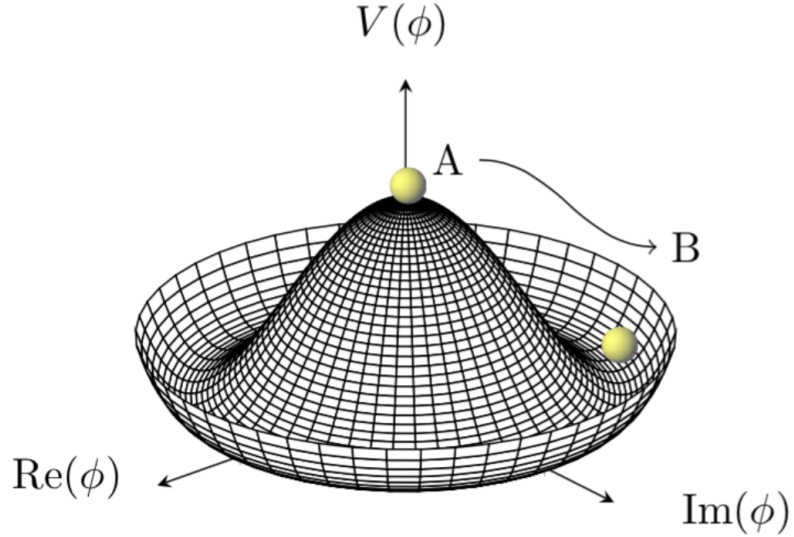


Figure 2.3: The Higgs potential in Eq. 2.1.4 is being plotted with respect to the imaginary ($\text{Im}(\phi)$) and real parts ($\text{Re}(\phi)$) of the Higgs field, leading to the name of the *Mexican hat* potential. At the minimum value of the potential (B), it no longer conserves the rotational symmetry, or a so-called process of spontaneous symmetry breaking.

According to Eq. 2.1.4, the Higgs potential has two free parameters, which are the mass parameter m^2 and the self-coupling λ . The only condition for the potential to have a minimum is that $m^2 \geq 0$ and $\lambda > 0$. As a result, the Higgs potential looks like a shape of a *Mexican hat*, shown in Figure 2.3. The term then can be rewritten as:

$$V(\phi) = \frac{m^2}{2} \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2 \quad (2.12)$$

in which the minimum of the potential is at $\phi^\dagger \phi = \frac{m^2}{2\lambda}$ or v for the (VEV). This implies that the Higgs field has acquired a non-zero VEV while spontaneously breaking the electroweak symmetry at the minimum of the potential.

At this point, the Higgs field can be expanded around the minimum with a freely-chosen ground state of $\begin{pmatrix} 0 \\ v \end{pmatrix}$ as:

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.13)$$

Plugging-in the expansion of the Higgs field into the Higgs potential term :

$$V = \frac{1}{2} (h^0)^2 + \frac{1}{3!} (h^0)^3 + \frac{1}{4!} (h^0)^4 = \frac{m_h}{2} (h^0)^2 + \quad (2.14)$$

where the first term is the mass term of the Higgs boson, the second term is the cubic self-interaction term, and the third term is the quartic self-interaction term. The mass term of the Higgs implies that the Higgs mass $m_h = \sqrt{2} \frac{v}{f}$, and is measured to be 125 GeV experimentally.

In addition, the kinematic term of Eq. 2.1.4 can also be expanded around the minimum of the potential as:

$$(D_\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2} \left(\frac{g_2}{2} v \right)^2 (W_1^2 + W_2^2) + \frac{1}{2} \left(\frac{v}{2} \right)^2 (W_3 - B)^2 \begin{pmatrix} g_2^2 & g_1 g_2 \\ g_1 g_2 & g_1^2 \end{pmatrix} \begin{pmatrix} W^3 \\ B \end{pmatrix} + \quad (2.15)$$

In Sec. 2.1.4, the gauge bosons of the electroweak sector can be redefined in terms of the mass eigenstates. The kinematic term of the Higgs field can be rewritten as:

$$\begin{aligned}
(D \quad) (D \quad) = & M_W^2 W^+ W^- + \frac{1}{2} (A \quad Z) \begin{pmatrix} 0 & 0 \\ 0 & M_Z^2 \end{pmatrix} \begin{pmatrix} A \\ Z \end{pmatrix} + \frac{g_2^2 v}{2} h^0 W^+ W^- \\
& + \frac{g_1^2 + g_2^2}{4} v h^0 Z Z + \frac{g_2^2}{4} h^0 h^0 W^+ W^- + \frac{g_1^2 + g_2^2}{8} v^2 h^0 h^0 Z Z
\end{aligned} \tag{2.16}$$

where $M_W = \frac{1}{2} v g_2$ and $M_Z = \frac{1}{2} v \sqrt{g_1^2 + g_2^2}$ are the masses of the W and Z bosons, respectively. The last four terms are the interactions of the Higgs boson with the W or Z bosons. Specifically, the coupling strength of the Higgs boson with the W bosons is $\frac{2m_W^2}{v}$, unlike the coupling of the Higgs boson to fermions from the Yukawa term.

Moreover, the spontaneous symmetry breaking leading to the three massive gauge bosons and one massless gauge boson is consistent with the Goldstone theorem, which states that the number of massless bosons is equal to the number of broken generators of the symmetry group. Particularly, one of the four degrees of freedom of the Higgs field is the radial component of the Higgs field, and remains massive because the potential is not flat in this direction. The other three degrees of freedom are the Goldstone bosons, and are massless because the potential is flat in these directions. In the case of the Higgs mechanism, the Goldstone bosons are absorbed by the W and Z bosons to become massive, and the photon remains massless as a result of the unbroken U(1) symmetry.

Production modes

Since the Yukawa and Higgs terms in Eq. 2.1.4 indicate that the fermions and bosons interact with the Higgs boson by a coupling strength, that primarily depends on mass of the particles, the Higgs boson is likely to be produced from

vector bosons, and third generation fermions rather than light fermions. Figure 2.4 illustrates the main Higgs production modes. Their cross-sections are varying from the most dominant to rare production as $gg \rightarrow H$, $q\bar{q} \rightarrow q\bar{q}H$, $q\bar{q} \rightarrow WH$, ZH and $gg \rightarrow q\bar{q} \rightarrow t\bar{t}H$, respectively. As a matter of fact, at the proton-proton collision of $\sqrt{s} = 13$ GeV the gluon fusion mode ($gg \rightarrow H$) is the most dominant production mode of the Higgs boson with a cross-section of 44.1 pb because the Higgs boson interacts with the top quark, in the top-quark loop as shown in Figure 2.4. As expected, the top quark is the heaviest fermion in the Standard Model and is heavier than the vector bosons. The vector-boson fusion ($q\bar{q} \rightarrow q\bar{q}H$) is the second most dominant production mode of the Higgs boson with a cross-section of 3.78 pb with the reason along the same line as the gluon fusion. The other two production modes are associated production with a vector boson ($q\bar{q} \rightarrow WH$, ZH), and associated production with a pair of top quarks ($gg \rightarrow q\bar{q} \rightarrow t\bar{t}H$), which are the third and fourth most dominant production modes of the Higgs boson with cross-sections of 2.25 pb and 0.51 pb, respectively. It is important to note that the $q\bar{q} \rightarrow WH$ has a cross-section of 1.37 pb, which is larger than the cross-section of $q\bar{q} \rightarrow ZH$ of 0.88 pb [47]. This is because the W boson is lighter than the Z boson, and the Higgs boson is more likely to be kinematically produced from the virtual W/Z boson radiating off the Higgs boson and the on-shell W/Z boson. For the search for displaced vertices, only the gluon fusion and association with a vector-boson production modes are considered, as they are the most effective to enhance the trigger efficiencies (Sec. 5.2) used in this analysis.

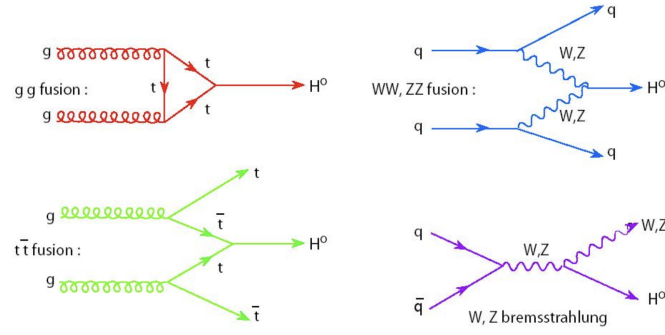


Figure 2.4: Four dominant production modes of the 125-GeV Higgs boson. (Top) the gluon-fusion process is in red and the vector-boson production is in blue. (Bottom) the associated production with a top quark is in green and the associated production with a vector boson is in violet [66]. The search for displaced vertices studies the production of the SM Higgs boson via gluon-fusion and associated vector-boson processes from analyzing the exotic Higgs decay.

Decay modes

With the Higgs boson mass of 125 GeV, the Higgs boson has a lifetime of 10^{-22} seconds, and can decay to a pair of fermions with a branching ratio that is proportional to the square of the fermion mass. Although the Higgs boson mass is less than twice the mass of Z boson mass, the decay channel to a pair of Z/W boson and virtual Z/W boson is possible and is the dominant decay mode of the Higgs boson. Figure 2.5 shows the Higgs decay modes and their branching ratios in a narrow range near the Higgs mass. In particular, the dominant decay modes are $H \rightarrow bb$ and $H \rightarrow WW$, followed by $H \rightarrow gg$, $H \rightarrow \tau\tau$ and $H \rightarrow c\bar{c}$ and $H \rightarrow ZZ$. The $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ decay modes contribute much lower branching fractions because the decays involving diphotons and $Z\gamma$ are loop induced [47]. Of all these decay modes, the $H \rightarrow ZZ$ decay mode can appear invisibly in the detector because the Z bosons can decay to neutrinos. This in-

visible decay mode of the Higgs boson ($H \rightarrow \text{inv.}$) is particularly interesting for the search for dark matter. The current upper limit constraint on the branching fraction of invisible decays of the Higgs boson is 0.16 [79]. In turn, this $H \rightarrow \text{inv.}$ is also the limit on the branching ratio of the Higgs boson decaying to long-lived particles, which is one focus of this analysis (Sec. 2.4.2).

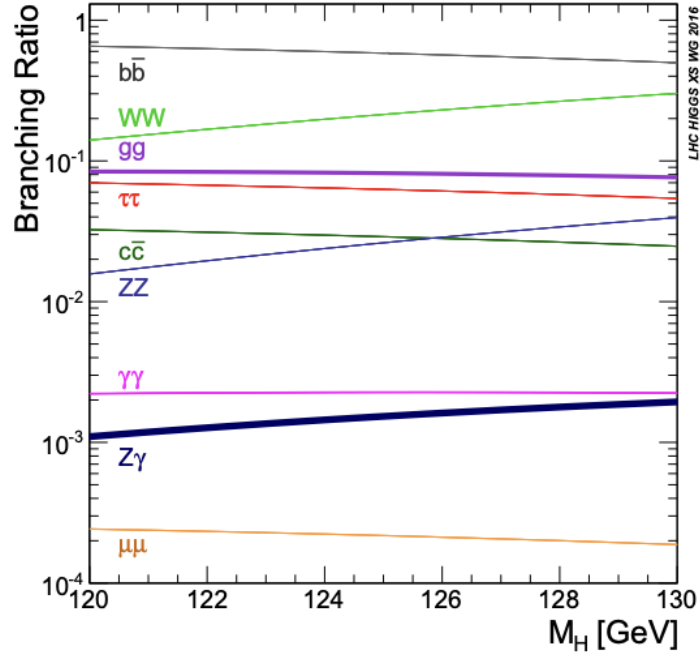


Figure 2.5: The branching ratios of the SM Higgs boson based on the Standard Model prediction near $m_H = 125$ GeV. The theoretical uncertainties are indicated as bands [47].

2.2 Tools to Study Long-lived Particles

The ability to predict sub-nuclear interactions is built upon the requirement of space-time symmetry and the formalism of quantum mechanics [54] as discussed in Sec. 2.1.2. In special relativity, Lorentz invariance is a fundamental symmetry that is preserved in all inertial frames of reference. As a consequence,

a particle can possess certain invariant quantities such as *mass* and *proper lifetime*. In particular, the proper lifetime (or τ) of an unstable particle is the probability of the particle to survive for a certain time before decaying in its own rest frame. It follows the differential equation [61].

$$\frac{dP}{dt} = -\frac{1}{\tau} P \quad (2.17)$$

which is equivalent to the exponential distribution of the decay probability

$$P(t) = e^{-t/\tau} \quad (2.18)$$

For each unstable particle, the rate to decay to daughter particles ($A \rightarrow f$) can vary by processes. However, the total decay rate, which is the sum of all partial decay rates, is constant, and is equal to the reciprocal of the lifetime.

In the case of particle collision process such as $A + B \rightarrow 1 + 2 + 3 + \dots + n$, cross-section is the rate of particle A scattering off particle B to produce particles 1, 2, 3, ..., n. Cross-sections are proportional to the square of the matrix element of the interaction, and the phase space of the final state particles. For calculating the partial decay rate, one can use the Fermi Golden Rule to compute

$$\Gamma(A \rightarrow f) = \frac{1}{2m_A} \int d\Omega_n |M(A \rightarrow f)|^2 \quad (2.19)$$

where $M(A \rightarrow f)$ is the *invariant matrix element*, and $d\Omega_n$ is the *phase space* element for the final state particles. Generally, the matrix element is a function of the coupling constants and the momentum of the particles in the process, and is calculated from the Feynman diagrams [61].

In addition, the total decay rate is also interpreted as the *total width* of a particle. By the uncertainty principle, which states that the lifetime of a particle is inversely proportional to the energy uncertainty of the particle, the total width of a particle is related to its mass uncertainty. Particles with long lifetime have a small mass uncertainty or a narrow mass resonance, and vice versa. Long-lived particles are usually defined as particles that live for 10^{-10} seconds before decaying in their rest frames. They commonly exist in the Standard Model. Long-lived particles in the Standard Model have a wide range of lifetimes, from 10^{-24} seconds for the W boson to 10^{-12} seconds for B-hadrons, as shown in Figure 4.2. Mechanisms for long-lived particles to slowly decay can be explained by the strength of the coupling constant in the matrix element that is small, or the phase space of the final state particles that is limited. Experimentally, they can be detected as *displaced vertices* in the detector.

2.3 Limitations of the Standard Model

The success of the Standard Model as a theory of fundamental physics is undeniable. It has been tested to high precision by many experiments, and has been used to predict the existence of particles such as the top quark and the Higgs boson. However, the Standard Model is not a complete theory of nature, and has limitations that are not yet understood. These limitations are discussed in this section.

2.3.1 Dark matter and dark energy

The Standard Model does not explain the existence of *dark matter* and *dark energy*, which are the two most abundant components of the universe. Dark matter is a form of matter that does not interact with electromagnetic radiation, and is responsible for the gravitational force that holds galaxies together. Dark energy is a form of energy that is responsible for the accelerated expansion of the universe. The existence of dark matter and dark energy is supported by many observations. For instance, the puzzle from the rotation curve of the Andromeda Galaxy gives the first critical clue for the new invisible matter. Classical theory of gravity predicts a galaxy's rotation curve based on the mass at the galactic center. The model, hence, predicts $v \propto R^{-1/2}$ for the galaxy's orbital velocity, where R is the orbital radius. However, the observed rotation curve of the Andromeda Galaxy is flat at large orbital radii [64], which implies that there is more matter in addition to the luminous content. This missing mass is not directly observed and is called dark matter. Other evidence at galactic scales [60] [17] [15] indicate that dark matter only interacts with other matters and itself feebly through the gravitational interaction. According to *Cosmic Microwave Background (CMB)*, that maps out the galactic formation since the first observable light, dark matter is much more abundant than a normal luminous matter by a factor of five. Particularly, the *Λ CDM cosmological model*, which is the standard model of cosmology, requires the energy-matter density of approximately 5% from normal baryonic matter, 23% from dark matter, and 72% from dark energy to precisely explain the power spectrum fitting of the CMB data [2]. This constraint is a strong evidence that the Standard Model is incomplete, and needs an extension to explain the nature of dark matter and dark energy.

2.3.2 Hierarchy problem

Many particle theorists believe that the Standard Model is incomplete because it does not explain the *hierarchy problem*. The hierarchy problem is the question of why the mass of the Higgs boson is so much smaller than the Planck mass, which is the scale at which quantum gravity effects become important. In particular, the Higgs mass is sensitive to the quantum corrections from virtual particles in the one-loop contributions in Figure 2.6, which are quadratically divergent [37]. Given that the Higgs mass is m_H , the one-loop correction to the Higgs mass is

$$\delta m_H^2 = \frac{\Lambda^2}{32\pi^2} \left[6y_t^2 + \frac{1}{4}(9g^2 + 3g'^2) + 6\lambda \right] \quad (2.20)$$

where Λ is the ultraviolet cutoff, y_t is the top quark Yukawa coupling, g and g' are the SU(2) and U(1) gauge couplings, and λ is the Higgs self-coupling.

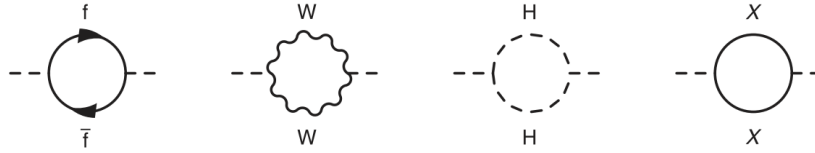


Figure 2.6: Contributions to the one-loop correction of the Higgs boson self-energy from virtual fermionic and bosonic particles from the left to a new massive particle to the rightmost [78].

If Λ , which is the scale of new physics, is around the Planck scale, the correction is of the order of 10^{19} GeV, which is much larger than the Higgs mass of approximately 125 GeV. This discrepancy is considered as *the big hierarchy problem*, and has puzzled physicists for many years. One solution to the hierarchy problem that protects the Higgs boson mass from being sensitive to high-energy scales is to introduce new particles that cancel the Standard Model contributions in the quadratic divergences of δm_H^2 . These particles are called *supersymmetric*

particles, and they are predicted by the theory of *supersymmetry*, discussed in Sec. 2.4.1. In order to give the observed Higgs mass, these particles must have masses around the electroweak scale, or a few TeV, and were expected to be discovered at the Large Hadron Collider (LHC). However, no evidence for supersymmetry has been found so far.

On the other hand, if μ is close to the electroweak scale, m_h^2 is of the order of 10^2 GeV, which is comparable to the Higgs mass, giving rise to *the little hierarchy problem*. Although the one-loop correction of the Higgs mass seems to be mathematically ad-hoc, the hierarchy is not merely a regularization issue. For example, by introducing a new scalar field that couples to the Higgs boson, resulting correction of the Higgs mass demonstrates that the hierarchy problem is physical and is subjected to energy scales of such as a new scalar field. When the Higgs-scalar interaction term such as $-\frac{1}{2} \kappa H^2 S^2$ is added to the Standard Model, the one-loop correction for the Higgs mass becomes [37]

$$m_h^2 = \frac{\kappa}{16\pi^2} \left[\mu_{UV}^2 - 2m_S^2 \log\left(\frac{\mu_{UV}}{m_S}\right) + O(m_S^2) \right] \quad (2.21)$$

where m_S is the mass of the new scalar field, and μ_{UV} is the ultraviolet cutoff. The correction is now logarithmically divergent, and is sensitive to the mass of the new scalar field at the electroweak scale. This *little hierarchy problem* is also a motivation for the search of new scalar fields at the LHC, for more discussion in Sec. 2.5.

2.4 Physics beyond the Standard Model

2.4.1 Supersymmetry

The issue of the hierarchy problem as mentioned in Sec. 2.3.2 can be addressed by introducing a new symmetry, which relates fermions and bosons, called *supersymmetry*. A supersymmetric operator (Q) transforms a bosonic state to a fermionic state, and vice versa. The single-particle quantum state that obeys the supersymmetry algebra¹ is called *supermultiplets*, which has both fermion and boson states that are degenerate in mass, electric charges, and other quantum numbers simultaneously except spins. States with this property are called *superpartners*. As a result, the quadratic divergences of any Standard Model particles in the Higgs mass ($\propto \Lambda^2$) are canceled by the contributions from their superpartners, which are relatively different by minus signs. The elegance of this cancellation is that the Higgs mass is insensitive to the ultraviolet cutoff [55]. Another consequence of supersymmetric algebra is spin difference of a pair of superpartners, which must be $1/2$. This is mainly due to the equality of fermionic and bosonic degrees of freedom and the renormalisability of the extended theory. Particularly, the minimal extension of the Standard Model by supersymmetry is called the *Minimal Supersymmetric Standard Model* or *MSSM*, which is the simplest model that includes the minimal number of superpartners to the Standard Model particles. The extended theory is composed of the following particle contents:

¹The Q operator has a hermitian conjugate operator $Q^\dagger$. They satisfy $\{Q, Q^\dagger\} = P$, where P is the 4-vector momentum generator of spacetime translations. In addition, $[Q, Q] = [Q^\dagger, Q^\dagger] = 0$ and $[P, Q] = [P, Q^\dagger] = 0$

- **Chiral supermultiplets** are the superpartners of the left-handed fermions and the right-handed anti-fermions. They are called *sfermions* for the scalar superpartners of the fermions, including *squarks* and *sleptons*, and *higgsinos* for the fermionic superpartners of the Higgs boson. These chiral supermultiplets have spin-0 and spin-1/2, respectively. Note that the Higgs boson, despite having a spin-0, cannot be the only Higgs doublet in the MSSM since this leads to the gauge anomaly in the electroweak sector of the MSSM. The SM Higgs boson in turn is a linear combination of neutral scalar components of the two Higgs chiral supermultiplets in the MSSM, which are responsible for the mass of the up-type quarks, the down-type quarks and leptons.
- **Gauge supermultiplets** are the superpartners of the gauge bosons. They are called *gauginos* for the fermionic superpartners of the gauge bosons. In $SU(3)_c$ sector, the gauginos are called *gluinos* which are the spin-1/2 color-octet supersymmetric partner of gluon. In $SU(2)_L \times U(1)_Y$ sector, the gauginos are called *wino* and *bino*. After electroweak symmetry breaking, their mixtures give rise *zino* and *photino*, which are superpartners of the Z boson and the photon, respectively.

The particle content of the MSSM is shown in Table 2.1 and Table 2.2. However, the MSSM cannot be complete without the explanation of their interactions. In particular, the interactions of the gauge fields that have been promoted to the vector superfields are shown by the following superpotential [56]:

$$W = H_u H_d + y_u Q H_u u^c + y_d Q H_d d^c + y_e L H_d e^c \quad (2.22)$$

where H_u and H_d are the up-type and down-type Higgs superfields, while Q , L , u^c , d^c , and e^c are the matter superfields. The superpotential also gives rise to the Yukawa couplings (y_u , y_d , y_e) of the quarks and leptons to the Higgs bosons, and the μ term gives mass to the two Higgs fields. Another important consequence is that the Lagrangian of the MSSM has an exact symmetry called *R-parity*, which is defined as $R = (-1)^{3B+L+2S}$, where B, L, and S are the baryon number, lepton number, and spin of the particle. Most importantly, the R-parity is odd for the SM particles and even for the superpartners, which imply that the lightest supersymmetric particle is stable and can be the dark matter candidate. Nevertheless, the MSSM must undergo supersymmetry breaking to give masses to the superpartners since so far they are not observed in nature at the energy scale equivalent to their SM counterparts. The supersymmetry breaking is achieved by adding a *soft supersymmetry-breaking terms* to the MSSM *effective* Lagrangian, which are the mass terms for the superpartners, and the trilinear and bilinear couplings between the superpartners and the Higgs bosons. The challenge posted to this solution is that the soft supersymmetry-breaking terms must be small enough to avoid the reintroduction of the hierarchy problem, and large enough to give masses to the superpartners beyond the TeV scale. In addition, they are prone to introduce flavor mixing and CP violation, contradicting the observations. Hence, to avoid some pitfalls, alternative modifications of the MSSM are proposed and discussed in Sec. 2.4.1.

Table 2.1: Chiral supermultiplets of the Minimal Supersymmetric Standard Model. Superpartners of quarks and leptons are spin-0 squarks and sleptons while the two higgsinos are spin-1/2 Weyl fermions, whose linear combination of neutral scalar components is the SM Higgs boson.

Names		spin 0	spin 1/2	$SU(3)_C \ SU(2)_L \ U(1)_Y$
squarks, quarks (3 families)	Q	$\begin{pmatrix} \tilde{u}_L & \tilde{d}_L \end{pmatrix}$	$\begin{pmatrix} u_L & d_L \end{pmatrix}$	$\begin{pmatrix} \mathbf{3} & \mathbf{2} & \frac{1}{6} \end{pmatrix}$
	$\bar{u}$	$\tilde{u}_R$	u_R	$\begin{pmatrix} \bar{\mathbf{3}} & \mathbf{1} & \frac{2}{3} \end{pmatrix}$
	$\bar{d}$	$\tilde{d}_R$	d_R	$\begin{pmatrix} \bar{\mathbf{3}} & \mathbf{1} & \frac{1}{3} \end{pmatrix}$
sleptons, leptons (3 families)	L	$\begin{pmatrix} \tilde{\nu} & \tilde{e}_L \end{pmatrix}$	$\begin{pmatrix} \nu & e_L \end{pmatrix}$	$\begin{pmatrix} \mathbf{1} & \mathbf{2} & \frac{1}{2} \end{pmatrix}$
	$\bar{e}$	$\tilde{e}_R$	e_R	$\begin{pmatrix} \mathbf{1} & \mathbf{1} & 1 \end{pmatrix}$
Higgs, higgsinos	H_u	$\begin{pmatrix} H_u^+ & H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ & \tilde{H}_u^0 \end{pmatrix}$	$\begin{pmatrix} \mathbf{1} & \mathbf{2} & +\frac{1}{2} \end{pmatrix}$
	H_d	$\begin{pmatrix} H_d^0 & H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 & \tilde{H}_d^- \end{pmatrix}$	$\begin{pmatrix} \mathbf{1} & \mathbf{2} & -\frac{1}{2} \end{pmatrix}$

Table 2.2: Gauge supermultiplets of the Minimal Supersymmetric Standard Model (MSSM). Superpartners of gluon, W and B bosons are spin-1/2 supersymmetric particles.

Names	spin 1/2	spin 1	$SU(3)_C \ SU(2)_L \ U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$\begin{pmatrix} \mathbf{8} & \mathbf{1} & 0 \end{pmatrix}$
winos, W bosons	$\tilde{W} \ \tilde{W}^0$	$W \ W^0$	$\begin{pmatrix} \mathbf{1} & \mathbf{3} & 0 \end{pmatrix}$
bino, B boson	$\tilde{B}^0$	B^0	$\begin{pmatrix} \mathbf{1} & \mathbf{1} & 0 \end{pmatrix}$

R-parity conservation

The MSSM has a symmetry called *R-parity*. R-parity equal to 1 for the SM particles and R-parity equal to -1 for the superpartners. If R-parity is conserved, it implies that every decay vertex must have an even number of supersymmet-

ric particles or *sparticles*. If such an R-parity conserving (RPC) sparticle is produced, it must decay to an odd number of sparticles. Otherwise, it is possible that the sparticle is the lightest supersymmetric particle (LSP), and is stable. The LSP is a good candidate for WIMP dark matter, and can be detected as missing transverse momentum in the detector. The R-parity conservation also implies that the LSP cannot decay to the SM particles, and must be neutral because the electrically-charged LSP is cosmologically disfavored. The neutralino is the most popular candidate for the LSP, and is a mixture of the bino, wino, and higgsino.

In collider experiments such as the LHC (Sec. 3.1), the sparticles are produced in pairs, and decay to the LSP. The LSP escapes the detector without interacting with the detector material, and is detected as missing transverse momentum (Sec. 4.6). The missing transverse momentum is the imbalance of the transverse momentum of the particles in the detector, and is a signature of new physics beyond the Standard Model. A popular search for new physics is called *monojet* search, where a jet is produced in association with missing transverse momentum. The monojet search is sensitive to the production of sparticles at the LHC, and is used competitively to set limits on the masses of the RPC particles. Other searches for RPC particles are also compatible with the final state with multijet or a single lepton/photon, but are less motivated. However, these analyses have already set stringent limits up to the TeV scale of the RPC particles. This opens up an opportunity, that requires new ideas, to search for a more complicated phenomenology under the MSSM framework.

R-parity violation

The R-parity is a symmetry associated with the MSSM, but it is not a fundamental symmetry, and can be violated. There are two main mechanisms for *R-parity violation (RPV)* in the MSSM. The first mechanism is by adding the explicit RPV terms to the superpotential whereas the second mechanism is by spontaneous breaking R-parity by letting neutral superpartners acquiring VEV. Either mechanism leads to the decay of the LSP to the SM particles, and the LSP is no longer stable. As a result, the neutralino or other potential LSPs is not a dark matter candidate in this model. However, the existence of gravitino as a superpartner of the graviton in the *supergravity theory* can be a dark matter candidate due to its decay strength that is suppressed by the gravitational coupling. However, its lifetime is much greater than the age of the universe and none of existing experiments to date can be sensitive to such detection. On the bright side, if R-parity is violated, rich and diverse phenomenology of the MSSM can manifest at collider experiments. This includes but is not limited to the possibility of L-violation, B-violation, and B-L violation, which can be probed by unique final states in the detector. For example, if the L-violation is dominant, the decay of LSP produces additional leptons. If B-violation dominates, the decay of the LSP produces additional jets. In addition, the lifetime of LSP is also determined by parameters in the explicit RPV terms, and can be long-lived. The long-lived LSP can be detected as a displaced vertex. The search for RPV sparticles is a complementary search to the RPC particles, and is a new direction for the search of new physics beyond the Standard Model.

The two R-parity violating mechanisms are explained in the following [56]:

- **Explicit R-parity breaking** introduced RPV terms to the superpotential with 45 RPV coupling parameters. The terms can be written as:

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k + \lambda_i L_i H_u \quad (2.23)$$

where the λ , λ' , and λ'' couplings are responsible for L-violation, B-violation, and B-L violation, respectively. The RPV terms can be constrained by the limits from the proton decay, the neutrino masses, and the electric dipole moments of the neutron and the electron. For instance, the proton decay amplitude is proportional to $\frac{1}{M_d^2}$. Hence, the couplings must be small enough to be consistent with the stringent proton decay limits. On the other hand, the λ'' terms are much less constrained by the experimental limits of neutrinoless double beta decay. This work also benefits from this less constrained parameter space to search for the RPV particles via B-violation processes.

- **Spontaneous R-Parity breaking** avoids the proton decay constraints automatically by letting the neutral superpartners acquire VEVs. There are two main types of these models differing by their *B-L symmetry breaking* scale.

- **Global B-L symmetry:** The MSSM Lagrangian in this model is conserved by R-parity, as well as the B-L symmetry. However, once one of sneutrinos in the model acquires VEVs, which leads to a Lagrangian that conserves baryon number, but violates lepton number, up to the magnitude of $\tilde{\nu}_l$ VEV, both symmetries are globally broken. A critical consequence of the B-L global spontaneous symmetry breaking is the prediction of a massless *Majoron* as a Goldstone boson. Accordingly, if $\text{Re}(\tilde{\nu}_l) \gg M_Z$, the invisible decay

width of a Z boson should enhance significantly. Given the precise measurement of Z-boson decay width, this assumption of VEV being nonzero is disfavored. Alternatively, the model may introduce the SM right-handed neutrino (N) and its superpartner ($\tilde{N}$). Similarly, the superpartner acquires VEVs, and the B-L global symmetry is broken spontaneously. Since the Majoron field after the spontaneous breaking of global lepton in this model is a linear combination of the $SU(2)_L$ singlet fields, it does not couple to the Z boson, and can avoid the invisible decay width constraint.

- **Local B-L symmetry:** The R-parity in this model is automatically protected by the local B-L symmetry after the SM gauge group is extended by the $U(1)_{B-L}$ gauge group. With a similar mechanism that a right-handed sneutrino acquires VEVs, the local B-L symmetry is spontaneously broken, and the R-parity is violated dynamically. Particularly, the result is that the gauge symmetry is reduced to the SM gauge boson, while the Majoron field absorbs the longitudinal mode of the B-L gauge field to acquire mass. Additionally, this model also predicts the mechanism responsible for neutrino masses through a *seesaw mechanism*.

Minimal flavor violating RPV SUSY

In contrast to the most common assumptions of the MSSM, including R-parity conservation and flavor universality, the RPV SUSY benchmark models in this search is based on the MSSM under a single assumption of a *Minimal Flavor Violating (MFV)* symmetry[36]. As the authors note, this assumption protects

a model from the stringent constraints of both the proton decay and flavor-changing neutral currents because R-parity becomes an approximate accidental symmetry of the low-energy Lagrangian. Nevertheless, the explicit R-parity breaking terms determined by the flavor section allow the LSP decaying to SM particles. The model is built based on the observation that the flavor couplings of the MSSM in the superpotential (Eq. 2.4.1) are all small compared with the term. In turn, this observation suggests an analysis of the possibility that some spurious symmetries are preserved by the μ -term but are broken by the Yukawa couplings. The model is then constructed by the following anomaly-free gauge group [56]:

$$G_{LR} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_{Q_L} \times SU(3)_{Q_R} \times SU(3)_L \times SU(3)_R \quad (2.24)$$

where the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken to the SM group $SU(2)_L \times U(1)_Y$ by the VEVs of the Higgs fields. The $SU(3)_{Q_L} \times SU(3)_{Q_R}$, and $SU(3)_L \times SU(3)_R$ are the flavor symmetries of the quark and lepton sectors, respectively. However, the MFV framework proposes that the flavor symmetries are broken by a set of spurions, which are the Yukawa couplings Y_u , Y_d , Y_N and Y_e . Particularly, Y_N is the Yukawa coupling of the right-handed neutrinos, which is responsible for the neutrino masses through the seesaw mechanism. In addition, the model under the assumption of massless neutrino proves that the holomorphic spurions Y_u , Y_d , and Y_e can necessarily break $SU(3)^5$ flavory symmetry. This assumption is in favor of an effectively-stable proton. Therefore, the constraint on proton decays mainly impacts the neutrino sector in this MFV framework [36].

Essentially, the smallness of the Yukawa couplings in the MFV framework

is the key to the suppression of the flavor-changing neutral currents and the proton decay. However, the deviation from the flavor universality is dominant by the $O(1)$ top Yukawa coupling. As a result, the MFV framework proposes that the LSP is the top superpartner ($\tilde{t}_1$), or the *stop* particle. The authors of [36] compute the lifetime of the stop particle as:

$$\tau_{\tilde{t}} \approx (2 - m) \left(\frac{10}{\tan \beta} \right)^4 \left(\frac{300 \text{ GeV}}{m_{\tilde{t}}} \right) \left(\frac{1}{2 \sin^2 \theta_{\tilde{t}}} \right) \quad (2.25)$$

Within this model, the stop particle can decay as a displaced vertex when the $\tan \beta$ and the $m_{\tilde{t}}$ are very small. Figure 2.7 (left) shows the shaded regions in the parameter space of the stop masses and possible lifetimes that are viable. If the stop particle is the LSP, the decay of the stop particle is mostly to bottom and strange quarks by 90% and the rest is to bottom (or strange) and down quarks. Hence, the final state of a pair production of stop particles is expected a pair of b-jets (Sec. 4.5) in addition to other jets. The decay diagram of the stop decay is shown in Figure 2.8 (left).

Alternatively, if the LSP is neutralino or gluino, the decay of the LSP is mostly to the top quark and the stop particle. The decay diagram of the neutralino or gluino decay is shown in Figure 2.8 (right). In the case that this diagram is dominant, the neutralino/gluino LSP has a substantial lifetime. Similar to the previous scenario of the stop, the lifetime of LSP is highly dependent to $\tan \beta$ and the $m_{\tilde{t}}$ as shown in Figure 2.7 (right). The lifetime of this LSP scenario follows [36]:

$$c_{\tilde{N}} \approx (12 - m) \left(\frac{20}{\tan \beta} \right)^4 \left(\frac{300 \text{ GeV}}{m_{\tilde{N}}} \right) \quad (2.26)$$

If R-parity is conserved for the production of superpartners in pairs, the final state of a pair production of neutralino/gluino or stop is expected to have a pair of displaced vertices. Under R-parity violation of these LSP candidates, each LSP decays to SM particles, associated with jets of the displaced vertices. This is a unique signature of the MFV framework for this work.

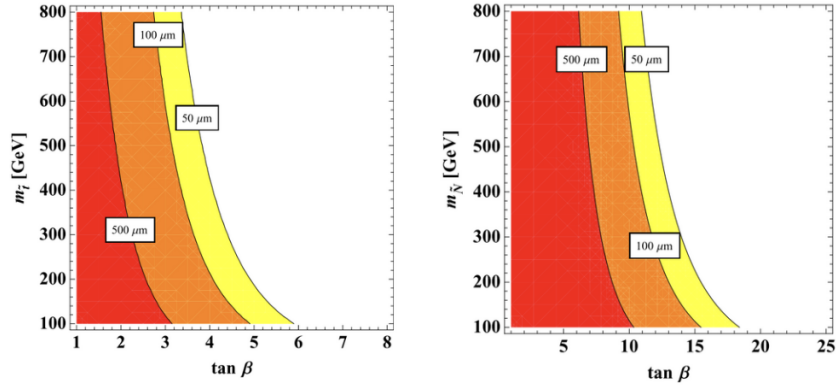


Figure 2.7: Three different shaded regions in the parameter space of the stop (left) and neutralino/gluino (right) by mass and $\tan \beta$ from three lifetime examples based on the MFV framework [36].

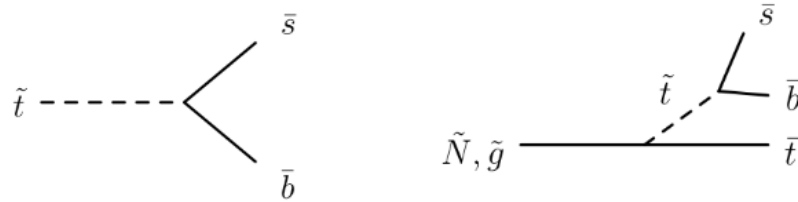


Figure 2.8: The dominant decay channel of stop (left) and neutralino/gluino (right) according to the MFV framework [36].

2.4.2 Hidden sectors

In Sec. 2.3.2, the hierarchy problem is explained and is a motivation for the search of new scalar fields at the LHC. Supersymmetry (Sec. 2.4.1) is one of the solutions to the hierarchy problem, but it is not the only solution. The other solution to be discussed in this section is to introduce a new symmetry in a new sector that is not related to the SM particles, called *hidden sector*. The hidden sector is a new sector of particles that are not charged under the SM gauge group, but interacts with the SM particles through the Higgs portal for instance. More importantly, it needs to provide a mechanism that protects the Higgs mass from the high-energy scales. Consequently, this gives rise to the phenomenology of an exotic decay of the SM Higgs boson to the hidden sector particles. If the hidden sector particles are often long-lived, and can be detected as displaced vertices in the CMS detector. Our search for displaced vertices can be sensitive to discovering the hidden sector particles, and can pave a new direction for the search of new physics beyond the Standard Model.

In particular, most solutions to hierarchy problem require top partners. Colored quark partners such as stop particle in Supersymmetry are constrained experimentally at electroweak scale, and currently pushed to a TeV scale. Alternative theories that solve the hierarchy problem by introducing top partners uncharged under the SM gauge group are proposed in *Twin-Higgs* and *Folded-SUSY* models [34]. Top partners in these theories are colorless and can resolve the *little hierarchy problem* by canceling the quadratic divergences in the Higgs mass from the one-loop level up to the energy cutoff at the $O(5 - 10 \text{ TeV})$ scale, as shown in Eq. 2.3.2. Due to the discrete symmetries imposed in both theories, the uncolored partners couple to the SM Higgs boson as similar as its coupling

to the top quark [18].

As a result, exotic Higgs decays arise naturally in such models and are fully encapsulated by only three free parameters which are mass of the hidden sector particle (m_X), its lifetime (c_X), and the branching ratio of $\text{Br}(h \rightarrow XX)$. Therefore, it is well-motivated to study the exotic Higgs decays in the search for new physics beyond the Standard Model through unique signatures such as displaced vertices or precision measurement of the Higgs properties. However, existing constraints on the SM Higgs boson properties leave room for the exotic Higgs branching ratio below 10 percent, to be discussed more in Sec. 2.5.2.

Although these top-down theories are built upon the concept of *Neutral Naturalness* in order to solve the little hierarchy problem, they can be realized from the bottom-up approach such as a singlet extension of SM or *two-Higgs-doublet model* (2HDM) [39] [5].

Singlet extension of SM

The singlet extension of the SM is a simple extension of the SM by adding a real scalar field called *singlet* to the Higgs sector of the SM lagrangian. Under the assumption of the Z_2 symmetry, the quartic polynomial potential of the singlet field is given by [39]:

$$V(H, S) = \frac{1}{2} m_H^2 H^2 + \frac{1}{2} m_S^2 S^2 + \frac{1}{4} \lambda_H H^4 + \frac{1}{4} \lambda_S S^4 + \frac{1}{2} \lambda_{HS} H^2 S^2 \quad (2.27)$$

where H is the SM Higgs doublet, and S is the singlet field. The m_H and m_S are the mass parameters of the Higgs doublet and the singlet, respectively. The

and λ_4 are the quartic couplings of the Higgs doublet and the singlet, respectively. The λ_5 is the coupling between the Higgs doublet and the singlet.

If Z_2 symmetry is broken, while the exotic decay of the SM Higgs boson to a pair of the singlets is possible by the cubic term in the potential, the singlet can decay to SM particles via the mixing with the Higgs boson. Otherwise, the singlet does not decay and can be a dark matter candidate as long as the Z_2 symmetry is hold. In addition to the singlet scalar extension, exotic Higgs decays are phenomenologically viable when the singlet is a complex scalar or fermion or a vector boson with the lifetime of the singlet that is primarily determined by the mixing angle between the singlet and the Higgs boson. However, the mixing angle is constrained by the Higgs signal strength measurements. One of hidden sector models that can be realized from the singlet extension of the SM is the *Hidden Valley* scenario [76] [75]. The Hidden Valley is realized when the mixing is very small and the valley particles are forbidden to decay to hidden sector particles. Instead, valley particles decay to SM particles. With strong confinement in hidden valleys, the valley particles can hadronize and produce QCD jets of hidden valley particles.

Singlet extension of 2HDM

In a manner analogous to the singlet extension of the SM, the singlet extension of the 2HDM is a simple extension of the 2HDM by adding a scalar field called *singlet* to the Higgs sector of the 2HDM lagrangian. Particularly, the 2HDM is a model that introduces a second Higgs doublet to the SM Higgs sector. With more free parameters from the additional Higgs doublet, the 2HDM with a singlet extension can have rich phenomenology of exotic Higgs decays, where hid-

den sectors can be realized. However, some observations from the 2HDM also exist in the supersymmetric model such as the *Next-to-Minimal Supersymmetric Standard Model (NMSSM)*, the singlet extension of the 2HDM has been constrained by experimental data. An alternative approach is to assume that the two Higgs doublets acquire VEVs, that are real and aligned, so that the fermion couplings of the lightest Higgs bosons is the same as those of the SM Higgs boson. Although the singlet has no direct Yukawa couplings to the SM fermions, it can decay to the SM particles through the mixing with the two Higgs doublets as similar as the mechanism in the previous section.

This simplified extension of the 2HDM has an explicit realization in Twin Higgs models in which two copies of the SM particle content are related by a Z_2 symmetry [5]. As a result, one Higgs doublet is charged under the SM gauge group, while the other Higgs doublet is charged under the mirror gauge group. In Twin Higgs models, the lightness of the SM Higgs mass arises naturally because it is a pseudo-Goldstone boson of an approximate global $SU(4)$ symmetry spontaneously broken to $SU(3)$ at the scale of the top partners. In fact, the Twin Higgs models predict the physical mass of the pseudo-Goldstone boson up to the quadratically divergent corrections from the SM top and top partners by

$$m_h^2 = \frac{3}{4} \frac{y_t^2 + \hat{y}_t^2}{2} \quad (2.28)$$

If the Z_2 symmetry is exact leading to the top (y_t) and twin-top ($\hat{y}_t$) Yukawa couplings, the cancellation is satisfied and the Higgs mass is protected from the high-energy scales.

Alternatively, the minimum variant of the Twin Higgs model is the *Fraternal Twin Higgs model* [34]. This minimal setup does not require a complete copy of SM particle content to the hidden/mirror sector. Without any first and second

generation partners being lighter than the top partner, the hidden sector bound states such as glueballs or bottomonia can exist at the bottom of the mirror sector spectrum [41]. These bound states may have the same spin and angular momentum quantum numbers as the SM Higgs boson. However, they can decay to the SM particles, shown in Figure 2.9, through the mixing with the Higgs boson as a typical signature of the hidden sector [5]. The lifetime of the lightest glueball decaying to a pair of SM particles is predicted to be [51]:

$$\tau \approx 18 \text{m} \left(\frac{10 \text{GeV}}{m_0} \right)^7 \left(\frac{f}{750 \text{GeV}} \right)^4 \quad (2.29)$$

where m_0 is the mass of the lightest glueball, and f is the scale of the electroweak symmetry breaking. Apparently, the lifetime of the lightest glueball is highly dependent on its mass. The decay length is a function of the mass of the lightest glueball, as shown in Figure 2.10, with the lifetime uncertainty of 25% due to the uncertainty of the glueball decay width [41].

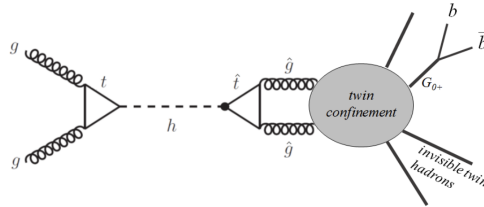


Figure 2.9: Illustration of the exotic Higgs decay at a hadron collider. The SM Higgs decays through a twin-top loop into a pair of twin gluons, which hadronize in the hidden sector but then a bounded glueball state decays back to a pair of SM bottom quarks [34].

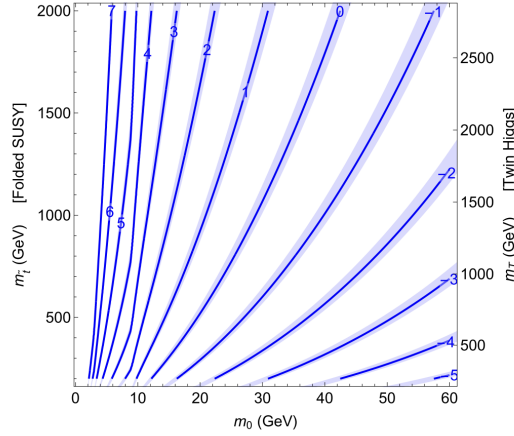


Figure 2.10: Each contour line shows $\log_{10} c$ m_0 of the lightest gluon by the Twin Higgs and Folded SUSY theories. The blue bands correspond to uncertainties from theories. [41].

2.5 Previous Constraints on Long-lived Particles

2.5.1 Exclusion limits on RPV SUSY models

The search for displaced vertices was performed in the past using Run-2 data as in this analysis, but it was optimized for sensitivity to high-mass lightest supersymmetric particles (or LSPs) in the RPV SUSY benchmark models, leaving low-mass LSP uncovered. Nevertheless, the previous analysis [70] has set the most stringent limits at 95% confident level on certain ranges of mass points and lifetimes of the RPV SUSY particles to date. Although the search was largely model-independent, two RPV SUSY models, the stop LSP with di-jet final state and the neutralino/gluino LSP with multi-jet final state, were used as benchmarks.

The RPV SUSY neutralino/gluino model with mass of 2400 GeV is compared with other long-lived particle searches in Figure 2.11. The displaced-vertex

search (green) is complementary to the other two searches (blue and red), and is the most competitive in the LSP lifetime range of 1-10 mm. Particularly, the displaced-vertex search exploits the analysis strategy (more discussion in Sec. 5) that reduces background from material interactions, and optimizes the search sensitivity to the LSP decaying within the tracker. A more comprehensive result of the previous analysis is shown in Figure 2.12 by the contour 2D distributions of cross-sections () times branching ratios squared (B^2) at observed 95% confident level of upper limits of stop LSP (right) and gluino/neutralino LSP (left) from observation (full lines) and from expectation (dashed lines).

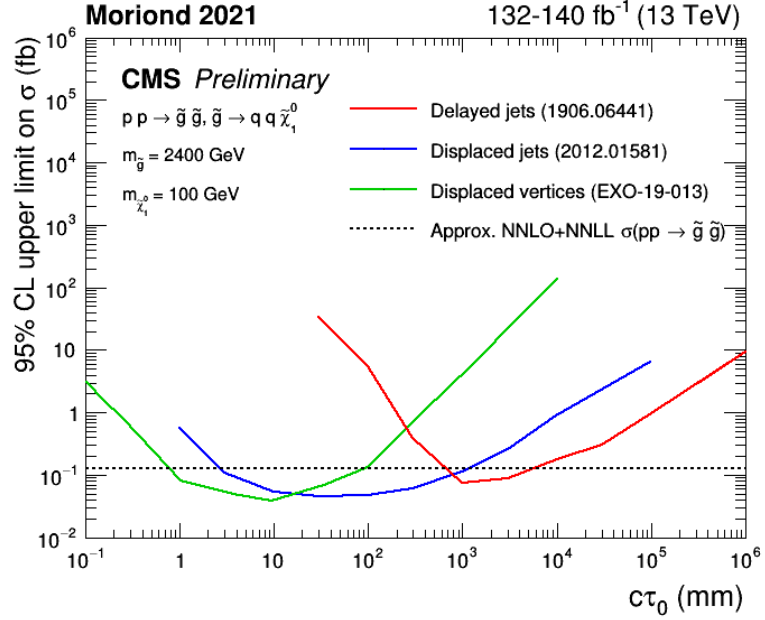


Figure 2.11: Comparison of search sensitivity by lifetime ranges of LSP in three analysis efforts at CMS. The previous iteration of this analysis is competitive in range of lifetimes between 1-10 mm of the 2400-GeV neutralino (green). The other analyses (blue and red) do not limit the search within a beampipe and can target LSP decaying beyond tracker [30].

Although the previous search observed zero excess, the analysis excluded signals with pair-production LSPs with cross-section larger than 0.08 fb with

mass points between 800 and 3000 GeV and mean proper decay lengths between 1 and 25 mm. For the range of mean proper decay lengths of 0.6-90 mm, the limits exclude their masses up to 2500 GeV. A less stringent limit is set on the exclusion limit of neutralino masses up to 1100 GeV for a subset of the previous decay lengths, which is 0.6-70 mm. The observation excludes stop LSPs with masses up to 1600 GeV for mean proper decay lengths of 0.4-80 mm. On the other hand, Figure 2.12 shows that around the proper decay length of 30 mm of the 2500-GeV multijet signal and of 15 mm of the 1750-GeV dijet signal are where the search for displaced jets [71] starts to be as stringent as the search for displaced vertices.

2.5.2 Exclusion limits on exotic Higgs models

The search for exotic Higgs decays has been performed by other analyses (Sec. 6.1) using Run-2 data, as well as Run-3 data for the most recent results. However, the previous analysis was not sensitive to low-mass long-lived particles (LLPs). Figure 2.13 compares various CMS searches for exotic Higgs decaying to a pair of neutral LLPs. Different assumptions for the branching fraction of the LLP with mass of either 40 or 55 GeV decaying to a pair of SM particles are presented. The assumption is either an LLP decaying hadronically to displaced jets or leptonically to displaced leptons. Across the LLP lifetimes between 0.1 mm to 10 km, a leptonic decay of LLPs such as the analysis on displaced dimuon (light blue) has set the most stringent exclusion limit on the branching ratio of exotic Higgs decaying to LLPs. For example, for medium proper decay lengths ranging between 1 mm to 0.1 m, the exclusion limit at 95% CL with mass of 40 GeV is in the order of $O(10^{-5})$. Although the search for exotic Higgs decays

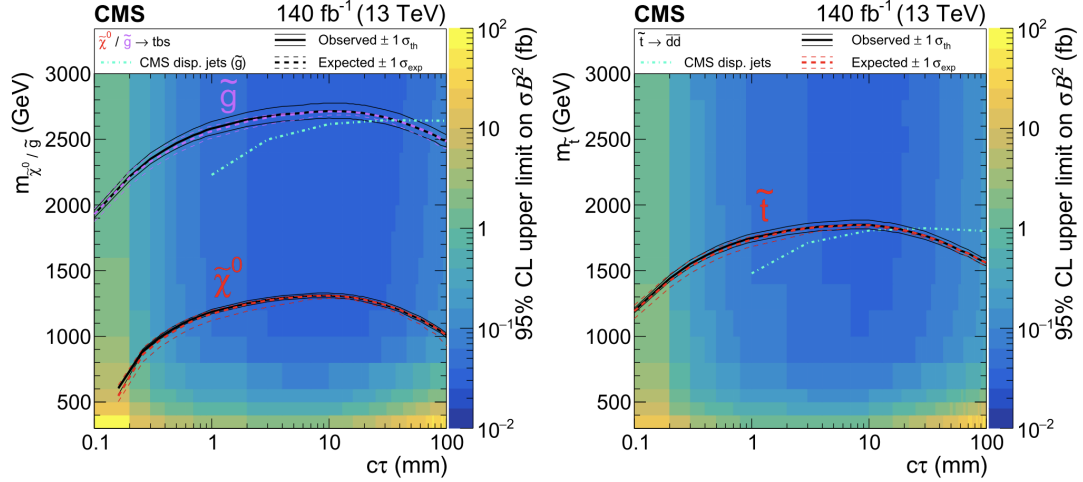


Figure 2.12: The production of gluino/neutralino LSP cross-section and branching fraction to multi-jet final state (left) and the production of stop LSP cross-section and branching fraction to di-jet final state, as a function of mass points and lifetimes. The overlaid mass-lifetime exclusion curves assume pair-production cross-sections for the neutralino LSP (red), gluino LSP (purple) and stop LSP cross-sections with 100% branching fraction of each specified decay mode. The solid black lines represent the observed limits at 95% CL while the dashed colored lines represent median expected limits at 95% CL. The thin black lines represent the uncertainties of the observed limit of theoretical cross-sections, and the thin dashed colored lines represent the region containing 68% of the expected limit distribution under the background-only hypothesis. The observed limits from the CMS displaced jets search [71] are also shown in teal for comparison [70].

via LLPs decaying hadronically is more challenging to place a tighter limit than its leptonic search counterpart, the search for displaced jets (green) is the most sensitive to such decays for the same medium range with the exclusion limit at 95% CL as low as 10^{-3} . However, for low proper decay lengths below 1 mm, the exclusion limit of exotic Higgs decays exists only from two leptonic searches, namely the displaced dimuon (light blue) and the dimuon scouting (violet), no hadronic decay of LLPs is excluded at 95% CL in this parameter space. With the

search of displaced vertices being sensitive to this low-lifetime parameter space, it gives an opportunity for this work to fill in the gap of the CMS exotic higgs decay exclusion limit.

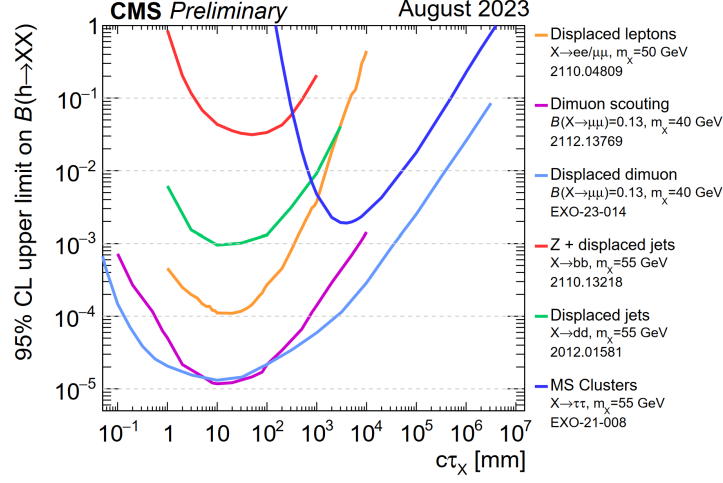


Figure 2.13: The 95% CL observed exclusion limit from various CMS searches for a pair of neutral long-lived particles (X) with mass of either 40 GeV or 55 GeV, decaying from the standard model Higgs boson (h). The branching fraction of this decay is shown as a function of the long-lived particle’s proper lifetime. For hadronic decays of the long-lived particles, the exclusions shown for Z+displaced jets, displaced jets, and hadronic MS analyses assume X decays with 100% branching fraction to bb, dd, $\tau\tau$, respectively. Leptonic decays have different assumptions [31].

In addition to the LLP mass hypothesis above 40 GeV, the exclusion limits based on LLP masses below 40 GeV exist. For instance, the search for displaced jets, which is sensitive to the medium proper decay lengths, reports their results using Run-3 dataset, as shown in Figure 2.14. They set the exclusion limit at 95% CL on the observed branching fraction of the exotic Higgs decays to LLPs with masses from 10 to 55 GeV. The high mass tends to have a lower branching fraction limit, while the low mass tends to have a higher branching fraction limit. This tendency is unlikely due to the branching fraction of $\text{Br}(H \rightarrow SS)$ be-

ing mass dependent, but rather due to the sensitivity of the search for displaced jets to the LLPs becoming limited at low masses.

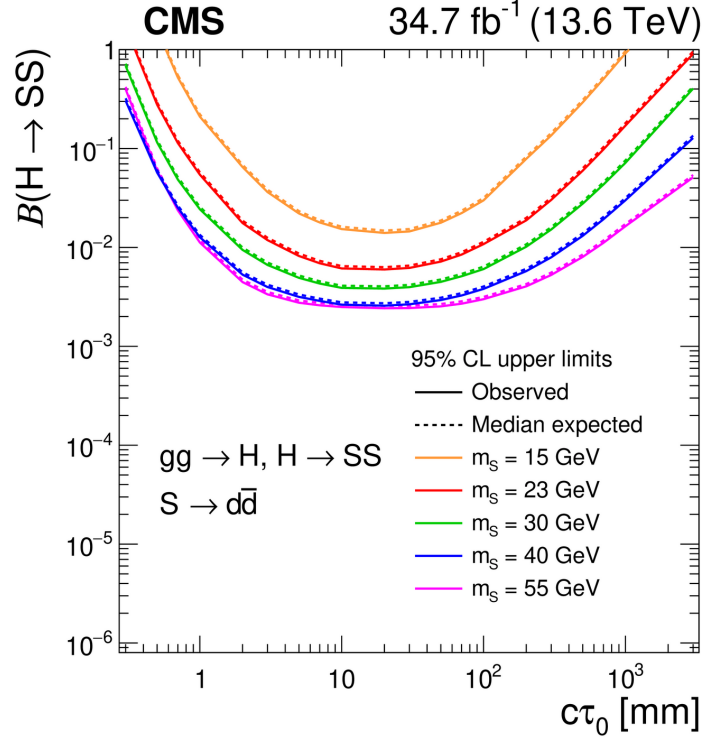


Figure 2.14: The 95% CL upper limits on the branching fraction $\text{Br}(H \rightarrow SS)$, $S \rightarrow d\bar{d}$, for different LLP masses and proper decay lengths. The solid (dashed) lines represent the observed (median expected) limits [32].

CHAPTER 3

EXPERIMENTAL APPARATUS

3.1 The Large Hadron Collider

The largest particle collider in the world, the Large Hadron Collider (LHC), is located at CERN in Geneva, Switzerland. Although there are two main categories of particle accelerators, the linear and the circular accelerators, the LHC is a circular accelerator with a circumference of 27 km and is built in the tunnel of the previous Large Electron-Positron Collider (LEP) 100 m underground. It is designed to collide a large number of hadrons such as protons or heavy-nuclei at a center-of-mass energy ($\sqrt{s}$) up to 14 TeV every second. To operate the LHC at an impressive collision rate of 40 MHz, the LHC is equipped with a series of pre-accelerators and a diverse set of superconducting magnets to guide a beam of particles in a circular path.

Figure 3.1 illustrates the layout of the LHC accelerator complex at CERN. Of particular significance, the collisions of proton beams are studied in this thesis. To deliver proton beams, the series of pre-accelerators begin with a tank of hydrogen gas, where protons are stripped from the hydrogen atoms by an electric field. Protons are then accelerated to 50 MeV by the linear accelerator, and are injected into the Proton Synchrotron Booster (PSB) where they are accelerated to 1.4 GeV. Next, they are injected into the Proton Synchrotron (PS) where they are accelerated to 25 GeV, and then into the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV. Finally, beams of protons are split into two beam pipes around the LHC ring, where they are further accelerated or "ramp-up" to the final energy of 6.5 TeV for the center-of-mass energy of 13 TeV, and rotated

in opposite directions by the LHC magnet system.

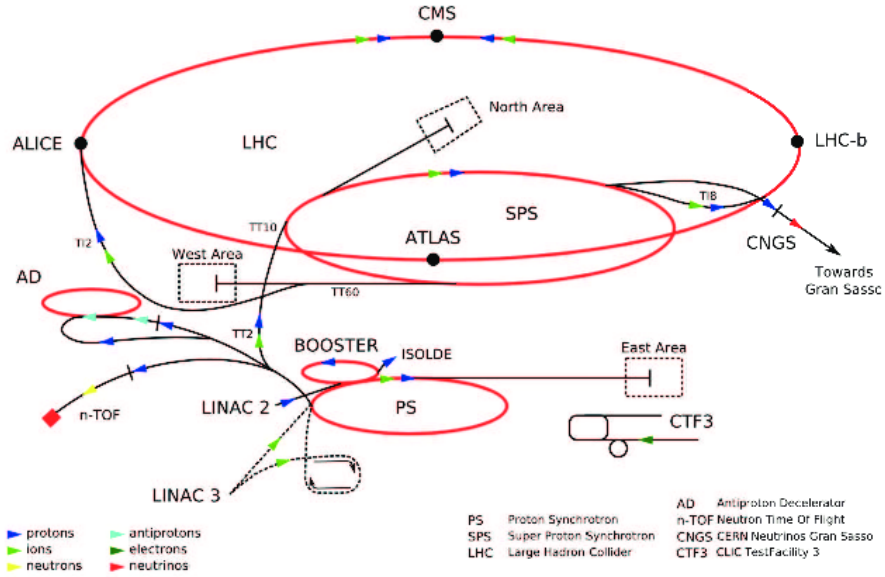


Figure 3.1: Schematic view of the CERN accelerator complex for delivering a pair of counter-rotating proton beams to the LHC [45].

In the process of transporting proton beams, there are a variety of magnets as well as radio-frequency (RF) cavities. While the RF cavities transfer energy to proton beams with electric fields oscillating at 400 MHz for motivating a bunch structure, the magnets drive proton beams around the LHC ring. Of many thousands of powerful magnets, two kinds of LHC magnets that are the most important for steering them along a circular path and focusing them to the major axes are 1,232 dipole magnets and 392 quadrupole magnets, respectively. Particularly, protons in each bunch experience varying centripetal forces based on

magnitude of magnetic fields, proton momentum, and their radii from the center of the ring. The distribution of dipole magnetic fields on the cross-sectional area of the LHC ring is shown in Figure 3.2. However, the quadrupole magnets are used to protect the beam of protons from dispersion, and to focus it to have a small cross-sectional area for *high luminosity*. As a result, the proton beam has a multi-bunch structure. Each proton beam can contain up to 2808 colliding bunches of protons with roughly $1.1 \cdot 10^{11}$ protons per bunch in the LHC ring of the 27-km circumference.

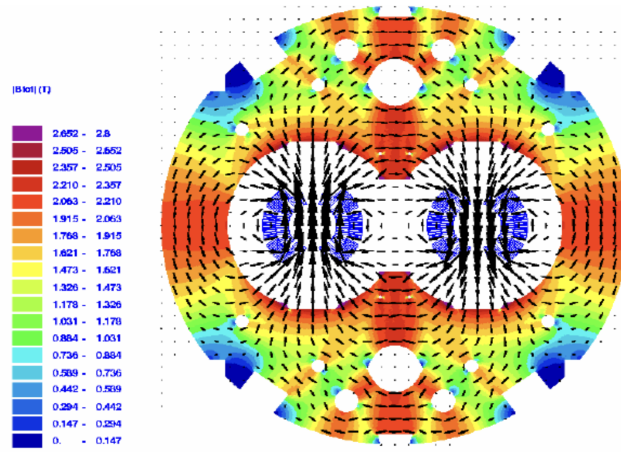


Figure 3.2: The distribution of dipole magnetic flux across a cross-sectional area of the LHC ring [43].

Luminosity as mentioned previously is a critical variable determining the statistics of data collected in this analysis and many other analyses. There are two types of luminosity: instantaneous luminosity and integrated luminosity. The first type quantifies the rate of proton-proton interactions per unit time per unit area, while the second type quantifies the total number of interactions over a period of time per unit area. Therefore, instantaneous luminosity depends on the number of protons in the two beams, their overlapped cross-sections, the frequency of the bunch crossing, and the number of bunches in each beam.

In particular, the LHC is designed to deliver instantaneous luminosities up to $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ or 0.02 pb^{-1} per second, where 1 barn is 10^{-24} cm^2 . The integrated luminosity which depends on periods of data collected by the CMS experiment (right) and the ATLAS experiment (left) delivered by the LHC is shown in Figure 3.3.

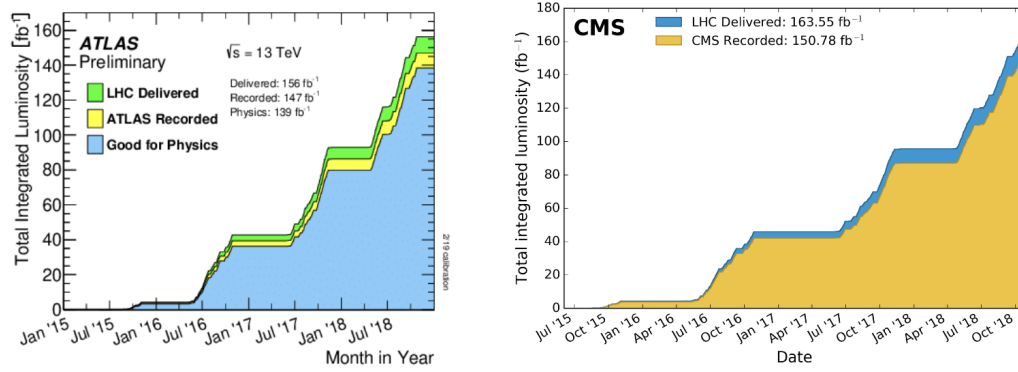


Figure 3.3: Comparison of integrated luminosities at the CMS experiment [28] (right) and the ATLAS experiment [52] (left). The luminosities are compared over the data-taking periods between January 2015 to October 2018 as delivered by the LHC and as recorded by each experiment.

3.2 The Compact Muon Solenoid

The Compact Muon Solenoid or “CMS” for short is one of the four main physics experiments at the LHC. It is a general-purpose detector designed to measure the properties of particles produced in the proton-proton collisions at the LHC. The CMS mission as a world-renowned particle physics laboratory is not limited to the search for the Higgs boson particle, that was discovered in 2012, but also extends to the search for new physics beyond the Standard Model, as in this

search, and to perform the precision measurement of the properties of the SM particles. While CMS as a collaboration is an international effort with more than 4000 scientists from 200 institutions in 40 countries taking on the same mission, CMS as a detector though is a complex apparatus. It has a cylindrical shape and a length of 21.6 m, a diameter of 15 m, and a weight of 14000 tons. The CMS detector located at Cessy, France opposite to the ATLAS detector at Meyrin, Switzerland, shown in Figure 3.4, has a compact design compared to the ATLAS detector, and is composed of several subdetectors and subsystems. The layers of the cylindrical subdetectors from the outermost to the innermost are the muon system (Sec. 3.2.2), the solenoid magnet (Sec. 3.2.3), the hadronic calorimeter (Sec. 3.2.4), the electromagnetic calorimeter (Sec. 3.2.5), the tracker (Sec. 3.2.6- 3.2.7), and the LHC beam pipe. Figure 3.5 shows these subdetectors comprising the CMS detector in the r - (or x - y plane). More details of each subdetector are explained in the corresponding sections.

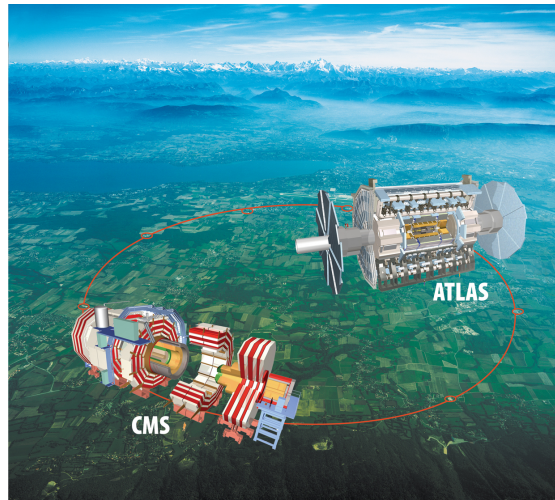


Figure 3.4: Overview of the two enlarged LHC experiments. The Compact Muon Solenoid (CMS) detector is compared with the ATLAS detector located on the opposite site of the LHC ring at CERN [77].

Two beams of protons delivered by the LHC as mentioned in Sec. 3.1 collide

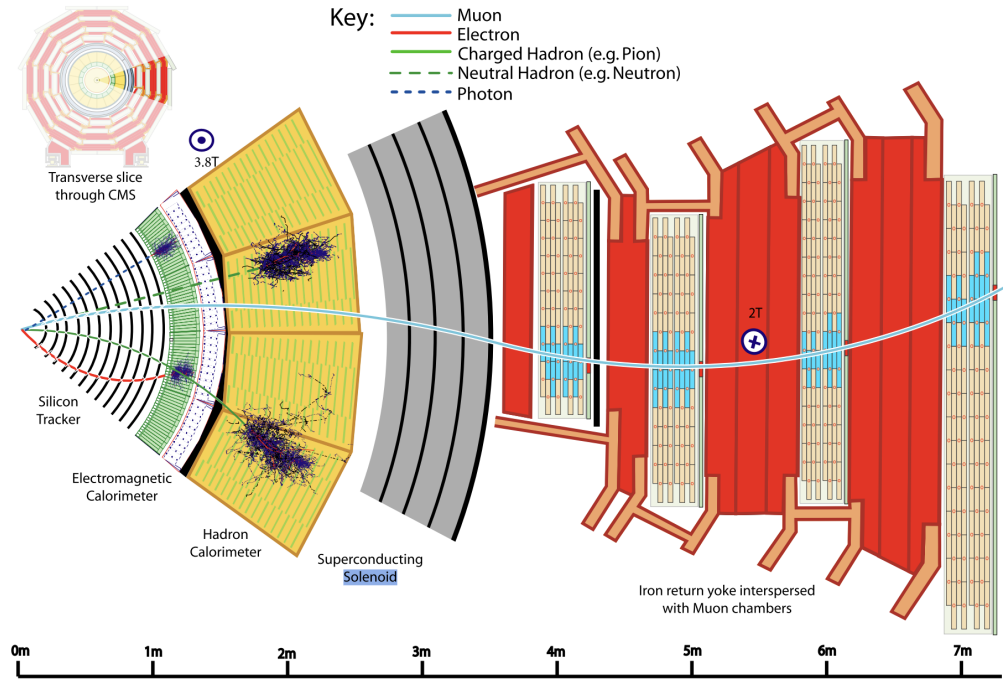


Figure 3.5: The layout of the Compact Muon Solenoid (CMS) detector in the r - ϕ plane. Subdetectors and subsystems from the innermost to the outermost are the tracker, the electromagnetic calorimeter, the hadronic calorimeter, the solenoid magnet, and the muon system. Particles with different types transverse the CMS detector uniquely.

at the interaction point, which is calibrated to be approximately at the center of the LHC beam pipe and at the center of the CMS detector. Once the collision takes place, particles produced are detected by specialized subdetectors with different technologies and designs. Shifting crews stationed at the CMS control room in Cessy, France or remote operating control (ROC) rooms monitor run conditions and operate technical components of the experiment in real-time. Meanwhile, online data streams of collision data called “events” are reconstructed for identifying physics objects and determining their properties such as energy, and momentum in order to form a trigger decision (Sec. 3.3). “Triggered

events” are stored for more demanding offline analysis by teams of physicists. The coordinate system for calculating particle trajectory and momentum measurement is explained in Sec. 3.2.1.

3.2.1 Coordinate system

The coordinate system of the CMS detector is a right-handed Cartesian coordinate with the origin at the nominal interaction point (IP) in the center of the detector. The x-axis points to the center of the LHC ring, the y-axis points upward, and the z-axis points along the beam pipe in the counter-clockwise direction. The azimuthal angle ϕ is measured in the x-y plane from the x-axis, and the polar angle θ is measured from the z-axis. However, in particle physics in which particles with the same fundamental properties such as mass and proper lifetime appear with different characteristics in the subdetectors because of Lorentz boost (), the pseudorapidity (η) is used instead of the polar angle (θ). In particular, the pseudorapidity is an approximate quantity for the rapidity (y) in the relativistic limit. They are defined as:

$$\eta = -\ln[\tan(\frac{\theta}{2})] \quad (3.1)$$

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (3.2)$$

The rapidity or approximately the pseudorapidity is a useful variable because it is invariant under Lorentz boost along the beam axis (i.e. z-axis). Consequently, the distance R between two relativistic particles in the η plane,

that is defined as $R = \sqrt{(\frac{E}{m_0 c^2})^2 + (\frac{p}{m_0 c})^2}$, is also a Lorentz invariant quantity.

3.2.2 Muon system

The muon system is shown in Figure 3.6. It has been designed to precisely measure muon momentum, and reconstruct muon trigger object. With the lifetime of muons of around $2.2 \mu s$, the muon system is the outermost subdetector. It can be divided into three main regions of η . The barrel region has $|\eta| < 0.9$, equipped with drift tubes (DT) and resistive plate chambers (RPC). The endcap region has $1.2 < |\eta| < 2.4$, equipped with cathode strip chambers (CSC) and resistive plate chambers (RPC). However, there exists the overlapped region with some components from both regions between $0.9 < |\eta| < 1.2$.

All subdetectors of the muon detection system, including Gas Electron Multiplier (GEM) commissioned in Run-3, are operated by gaseous tracking-based concepts. Owing to the location of these subdetectors covering in r and ϕ , their resolutions and acceptance efficiencies vary by subdetector specifications as listed below.

- **Drift tubes (DT):** located in the barrel region. They are made of rectangular aluminum tubes with a cross-section size of $4.2 \times 1.3 \text{ cm}^2$, and are filled with a gas mixture of 85% Ar and 15% CO_2 . The tubes are arranged in four layers, and are aligned in the r - ϕ plane. The muon passing through the tube ionizes with gas. Electrons are then drifted to the anode wire, made of charged-gold plate on a stainless steel, in the center of the tube. The drift time of the electrons is measured to determine the position of the muon. The DTs have a spatial resolution of 250-300 μm in the r - ϕ plane,

and 250 μm to 600 μm from low to high η .

- **Cathode strip chambers (CSC):** located in the endcap region. They are made of anode wires alternating with mostly-perpendicular cathode strips, and are filled with a gas mixture of 40% Ar, 50% CO_2 , and 10% CF_4 . The CSCs are arranged in four layers, and can provide a much faster read-out to accommodate a high particle flux in the endcap region. The CSCs have a spatial resolution of 75 μm for ME1/1 chambers and 150 μm for the others [69].
- **Resistive plate chambers (RPC):** located in both the barrel and the endcap regions. They are made of two parallel plastic plates filled with a gas mixture of 95.2% $\text{C}_2\text{H}_2\text{F}_4$, 4.5% iso- C_4H_{10} , and 0.3% SF_6 to induce an avalanche of electrons, that are then collected by the anode strips. Signals, though, are read out by induced charges on the highly-resistive cathode strips. The RPC main purpose is to complement the muon trigger system, and to measure timing information precisely with a time resolution of 1 ns. However, the cost from having a better timing resolution brings about a relatively poorer spatial resolution of 1.5 cm.
- **Gas Electron Multiplier (GEM):** located in the endcap region and are the newest addition to the muon system. They have similar structure and gas mixture to CSCs, but include microscopic holes in a larger bulk to amplify signals. These holes are applied high electric field to induce electron avalanches after muons are ionized.

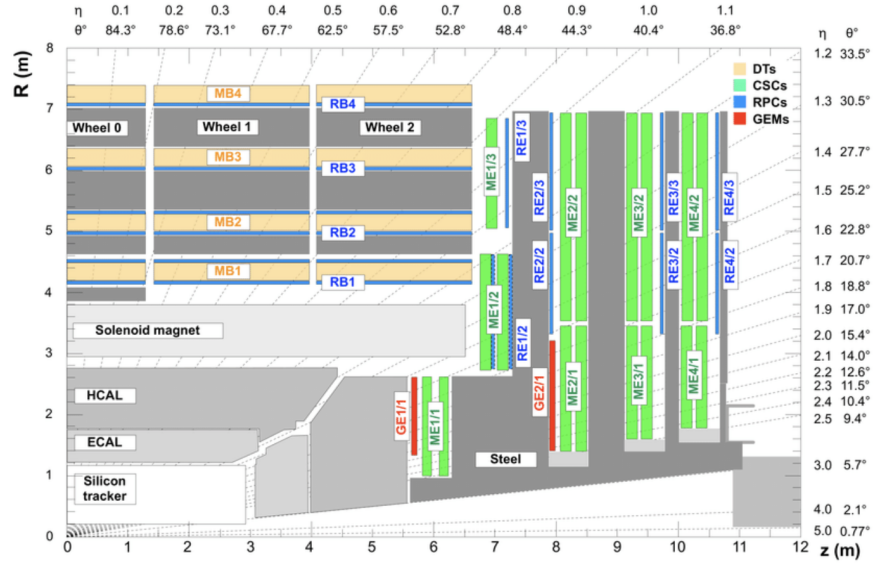


Figure 3.6: The layout of the muon system in the r - z quadrant of the CMS detector. The Muon Barrel (MB) with drifting tubes is shown in orange and the Muon Endcap (ME) with cathode strip chambers is shown in green. Resistive plate chambers are spread out in both regions. Gas Electron Multipliers are shown in red [57].

3.2.3 Solenoid Magnet

Without a magnet to bend charged particles by Lorentz force in the r plane, the crucial information to distinguish particles by their momenta and charges is lost. Powerful magnets at the LHC are major components for studying particle physics at collider experiments. Notably, the CMS experiment has its name from operating a *superconducting solenoid magnet*. The solenoid magnet is made of a cylindrical coil, that is 13 m long, 6 m in diameter, and weights 220 tons. The magnetic field is 3.8 T, and is produced by a current of 19.5 kA running under a superconducting condition by the liquid helium cooling system at the temperature of 4.5 Kelvin. At this condition, no energy is lost from the current, and the magnetic field is maintained for a long period of time. To accommodate

such a condition, the cylindrical coil is made of NbTi superconducting material. As a result, the magnetic field is strong enough to bend charged particles. Generally, it can bend charged particles, depending on their momentum and mass, by a few centimeters to a few meters from their trajectories. Figure 3.5 shows the layout of the solenoid magnet in the CMS detector located between the hadronic calorimeter (Sec. 3.2.4) and the muon system (Sec. 3.2.2).

3.2.4 Hadronic Calorimeter

The first calorimeter system to mention is designed to measure energy of hadrons from the process of hadronisation, so-called hadronic calorimeter or *HCAL*. There are four regions of HCAL, the barrel region (HB), the endcap region (HE), the outer region (HO), and the forward region (HF). HB has $1.3 < \eta < 1.5$, equipped with brass absorbers and plastic scintillators. HE has $1.5 < \eta < 3.0$, equipped with steel absorbers and plastic scintillators, similar to components of HO of $3.0 < \eta < 5.0$. On the other hand, HF with $3.0 < \eta < 5.2$ is equipped with quartz fibers and steel absorbers. Figure 3.7 shows the layout of HCAL sub-detectors in a quarter view of the CMS detector. These HCAL subdetectors are composed of two main materials, which are the absorber and the scintillator. The absorber is a material that induces the hadronic shower of hadrons, and the scintillator is a material that emits light from the production of charged particles passing through it. Scintillation light is then collected by photodetectors to convert signals into deposited energy. They are arranged in alternating layers as a *sampling calorimeter*. Although the HCAL coverage is up to 5.2 , this analysis relies on information of jets and leptons reconstructed by HCAL in the region of 3.0 . The resolution of HCAL is determined by the granularity

of the scintillator and the absorber, and is minimally affected by radiation damage from LHC. The HCAL resolution is approximately $110\%/\sqrt{E}$ [67], where E is the energy of the hadron. For example, the energy resolution of a 100 GeV hadron is $\sim 10\%$ of the true energy.

3.2.5 Electromagnetic Calorimeter

Next calorimeter system, located at a smaller radius than HCAL shown in Figure 3.5, is designed to measure energy of electrons and photons from the process of electromagnetic showering. It is called electromagnetic calorimeter or *ECAL*. Figure 3.7 demonstrates that ECAL is composed of two main regions, the barrel region (EB) and the endcap region (EE). The EB has the coverage of $1.479 < \eta < 1.79$, while the EE coverage is $1.479 < \eta < 3.0$. Both ECAL subdetectors are equipped with lead tungstate (PbWO_4) crystals, which are sensitive to scintillation light produced by the electromagnetic showering. The scintillation light is collected by photodetectors such as photodiodes. ECAL is a *homogeneous calorimeter*, where entire energy of particles is converted into electrical signals by the process of ionization. Crystals composing ECAL also determine its resolution that depends on temperature, and is minimally affected by radiation damage from LHC. In order to maintain a desired ECAL resolution, they operate at a temperature of 18 ± 0.05 C, and must be kept within 0.1 C of its peak temperature for optimal performances. The resolution of ECAL is approximately $2.8\%/\sqrt{E}$ [67], where E is the energy of the electron or photon. As an example, the energy resolution of a 100 GeV electron is $\sim 3\%$ with respect to the true energy.

m^2 . By having fine-grained pixels, its main purpose is to measure a track trajectory of a charged particle up to ± 2.5 correctly, and to reconstruct the primary and secondary vertices from tracks. Charged particles that traverse through the silicon pixel interact with doped silicon layers and transfer enough energy to free their electrons. These electrons can then be collected by applied high voltage (HV) bias to provide signals in the sensor, that is controlled by readout chips (ROCs). It is worth mentioning here that collision events both in data and simulation may have a byproduct such as quarks. If they travel beyond the tracker with high p_T , the reconstruction becomes challenging because no tracks are associated with them. As a result, these quarks are less likely to have associated jets (more discussion in 5.8.1).

The pixel detector is composed of two separated components, namely FPIX for forward pixel detector and BPIX for barrel pixel detector shown in Figure 3.8. The FPIX is located in the endcap region of $1.4 < |\eta| < 2.5$ with three layers of pixel detectors. On the other hand, the BPIX is located in the barrel region of $|\eta| < 1.4$ with four layers of pixel detectors. These pixel layer configurations are based on the data-taking period between 2017 to 2018, and are upgraded during the Winter Shutdown of 2016-2017 to improve the tracking efficiency and resolution (i.e. from the phase-0 pixel detector to the phase-1 pixel detector). In 2016, with the phase-0 pixel detector, the number of layers in each region are less than the phase-1 pixel detector in 2017-2018 by one. In addition to the number of layers, the radius of these layers were also different between the two phases.

To transmit data faster for accommodating for higher instantaneous luminosity for the HL-LHC era (Sec. 6.2), each pixel module on each layer is also installed with upgraded ROCs that are capable of transmitting digitized data

at 160 Mb/s via an analog-to-digital converter (ADC) in the chip from analog signals. The ROC system is connected to the front-end electronics installed on the detector volume to monitor and send online data to the trigger and data acquisition systems (Sec. 3.3).

In total, there are 1856 silicon sensor modules in the phase-1 detector. ROCs on each module are bump-bonded to its surface, and housed a total of 4160 individual silicon pixels, with a standard area of $100\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$, arranged into a 52 by 80 grid. This upgrade results in a better resolution of the pixel detector, which is approximately $12\text{ }\mu\text{m}$ in the r - plane and $24\text{ }\mu\text{m}$ in the z -coordinate [72]. In contrast, the resolution of the pixel detector in the r - plane and the z -coordinate was $18\text{ }\mu\text{m}$ and $35\text{ }\mu\text{m}$, respectively, in the phase-0 pixel detector at the beginning of Run-I [22]. Thanks to finer granularity of the pixels, overall track impact parameter resolution has improved by at least 25% [62] from the upgrade.

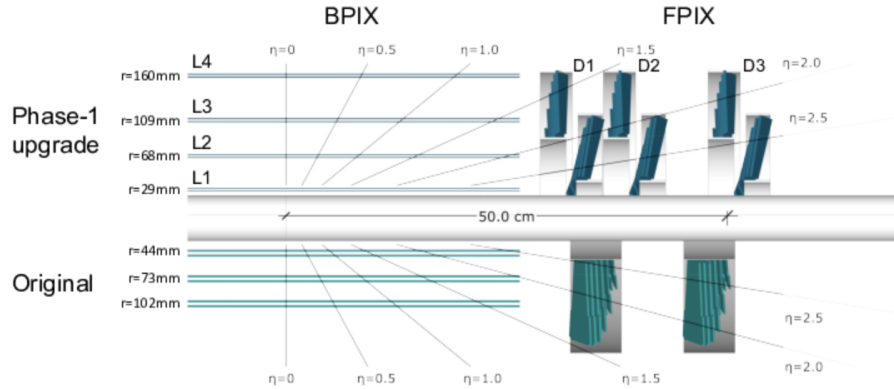


Figure 3.8: Comparison of the phase-1 pixel upgrade (top-half) and the phase-0 pixel (bottom-half). The phase-1 pixel has more layers than the phase-0 pixel. Each layer of the BPIX is placed at a larger radius than before. The BPIX and FPIX subcomponents are shown in the barrel and endcap, respectively [72].

3.2.7 Silicon Strip Tracker

The next tracker located at the outer radius surrounding the inner pixel detector as shown in Figure 3.5 is called *the outer tracker* or *the strip tracker*. The strip tracker is where the trajectory of a charged particle is extrapolated by hits measured in each strip module layer by layer to derive tracking parameters. The layout of strip trackers are illustrated in Figure 3.9 based on Run-2 (left) and for the future HL-LHC (right). In Run-2, the strip tracker is divided into four main subcomponents, which are the Tracker Inner Barrel (TIB), the Tracker Inner Disks (TID), the Tracker Outer Barrel (TOB), and the Tracker Endcap (TEC). The TIB, TID, and TOB are located in the barrel region, while TEC are located in the endcap region. The strip modules can vary by types with three main elements, which are one or two silicon sensors, mechanical support, and read-out electronics. The separation between two silicon sensors is called *pitch* ranging between 80-205 μm , and determining hit resolution. Strip modules operate with the same principle as pixel modules by detecting charged particles. However, signals from strip modules can be amplified by Analogue Pipeline Voltage (APV25) chips operating at a constant frequency of 40 MHz for correcting bunch crossing identification and for reducing noise. However, the APV25 chips were malfunctioning in the late 2015 and early 2016, resulting in the two separated data samples in 2016 which are 2016 preVFP (or 2016APV) and 2016 postVFP (or 2016) samples, to be referred to in Sec. 5.1. The issue observed by a reduction of signal-to-noise was caused by a slow discharge of the amplifier because of the saturation of analog-to-digital converters. [26].

The coverage of the strip tracker is up to ± 2.5 similar to the pixel tracker, but it extends to the radii up to 116 cm and the z-coordinate up to 280 cm. In

terms of hit position resolutions, the strip tracker has a resolution of 13–38 μm in the r -plane of TIB, and of 18–47 μm in the r -plane of TOB and TEC [16]. In addition to the hit resolution, the overall hit efficiency of the strip tracker is above 99% across detector regions in Run-2 [74]. Nevertheless, there has been an undergoing effort for the phase-2 upgrade of the strip tracker to be commissioned for the HL-LHC in order to improve the tracking resolution and efficiency (Sec. 6.2).

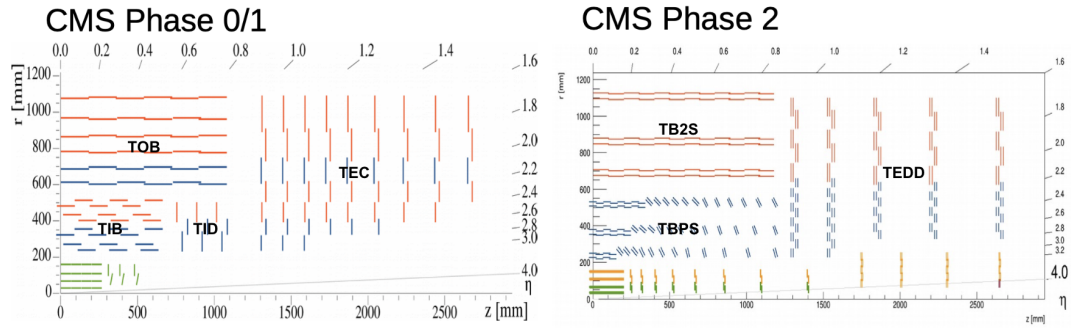


Figure 3.9: Comparison of the phase-0/phase-1 tracker (left) and the phase-2 tracker (right) for HL-LHC. The phase-0/phase-1 tracker has four main subcomponents which are TIB, TID, TOB, and TEC while the phase-2 tracker has three main subcomponents which are TB2S, TBPS, and TEDD. The inner pixel trackers are shown in green/orange and the outer strip trackers are shown in blue/red [11].

3.3 CMS Trigger and Data Acquisition

The LHC produces proton-proton collisions at a rate of 40 MHz. However, the CMS detector can only record data at a rate of 1 kHz due to the limitation of the data storage and processing. In fact, the amount of data delivered by the

LHC to the CMS experiment are mostly soft collisions of hadrons, which are not kinds of events that most physics analyses, including this search, are interested. Hence, to reduce the data rate and only record interesting physics events, the decision-making system called the *trigger* is operated in two tiers. The first tier is the *Level-1 trigger* (L1), and the second tier is the *High-Level Trigger* (HLT). The L1 trigger is a hardware-based system that reduces the data rate from 40 MHz to 100 kHz by reconstructing low-resolution objects from subdetector signals and selecting events based on that information within $3.8 \mu\text{s}$. The L1 trigger system is mainly implemented on Field Programmable Gate Arrays (FPGAs), as well as other programmable memory lookup tables for running real-time algorithms. The schematic L1 trigger is shown in Figure 3.10. As shown, there are only two main subdetectors that involve in the L1 trigger, namely the calorimeter and the muon systems. In the future, the L1 trigger system will be upgraded to the Phase-2 trigger system for the HL-LHC and the tracker will be included in the L1 trigger system, to be discussed in Sec. 6.2.1.

In Figure 3.10, the calorimeter and the muon subdetectors send information such as bunch-crossing identifications (BCIDs), E_T , and track parameters to the *Regional Calorimeter Trigger*, the *Regional Muon Triggers* as well as the *Trigger Primitives* (TPs). The regional triggers are used to form physics objects such as electrons, photons, coarse track parameters, and missing transverse momentum to their corresponding global triggers, which are the *Global Muon Trigger* (GMT) and the *Global Calorimeter Trigger* (GCT). The GCT is responsible for sorting the electrons and photons, and constructing jets in order to calculate missing transverse energy. On the other hand, the GMT removes duplication from muon subdetectors and calculates global quantities for muons such as muon identification and momentum. While the GMT and the GCT pass the information to

the Global Trigger, which makes the final decision to accept or reject the event for HLT decisions, events are continuously and circularly buffered in millions of readout channels from subdetectors to the *data acquisition system* (DAQ). Events that are rejected by the Global Trigger are overwritten by the next event, and its information is impossible to be recovered [35]. By following this protocol and control from the *Trigger Control System* (TCS), the DAQ systems safeguard the trigger rate within the 100kHz threshold.

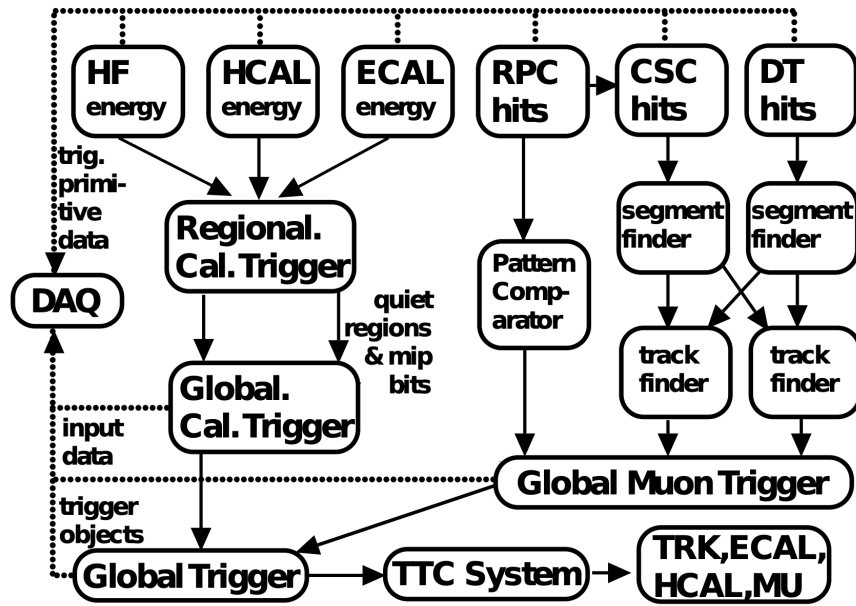


Figure 3.10: L1 trigger system composed of the lower-level calorimeter and muon triggers in combination with the DAQ system for trigger rate control [53].

After the Level-1 (L1) triggers process the data, the raw data is structured into events containing physics objects through *event reconstruction* and event information through *bunch-crossing identification (BCID)*. This structuring facilitates further processing and decision-making in subsequent steps. These events are then passed on to the second trigger tier, which composes of the *HLT* systems. There are many more HLT trigger paths than the two L1 trigger paths

because the HLT triggers are software-based algorithms. They are more sophisticated and time-consuming. Nevertheless, the HLT systems filter the data streams from 100 kHz down to only 1 kHz within the decision time of $O(100)$ ms. The HLT triggers that this analysis are dependent on are discussed in Sec. 5.2.1.

CHAPTER 4

EVENT RECONSTRUCTION

The CMS experiment at the LHC as described in the previous chapter studies fundamental particles that are produced from events of proton-proton collisions. These particles are not seen by bare eyes, but are reconstructed from their interactions with the detector. In particular, particles attributed by charges, spins, proper lifetimes, masses and decay modes are uniquely identified, and are reconstructed differently as physics objects. In reverse, in order to correctly deduce physics objects as fundamental particles, information from all subdetectors is combined, and the reconstruction is done by the *particle flow algorithm* (Sec. 4.3). The reconstruction of physics objects is performed both in real-time for online reconstruction and on tapes or disks for offline reconstruction. While online physics objects are crucial for increasing *trigger* efficiency (Sec. 5.2.1), physics objects such as displaced vertices in this search are reconstructed by a specialized algorithm (Sec. 5.3.3). They can be optimized with unlimited offline resources to enhance signal sensitivity.

4.1 Detectors of Elementary Particles

Generally, there are two types of particle detectors. The first kind is a tracker (Sec. 3.2.6 and Sec. 3.2.7). The tracker is a subdetector that is sensitive to *charged particles*, and is used to measure momentum of particles from their trajectories in a magnetic field. Along a track trajectory, energy is deposited from a charged particle losing energy to the tracker material such as silicon. The second kind is a calorimeter (Sec. 3.2.5 and Sec. 3.2.4). The calorimeter is a subdetector that is sensitive to both *charged particles* and *neutral particles*. Its objective is to convert

entire energy of particles into electrical signals by the process of ionization, and to measure the energy of these particles. For muons, unlike other fundamental particles, they can penetrate through the tracker and the calorimeter with minimum ionization. Muons are detected by the muon system (Sec. 3.2.2).

4.1.1 Charged particles

Particles with positive or negative charges are bent under an influence of a magnetic field. The curvature of a charged particle is inversely proportional to its momentum, and is measured by the tracker. In the CMS detector, charged particles that miss the chance to interact with the tracker may interact with one of the two calorimeters, and deposit entire energy in such a calorimeter. Since material compositions of the tracker and the two calorimeters are different, the energy loss of a charged particle in the tracker is different from the energy loss in the calorimeter per length. The tracker at the CMS experiment is made of silicon, with a low atomic number, while the calorimeters are made of lead tungstate, with a high atomic number as described in Sec. 3.2.5 and Sec. 3.2.4. As a charged particle passages through the detectors, it not only loses energy by ionizing an electron from each atom in the material, but its flight direction is also deflected by a momentum transfer to nearby electrons. Collectively, this effect results in *multiple scattering* or *Coulomb scattering*. The atomic number (Z) of detector materials is a key factor determining the amount of multiple scattering. Particularly, the magnitude of multiple scattering is proportional to Z^2 . Therefore, charged particles lose energy in the calorimeters more than in the tracker, and the tracker generally has a better energy resolution than the calorimeters.

In fact, energy loss also contributes to a track resolution. To determine the resolution of a charged particle track, the distribution of scattering angles due to the Coulomb scattering is approximately Gaussian. The width of the distribution for quantifying a track resolution is proportional to the square root of the thickness of the material, and inversely proportional to the momentum of the particle. Specifically, the projected 2D-angular distribution is shown below [82]

$$\sigma_\theta = \frac{13.6 \text{ MeV}}{cp} z \sqrt{\frac{x}{X_0}} [1 + 0.038 \ln(\frac{xz^2}{X_0^2})] \quad (4.1)$$

where p , c and z are the momentum, the velocity, and the charge of the particle, respectively. x/X_0 is the thickness of the scattering path in the material.

Furthermore, an important quantity for determining energy loss of a charged particle is the *critical energy* E_c . It is a minimum energy in which a charged particle can emit a photon by the *bremsstrahlung* process, instead of being ionized by the material. For instance, the critical energy of an electron is 40 MeV in silicon and is 7.5 MeV in lead [42]. This effect only impacts highly-relativistic charged particles. The energy loss in the bremsstrahlung process slows down charged particles by emitting a photon, that can be detected by the ECAL calorimeter. Since this effect happens infrequently, it is quantified by the average energy loss per unit length, called the *radiation length* X_0 , which is similarly dependent on the atomic number. In addition, a relativistic particle such as an electron that produces *bremsstrahlung* radiation can also trigger the *pair production* of an electron and a positron induced by the emitted photon. These two processes in an iterative combination are called the *electromagnetic shower*, as mentioned in Sec. 3.2.5.

4.1.2 Neutral particles

Complementing to charged particles is neutral particles. Neutral particles are not deflected by a magnetic field, and are not detected by the tracker. They only interact with the calorimeters. As we have discussed in Sec. 3.2, there are two types of the calorimeters at the CMS experiment, the electromagnetic calorimeter and the hadronic calorimeter. Although photons are electrically neutral, they are force carriers of electromagnetic interactions (Sec. 2.1.4). Hence, they deposit energy in the electromagnetic calorimeter by the mean of electromagnetic processes. Its radiation length is characterized by the same definition as for electrons as discussed in Sec. 4.1.1. Nevertheless, the critical energy of photons is the cross-over for low-energy photons to experience *photoelectric effect* and high-energy photons to experience *pair production*. In fact, their critical energy for the pair-production process must be at least twice the rest mass energy of an electron, which is approximately 1.02 MeV to create an electron-positron pair.

Other neutral particles are neutral hadrons. They vary by masses, proper lifetimes, and decay products. For instance, the detection of a short-lived kaon (K_S) is from its decay product to either a pair of charged pions with opposite signs or a pair of neutral pions. It is worth noting that the former decay can appear in the tracker as a displaced vertex.

Generally, hadronic products from a particle decay such as this can interact with atomic nuclei via strong interaction (Sec. 2.1.3), leading to a scattering of hadrons, regardless of charges. This hadronic scattering is quantified by the *nuclear interaction length* λ_I , which is the mean free path of a hadron in the material. It may travel for an order of λ_I before colliding inelastically with a nuclei and producing secondary hadrons. The process from a hadronic decay prod-

uct causing secondary hadronic products and so on is called *hadronic shower*. It is much more complicated to sample than *electromagnetic shower*. Similarly, for the decay process via a weak interaction that can extend over a longer distance, hadronic shower is the primary source of energy deposition in the hadronic calorimeter. Hence, the design of hadronic calorimeters needs to consider a large volume of material to sample hadronic showers, and to segment it for minimizing an error from sampling.

4.2 Primary vertices and beam spot

The primary vertex is the point where a proton-proton collision occurs either elastically or inelastically. With multiple bunches of protons colliding in the same crossing, the number of primary vertices is roughly 32 in Run-2. Each primary vertex is reconstructed by prompt tracks that intersect at a point of closest approach along the beamline. The primary vertex that has the highest sum of transverse momenta from tracks is used as a reference point for the event reconstruction. Other vertices, known as *pileup*, are considered as contamination and can affect the accuracy of physics object reconstruction in an event. For example, the search for long-live particles (LLPs) is looking for a signature of a displaced vertex which is a secondary vertex corresponding to the decay of an LLP, and is separated from the primary vertex that produces the LLP macroscopically. Pileup tracks can be misidentified as actual tracks in the secondary vertex, and can become a source of background in the search. The procedure of reconstructing secondary vertices in this search will be discussed in detail in Sec. 5.3.3.

Another reference point used in the displaced-vertex search is the beamspot. Unlike primary vertices, it is not a vertex from a particle decay. It is an average point where the proton beams collide, and is used as a reference point for the alignment of the detector. Some characteristics of a beamspot such as its width and position are corresponding to the quality of each luminosity section collected from the LHC data every 23 seconds. In particular, the beamspot position is measured from the distribution of impact parameters of all prompt tracks in the same luminosity section, while the beamspot width is determined by the distribution of primary vertices. The size of a beamspot, which is 100 μm in the transverse plane, indeed motivates one of the selection cuts (Sec. 5.3.4) applied to reconstructed displaced vertices. This helps in improving the accuracy of vertex reconstruction by reducing the impact of pileup and other background.

4.3 Particle flow algorithm

Different particles have different signatures in the detector, and are reconstructed differently as described in Sec. 4.1. By combining information from all subdetectors, the *particle flow algorithm* or *PF algorithm* is the CMS tool to identify particles being produced along with their decay products, either with or without missing energy from a collision. The PF algorithm relies on a strong magnetic field, a high granularity of the tracker, a coarse granularity of the calorimeters, and a high resolution of the muon system to distinguish particles with similar decays or interactions. It performs in two steps. First, it reconstructs tracks of charged particles from the tracker, and energy clusters of photons and neutral hadrons from the calorimeters. Second, it connects tracks with energy clusters to form physics objects such as electrons, muons, photons, and jets, depending

on their detection characteristics.

To be specific, first hits in the tracker are combined iteratively to reconstruct tracks (or charged particles) in the collision. The initial iteration optimizes the purity of tracks that are *prompt* or emanating from primary vertices. The subsequent iterations optimize the purity of *displaced* tracks associated with secondary vertices. For each iteration, the track reconstruction starts from finding initial seeds or hits in the inner track layers and is built radially outward. The track projection step finds compatible hits to the initial seeds with a beamspot constraint and estimate the track trajectory using five tracking parameters. These tracking parameters are the transverse impact parameter (dx_{y0}), the transverse momentum (p_T), the azimuthal angle (ϕ), the longitudinal impact parameter (dz_0), and the pseudorapidity (η). They are used as inputs to the *Kalman* filter for track fitting. Additional smoothing and filtering to remove outlier hits may be applied to improve the track quality. The next iteration with looser criteria for tracking is performed to find tracks that are missed in the previous iteration, and to remove duplicated tracks.

After completing all steps iteratively, the CMS results [67] shows that the misreconstructed track rate is minimized at a few percent while the reconstruction efficiency of charged particles with $p_T > 1$ GeV is above 90%. For charged hadrons that are energetic and not reconstructed by the tracker, they are reconstructed by the hadronic calorimeter, but can be misidentified as photons or neutral hadrons. As a result, the tracking efficiency declines beyond p_T of 10 GeV, as shown in Figure 4.1.

The last few iterative steps, in spite of having lower fractions of remaining hits, can be substantial for muon reconstruction. To reconstruct muons, there

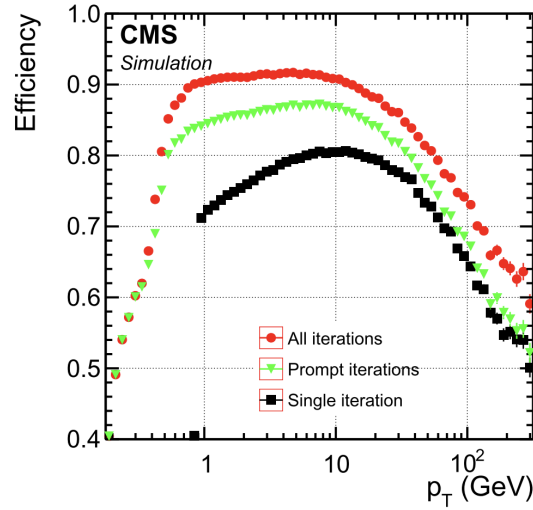


Figure 4.1: The tracking efficiency of charged hadrons as a function of the transverse momentum (p_T) in region with $\sqrt{s} = 2.5$. Efficiency from the global combinatorial tracking (black), and from the iterative tracking of prompt tracks (green) and of all tracks (red) [67].

are three types of muon candidates. They are *global muons*, *tracker muons*, and *standalone muons*. Global muons are reconstructed by the tracker with at least one track segment matching in the muon system, attributing to muon candidates with high momentum precision. Tracker muons are reconstructed by the tracker only to measure muons with low momentum. On the other hand, standalone muons are reconstructed by the muon system only to measure muons with high momentum. With this strategy, the reconstruction efficiency of muons by the PF algorithm is about 99% [67].

Another Particle Flow (PF) element is an energy cluster in calorimeters. Its algorithm starts from defining *cluster seeds*, which are neighboring cells with energy deposits above a certain energy threshold. Any cells that are adjacent to the cluster seeds with at least a shared corner and have energy per cell above twice the noise level are added to the cluster. This is an iterative process for re-

constructing *topological clusters*, that is postulated by the *Gaussian-mixture model*. This model has a fixed width of the Gaussian function, but other parameters are optimized by the *Expectation-Maximization* algorithm [67] for precise position and total energy of a topological cluster. Specifically, each calorimeter subdetector, including two more preshower layers, has different parameters for the number of neighboring cells, energy threshold, and the Gaussian width to form energy clusters in the process. The only exception is HF that forms an energy cluster directly from each hadronic or electromagnetic calorimetric cell without further clustering.

With primitive physics objects; tracks and energy clusters, the PF algorithm links them to form a sequence of physics objects, which are electrons, isolated photons, non-isolated photons, and hadrons, respectively. Since electrons can radiate photons via *bremsstrahlung* radiation, and photons can convert to electron-positron pairs, their PF algorithm is done together to resolve the complexity of the reconstruction in ECAL. Consequently, ECAL clusters in the same region of η are combined into superclusters (SCs). Tracks that are linked to ECAL SCs with low χ^2 imply low probability of photon conversion, and are identified as electrons. The remaining ECAL SCs are ECAL-based electrons or photons. These ECAL-based electrons have their tracks refitted with a Gaussian sum filter (GSF) to improve the resolution of the electron momentum before feeding track and cluster information to a *multivariate analysis* algorithm to classify them as electrons or not. The rest of ECAL SCs are considered as isolated photons if they are energetic and not linked to any tracks, or non-isolated photons if their ECAL clusters are consistent with HCAL clusters.

At this point, the remaining physics objects are non-isolated photons,

charged and neutral hadrons. Similar to identifying isolated photons as explained, HCAL clusters that are not matched to tracks are considered neutral hadrons. On the other hands, if they are matched to ECAL clusters and linked to tracks, they are classified as charged hadrons.

4.4 Jets

The manifestation of quarks and gluons is in the form of jets. As protons made up of quarks bound by gluons are collided at the LHC, the primary physics objects being produced are jets. The timescale to form jets is larger than the scattering time between quarks, and leads to a collimated spray of hadrons. In order to capture messy information of hadronic showers, all hadrons and photons are clustered by the *jet algorithm*. In fact, 65% of the energy in a jet is carried by charged hadrons, 25% of the energy is carried by photons, and the rest is carried by neutral hadrons [67]. As we have discussed in Sec. 4.3, the PF algorithm is designed to optimize hadron reconstruction, including jets. Therefore, the PF algorithm also contributes to the source of uncertainty in jet reconstruction such as the energy scale and resolution, and the jet identification efficiency.

For this analysis of displaced vertices with jet final states, there are two main types of jets. The first kind is *PF jets*, which are a collection of PF elements from all sub-detectors clustered by the *anti- k_T* algorithm with a cone size of 0.4 around the jet axis [12]. The second kind is *calo jets*, which are reconstructed using energy deposits in the calorimeter cells, supplementing the information from PF jets. Although calojets are simpler to reconstruct, they are not intended

to identify particles.

The number of jets is proportional to the number of proton collisions. As mentioned previously, the leading primary vertex suffers from a *pileup* effect. The more protons are collided, the more challenging pile-up mitigation will be. In particular, jets from different proton collisions start to overlap. Charged particles or tracks from other proton collisions can be misidentified as tracks emanating from the primary vertex, or misreconstructed tracks contributing to other jets. The standard procedure of PF jets to reduce the pileup effect and detector noise is done by *jet energy corrections* (JEC). For instance, PF jets are matched to particle-level jets and applied a correction on jet's p_T as a function of jet's p_T . Additionally, the Standard Model processes with a pair of jets (or dijet) are corrected for *jet response* in simulation, based on jet response in data. After all corrections are applied, the jet energy resolution is reported at 15–20% for 30-GeV PF jets, 10–15% for 100-GeV PF jets and 5–10% for 1-TeV PF jets [67]. For jet reconstruction in which jets are produced along with other physics objects such as leptons, more criteria to isolate jets from other physics objects are applied. The criteria may include the R between jets and leptons, or between jets and other jets.

4.5 Heavy flavor tagging

In addition to the reconstruction of jets, identifying the quarks from which these jets originate is crucial for many physics analyses, including the search for displaced vertices. Among various hadronic decays, the decay of b-hadrons and c-hadrons are the primary sources of jets with displaced vertices. Specifically,

b-quarks and c-quarks, despite having different masses, decay in an order of 10^{-12} seconds in their rest frames. The timescale is large enough for their decays to be displaced from the primary vertex. Thus, b-jets and c-jets tend to have distinctive features such as displaced tracks, secondary vertices, and soft leptons, which are not expected in jets from light quarks or gluons. Because of these features, the heavy-flavour tagging algorithm is developed, exclusively for b-jet identification and c-jet identification, to enhance signal sensitivity in a number of searches with the final state of heavy-flavour jets or displaced vertices.

In recent years, heavy-flavor taggers have utilized machine learning tools. Discriminating variables, including properties of secondary vertices in jets, are fed into neural networks to classify jets as b-jets, c-jets, or light jets. B-jet identification algorithms have evolved from using only track information (JP/JBP taggers) to combining track and secondary vertex information (CSV taggers). B-tagging efficiency ranges from 50% to 70% with a 1% misidentification rate for light jets at a medium working point. On the other hands, c-jet identification algorithms also exist but require additional training due to lower c-jet tagging scores, attributed to the shorter lifetime and lower masses of c-hadrons compared to b-hadrons. The c-tagging efficiency without further training is reported at 12% [68].

Common discriminating variables include the 3D impact parameter (IP) significance of the first four tracks and/or properties of secondary vertices (SVs). For the track variables, they are weighted higher in the JBP tagger or used as input for the CSV tagger. Variables associated with SVs reconstructed using the Adaptive Vertex Fitter (AVF) or Inclusive Vertex Finder (IVF) algorithms are exclusively used in CSV taggers. These vertex variables include the number of

tracks, invariant mass of tracks, and 2D flight distance to the primary vertex.

For this analysis, the CSV tagger is used in most datasets, except in 2018 that the DeepCSV tagger is used. It is an advanced version of the CSV tagger, that has been developed to improve b-tagging efficiency while maintaining the same misidentification rate. B-jet taggers at medium and loose working points are used in online and offline b-jet selection of this displace-vertex search.

4.6 Missing Transverse Momentum

Apart from all reconstructed physics objects, that interact with the detector, there are particles that do not interact with the detector. They are missing pieces from the vectorial sum of all transverse momentum in an event, which is expected to be zero. Neutrinos are the Standard Model particles that are not detected by the CMS detector, and can contribute to missing transverse momentum (*MET*) in the event reconstruction. More interestingly, missing transverse momentum can be a signature of new physics beyond the Standard Model, such as dark matter particles that do not interact with the detector as well. *MET* is calculated by the negative vectorial sum of the transverse momentum of all reconstructed physics objects as $p_T^{\text{miss}} = -\sum p_{T,i}$. However, jets that contribute to the sum can be corrected as described in Sec. 4.4. Consequently, such *MET* is implicitly applied essential corrections, and is used in this analysis.

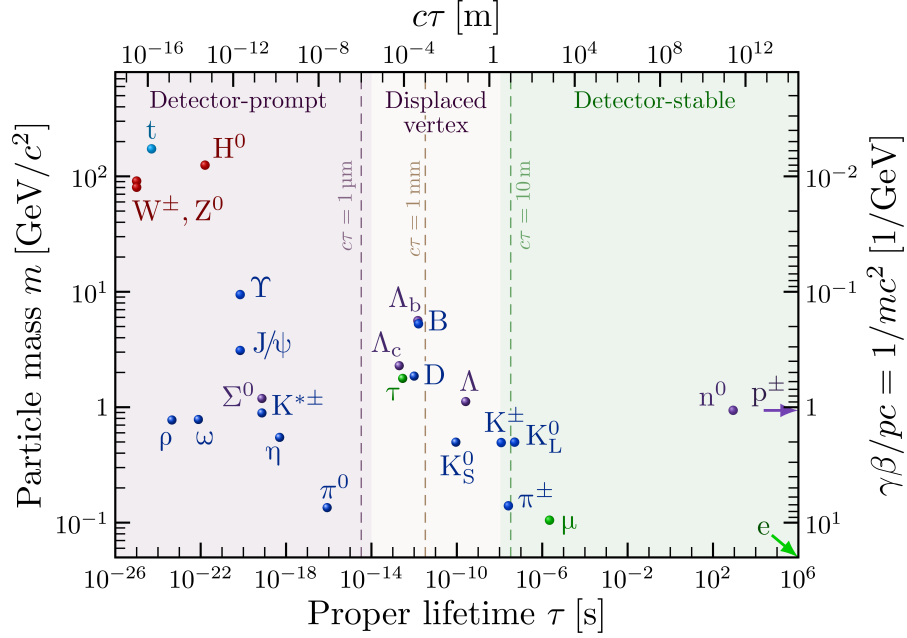


Figure 4.2: The mass and lifetime of representative particles in the Standard Model. The mass variables are shown on the vertical axes and the lifetime variables are shown on the horizontal axes. The particles are divided into three categories: detector-prompt, displaced-vertex, and detector-stable [58].

4.7 Experimental Signatures of Long-lived Particles

Long-lived particles (LLPs) that are produced from the primary vertex and travel for some distances before decaying form the experimental signature of *displaced vertices*. In detecting a displaced vertex, the vertex is reconstructed from tracks of charged particles decaying from an LLP. These tracks are required to separate from the primary vertex significantly. Essentially, this separation is determined by the resolution of the tracking system, as well as the *decay length* (L) of the LLP. This variable is related to its proper lifetime τ , *Lorentz factor* γ and normalized velocity β (or v/c), as shown in the equation

$$L = \gamma c \quad (4.2)$$

where c is the speed of light. *Lorentz boost factor* (or γ) is composed of β , a normalized velocity of the particle, and γ , a Lorentz factor defined as $\gamma = \frac{1}{1 - \beta^2}$.

Since *tracks* are charged particles, they are bent by a magnetic field. The curvature of a track is inversely proportional to the transverse momentum of the particle. Additionally, the closest approach of a track with respect to a primary vertex determines its *impact parameter*. However, a track's *impact parameter uncertainty* is correlated to tracking system properties, including multiple scattering of a particle in the detector material, and the number of *hits* in the tracker. Whether the quality of a track is predetermined by a charged particle's properties or constrained by materials in the tracker, both are crucial for the success of the displaced-vertex reconstruction.

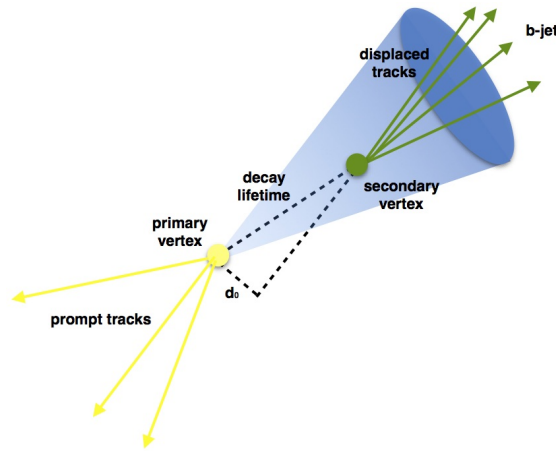


Figure 4.3: Prompt tracks are emanated from the primary vertex while displaced tracks are emanated from a secondary vertex. The secondary vertex is a displaced decay position of a long-lived particle such as b-hadrons, observable as b-jets [65].

In addition to the aforementioned variables of tracks, the properties of dis-

placed vertices are undoubtedly important for the discovery of LLPs. They include the number of tracks in a vertex, its invariant mass, and the significance of the vertex displacement. The last variable is a ratio of the separation between the reconstructed vertex and the primary vertex divided by its uncertainty, and is used to distinguish a real vertex from a *fake vertex*. Expectedly, a fake vertex is a random crossing of displaced tracks.

Moreover, physics concepts behind the decay length of an LLP predetermine the success of its vertex reconstruction. As mentioned in Sec. 2.2, the probability of a long-lived particle to decay is exponential, and depends on the lifetime of a particle in its rest frame. In a laboratory frame, however, the decay length depends on the Lorentz boost (γ) of a particle. For example, a particle with a lifetime of 10^{-12} seconds and a Lorentz boost of 100 has a mean decay length of 3 meters. This means that such a particle is likely to form a decay vertex beyond the tracker, which is not sensitive to this search. Therefore, the design of an LLP analysis needs to determine which subdetector can detect long-lived particles based on their physical properties and final states, and whether the search can be optimized within that detector volume.

CHAPTER 5

SEARCH FOR LONG-LIVED PARTICLES

5.1 Datasets and samples

5.1.1 Data samples

The search for displaced vertices is performed on the data collected by the CMS experiment at the LHC. The data-taking period is divided into three years: 2016, 2017, and 2018. Each year has different instantaneous luminosities and pileup conditions. Consequently, the total integrated luminosity is 35.9 fb^{-1} , 41.5 fb^{-1} , and 59.7 fb^{-1} , respectively. By combining data collected in all three years, the total luminosity is 137.1 fb^{-1} at a center-of-mass energy ($\sqrt{s}$) of 13 TeV in proton-proton (pp) collisions. Specifically, these datasets are part of the Run-2 campaign at the LHC. Our displaced-vertex search is divided exclusively to two sub-analyses, namely events selected by a logical OR combination of b-jet triggers or displaced-jet triggers, and of single-muon or single-electron triggers. Hence, data and simulated samples are specified by trigger selection.

As mentioned in Sec. 3.2.7, the 2016 samples are separated based on the issue with APV25 chips. The samples affected by this issue are denoted as "2016 APV" (or "2016 preVFP/ HIPM"). The samples resolved from this issue are denoted as "2016" (or "2016 postVFP/ non-HIPM"). The datasets of these periods, as well as from 2017 and 2018 data-taking periods, are listed below. They are categorized based on the triggers they pass:

- Single-muon and single-electron triggers: Table 5.1

- B-jet triggers: Table 5.2
- Displaced-jet triggers: Table 5.3

Note that the analysis uses the legacy samples for 2016, 2017, and 2018, corresponding to the global tag of `106X_dataRun2_v37`.

Table 5.1: SingleMuon and SingleElectron MiniAODv2 datasets used for 2016-2018.

Era	Dataset	Run range	Int. lumi. (fb ⁻¹)
2016B(APV)	/SingleMuon/Run2016B-ver2_HIPM_UL2016_MiniAODv2-v2	273150 275376	5.83
	/SingleElectron/Run2016B-ver2_HIPM_UL2016_MiniAODv2-v2		
2016C(APV)	/SingleMuon/Run2016C-HIPM_UL2016_MiniAODv2-v2	275656 276283	2.62
	/SingleElectron/Run2016C-HIPM_UL2016_MiniAODv2-v2		
2016D(APV)	/SingleMuon/Run2016D-HIPM_UL2016_MiniAODv2-v2	276315 276811	4.29
	/SingleElectron/Run2016D-HIPM_UL2016_MiniAODv2-v2		
2016E(APV)	/SingleMuon/Run2016E-HIPM_UL2016_MiniAODv2-v2	276831 277420	4.07
	/SingleElectron/Run2016E-HIPM_UL2016_MiniAODv2-v5		
2016F(APV)	/SingleMuon/Run2016F-HIPM_UL2016_MiniAODv2-v2	277932 278807	2.87
	/SingleElectron/Run2016F-HIPM_UL2016_MiniAODv2-v2		
2016F	/SingleMuon/Run2016F-UL2016_MiniAODv2-v2	278769 278808 ¹	0.58
	/SingleElectron/Run2016F-UL2016_MiniAODv2-v2		
2016G	/SingleMuon/Run2016G-UL2016_MiniAODv2-v2	278820 280385	7.65
	/SingleElectron/Run2016G-UL2016_MiniAODv2-v2		
2016H	/SingleMuon/Run2016H-UL2016_MiniAODv2-v2	281613 284044	8.74
	/SingleElectron/Run2016H-UL2016_MiniAODv2-v2		
2017B	/SingleMuon/Run2017B-UL2017_MiniAODv2_GT36-v2	297047 297483	4.80
	/SingleElectron/Run2017B-UL2017_MiniAODv2-v1		
2017C	/SingleMuon/Run2017C-UL2017_MiniAODv2_GT36-v2	299368 300283	9.63
	/SingleElectron/Run2017C-UL2017_MiniAODv2-v1		
2017D	/SingleMuon/Run2017D-UL2017_MiniAODv2_GT36-v2	302031 302663	4.25
	/SingleElectron/Run2017D-UL2017_MiniAODv2-v1		
2017E	/SingleMuon/Run2017E-UL2017_MiniAODv2_GT36-v2	303824 304797	9.32
	/SingleElectron/Run2017E-UL2017_MiniAODv2-v1		
2017F	/SingleMuon/Run2017F-UL2017_MiniAODv2_GT36-v2	305040 306460	13.5
	/SingleElectron/Run2017F-UL2017_MiniAODv2-v1		
2018A	/SingleMuon/Run2018A-UL2018_MiniAODv2-v3	315257 316995	14.0
	/EGamma/Run2018A-UL2018_MiniAODv2-v1		
2018B	/SingleMuon/Run2018B-UL2018_MiniAODv2-v2	317080 319310	7.09
	/EGamma/Run2018B-UL2018_MiniAODv2-v1		
2018C	/SingleMuon/Run2018C-UL2018_MiniAODv2-v2	319337 320065	6.94
	/EGamma/Run2018C-UL2018_MiniAODv2-v1		
2018D	/SingleMuon/Run2018D-UL2018_MiniAODv2-v3	320497 325175	31.9
	/EGamma/Run2018D-UL2018_MiniAODv2-v2		

¹ In the 2016F era, Runs 278769, 278801, 278802, 278803, 278804, 278805, and 278808 are considered as 2016's normal run conditions.

Table 5.2: BTagCSV MiniAODv2 datasets used for 2016-2018.

Era	Dataset	Run range	Int. lumi. (fb ⁻¹)
2016B(APV)	/BTagCSV/Run2016B-ver2-HIPM_UL2016	273150 275376	5.83
2016C(APV)	/BTagCSV/Run2016C-HIPM_UL2016	275656 276283	2.62
2016D(APV)	/BTagCSV/Run2016D-HIPM_UL2016	276315 276811	4.29
2016E(APV)	/BTagCSV/Run2016E-HIPM_UL2016	276831 277420	4.07
2016F(APV)	/BTagCSV/Run2016F-HIPM_UL2016	277932 278807	2.87
2016F	/BTagCSV/Run2016F-UL2016	278769 278808 ¹	0.58
2016G	/BTagCSV/Run2016G-UL2016	278820 280385	7.65
2016H	/BTagCSV/Run2016H-UL2016	281613 284044	8.74
2017B	/BTagCSV/Run2017B-UL2017	297047 299329	4.80
2017C	/BTagCSV/Run2017C-UL2017	299368 302029	9.63
2017D	/BTagCSV/Run2017D-UL2017	302031 302663	4.25
2017E	/BTagCSV/Run2017E-UL2017	303824 304797	9.32
2017F	/BTagCSV/Run2017F-UL2017	305040 306460	13.5
2018A	/JetHT/Run2018A-UL2018-GT36	315257 316995	14.0
2018B	/JetHT/Run2018B-UL2018-GT36	317080 319310	7.09
2018C	/JetHT/Run2018C-UL2018-GT36	319337 320065	6.94
2018D	/JetHT/Run2018D-UL2018-GT36	320500 325175	31.9

¹ In the 2016F era, Runs 278769, 278801, 278802, 278803, 278804, 278805, and 278808 are considered “non-HIPM.”

Table 5.3: DisplacedJet MiniAODv2 datasets used for 2016-2018.

Era	Dataset	Run range	Int. lumi. (fb ⁻¹)
2016B(APV)	/DisplacedJet/Run2016B-ver2-HIPM-UL2016	273150 275376	5.83
2016C(APV)	/DisplacedJet/Run2016C-HIPM-UL2016	275656 276283	2.62
2016D(APV)	/DisplacedJet/Run2016D-HIPM-UL2016	276315 276811	4.29
2016E(APV)	/DisplacedJet/Run2016E-HIPM-UL2016	276831 277420	4.07
2016F(APV)	/DisplacedJet/Run2016F-HIPM-UL2016	277932 278807	2.87
2016F	/DisplacedJet/Run2016F-UL2016	278769 278808 ¹	0.58
2016G	/DisplacedJet/Run2016G-UL2016	278820 280385	7.65
2016H	/DisplacedJet/Run2016H-UL2016	281613 284044	8.74
2017B	Not present	-	-
2017C	/DisplacedJet/Run2017C-UL2017	299368 302029	9.63
2017D	/DisplacedJet/Run2017D-UL2017	302031 302663	4.25
2017E	/DisplacedJet/Run2017E-UL2017	303824 304797	9.32
2017F	/DisplacedJet/Run2017F-UL2017	305040 306460	13.5
2018A	/DisplacedJet/Run2018A-UL2018-GT36	315257 316995	14.0
2018B	/DisplacedJet/Run2018B-UL2018-GT36	317080 319310	7.09
2018C	/DisplacedJet/Run2018C-UL2018-GT36	319337 320065	6.94
2018D	/DisplacedJet/Run2018D-UL2018-GT36	320500 325175	31.9

¹ In the 2016F era, Runs 278769, 278801, 278802, 278803, 278804, 278805, and 278808 are considered as 2016's normal run conditions.

5.1.2 Simulation samples

Signal

The exotic Higgs signals are the decay products of the SM Higgs boson, shown in Figure 5.2. The SM Higgs boson is produced by either gluon-gluon fusion (ggF or ggH) or associated vector-boson (VH). The mass points of the scalar particle (m_S) that is produced in a pair from the SM Higgs include 15 GeV, 40 GeV, and 55 GeV. However, exotic Higgs samples with the gluon-gluon fusion production are only available with c of 1 mm and 10 mm. Those intermediate life-

times are obtained from reweighting samples of existing lifetimes with the same desired mass point. Each exotic Higgs sample with a specific m_S and c is generated for approximately 50000 events for associated vector-boson Higgs production (ZH , W^+H , and W^-H) or approximately 100000 events for gluon-gluon fusion Higgs production. These exotic Higgs boson signal samples are generated with POWHEG [4]- [7] for the matrix element calculation and PYTHIA 8 [73] for the parton showering and hadronisation. Moreover, a truth-level filter with $H_T = 200$ GeV is imposed while the samples are generated in order to reduce computational time for events that won't satisfy kinematic filters in b-jet and displaced-jet triggers.

Simulated RPV SUSY signals are generated using PYTHIA 8 with the standard CP5 tune for the NNLO parton distribution functions. The gluino/neutralino and stop LSP mass are varied from 200 GeV to 3 TeV. Among these samples, the lifetimes of the long-lived particle are generated at c of 100 μ m, 300 μ m, 1 mm, 10 mm, and 30 mm. The RPV SUSY samples are generated with 100000-200000 events per mass, lifetime, and year.

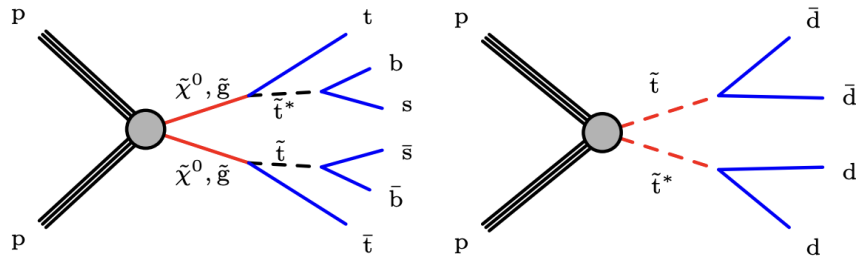


Figure 5.1: (Left) A simplified model of multijet signals. (Right) A simplified model of dijet signals. [70]

Benchmark models of these signal samples are shown in Figure 5.1. Moreover, these signal samples are produced with the full simulation of the CMS detector, and the event reconstruction algorithms as in the data samples. The

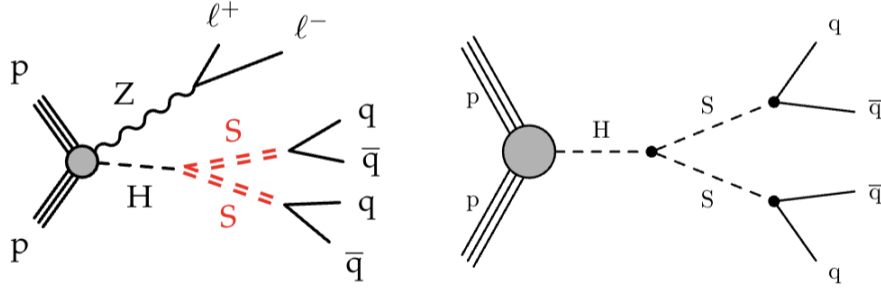


Figure 5.2: Simplified models of exotic Higgs decays via associated vector boson (i.e. Z boson) production (left) [80] and gluon fusion production (right) [32].

global tags used to produce these signal samples are listed in Table 5.4.

Table 5.4: Global tags used to produce signal samples from 2016-2018 data conditions.

Era	Global tag
2016(APV)	106X_mcRun2_asymptotic_preVFP_v11
2016	106X_mcRun2_asymptotic_v17
2017	106X_mc2017_realistic_v10
2018	106X_upgrade2018_realistic_v16_L1v1

Background

The dominant Standard Model backgrounds that pass single-lepton triggers are QCD, W +jets, Drell-Yan, $t\bar{t}$, and diboson events. Table 5.5, Table 5.6, Table 5.7, and Table 5.8 show these MC samples. These tables include their associated cross-sections, the number of generated events, and effective partial weights for the run conditions of the data-taking periods in 2016APV, 2016, 2017, and 2018.

The dominant backgrounds from the Standard Model processes that pass

b-jet triggers or displaced-jet triggers are QCD events and top quark pair or $t\bar{t}$ events. Table 5.9, 5.10, 5.11, and 5.12 show these MC samples and their associated cross-sections, the number of generated events, and effective partial weights for the run conditions of the data-taking periods in 2016APV, 2016, 2017, and 2018. Note that the global tags, as well as the CMS detector simulation and reconstruction, for background simulated samples by year are the same as in signal simulation.

Table 5.5: Background MC samples for single-lepton triggers in 2016APV.

Process	Cross-section (pb)	Number of events	Weight for 19.7fb ⁻¹
W(ℓ), 0-jet	5.3 · 10 ⁴	152373244	7.82
W(ℓ), 1-jet	8.8 · 10 ³	173468850	4.56
W(ℓ), 2 jets or more	3.3 · 10 ³	87929021	1.62
DY($\ell\ell$), 10 < M < 50 GeV	1.6 · 10 ⁴	25799525	16.41
DY($\ell\ell$), 50 < M < 100 GeV	5.3 · 10 ³	95170542	6.65
$t\bar{t}$	7.6 · 10 ²	99329745	0.16
WW	7.6 · 10 ¹	15859000	1.66
ZZ	1.2 · 10 ¹	1282000	0.43
WZ	2.8 · 10 ¹	7934000	2.14
QCD Mu Enriched; $p_T > 15$ GeV	2.39e5	8685279	541.111
QCD EM Enriched; 15 < p_T < 20 GeV	1.324e6	4062805	6408.168
QCD EM Enriched; 20 < p_T < 30 GeV	4.896e6	7156441	13452.908
QCD EM Enriched; 30 < p_T < 50 GeV	6.447e6	4361931	29063.689
QCD EM Enriched; 50 < p_T < 80 GeV	1.988e6	5440758	7185.034
QCD EM Enriched; 80 < p_T < 120 GeV	3.675e5	4847354	1490.817
QCD EM Enriched; 120 < p_T < 170 GeV	6.659e4	4852573	269.842
QCD EM Enriched; 170 < p_T < 300 GeV	1.662e4	1855461	176.137
QCD EM Enriched; $p_T > 300$ GeV	1104.0	1142775	18.997
QCD bcToE; 20 < p_T < 30 GeV	3.038e5	7913320	754.920
QCD bcToE; 30 < p_T < 80 GeV	3.623e5	7967312	894.187
QCD bcToE; 80 < p_T < 170 GeV	3.37e4	7690702	86.166
QCD bcToE; 170 < p_T < 250 GeV	2.125e3	7342849	5.691
QCD bcToE; $p_T > 250$ GeV	562.5	6856820	1.613

Table 5.6: Background MC samples for single-lepton triggers in 2016.

Process	Cross-section (pb)	Number of events	Weight for 17.0fb ⁻¹
W(l), 0-jet	5.3 · 10 ⁴	159895674	6.47
W(l), 1-jet	8.8 · 10 ³	167715035	2.97
W(l), 2 jets or more	3.3 · 10 ³	85825681	311.14
DY(ll), 10 < M < 50GeV	1.6 · 10 ⁴	23706672	12.63
DY(ll), 50 < M < 100GeV	5.3 · 10 ³	82448537	4.40
$t\bar{t}$	7.6 · 10 ²	110111829	0.14
WW	7.6 · 10 ¹	15821000	1.43
ZZ	1.2 · 10 ¹	1151000	1.52
WZ	2.8 · 10 ¹	7584000	0.48
QCD Mu Enriched, $p_T > 15$ GeV	2.39e5	17716270	547.846
QCD EM Enriched, 15 < p_T < 20GeV	1.324e6	7966910	6748.870
QCD EM Enriched, 20 < p_T < 30GeV	4.896e6	14166147	14035.331
QCD EM Enriched, 30 < p_T < 50GeV	6.447e6	8784542	29803.793
QCD EM Enriched, 50 < p_T < 80GeV	1.988e6	10590542	7623.092
QCD EM Enriched, 80 < p_T < 120GeV	3.675e5	9615795	1552.0480
QCD EM Enriched, 120 < p_T < 170GeV	6.659e4	9904245	273.036
QCD EM Enriched, 170 < p_T < 300GeV	1.662e4	3678200	183.497
QCD EM Enriched, $p_T > 300$ GeV	1104.0	2214934	20.241
QCDBCtoE, 15 < p_T < 20GeV	1.862e5	18671506	404.980
QCDBCtoE, 20 < p_T < 30GeV	3.038e5	14171260	870.587
QCDBCtoE, 30 < p_T < 80GeV	3.623e5	15238384	965.523
QCD bcToE; 80 < p_T < 170GeV	3.37e4	7690702	86.166
QCD bcToE; 170 < p_T < 250GeV	2.125e3	7342849	5.691
QCD bcToE; $p_T > 250$ GeV	562.5	6856820	1.613

Table 5.7: Background MC samples for single-lepton triggers in 2017.

Process	Cross-section (pb)	Number of events	Weight for 41.5fb ⁻¹
W(ℓ), 0-jet	5.3 · 10 ⁴	169421340	13.21
W(ℓ), 1-jet	8.8 · 10 ³	180015088	3.24
W(ℓ), 2 jets or more	3.3 · 10 ³	96032711	32.16
DY($\ell\ell$), 10 < M < 50 GeV	1.6 · 10 ⁴	68480179	12.17
DY($\ell\ell$), 50 < M < 100 GeV	5.3 · 10 ³	103344974	23.31
$t\bar{t}$	8.3 · 10 ²	249133364	0.14
WW	7.6 · 10 ¹	15883000	0.88
ZZ	1.2 · 10 ¹	2708000	0.32
WZ	2.8 · 10 ¹	7898000	0.28
QCD Mu Enriched, $p_T > 15$ GeV	2.39e5	17716270	547.846
QCD EM Enriched, 15 < p_T < 20 GeV	1.324e6	7966910	6748.870
QCD EM Enriched, 20 < p_T < 30 GeV	4.896e6	14166147	14035.331
QCD EM Enriched, 30 < p_T < 50 GeV	6.447e6	8784542	29803.793
QCD EM Enriched, 50 < p_T < 80 GeV	1.988e6	10590542	7623.092
QCD EM Enriched, 80 < p_T < 120 GeV	3.675e5	9615795	1552.0480
QCD EM Enriched, 120 < p_T < 170 GeV	6.659e4	9904245	273.036
QCD EM Enriched, 170 < p_T < 300 GeV	1.662e4	3678200	183.497
QCD EM Enriched, $p_T > 300$ GeV	1104.0	2214934	20.241
QCDBcToE, 15 < p_T < 20 GeV	1.862e5	18671506	404.980
QCDBcToE, 20 < p_T < 30 GeV	3.038e5	14171260	870.587
QCDBcToE, 30 < p_T < 80 GeV	3.623e5	15238384	965.523
QCDBcToE, 80 < p_T < 170 GeV	3.37e4	15571255	87.890
QCDBcToE, 170 < p_T < 250 GeV	2.125e3	15502839	5.566
QCDBcToE, 250 GeV < p_T	562.5	15557421	1.468

Table 5.8: Background MC samples for single-lepton triggers in 2018.

Process	Cross-section (pb)	Number of events	Weight for 59.7fb ⁻¹
W(l), 0-jet	5.3 · 10 ⁴	172138190	20.12
W(l), 1-jet	8.8 · 10 ³	184564696	6.03
W(l), 2 jets or more	3.3 · 10 ³	94925903	13.00
DY(ll), 10 < M_{ll} < 50GeV	1.6 · 10 ⁴	99288125	13.06
DY(ll), 50 < M_{ll} < 100GeV	5.4 · 10 ³	96233328	7.13
$t\bar{t}$	8.3 · 10 ²	341248786	0.16
WW	7.6 · 10 ¹	15679000	1.55
ZZ	1.2 · 10 ¹	3526000	0.50
WZ	2.8 · 10 ¹	7988000	1.51
QCD Mu Enriched; $p_T > 15$ GeV	2.39e5	17392472	820.139
QCD EM Enriched; 15 < p_T < 20GeV	1.324e6	7899865	10002.740
QCD EM Enriched; 20 < p_T < 30GeV	4.896e6	14328846	20392.987
QCD EM Enriched; 30 < p_T < 50GeV	6.447e6	8574589	44874.023
QCD EM Enriched; 50 < p_T < 80GeV	1.988e6	10524400	11273.783
QCD EM Enriched; 80 < p_T < 120GeV	3.675e5	9468372	2316.502
QCD EM Enriched; 120 < p_T < 170GeV	6.659e4	9677904	410.656
QCD EM Enriched; 170 < p_T < 300GeV	1.662e4	3714642	267.033
QCD EM Enriched; $p_T > 300$ GeV	1104.0	16549971	3.981
QCD bcToE; 15 < p_T < 20GeV	1.862e5	14061214	790.328
QCD bcToE; 20 < p_T < 30GeV	3.038e5	15358726	1180.547
QCD bcToE; 30 < p_T < 80GeV	3.623e5	15186397	1423.850
QCD bcToE; 80 < p_T < 170GeV	3.37e4	15735786	127.818
QCD bcToE; 170 < p_T < 250GeV	2.125e3	15767690	8.043
QCD bcToE; $p_T > 250$ GeV	562.5	2215994	15.150

Table 5.9: Background MC samples for b-jet triggers and displaced-jet triggers in 2016APV.

Process	Cross-section (pb)	Number of events	Weight for 19.7fb ⁻¹
QCD, 200 < H_T < 300GeV	1.6 · 10 ⁶	52503973	588.4
QCD, 300 < H_T < 500GeV	3.2 · 10 ⁵	52664292	140.4
QCD, 500 < H_T < 700GeV	3.0 · 10 ⁴	58559243	10.5
QCD, 700 < H_T < 1000GeV	6.4 · 10 ³	45526707	3.13
QCD, 1000 < H_T < 1500GeV	1.1 · 10 ³	14081307	1.59
QCD, 1500 < H_T < 2000GeV	1.1 · 10 ²	10300081	0.21
QCD, $H_T > 2000$ GeV	22	5080758	0.09
$t\bar{t}$	7.6 · 10 ²	99329745	0.16

Table 5.10: Background MC samples for b-jet triggers and displaced-jet triggers in 2016.

Process	Cross-section (pb)	Number of events	Weight for 17.0fb ¹
QCD, 200 H_T 300GeV	1.6 · 10 ⁶	43481129	608.8
QCD, 300 H_T 500GeV	3.2 · 10 ⁵	52221303	117.7
QCD, 500 H_T 700GeV	3.0 · 10 ⁴	59109804	9.74
QCD, 700 H_T 1000GeV	6.4 · 10 ³	46439412	2.52
QCD, 1000 H_T 1500GeV	1.1 · 10 ³	12675816	1.5
QCD, 1500 H_T 2000GeV	1.1 · 10 ²	9387470	0.2
QCD, H_T 2000GeV	22	4980828	0.08
$t\bar{t}$	7.6 · 10 ²	110111829	0.14

Table 5.11: Background MC samples for b-jet triggers and displaced-jet triggers in 2017.

Process	Cross-section (pb)	Number of events	Weight for 41.5fb ¹
QCD, 300 H_T 500GeV	3.2 · 10 ⁵	57097305	242
QCD, 500 H_T 700GeV	3.0 · 10 ⁴	68221113	20.2
QCD, 700 H_T 1000GeV	6.4 · 10 ³	45774525	5.46
QCD, 1000 H_T 1500GeV	1.1 · 10 ³	15420054	3.21
QCD, 1500 H_T 2000GeV	99	7711548	0.35
QCD, H_T 2000GeV	20	5451735	0.15
$t\bar{t}$	8.3 · 10 ²	249133364	0.14

Table 5.12: Background MC samples for b-jet triggers and displaced-jet triggers in 2018.

Process	Cross-section (pb)	Number of events	Weight for 59.7fb ¹
QCD, 300 H_T 500GeV	3.2 · 10 ⁵	55198123	335
QCD, 500 H_T 700GeV	3.0 · 10 ⁴	58437786	29.3
QCD, 700 H_T 1000GeV	6.4 · 10 ³	47725353	8.01
QCD, 1000 H_T 1500GeV	1.1 · 10 ³	15685044	4.4
QCD, 1500 H_T 2000GeV	99	10615310	0.54
QCD, H_T 2000GeV	20	4532754	0.23
$t\bar{t}$	8.3 · 10 ²	341248786	0.16

5.2 Triggers and Preselection

5.2.1 Trigger Selection

The final state of all signal models targeted by this search is a pair of displaced vertices (DVs) that each decays to two or more quarks. Due to color confinement, these quarks hadronize and appear in the detector as at least four jets. Each event is expected to have displaced vertices constructed from displaced tracks in jets, resembling the decay of b-hadrons. Hence, the *online event selection* for our targeted signals relies on *b-jet triggers* and *displaced-jet triggers*. Table 5.15 and Table 5.16 show the b-jet trigger and displaced-jet trigger paths by data-taking years, respectively. However, an event only needs to satisfy one of these triggers to be selected because the online-trigger decision is made by a logical OR. While b-jet triggers are more efficient at selecting events with a displacement of LLP displaced vertices similar to b-quark decay vertex, displaced-jet triggers are more efficient at selecting LLPs with lifetimes greater than 10 mm. This is beyond b-hadron lifetimes. Figure 5.3 illustrates the complementary power of using these two triggers operated by a logical OR at online event selection. As a result, the efficiency of selecting LLPs is as high as 85% across different values of the search variable d_{BV} , defined as the sum of two vertex displacements from a beamspot in the transverse plane.

For exotic Higgs decays, the SM Higgs boson can be produced via several modes, shown in Sec. 2.4. The two Higgs production modes for the study of exotic Higgs signals are gluon-gluon fusion and vector-boson association. Although gluon-gluon fusion is the dominant production mode of the Higgs boson, vector-boson associated production offers the opportunity to trigger on a

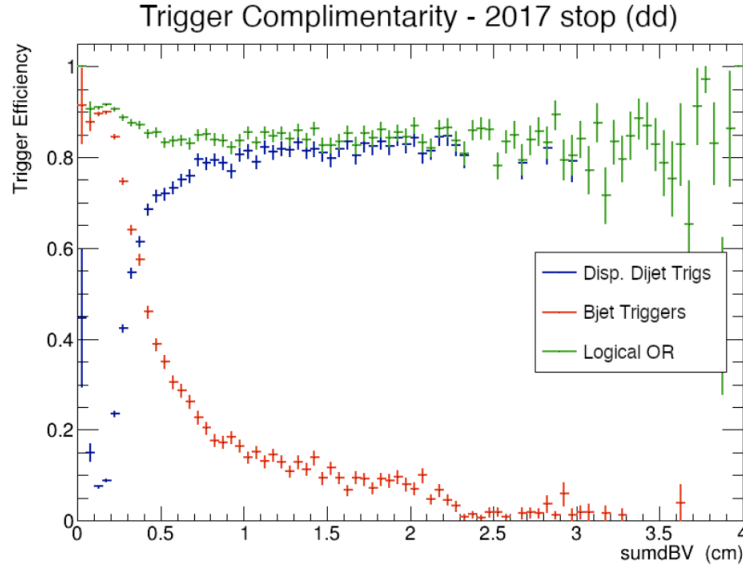


Figure 5.3: Trigger efficiency as a function of d_{BV} for online event selection using displaced-dijet triggers (blue), b-jet triggers (red), and their logical OR (green). These events are in the signal region and are from the sample of dijet signal MC with all down-quark final state and LLP mass of 300 GeV and 400 GeV in 2017. Figure credit: Shaun Hogan.

well-reconstructed muon(electron). In particular, the gluon-gluon fusion process produces the SM Higgs boson in association with recoiling jets, in addition to jets associated with displaced vertices of the exotic Higgs decay. Unlike this, the vector-boson associated production produces the Higgs boson from the radiation of the *off-shell* W or Z boson. The remaining *on-shell* W or Z boson then decays to a lepton and a neutrino or a pair of leptons, respectively. One of these leptons can be detected by the *single-lepton triggers* listed in Table 5.13 for electrons and in Table 5.14 for muons. The neutrino, however, contributes to the missing transverse momentum, and provides an opportunity to study systematic uncertainties of single muon/electron triggers by using the MET trigger as is done in Sec. 5.8.1.

The decisions and capabilities to select events in real-time of the same trigger path may differ by year, but this variation generally stems from variable thresholds, based on either kinematic or displacement of physics objects. The main functionality of each trigger path has the following details:

- **Single-electron triggers** select events with at least one electron. The electron trigger object is reconstructed by the ECAL and the tracker, relying on the Gaussian sum filter (GSF) as discussed in Sec. 4.3. In this analysis, the single-electron trigger is used to select exotic Higgs signals.
- **Single-muon triggers** select events with at least one muon. The muon trigger object is reconstructed by the muon system and the tracker. Similar to the single-electron trigger, the single-muon trigger is used to optimize for exotic Higgs signals. Furthermore, it is used to study the systematic uncertainties of b-jet and displaced-jet triggers.
- **B-jet triggers** select events with at least two b-tagged jets. B-tagging is performed using either the CSV tagger (in 2016 and 2017) or the DeepCSV tagger (in 2018). The b-tagging efficiency is optimized to be at least 70% at the medium working point, as discussed in Sec. 4.5, despite varying b-tagging thresholds across years. Additionally, there are two main b-jet triggers: the di-jet and tri-jet triggers. They complement each other to include both energetic and less-energetic b-jets in the event selection.
- **Displaced-jet triggers** select events with at least two displaced jets. Displaced jets are defined by the number of prompt and displaced tracks in calorimeter jets (Calojets). A track is considered prompt if it satisfies $d_{xy} < 1$ mm, and displaced if it satisfies $d_{xy} > 0.5$ mm and $d_{xy} < d_{xy} < 5$. To select displaced-jet events, regardless of jet kinematics, two complemen-

tary displaced-jet triggers are used.

- **MET triggers** select events with missing transverse momentum from neutrinos or invisible new particles. The missing transverse momentum is calculated by the negative vectorial sum of the transverse momentum of all reconstructed physics objects, as discussed in Sec. 4.6. The MET trigger is only relevant to the systematic studies of single-lepton triggers.

In 2017, a logical-OR combination of displaced-jet and b-jet triggers results in trigger efficiencies ranging from 5% to over 99% for the dijet and multijet RPV benchmark models, and between 1% to 12% for the exotic Higgs model. Similar trigger efficiencies are observed in other years for each benchmark model. However, as LLP lifetimes increase beyond 10 mm, the 2016 trigger efficiencies tend to decrease significantly, while the 2017 and 2018 trigger efficiencies remain stable.

For a logical-OR combination of single muon and single electron triggers in 2017, the trigger efficiency to select exotic Higgs signals produced in association with a vector boson is about 43% in the $Z(H \rightarrow SS)$ production mode and 24% in the $W^+(H \rightarrow SS)$ or $W^-(H \rightarrow SS)$ production modes, as shown in Figure 5.4 (bottom left). These trigger efficiencies are constant across lifetimes and mass points of a long-lived particle (S), as the triggers select events solely based on the Higgs production modes. In 2018, the combined leptonic trigger efficiency is about 53% in the $Z(H \rightarrow SS)$ production mode, and around 35% in the $W^+(H \rightarrow SS)$ production modes, as shown in Figure 5.4 (bottom right). Conversely, the combined leptonic trigger efficiencies in 2016APV and 2016 are significantly lower than those in 2017 and 2018 for these associated production modes of the exotic Higgs signals, being 25% and 13% in the $Z(H \rightarrow SS)$ and

W (H $\rightarrow SS$) production modes, respectively, as shown in Figure 5.4 (top). This variation in trigger efficiency across years is due to the different trigger paths used in each year, as shown in Table 5.13 and Table 5.14. For instance, selected leptons in 2017 must pass online filters with p_T thresholds of 35 GeV for electrons and 27 GeV for muons, while in 2018, the thresholds are 32 GeV for electrons and 24 GeV for muons. Therefore, the trigger efficiency is higher in 2018 than in 2017. Although the p_T threshold of selected electrons is lower in 2016 than in other years, the tracker and ECAL are less efficient in reconstructing electrons in 2016, resulting in a lower trigger efficiency than in 2017 and 2018.

Table 5.13: single-electron triggers by year of data taking.

Run Period	Single-electron trigger paths
2016(APV) and 2016	HLT_Ele27_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Ele50_CaloIdVT_GsfTrkIdT_PFJet165
2017	HLT_Ele35_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Ele50_CaloIdVT_GsfTrkIdT_PFJet165
2018	HLT_Ele32_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Ele50_CaloIdVT_GsfTrkIdT_PFJet165

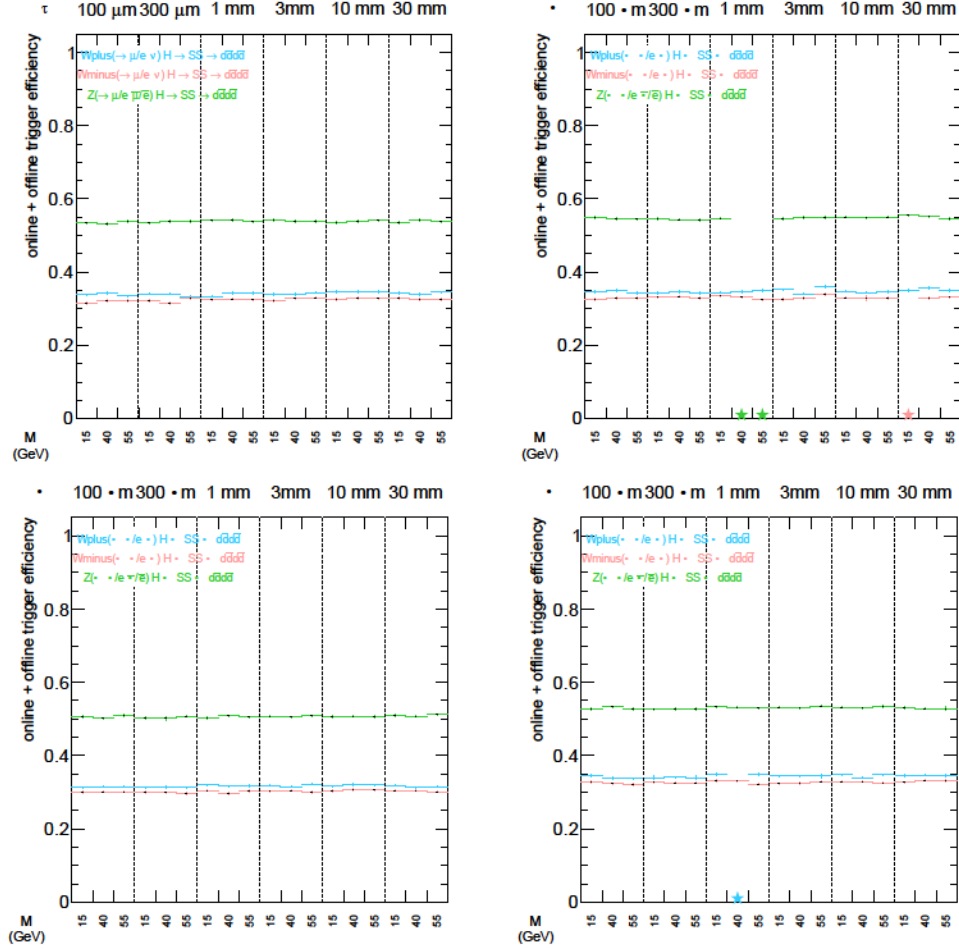


Figure 5.4: Trigger efficiency (i.e. fraction of processed simulated events passing the logical OR of single muon and single electron triggers and offline trigger selection for that year) as a function of LLP mass and lifetime for the exotic Higgs model in 2016APV (top left), 2016 (top right), 2017 (bottom left), and 2018 (bottom right). The efficiency is shown for the $Z(H \rightarrow SS)$ production mode (green), the $W^+(H \rightarrow SS)$ production mode (blue), and $W^-(H \rightarrow SS)$ production mode (pink)

Table 5.14: single-muon triggers by year of data taking.

Run Period	Single-muon trigger paths
2016(APV) and 2016	HLT_IsoMu27 HLT_Mu50
2017	HLT_IsoMu27 HLT_Mu50
2018	HLT_IsoMu24 HLT_Mu50

Table 5.15: b-jet triggers by year of data taking.

Run Period	B-jet trigger paths
2016(APV) and 2016	HLT_QuadJet45_TripleBTagCSV_p087 HLT_DoubleJet90_Double30_TripleBTagCSV_p087 HLT_DoubleJetsC100_DoubleBTagCSV_p014_DoublePFJetsC100MaxDeta1p6
2017	HLT_DoublePFJets100MaxDeta1p6_DoubleCaloBTagCSV_p33 HLT_PFHT300PT30_QuadPFJet_75_60_45_40_TriplePFBTagCSV_3p0
2018	HLT_DoublePFJets116MaxDeta1p6_DoubleCaloBTagDeepCSV_p71 HLT_PFHT330PT30_QuadPFJet_75_60_45_40_TriplePFBTagDeepCSV_4p5

Table 5.16: displaced-jet triggers by year of data taking.

Run Period	Displaced-jet trigger paths
2016(APV) and 2016	HLT_HT350_DisplacedDijet40_DisplacedTrack HLT_HT650_DisplacedDijet80_Inclusive
2017	HLT_HT430_DisplacedDijet40_DisplacedTrack HLT_HT650_DisplacedDijet60_Inclusive
2018	HLT_HT430_DisplacedDijet40_DisplacedTrack HLT_HT650_DisplacedDijet60_Inclusive

5.2.2 Event Preselection

To minimize the uncertainty of online trigger selection, the *offline event selection* is applied to the events selected by each corresponding trigger. The offline event selection is based on well-reconstructed physics objects after events have been selected by at least one trigger path. This allows for more accurate information retention compared to the triggered objects. Consequently, the offline event selection is slightly more stringent than the online event selection but still mirrors the same selection cuts to maintain a high yield. The offline selection cuts corresponding to the 2017 triggers are shown in Table 5.17. The offline filters are divided into two categories: *kinematic filters* and *displaced filters*.

Table 5.17: Offline event selection cuts by two filter types in 2017.

Online triggers	Offline kinematic filters	Offline displaced filters
b-tagged di-jet trigger	$(0, 1) \leq 1.6$ leading PFjet ¹ $p_T \geq 125$ GeV sub-leading PFjet ¹ $p_T \geq 125$ GeV	at least two PFjets with $p_T \geq 80$ GeV pass loose DeepJet b-tagging
b-tagged tri-jet trigger	the number of PFjets ¹ ≥ 4 PFjets ¹ with $p_T \geq 90, 75, 55, 55$ GeV scalar (HT) of PFjets ¹ (with $p_T \geq 30$) GeV ≥ 350 GeV	at least three PFjets with $p_T \geq 20$ GeV pass loose DeepJet b-tagging
default displaced di-jet trigger	leading Calojet $p_T \geq 40$ GeV sub-leading Calojet $p_T \geq 40$ GeV $(0, 1) \leq 2.0$ scalar (HT) of Calojets (with $p_T \geq 30$ GeV) ≥ 430 GeV	None
inclusive displaced di-jet trigger	leading Calojet $p_T \geq 60$ GeV sub-leading Calojet $p_T \geq 60$ GeV $(0, 1) \leq 2.0$ scalar (HT) of Calojets (with $p_T \geq 30$ GeV) ≥ 650 GeV	None
single-electron trigger	tight electron $p_T \geq 38$ GeV	None
single-muon trigger	medium muon $p_T \geq 30$ GeV	None

¹ Matched with online jet by $R \leq 0.14$

Particularly, jet filters relating to the kinematic variables such as p_T , the scalar sum of jet p_T (H_T), as well as the matching angle between the leading and sub-

leading jets, or online and offline jet. These filters are determined by minimizing the difference in trigger efficiencies between data and simulation. This kinematic trigger efficiency is defined as the ratio of the number of events that pass the `HLT_IsoMu27` trigger and all offline filters to the number of events that pass the numerator selection except the kinematic filter of study. Both data and simulated events have trigger efficiencies that are computed analogously. For each offline kinematic filter, the offline variable threshold is chosen when its corresponding ratio reaches 95%. Differences in the efficiency to pass offline thresholds between data and simulation are counted as systematic uncertainty, and are studied in Sec. 5.8.1.

Displaced filters are more complicated to replicate using offline selection than kinematic filters. This is because displaced filters pertain to a variety of variables, not only prompt and displaced tracks but also multi-variant b-tagging scores. Events firing displaced-jet triggers are not required to satisfy any offline displaced filters. On the other hand, the two b-jet triggers have a minimum number of online b-tagged jets included in the online filters. We require a minimum number of offline b-tagged jets to match the trigger selection. The definition of offline b-tagged jets is optimized based on three parameters: a b-tagging algorithm, a b-tagging working point, and a minimum b-jet p_T . These parameters are tuned by maximizing the trigger efficiency of b-jet triggers in signal-like events. Loose working points at low p_T thresholds are chosen as shown in Table 5.17. This set of b-jet parameters provides high signal yields while controlling systematic uncertainty at a similar level as other choices. This choice of offline selection also agrees with the truth information of b-jet decays more than other choices in signal simulation.

For single-lepton triggers, only kinematic filters such as electron's p_T or muon's p_T are applied to offline event selection, as shown in Table 5.17.

5.3 Displaced vertex reconstruction

This section describes the vertex reconstruction procedure. It includes choosing displaced tracks and clustering them into reconstructed vertices in multiple steps. The last procedure is to select these vertices satisfying quality criteria to distinguish signal from background, and define the signal region.

5.3.1 Track selection

In order to reconstruct a displaced vertex from tracks, a selection of tracks is based not only on the quality of the tracks but also on the impact parameter significance of the tracks. These selected tracks are called *seed tracks*. The initial selection criteria apply basic quality requirements to choose “selected” tracks, i.e., those that are of high quality but not necessarily displaced. These quality requirements are:

- $p_T \geq 1 \text{ GeV}$
- $(r_{\min} = 1)$ or $(r_{\min} = 2 \text{ and } n_{\text{lost innerhits}} = 0)$, where $r_{\min}$ is defined as the index of the innermost pixel tracker layer with a hit
- $n_{\text{pxl}} \geq 2$
- $n_{\text{stl}} \geq 6$

Although the selection cut on the number of layers in the strip tracker with hits (n_{stl}) was not evenly efficient across all regions in 2016 due to inconsistent loss of hits from increasing luminosity, the issue was resolved by the new phase-1 pixel upgrade in 2017 and 2018. As a result, the selection cut remains the same throughout this Run-2 analysis, similar to other selection cuts. In addition, the track resolution also improved after this upgrade. Figure 5.5 shows the distributions of tracks' impact parameter uncertainties, which are lower on average in 2017 and 2018 than in 2016.

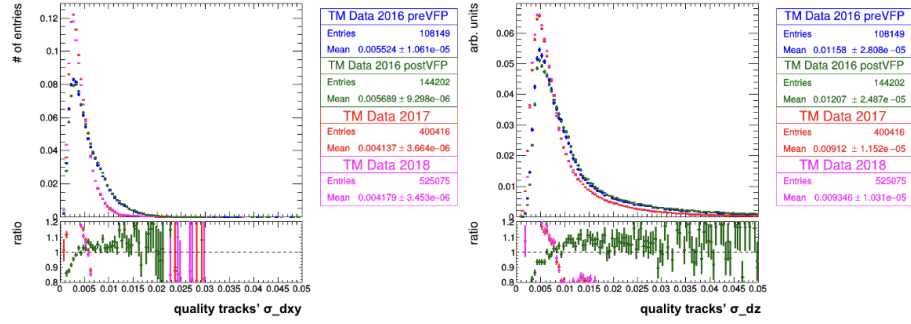


Figure 5.5: Comparison of the impact parameter uncertainty of selected tracks in a random jet in a transverse plane (left) and along the beamline (right) of data in 2016 preVFP (blue), 2016 postVFP (green), 2017 (red), and 2018 (magenta).

Despite better performance of the tracker from 2017 onward, dead modules still exist, causing tracking inefficiency in the previous iteration. To recover good tracks that pass through dead modules, we accept tracks that lack a hit in the first pixel layer because of dead modules. As a result, the yield increases by 10% from relaxing the innermost hit requirement (r_{min}). Generally, this relaxed condition provides satisfactory quality of tracks as long as all other layers have hits. Figure 5.6 shows the complementary distributions of tracks in (left) and (right) that could have failed the $r_{\text{min}} = 1$ selection (left) in the top figures.

With this relaxed condition imposed on the track selection, Figure 5.6 (bottom) shows that the inefficiencies in the η and p_T distributions of tracks are recovered.

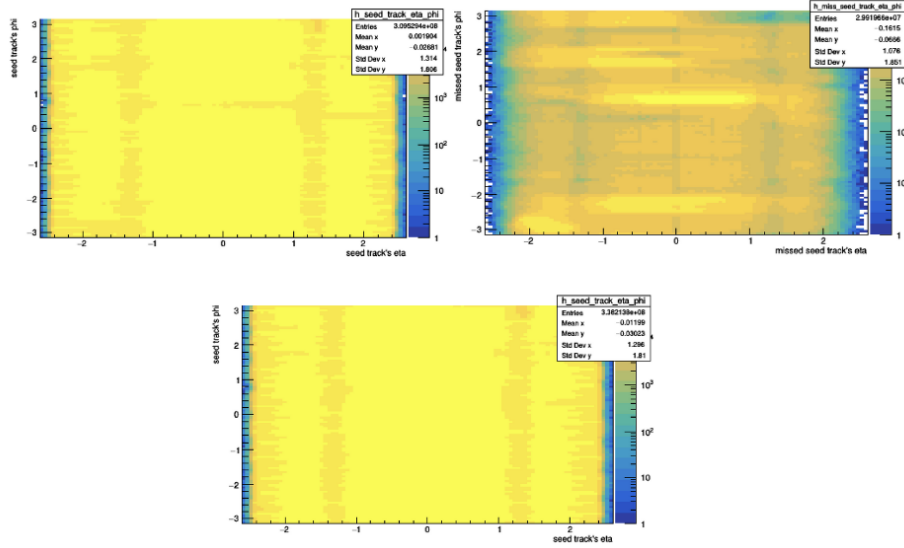


Figure 5.6: The 2D η and p_T distributions of seed tracks before relaxing $r_{\min}$ requirement (top left), after relaxing the cut (bottom) to include those missing seed tracks that satisfy $r_{\min} = 2$ and $n_{\text{lost innerhits}} = 0$ (top right) from the $t\bar{t}$ MC sample in 2017. After combining these sets of seed tracks, the inefficiencies are recovered (bottom). Note that the z-axis is in a log-scale.

None of the track quality cuts mentioned so far preferentially select displaced tracks. For the selection of displaced tracks, the 2D impact parameter significance of tracks is required to be greater than 4, with respect to a beamspot. The following requirement is called a "displaced criterion":

- $\frac{d_{xy}}{\sigma_{dxy}} \geq 4$

which is referred to as d_{xy} . The ratio of the 2D impact parameter in the transverse plane to its uncertainty. The impact parameter is the distance of the closest approach of the track to the beamspot. The uncertainty has been

rescaled in simulation to have the same performance as in data, to be discussed in Sec. 5.3.2. The requirement on d_{xy} suppresses most background from SM processes. The distributions of the impact parameter significance of selected tracks in signal MC with different lifetimes and background MC are shown in Figure 5.7 and Figure 5.8 (bottom right). The distributions of other selection variables are shown in the rest of Figure 5.7 and Figure 5.8. The number of all tracks before applying selection cuts and the number of seed tracks after applying all selection cuts are shown in Figure 5.9 and Figure 5.10.

Of all selection criteria, the displaced criterion is the most sensitive for distinguishing signal from background. More discussion of the impact of relaxing the displaced criterion on displaced-vertex reconstruction is in Appendix A.

5.3.2 Track error rescaling

The selection of tracks in Sec. 5.3.1 is aimed at finding displaced tracks with good quality that are consistent with the decay of long-lived particles. However, the tracking efficiency depends heavily on the uncertainty of track impact parameters. These uncertainties can be different between data and simulation. In particular, the uncertainty is attributed to the impact parameter of a track in a transverse plane (d_{xy}) and along the beamline (d_z). These uncertainties correspond to elements of the track's covariance matrix. Although a covariance matrix is usually composed of the uncertainties of all track parameters, the search for displaced vertices is sensitive mainly to the impact parameter uncertainties. In particular, the displaced criterion of the search imposes the 2D impact parameter significance ($d_{xy}/\sigma_{d_{xy}}$) to selected tracks being greater than four. Therefore,

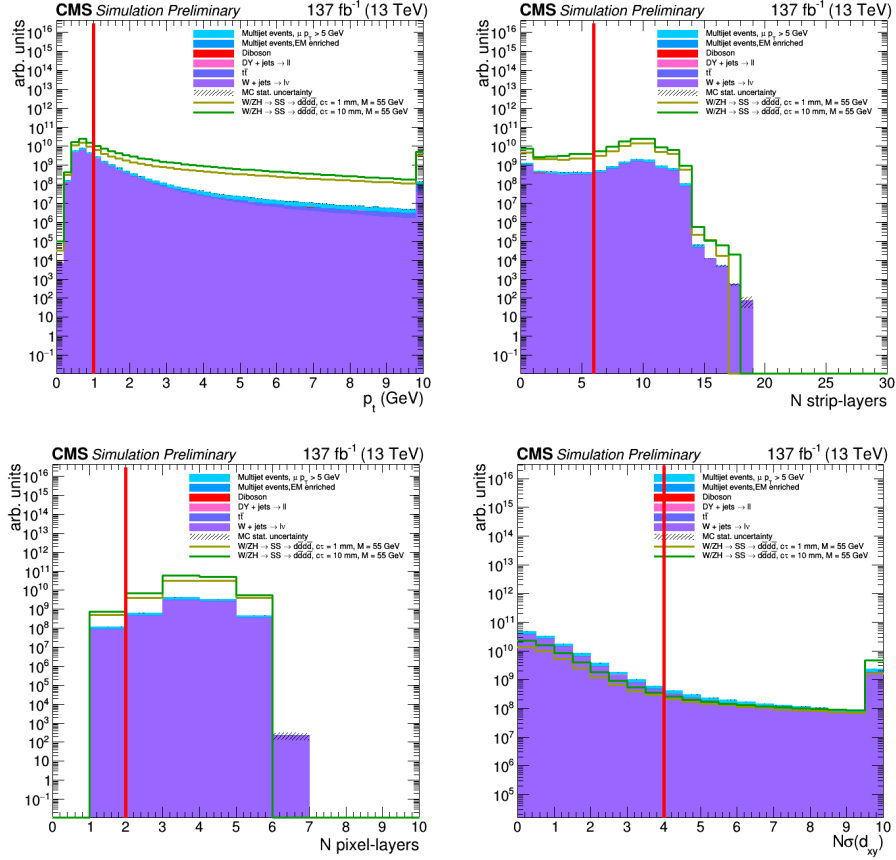


Figure 5.7: The log-scaled distributions of p_T (top-left), number of strip layers (top right), number of pixel layers (bottom left), and n_{dxy} (bottom right), tracks to the right of the red line pass the variable criterion. Tracks in $t\bar{t}$ (navy), lepton-enriched QCD (blue), diboson (red), Drell-Yan (pink) and W+jets (violet) simulation along with exotic Higgs signals via an associated vector boson (VH), which are 1-mm 55-GeV (green), and 10-mm 55-GeV (yellow), are in events selected by single lepton triggers. Each plot is “n-minus-one”, meaning that all cuts have been applied except the one shown. While background events are normalized to SM cross sections and run-2 luminosity, signal distributions are normalized by expected signal yields multiplied by 10⁸.

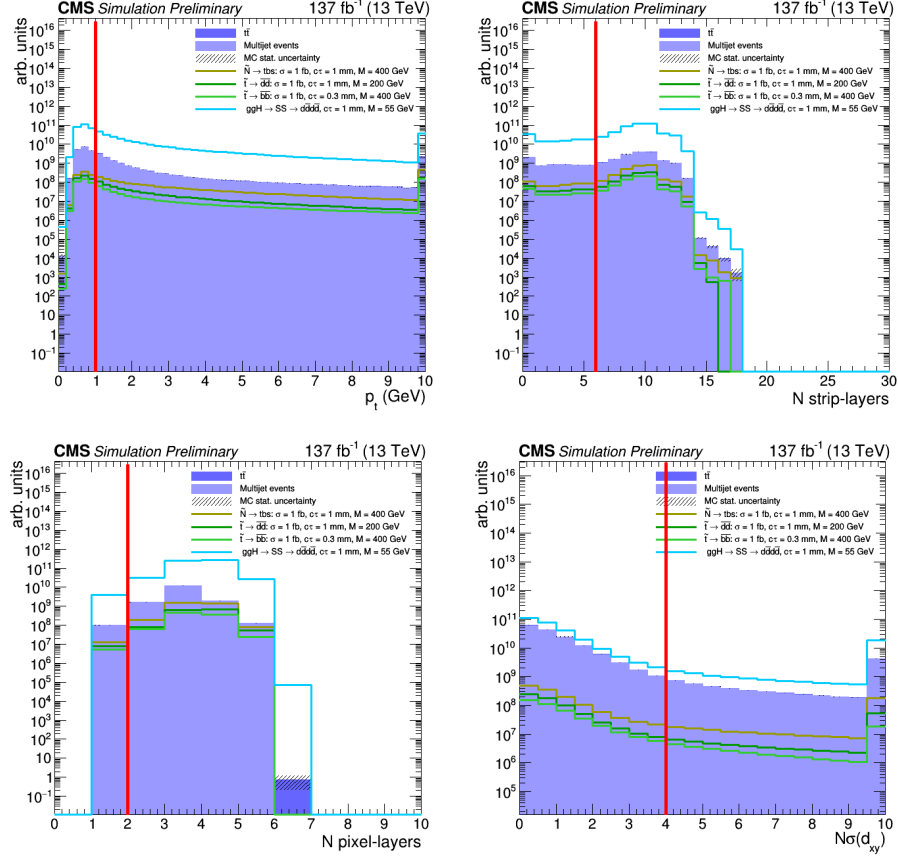


Figure 5.8: The log-scaled distributions of p_T (top-left), number of strip layers (top right), number of pixel layers (bottom left), and n_{dxy} (bottom right), tracks to the right of the red line pass the variable criterion. Tracks in $t\bar{t}$ (navy) and QCD (violet) simulation along with RPV multijet (yellow), RPV dijet (green) and exotic Higgs decays via gluon fusion (blue), are in events selected by displacement triggers. Each plot is “n-minus-one”, meaning that all cuts have been applied except the one shown. While background events are normalized to SM cross sections and run-2 luminosity, signal distributions are normalized by expected signal yields multiplied by 10^8 .

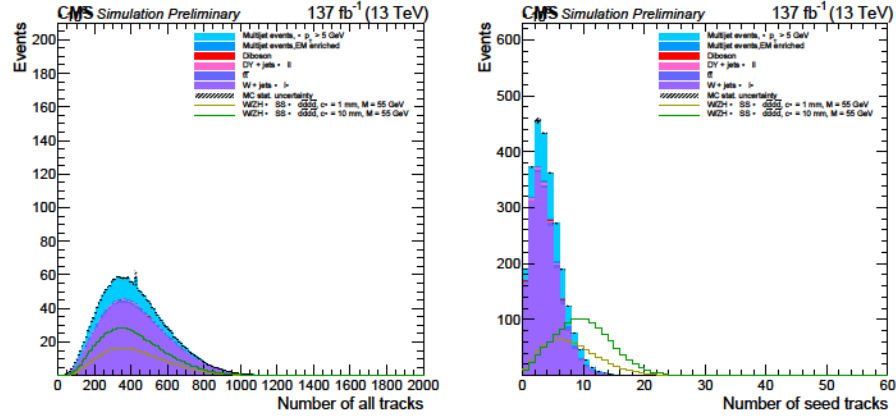


Figure 5.9: Distributions of all tracks (left), and seed tracks (right) for $t\bar{t}$ (navy), lepton-enriched QCD (blue), diboson (red), Drell-Yan (pink) and W+jets (violet) simulation along with exotic Higgs signals via an associated vector boson (VH), which are 1-mm 55-GeV (green), and 10-mm 55-GeV (yellow), in events selected by single lepton triggers. While background events are normalized to SM cross sections and run-2 luminosity, signal distributions are normalized by expected signal yields multiplied by 10^6 .

only the uncertainties of track impact parameters and their correlation must be rescaled. This method of deriving a scale factor and applying it directly to track uncertainty variables is called *track error rescaling*.

Additionally, track error rescaling is used in fitting tracks to form displaced vertices. The *Kalman filter*, discussed in Sec. 5.3.3, uses corrected covariance matrices at all steps of vertex reconstruction. As expected, track error rescaling can also impact the goodness of the vertex refitting. Moreover, steps such as track arbitration and pile-up track mitigation are sensitive to the track uncertainty variables because their decisions are based on the track impact parameter significance with respect to the vertex either in the transverse plane or along the beamline. The last place that track error rescaling can be important is the vertex

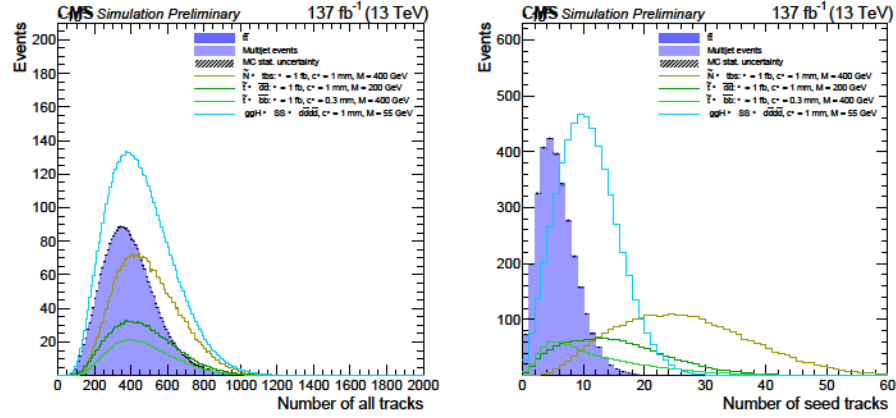


Figure 5.10: Distributions of all tracks (left), and seed tracks (right) for $t\bar{t}$ (navy) and QCD (violet) background simulation and signal simulation including RPV multijet (yellow), RPV dijet (green) and exotic Higgs decays via gluon fusion (blue). While background events are normalized to SM cross sections and run-2 luminosity, RPV signal and exotic Higgs signal distributions are normalized by expected signal yields multiplied by 10^8 , and 10^6 , respectively

selection, which is discussed in Sec. 5.3.4. In particular, one of the vertex selection cuts is based on the uncertainty in the vertex position (σ_{dBV}). The vertex refitting as mentioned previously directly propagates track uncertainties to the uncertainty of the vertex position.

The uncertainties of track impact parameters in all relevant planes depend on the track momentum because of multiple scattering. Therefore, the rescaling factor is applied to a track uncertainty variable as a function of the transverse momentum (p_T). Figure 5.11 illustrates the track rescaling procedure from left to right for correcting the 2D impact parameter uncertainty (σ_{dxy}) of simulated tracks in the barrel region. By starting from the left plot, the mean σ_{dxy} of all tracks from all four eras in the 2017 data is compared with the one in the background simulation. Combining datasets across eras, which have similar distri-

butions, increases statistics and reduces redundancy. The middle plot shows the resulting distribution (red) after combining all the four eras against the same simulated distribution (black) from the previous step. Lastly, the ratio of the mean $\langle d_{xy} \rangle$ between data and simulation as a function of p_T is shown in the right plot along with its fitting function, which is parameterized as:

$$y = [0] e^{[1] p_T + [2]} \quad (5.1)$$

where y is the ratio, p_T is the transverse-momentum value along the x-axis, $[0]$, $[1]$, and $[2]$ are the fit parameters.

This fitting function is applied to the uncertainty variables for simulated tracks. The distribution of the mean $\langle d_{xy} \rangle$ is shown as a function of p_T for *rescaled tracks* (black). This is compared to the expected distribution in data (red) in Figure 5.12. This track rescaling procedure is also applied to $\langle d_z \rangle$ and its correlation to $\langle d_{xy} \rangle$.

5.3.3 Vertex reconstruction

With a collection of *seed tracks* passing quality selection and displaced criterion in Sec. 5.3.1, the next step is to reconstruct a displaced vertex from these tracks. Ultimately, a displaced vertex is an estimated point where the long-lived particle decays. Our customized algorithm to reconstruct displaced vertices is discussed in this section. Since the search for long-lived particles aims to be a model-independent search with a few motivated benchmark models in Sec. 5.5, each step of the displaced-vertex reconstruction algorithm has been generalized

Example : Track Rescaling of $\langle d_{xy} \rangle$ for Barrel Tracks with $|\eta| < 1.5$

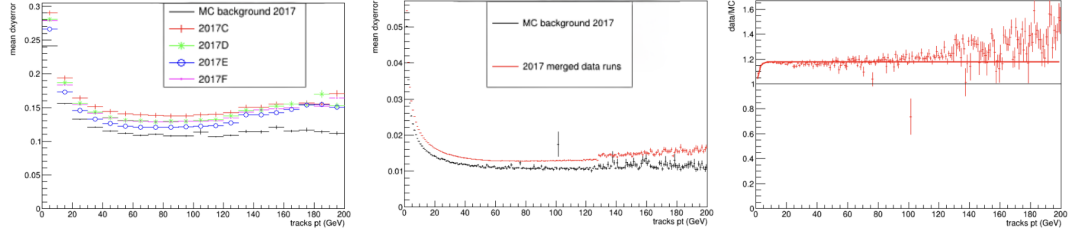


Figure 5.11: Demonstration of a generalized track rescaling procedure by deriving a correction for d_{xy} as a function of p_T for barrel tracks in 2017. (Left) Simulated tracks in background are in black, while tracks in data are separated by eras in colors. (Middle) All data are combined (red) to compare with the simulated tracks (black). (Right) Rescaling factors in p_T bins are derived from dividing the means of d_{xy} between distributions in the previous step, and are fitted with a track-rescaling function. Figure credit: Alec Duquette.

Example : $\langle d_{xy} \rangle$ vs p_T for Barrel Tracks with $|\eta| < 1.5$ after applying correction

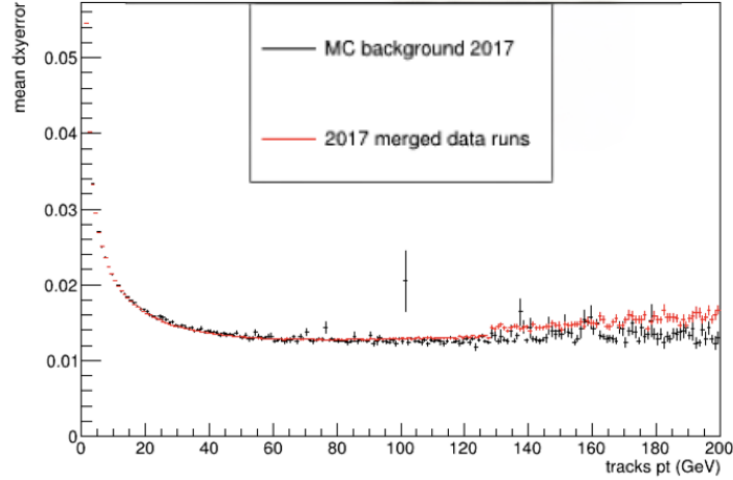


Figure 5.12: Comparison of the means of d_{xy} as a function of p_T between *rescaled tracks* in simulation and data tracks with the 2017 condition in the barrel, after the procedure in Figure 5.11. Figure credit: Alec Duquette.

for all signal models.

The algorithm is described in the following steps:

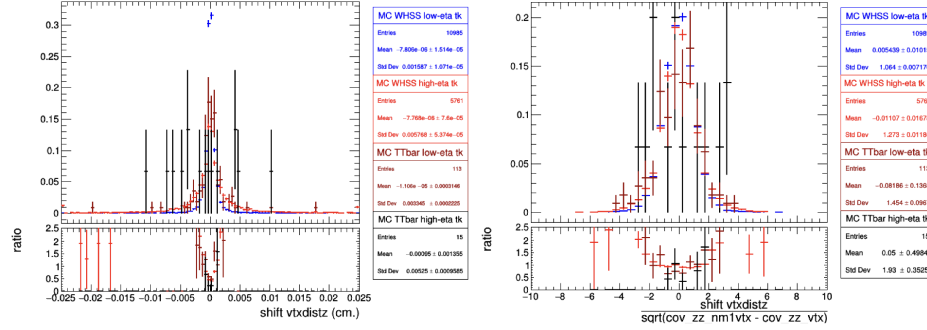


Figure 5.13: Comparison of the dz-shift significance (or normalized variable) on the right and the dz-shift on the left before the pileup-track removal criterion is chosen. Signal MC with low-tracks (blue) and high- tracks (red) as well as $t\bar{t}$ MC samples with low- tracks (brown) and high- tracks (black) are compared. Samples with high tracks have a requirement that $\chi^2_{\text{min}} < 1$. Samples with low tracks have a requirement that $\chi^2_{\text{min}} < 1$. See the text for the definitions of these two plotting variables.

- **Seed vertex reconstruction:** Every random pair of seed tracks forms a seed vertex. The track pair is fitted with the *Kalman* filter. The fit requires that the χ^2 per degree of freedom (ndof) is less than 5.
- **Track arbitration:** If a seed track is shared by at least two seed vertices from the previous step, then one of the following occurs:
 - **Merge two seed vertices:** Merge the vertices if they are separated in a three-dimensional (3D) distance by less than 4 times the uncertainty in that distance.
 - **Discard the shared track:** Discard the shared track from both vertices if the track's 3D impact parameter is greater than 5 times the uncer-

tainty of that impact parameter with respect to any vertices, where the uncertainty is computed from both the vertex and track position uncertainties. The ratio of the impact parameter to its uncertainty is called the *impact parameter significance*.

- **Assign a shared track:** Assign the shared track to the more compatible vertex if the track’s 3D impact parameter significance with respect to that vertex is less than 5 and is smaller than the impact parameter significance with respect to other vertex. However, if both vertices are compatible with a shared track and their 3D impact parameter significances are less than 1.5, the shared track is assigned to the vertex with more tracks.
- **Pile-up track mitigation:** Vertices at this step may be contaminated by pile-up tracks from other primary vertices in the same event. To remove them, a track is removed if the absolute shift significance of a vertex along the z coordinate is greater than 3. We define shift significance as the ratio of the shift in the vertex when the track is removed to the uncertainty¹ of that shift, or so-called “dz-shift significance”. Every track in a vertex is evaluated and tracks are considered until a vertex has only two tracks left.

Figure 5.13 shows the distributions of the dz-shift significance (right) and the dz-shift value (left) for signal-like vertices. The vertices in $t\bar{t}$ and signal MC with high- and low- tracks in 2017 are compared.

- **Split-vertex reconstruction:** Occasionally, two vertices are associated with the same LLP decay. These vertices are called “split vertices.” They are merged when they are close in a 3D distance within 300 μm and have an

¹The uncertainty is defined as the square root of the absolute difference between the diagonal covariance matrix element along the z-axis(or cov_{zz}) of the vertex after the track removal to the one before the track removal.

angular separation within 0.5 rad. In addition, to avoid merging primary vertices, the pair is only merged when both vertices are displaced from the beamspot by at least 100 fm . Similar to the previous steps, a newly-merged vertex is fitted with the *Kalman* filter and satisfies the χ^2/ndof less than 5. After resolving split vertices, long-lived particle (LLP) decays in RPV SUSY models have been improved with a vertex better representing a decay position of an LLP.

Figure 5.14 shows the distributions of a pair of signal-like vertices by their 3D separation (right) and 2D angular separation (left). The distributions before (light-green) and after (dark-green) applying the criteria to merge the vertex pair in the same multijet event are compared. The simulated multijet signal sample is one of the RPV signal samples along with dijet signal samples that split-vertices are observable by the small angular separation. In particular, a pair of long-lived particles in multijet and dijet signals with slow-moving and large-mass LLPs is expected to have a near π radian in their angular separation. The distributions of both variables after this merging step demonstrate the effectiveness of the split-vertex criteria in the search. It resolves the angular characteristic of a split-vertex pair and improves the search sensitivity by migrating $7\text{--}8\%$ of multijet signal events to a larger d_{VV} bin.

With the Higgs boson being produced and recoiling from the initial state radiation (ISR) jets, a pair of LLP decays is separated by a small distance and angle. The impact of the split-vertex criteria is minimal in this benchmark model.

- **Shared-jet mitigation:** One interesting jet characteristic, commonly found in 90% of background events but relatively rare in most signals, is the ex-

istence of a “shared jet.” A shared jet is a jet that contributes tracks to two reconstructed vertices. In signals, the fraction of shared-jet events varies. It ranges between 40–50% in the RPV SUSY models, depending on masses and lifetimes. However, the fraction is higher in the exotic Higgs model. The fraction is 75-90%, which makes sense because the Higgs decays to a pair of LLPs in the same hemisphere, unlike RPV SUSY models where LLPs decay in opposite directions. Since these fractions in signals depend on their intrinsic topology, simply removing all shared-jet configurations is not practical. Therefore, only unphysical shared jets are mitigated. Two types of shared jets are considered:

- **Singleton track:** This occurs when a single track or a “singleton” lies in the hemisphere opposite to its associated vertex displacement vector. This track is likely to be a misreconstructed track causing an unphysical shared jet that needs to be mitigated. Such a misreconstructed track is discarded from the vertex to be refitted. The new vertex must satisfy $\chi^2/\text{ndof} < 5$.
- **Multiple tracks:** This occurs when there are multiple tracks from both vertices simultaneously pointing to the same shared jet. This shared jet is physically possible when jets from two vertices overlap one another, resulting in an overlapped jet. Hence, this case of shared jets is not mitigated.

Figure 5.15 compares the 2D angular separation of a good track truly originating from a vertex (left) and a singleton likely to be a misreconstructed track (right) with respect to its associated vertex displacement vector. The criterion to remove a singleton is $\cos(\theta_{\text{track}}) > 0.9$ since the majority of good tracks tends to fall within an angular separation

between 0 to 2.

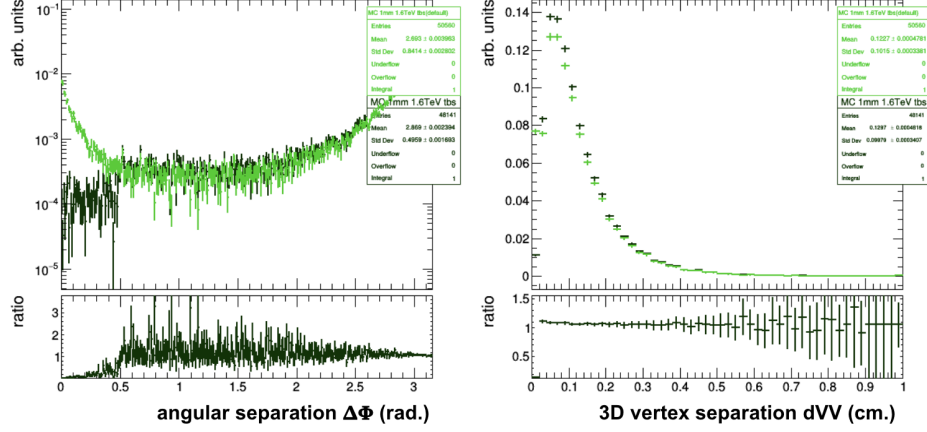


Figure 5.14: Comparison of the 3D vertex-position separation (right) and the 2D-angular separation (left) between any pairs of signal-like vertices in multijet-signal MC events with c of 1 mm and LSP mass of 1.6 TeV. A pair before merging split-vertices is shown in light green. A pair after resolving split-vertices by applying merging criteria is shown in dark green.

The main algorithm is defined as the steps from the seed vertex reconstruction to pile-up track mitigation, while the split-vertex reconstruction and shared-jet mitigation are added to improve signal sensitivity. The impact of shared-jet mitigation to reduce background events in signal region is approximately a factor of 2.5. Hence, it opens a venue to relax the impact parameter significance of seed tracks. Nevertheless, the study in Appendix A has shown that the displaced criterion is the most effective as $d_{xy} \gg d_{xy}^4$.

5.3.4 Vertex selection

After vertices are reconstructed in Sec. 5.3.3, there may be several candidates for displaced vertices in an event. To identify those that are signal-like, we impose

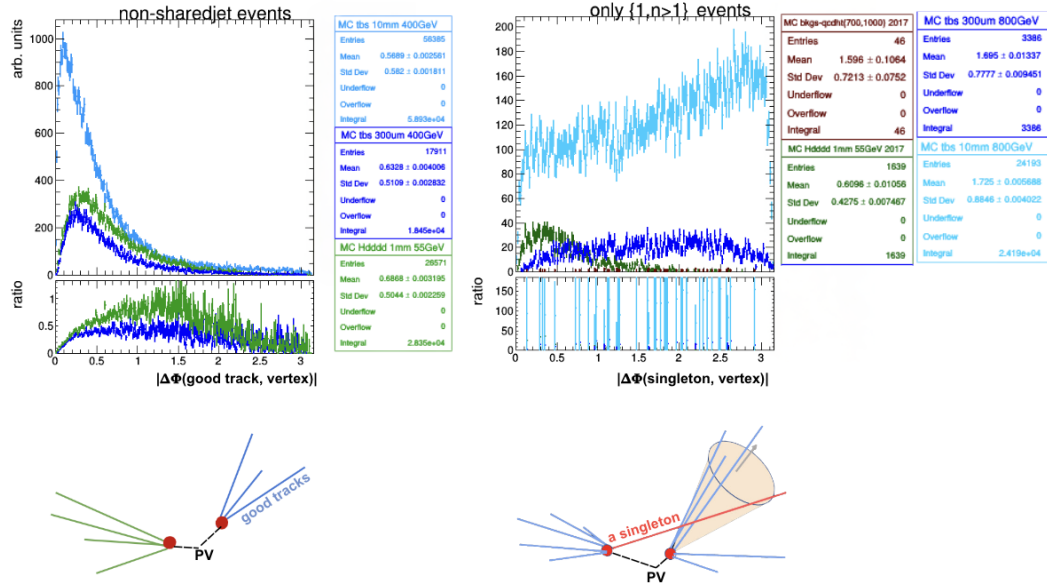


Figure 5.15: The 2D angular separation between a vertex's displacement vector from a beamspot and a 4-vector momentum vector of a vertex track. This is represented as $|\Delta\Phi(\text{good track, vertex})|$ or of a singleton as $|\Delta\Phi(\text{singleton, vertex})|$. (Left) The $|\Delta\Phi(\text{good track, vertex})|$ distributions are compared from various signals and tend to be less than 2. These signals include multijet with 400 GeV mass with 10 mm (light blue) and 300 m (dark blue) lifetime, as well as the exotic Higgs with 55 GeV mass and 1 mm lifetime (green). (Right) The $|\Delta\Phi(\text{singleton, vertex})|$ distributions are compared between background (brown) against multiple signals, including multijet with 800-GeV mass, 10-mm lifetime (light blue) or 300- m lifetime (dark blue), and the exotic Higgs with 55 GeV mass and 1 mm lifetime (green). The illustrations accompany a type of tracks associated with the variable being plotted.

the following vertex selection requirements:

- lying within the beam pipe to suppress vertices from material interactions (i.e. x-y distance of the vertex from the center of the beam pipe must be less than 20 mm in 2016 and 20.9 mm in 2017 and 2018)
- satisfying $d_{BV}^1 \leq 100$ m, which suppresses displaced primary vertices
- having at least five tracks
- having an uncertainty in d_{BV} , called $\sigma(d_{BV})$, of less than 50 m

The last three requirements in the above list are the same for 2016, 2017, and 2018 run conditions.

The last three requirements in the above list are the same for 2016, 2017, and 2018 run conditions. The relevant distributions for background and signal simulation are shown in Figure 5.16 and Figure 5.17. The first one uses the positions of the beam pipe center relative to the geometric center of CMS, which are (0.124, 0.070) cm in 2016, (0.113, -0.180) cm in 2017, and (0.171, -0.175) cm in 2018.

The vertex selection criterion based on the number of tracks per vertex (or ntrack/vertex) is the most powerful discriminating variable in the search for displaced vertices. It helps to distinguish signals from background. However, other vertex selection criteria are needed to preserve the signal region as a background-free region. d_{BV} has a minimum value to avoid selecting primary vertices. The maximum value is a radius with respect to a beamspot, which forms a circular constraint within the beampipe on a transverse plane, shown

¹The d_{BV} is the xy-separation of a vertex from the beamspot

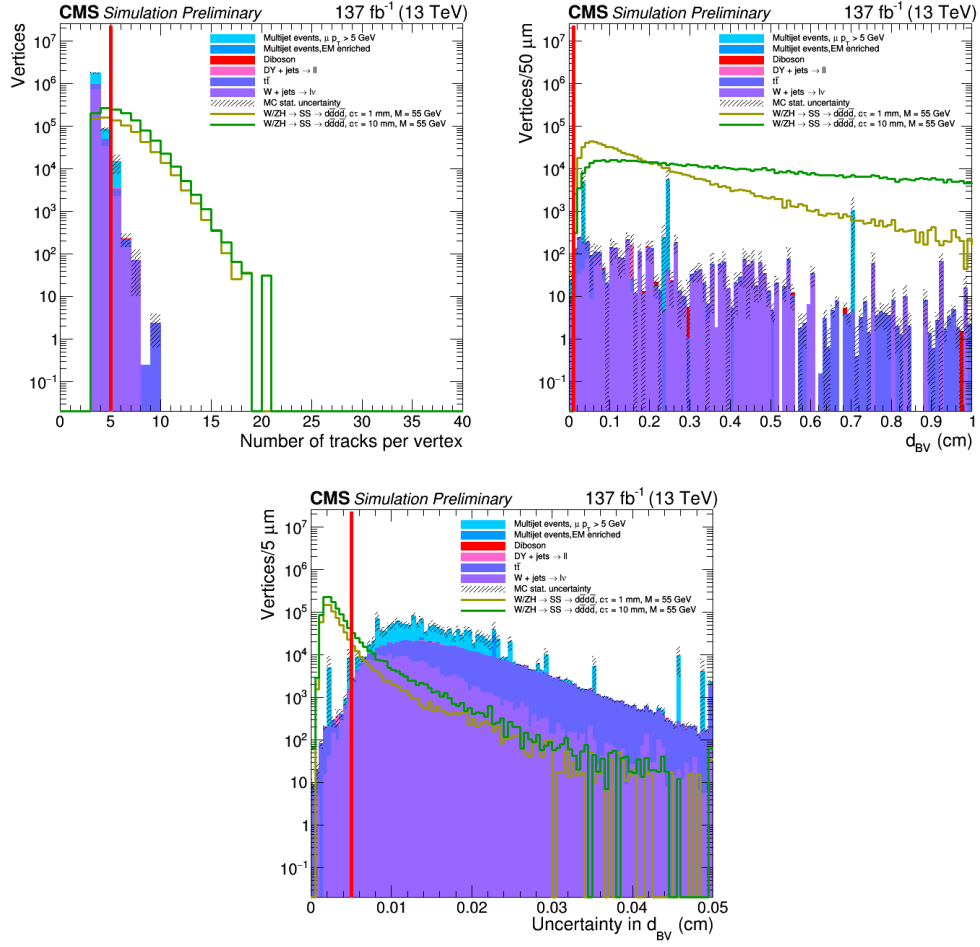


Figure 5.16: Comparisons between $t\bar{t}$ (navy), lepton-enriched QCD (blue), diboson (red), Drell-Yan (pink) and W+jets (violet) along with exotic Higgs signals via an associated vector boson (VH), which are 1-mm 55-GeV (green), and 10-mm 55-GeV (yellow) simulation of the three vertex selection requirements in one-vertex events. Each plot includes all vertex selection requirements except those on the plotted variable. Red lines show cut thresholds. The top left shows the requirement on number of tracks, which must be greater than 5. The top right shows the requirement on vertex displacement, which must be greater than 100 μ m. The bottom shows the requirement on d_{BV} , which must be less than 50 μ m. The Higgs are produced via W/Z-bosons and decay to a pair of long-lived scalars S of 1-mm 55-GeV (green), or 10-mm 55-GeV (yellow). While backgrounds are normalized to SM cross sections and run-2 luminosity, the signals are normalized assuming 100% $H \rightarrow SS$ branching fraction, multiplied by 10³.

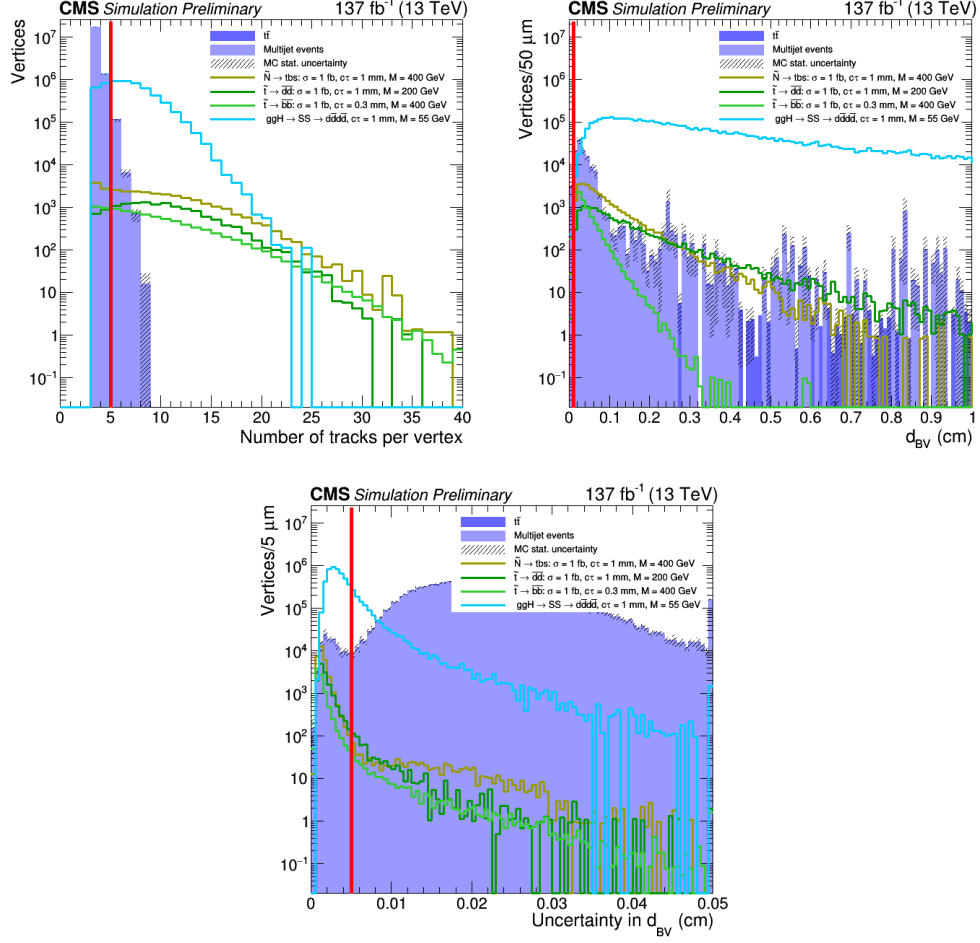


Figure 5.17: Comparisons between $t\bar{t}$ (navy) and QCD (violet) along with signal simulation including RPV multijet (yellow), RPV dijet (green) and exotic Higgs decays via gluon fusion (blue) of the three vertex selection requirements in one-vertex events. Each plot includes all vertex selection requirements except those on the plotted variable. Red lines show cut thresholds. The top left shows the requirement on number of tracks, which must be greater than 5. The top right shows the requirement on vertex displacement, which must be greater than 100 μm . The bottom shows the requirement on (d_{BV}) , which must be less than 50 μm . While backgrounds are normalized to SM cross sections and run-2 luminosity, the signals are normalized by expected yields multiplied by 10^3 . The RPV signal is assumed a 1 fb cross section and the exotic Higgs decay is assumed 100% $H \rightarrow SS$ branching fraction.

in Figure 5.18. This is a criterion to avoid selecting standard model particles interacting with the detector materials misidentifying as displaced vertices with multiple tracks. Lastly, the uncertainty of the 2D separation of a vertex from the beamspot (d_{BV}) is required to be less than 50 μm to suppress background from b-hadron decays. Since events being triggered by b-jet/displaced-jet triggers resemble b-hadron decays, the search becomes more sensitive to exotic Higgs signals, which tend to form a vertex with an uncertain position due to the collimation of the tracks associated with a reconstructed vertex. The criterion, therefore, has been relaxed from $d_{BV} = 25 \mu\text{m}$ to $d_{BV} = 50 \mu\text{m}$. Similarly, the relaxed cut is also applied to the RPV signals. Despite a more generous requirement on d_{BV} , new vertex reconstruction procedures such as shared-jet mitigation in Sec. 5.3.3 control the level of background in the signal region to be as close to zero.

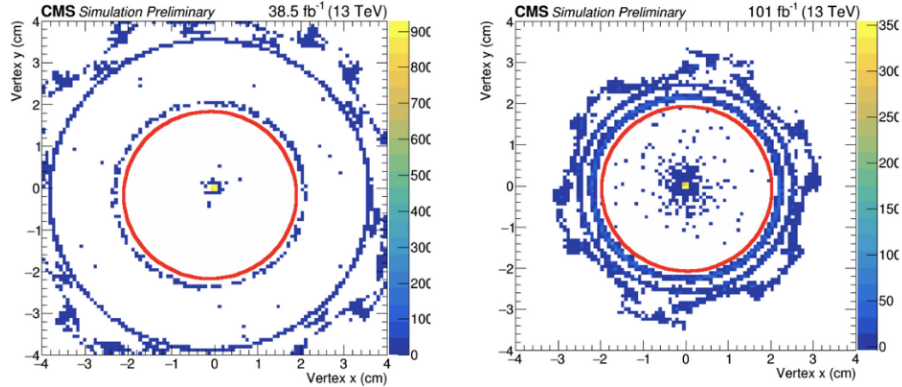


Figure 5.18: The x-y plane of the beamspot configuration for different years. (Right) The configuration in 2015 and 2016, showing the beamspot as yellow concentrated dots with its associated width. (Left) The configuration in 2017 and 2018, showing the beamspot as yellow concentrated dots with its associated width. The red circles on both plots represent the d_{BV} radius constraints, which are used to avoid selecting vertices from material interactions.

With these selection cuts applied to reconstructed vertices, the vertex number distributions of three-track, four-track, and five-or-more-track vertices are shown in Figure 5.19 as well as Figure 5.20. Signal-like vertices with at least five tracks are more common in signals than in background. The number of signal-like vertices in exotic Higgs events is around one vertex more than those in background events on average. In RPV SUSY signals, the number of signal-like vertices is even higher due to more massive long-lived particles such as stop or neutralino/gluino LSPs. Thus, the search region and control region (to be discussed in Sec. 5.4.1) are defined by the number of vertices in an event.

5.4 Search strategy

5.4.1 Signal and control region definition

Reconstructed vertices that pass the vertex selection criteria in Sec. 5.3.4 are referred to as “5-track” vertices due to the track-multiplicity selection. Similar to the previous displaced-vertex search with *HT*-triggers, the signal region is defined as events that have *at least two* 5-track vertices [70]. Such a search region is chosen to be distinctive from backgrounds, to be discussed in Sec. 5.4.3. Although signal yields are predicted using simulated events, the normalization of the background yield in the signal region is estimated using data with only one 5-track vertex.

We use a control region defined as events that have at least two vertices that pass all vertex selection criterion except that the number of tracks per vertex is either 3 or 4. In contrast with a signal region, the control region is mostly signal-

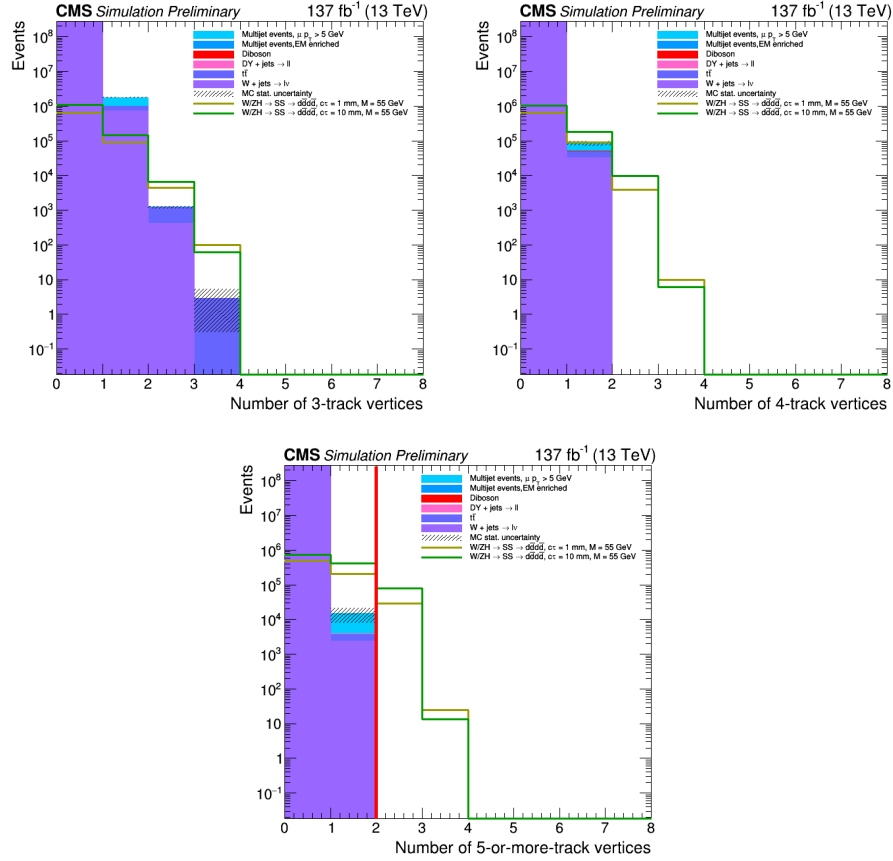


Figure 5.19: The number of 3-track (top left), 4-track (top right), and 5-track (bottom) vertices that satisfy a lepton trigger and all vertex requirements for simulated exotic Higgs signals and background, including $t\bar{t}$ (navy), lepton-enriched QCD (blue), diboson (red), Drell-Yan (pink) and W+jets (violet). The Higgs are produced via W/Z-bosons and decay to a pair of long-lived scalars S of 1-mm 55-GeV (green), or 10-mm 55-GeV (yellow). The signals are normalized assuming 100% $H \rightarrow SS$ branching fraction, multiplied by 10^3 .

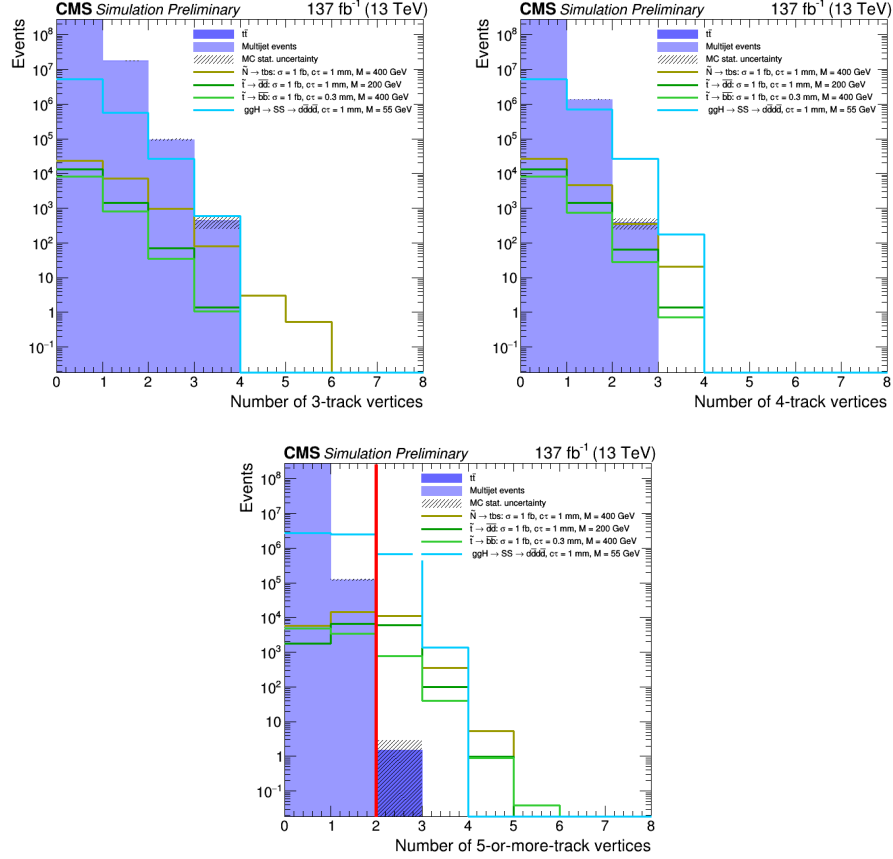


Figure 5.20: The number of 3-track (top left), 4-track (top right), and 5-track (bottom) vertices that satisfy a displacement trigger vetoed lepton events and all vertex requirements in simulated RPV multijet (yellow), RPV dijet (green) and exotic Higgs decays via gluon fusion (blue) signals and background, including $t\bar{t}$ (navy) and QCD (violet). The RPV signal is assumed a 1fb cross section and the exotic Higgs decay is assumed 100% $H \rightarrow SS$ branching fraction, multiplied by 10^3 .

free, making it suitable for background estimation and template construction (Sec. 5.4.2- 5.4.3).

5.4.2 Background template construction

The search variable in this analysis is the sum of two 2D displacements of two selected vertices with respect to a beamspot, denoted as d_{BV} . By constructing the d_{BV} distributions for signal and background events, the binned templates are derived and applied to data using maximum likelihood fitting. Specifically, the search template is divided into three bins in d_{BV} : 0-800 m , 800-1600 m , and 1600 m . The signal sensitivity is highest in the last two bins. In signals, two-vertex events are common, and the template is a direct distribution of d_{BV} . Several signal templates, as well as the constructed background templates, are shown in Figure 5.21 and Figure 5.22.

To derive a background template in data, we construct the d_{BV}^C by randomly selecting two one-vertex events. This method is also validated for the shapes of d_{BV} between data and simulation, creating a data-driven background template. It is reliable to use one-vertex events as input because two-vertex events are as correlated as two displaced vertices in background such as QCD or $t\bar{t}$. In fact, their displaced vertex is often formed by misreconstructed tracks that cross a cluster of tracks randomly. Hence, one-vertex events are sufficient to replicate the actual d_{BV} . However, the d_{BV}^C template from one-vertex events needs multiple corrections. These corrections concern nearby reconstructed vertices in the vertex reconstruction, primarily during the track arbitration and the split-vertex merging steps in Sec. 5.3.3.

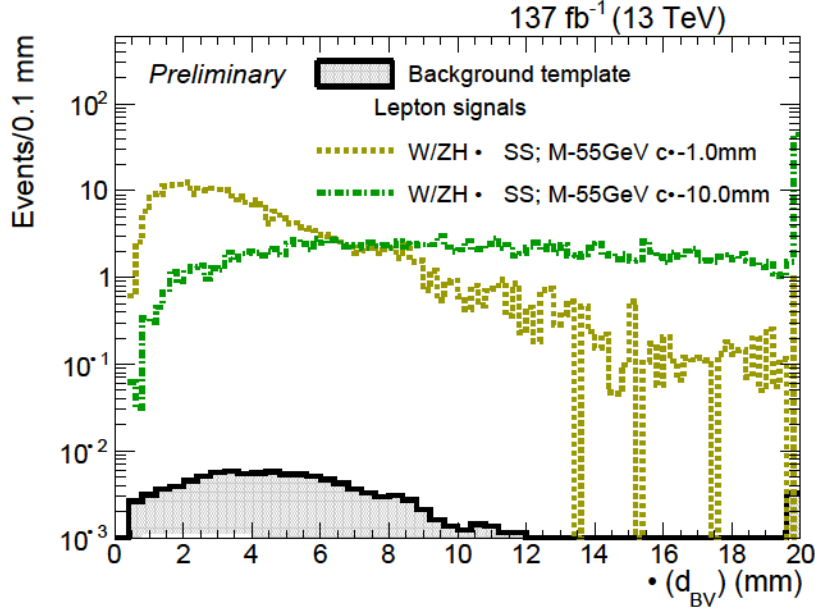


Figure 5.21: Comparison of Σd_{BV} template for ≥ 5 -track multiplicities between background simulation (gray shaded), and the VH 55-GeV signals with $c\tau = 1$ mm (yellow) and $c\tau = 10$ mm (green) using the single-lepton triggers. Plot made using all Run-2 conditions, which have been combined. Signal yields for normalization are based on $\text{Br}(H \rightarrow \text{SS}) = 100\%$

For sampling one-vertex events, d_{BV} and a uniform angular function of $1/\pi$ are selected to construct d_{VV}^C and Σd_{BV}^C . Since the decision to merge two vertices depends on their separation (d_{VV}), a penalty to find a nearby vertex-pair from d_{VV}^C must be propagated to Σd_{BV}^C . In order to derive such a penalty, the survival efficiency of vertex pairs as a function of d_{VV} is derived in background simulation. This function also depends on the number of tracks per vertex. Therefore, the construction of background templates is performed for each track-multiplicity category. The discrepancy in survival efficiencies between d_{VV}^C and d_{VV} is applied to the Σd_{BV}^C template. Finally, we derive Σd_{BV}^C templates, varying by the number of tracks per vertex, shown in Figure 5.23 and Figure 5.24.

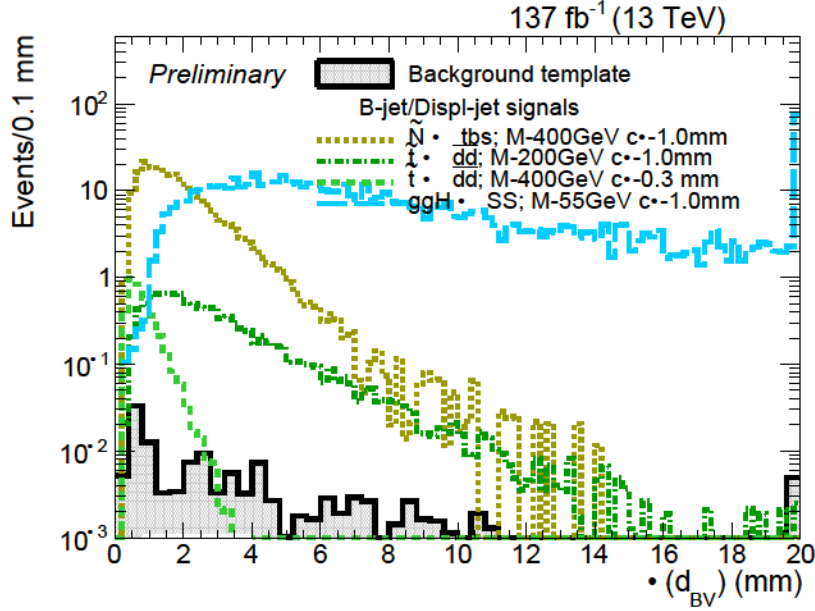


Figure 5.22: Comparison of Σd_{BV} template for ≥ 5 -track multiplicities between background simulation (gray shaded), RPV multi-jet benchmark model (yellow), RPV dijet benchmark model (green) and exotic Higgs (blue) hypotheses using the displaced vertex triggers. Plot made using only 2017 and 2018 run conditions, which have been combined. Signal yields for normalization are based on $\text{Br}(H \rightarrow \text{SS}) = 100\%$ and RPV cross-section of 1 fb.

To minimize statistical uncertainty associated with the background templates, the sampling procedure is performed repeatedly regardless of b-tagged events or not. The process continues until the number of one-vertex event pairs is 20 times greater than the total one-vertex events in data, as previously done [70]. For a validity check of the background template construction using simulation, the Σd_{BV} distributions in two-vertex events are compared to the Σd_{BV}^C templates. This validity check is termed *closure* if applied to data for unblinding. The comparison of Σd_{BV} distributions to Σd_{BV}^C templates is shown in Figure 5.23 and Figure 5.24, from simulated background selected by single lepton trigger and b-jet/displaced-jet triggers respectively.

In Figure 5.24, the agreement between the d_{BV}^C template and the simulated d_{BV} is within the statistical uncertainty of the simulation across categories. However, the Figure 5.23 shows a discrepancy between the d_{BV}^C template and the simulated d_{BV} near 1-3 mm. This discrepancy could be mitigated by correcting the fraction of b-tagged events of the template to match the b-tagged fraction in simulation. This is a work in progress.

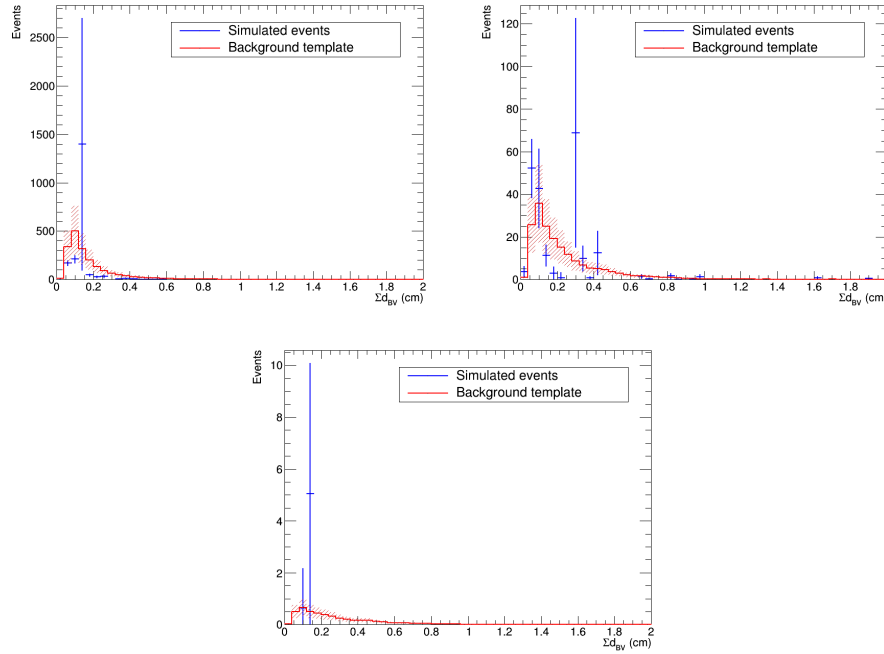


Figure 5.23: The comparison of 3-track two-vertex (top left), 3-track or 4-track two-vertex (top-right), and 4-track two-vertex (bottom) events by d_{BV} (or d_{BV}^C). Note that two-vertex templates are normalized to the predicted yield of a specific track-multiplicity category of the simulated Run-2 background, including QCD, W+jets, Drell-Yan, $t\bar{t}$, and diboson.

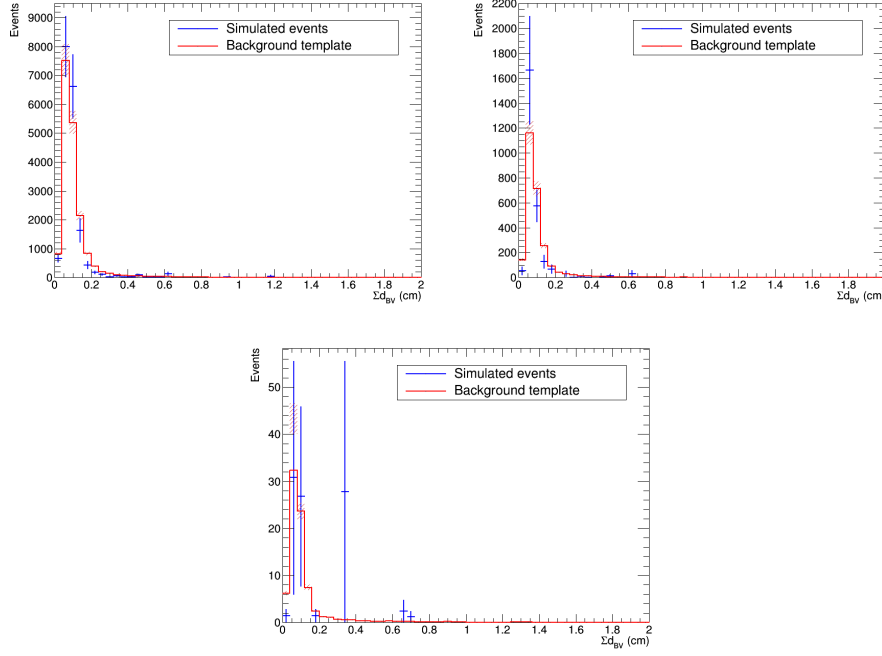


Figure 5.24: The comparison of 3-track two-vertex, 3-track or 4-track two-vertex, and 4-track two-vertex events from left to right by d_{BV} (or d_{BV}^C). Note that two-vertex templates are normalized to the predicted yield in a specific track-multiplicity category of the simulated Run-2 background, including $t\bar{t}$ and QCD.

5.4.3 Background template normalization

In the fits, we normalize the background template based on the results in Appendix B. The normalization is determined using the total yield of two-vertex events with 3 or more tracks and the proportions of the one-vertex events with 3, 4 or 5 or more tracks. The results are shown for lepton triggers in Table B.1- B.4 and for b-jet/displaced-jet triggers in Table B.5- B.8.

Any contamination of expected signal yields in the control region could lead to overestimation of the background in the signal region. However, the potential signal contamination is negligible in the current control region. This concern

Table 5.18: Predicted yield of 2-vertex events in background simulation by year in events passing single-lepton triggers.

		2016APV		2016		2017		2018	
3-track	3-track	33	3	81	4	317	27	1511	979
4-track	4-track	0.183	0.018	0.195	0.011	0.568	0.049	3.6	2.4
3-track	4-track	4.9	1.1	7.9	3.0	27	6	148	98
5-track	5-track	0	0	0.009	0.001	0.026	0.002	0.059	0.038

Table 5.19: Predicted yield of 2-vertex events in background simulation by year in events passing b-jet or displaced-jet triggers vetoed lepton events.

		2016APV		2016		2017		2018	
3-track	3-track	6623	714	3223	515	4132	982	4230	427
4-track	4-track	44	5	19	3	11	2	16	2
3-track	4-track	1084	124	495	84	420	112	519	68
5-track	5-track	0.518	0.057	0.129	0.021	0.100	0.024	0.068	0.007

will be discussed in Sec. 5.8.2.

5.5 Signal efficiency measurement

5.5.1 RPV SUSY signals

The simplified models of RPV SUSY signals are shown in Figure 5.1 for multijet (left), and for dijet (right). Since the lightest supersymmetric particles (LSPs) in these models are pair-produced from the interaction of protons, their decays

must conserve the total transverse momentum. As a result, if two LSPs are massive and slow-moving, their transverse momenta tend to be of the same order of magnitude and small, leading to "back-to-back" decays, where the two particles move in nearly opposite directions. It is less likely that their decays overlapped. Hence, LSP decays are isolated and are nearly impacted by the vertexing efficiency of another LSP decay in the same event. In addition, massive LSPs are more energetic, accompanied by more tracks associated with a displaced vertex, and are easily distinguished from background.

The signal yields of these models vary by signal efficiencies, that quantify the number of processed events passing online and offline trigger requirements as well as the event selection. Signal efficiencies by LSP mass points and lifetimes are shown in Figure 5.25, where its denominator is the total processed events. Signal efficiencies tend to be similar across multijet and dijet models of the same LSP mass and lifetime. On the other hand, within a specific RPV SUSY model, the signal efficiency increases in proportional to the LSP mass and lifetime. Moreover, the 2017 and 2018 data conditions are likely to have higher signal efficiencies because of the tracker that provides a better vertex reconstruction than the 2016 data condition.

The signal yield is calculated from the product of a signal efficiency (ϵ_{RPV}), the integrated luminosity in Run-2 ($\mathcal{L}$), the cross-section of pair-production (σ_{RPV}), and the square of the branching ratio of each LSP decay (BR^2):

$$N = \epsilon_{RPV} \mathcal{L} \sigma_{RPV} BR^2 \quad (5.2)$$

where the production cross-section for each RPV SUSY signal model is assumed to be 0.8, 0.25, and 0.15 fb for samples with $c = 0.3$, 1.0, and 10 mm, respec-

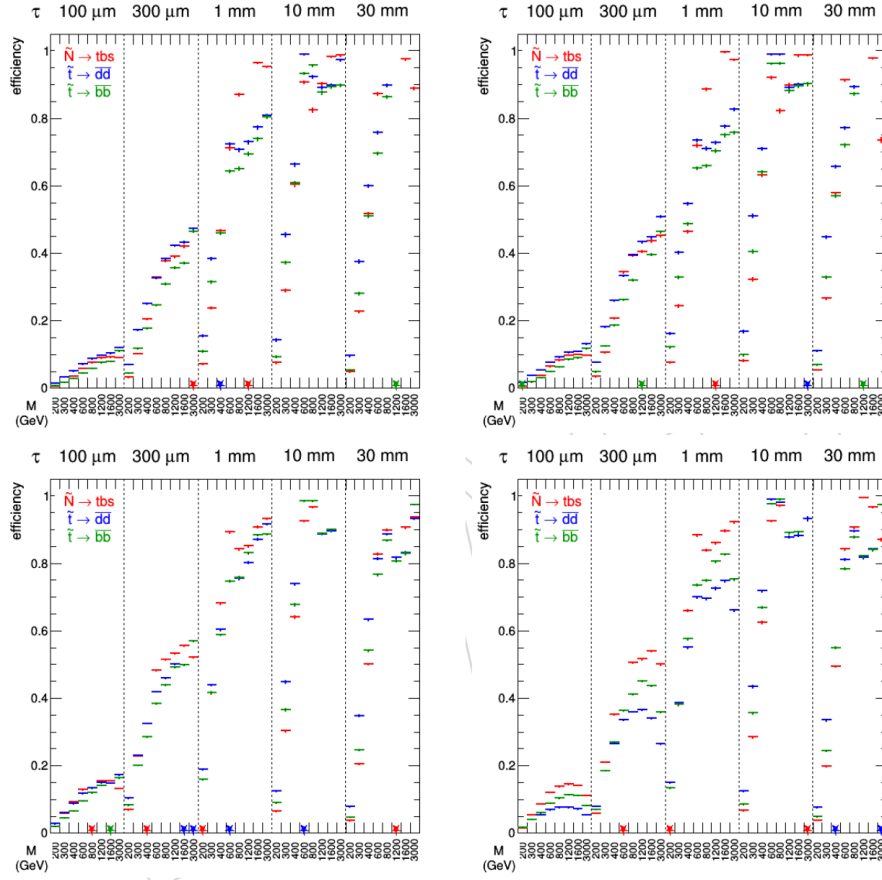


Figure 5.25: Signal efficiency (i.e. fraction of processed simulated events passing online and offline trigger requirements as well as the signal-region event selection) as a function of LSP mass and lifetime for RPV signal models in 2016APV (top left), 2016 (top right), 2017 (bottom left), and 2018 (bottom right). The efficiencies are shown for multijet signals (red), dijet signals with d-quark final state (blue), and dijet signals with b-quark final state (green). Figure credit: Shaun Hogan.

tively [70].

5.5.2 Exotic Higgs signals

Another BSM model that this search is sensitive to is the decay of the SM Higgs boson to a pair of scalar particles or long-lived particles (LLPs). Figure 5.2 shows two simplified Feynman's diagrams of exotic Higgs decays: one via the gluon-fusion Higgs production (right), and the other via the association of Z boson (left). In these two production modes, the SM Higgs is produced from the primary vertex promptly while recoiling against another jet (right) or radiating from a vector boson (left). This effect leads to a topology of LLP pairs that can be close in spatial and angular separation.

For exotic Higgs decays, we use three LLP mass (M_S) hypotheses: 15, 40, and 55 GeV. The 15-GeV mass is more boosted (i.e. large β) than higher-mass LLPs. It is kinematically allowed to decay almost back-to-back to another 15-GeV LLP decay. For example, the large opening angle distributions of the 15-GeV exotic Higgs signals produced by an associated Z-boson with 1-mm (red) and 10-mm (magenta) proper lifetimes are shown in Figure 5.26 (left). However, with a low mass itself, the daughter particles manifesting as a pair of jets are not well-separated in 3D angles, shown in Figure 5.26 (right). The boosted decay of 15-GeV LLPs results in a large vertex position uncertainty ($\sigma_{d_{BV}}$), causing low vertexing efficiency in this model. In contrast, the decay position of 55-GeV LLPs tends to separate from another decay in the same event by a right angle. Frequently, two 55-GeV LLP decays can overlap in angular separation and displacement. This leads to an overlapped "shared-jet" and overlapped

LLP decays, as shown in the 1-mm 55-GeV exotic Higgs signals in Sec. 5.3.3 and Sec. 5.8.1. Figure 5.26 (left) demonstrates a small 3D-angular separation between two 55-GeV LLP decay vertices at truth level, whereas Figure 5.26 (right) shows a wide 3D-angular separation between jets decaying from a 55-GeV LLP with 1-mm (green) or 10-mm (blue) proper lifetimes.

Exotic Higgs signal efficiencies across lifetimes and mass points are shown in Figure 5.27. Signal efficiencies increase with LLP mass as expected. Interestingly, the mean proper lifetimes between 1-3 mm seem to be the most sensitive region for this model instead of those beyond 3 mm as in the RPV SUSY models. The 2017 and 2018 data conditions provide higher signal efficiencies than 2016 data conditions.

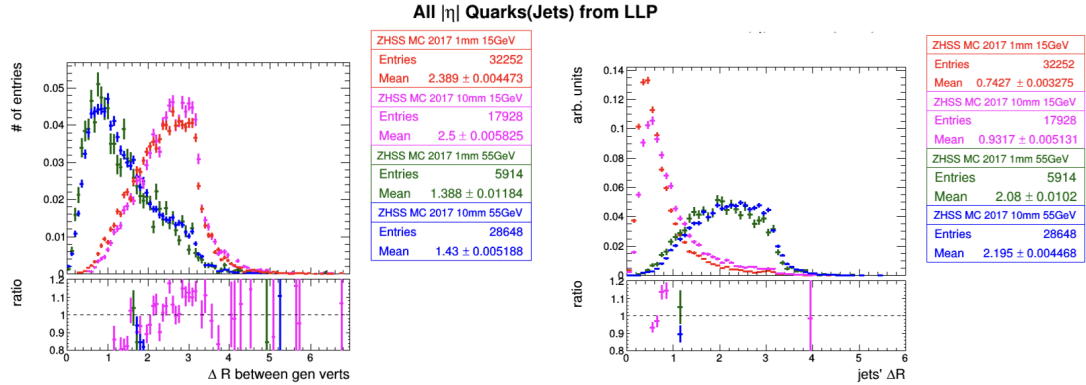


Figure 5.26: Comparison of 3D-angular separation of LLP decay vertices by truth information (left) and of a pair of jets associated with the same LLP (right) by lifetimes and mass points. The exotic Higgs signals via Z vector boson association in 2017 are 1 mm (red) and 10 mm (magenta) for 15-GeV LLPs, and 1 mm (green) and 10 mm (blue) for 55-GeV LLPs.

In addition to the vector-boson production mode shown in Figure 5.27, another production mode of the exotic Higgs signal is via gluon-fusion, which can

be selected by b-jet/displaced-jet triggers instead of single lepton triggers. The signal efficiencies for 55-GeV LLPs selected by these triggers are shown in Figure 5.28. Unlike the trend in the previous production mode, the signal efficiency peaks at around 10-mm proper lifetime up to 5%.

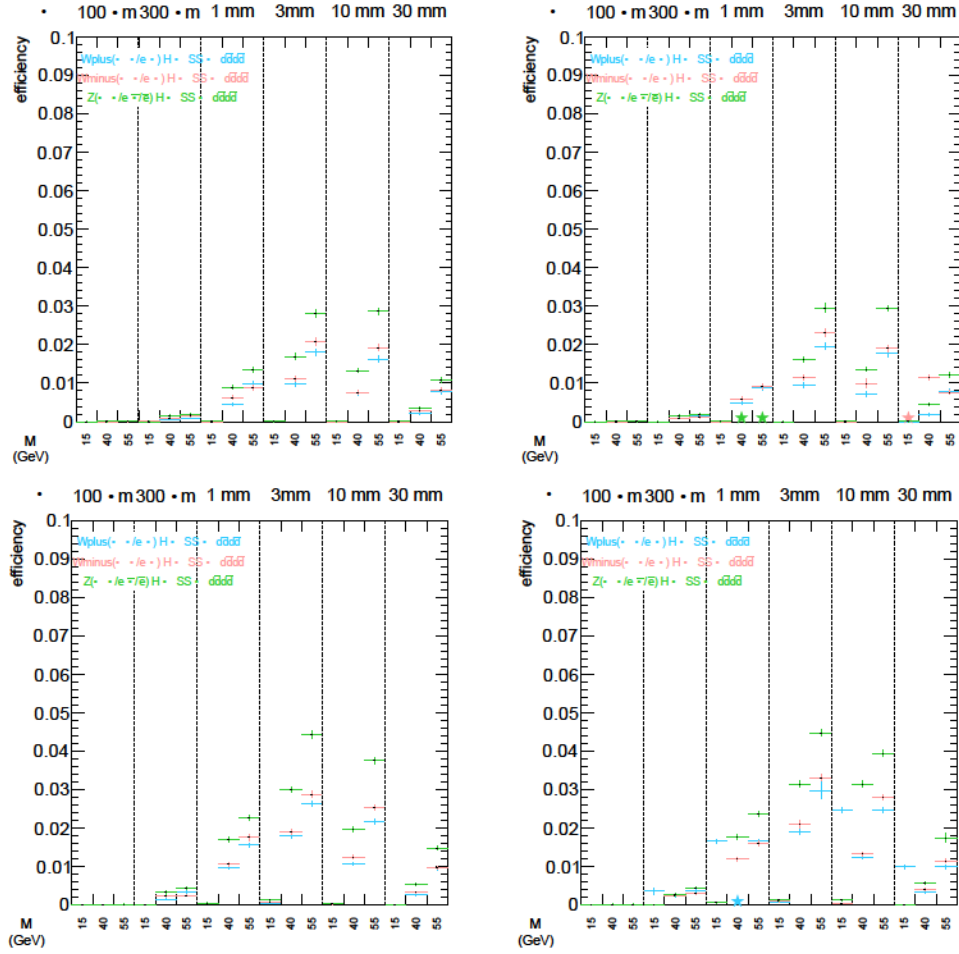


Figure 5.27: Efficiency for signal simulation to pass at least one trigger and its corresponding offline selection requirements for the exotic Higgs models with the Higgs boson produced via W^+ boson (blue), W^- boson (pink), and Z boson (green). The Higgs boson decays to a pair of long-lived scalars S under 2016APV (top left), 2016 (top right), 2017 (bottom left), and 2018 (bottom right) conditions as a function of mass and lifetime.

As a matter of fact, all exotic Higgs signal efficiencies in this analysis are

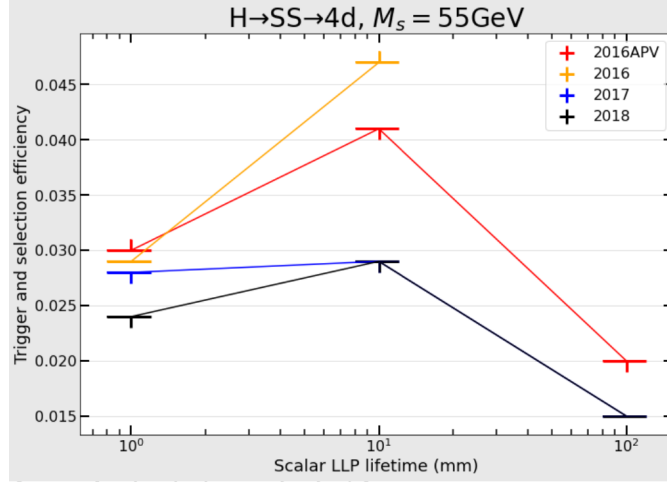


Figure 5.28: Signal efficiency (i.e. fraction of processed simulated events passing online and offline trigger requirements as well as signal-region event selection) as a function of lifetimes for exotic Higgs models with LLP mass of 55 GeV. The efficiencies are shown for 2016APV (red), 2016 (yellow), 2017 (blue), and 2018 (black) data conditions. Note the suppressed y-axis. Figure credit: Shaun Hogan.

low, but RPV SUSY signal efficiencies can be as high as nearly 100%. However, we can still expect high signal yields from exotic Higgs signals production because their production cross-sections are at least three orders of magnitude higher than the RPV SUSY predicted cross-sections. The associated Z boson and W boson production modes (VH) have cross-sections of 0.88 pb and 1.378 pb, respectively. In contrast, the gluon-fusion production mode (ggH) has a cross-section of 48.6 pb. Analogous to an estimation of signal yields for RPV SUSY models, the exotic Higgs signal yield can be expressed as:

$$N = \epsilon_{VH \text{ } ggH} \mathcal{L} \sigma_{VH \text{ } ggH} BR(H \rightarrow SS) \quad (5.3)$$

where the signal efficiency ($\epsilon_{VH \text{ } ggH}$) is the signal efficiency for finding a pair of selected vertices as mentioned, and the branching ratio ($BR(H \rightarrow SS)$) is as-

Table 5.20: Expected yields for benchmark signal modes before corrections. Higgs decays assume 100% branching fraction to SS . The RPV modes $\tilde{t} \rightarrow \bar{d}\bar{d}$ and $\tilde{g} \rightarrow tbs$ assume pair-production cross sections of 1 fb. The c of the LLP is given in the parentheses.

		3-track				4-track				5-track			
		1-vtx		2-vtx		1-vtx		2-vtx		1-vtx		2-vtx	
Triggered													
Lepton triggers													
$V(H \rightarrow SS), M_S = 55 \text{ GeV (1 mm)}$	18319 46	2253 16	113 3	2305 16	95 5 3 3	5122 24	726 9						
$V(H \rightarrow SS), M_S = 55 \text{ GeV (10 mm)}$	18924 43	2265 15	103 3	2801 16	147 3 3 9	6454 26	1223 11						
Displacement triggers vetoed lepton triggers													
$gg(H \rightarrow SS), M_S = 55 \text{ GeV (1 mm)}$	53158 218	5052 67	245 14	6153 74	255 15	22697 143	5915 73						
$\tilde{t} \rightarrow \bar{d}\bar{d}, M_{\tilde{t}} = 200 \text{ GeV (1 mm)}$	34 1 0 3	3 4 0 1	0 18 0 02	3 4 0 1	0 17 0 02	15 4 0 2	14 5 0 2						
$\tilde{t} \rightarrow \bar{d}\bar{d}, M_{\tilde{t}} = 400 \text{ GeV (0.3 mm)}$	101 8 0 3	9 1 0 1	0 42 0 02	8 3 0 1	0 32 0 02	39 1 0 2	9 1 0 1						
$^{-0} \tilde{g} \rightarrow tbs, M_{\tilde{g}} = 400 \text{ GeV (1 mm)}$	88 5 0 5	19 8 0 2	2 95 0 08	12 9 0 2	1 05 0 05	41 0 0 3	31 6 0 3						

sumed to be 1.0 for all exotic Higgs models, despite a current constraint on an invisible decay of the SM Higgs in Sec. 2.1.5.

5.6 Signal yields

Expected signal yields based on the calculation in Sec. 5.5 in 2017 from simulation appear in Table 5.20 for representative modes.

5.7 Background yields

The yield of simulated background events selected by single lepton triggers in Run-2 are in Table 5.21, while the vertex number distributions of three-track, four-track, and five-or-more-track vertices are shown in Figure 5.19. We observe no simulated background events with two or more 4- or 5-track vertices.

Analogously, the yield of simulated background events in Run-2 with two or more displaced vertices in the displaced-trigger channel are in Table 5.22. The vertex number distributions of three-track, four-track, and five-or-more-track vertices are shown in Figure 5.20. We observe no simulated background events with two or more 4- or 5-track vertices.

5.8 Systematic uncertainties

5.8.1 Systematic uncertainties in signal yields

In Sec. 5.5, signal yields are estimated from the signal efficiencies obtained from simulation as well as statistics of the collected data. There are uncertainties associated with both the signal efficiencies and the data statistics. In terms of the signal efficiencies in this LLP search, they are mainly driven by trigger efficiencies, and the reconstruction of physics objects such as selected tracks and displaced vertices. Pile-up effects, however, are mitigated and reduce signal efficiencies. On the other hand, the likelihood of a specific physics process is determined by the luminosity in the data-taking period and the center of mass energy of the proton-proton collision. Each source contributing to the systematic uncertainties of signal yields is explained in this section.

Track reconstruction

After track error rescaling is applied to tracks in simulation (Sec. 5.3.2), the track reconstruction efficiency is measured. The difference in tracking efficiencies in

Table 5.21: Yields of 1-vertex and 2-vertex events for various track multiplicities in Run-2 simulated background samples for the lepton triggers. All samples have been normalized to their expected cross-section.

Preselected			3-track				4-track				5-track							
			1-vertex		2-vertex		1-vertex		2-vertex		1-vertex		2-vertex					
dyjetstollM10	4504050	2122	3878	62	0	0	89	9	00	00	18	1	4	3	000	000		
dyjetstollM50	75439014	8685	60493	245	68	8	2770	52	2	2	1	5	358	7	18	9	000	000
qcdbctoept015	6469	80	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdbctoept020	51276	226	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdbctoept030	1191957	1091	2971	54	0	0	0	0	00	00	00	00	000	000	000	000		
qcdbctoept080	401836	633	4116	64	0	0	200	14	00	00	00	00	000	000	000	000		
qcdbctoept170	40105	200	359	18	5	2	0	0	00	00	00	00	000	000	000	000		
qcdbctoept250	12294	110	161	12	0	0	1	1	00	00	00	00	000	000	000	000		
qcdempt015	125400	354	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt020	2057090	1434	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt030	7276263	2697	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt050	4928146	2219	11273	106	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt080	1442483	1201	5931	77	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt120	336468	580	710	26	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt170	104417	323	418	20	0	0	0	0	00	00	00	00	000	000	000	000		
qcdempt300	9751	98	138	11	0	0	0	0	00	00	00	00	000	000	000	000		
qcdmupt15	92618427	9623	260189	510	1089	33	14606	120	00	00	2635	9	51	3	000	000		
ttbar	13172337	3629	173383	416	617	24	10416	102	1	9	1	4	855	3	29	2	000	000
wjetstolnu0j	268176637	16376	200638	447	120	10	8900	94	00	00	557	2	23	6	000	000		
wjetstolnu1j	132099086	11493	84890	291	57	7	3781	61	00	00	350	8	18	7	000	000		
wjetstolnu2j	58759942	7665	54017	232	67	8	2440	49	00	00	210	3	14	5	000	000		
ww	854213	924	711	26	2	1	38	6	00	00	4	4	2	1	000	000		
wz	235092	484	323	17	0	0	26	5	00	00	4	1	2	0	000	000		
zz	75893	275	152	12	0	0	8	2	00	00	1	3	1	1	000	000		
qcdpt15mupt5	168121	410	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
qcdpt20mupt5	2082796	1443	3654	60	0	0	0	0	00	00	00	00	000	000	000	000		
qcdpt30mupt5	12480776	3532	41759	204	0	0	1347	36	00	00	1347	1	36	7	000	000		
qcdpt50mupt5	12267402	3502	33385	182	0	0	1236	35	00	00	412	2	20	3	000	000		
qcdpt80mupt5	3306651	1818	10797	103	0	0	421	20	00	00	84	4	9	2	000	000		
qcdpt120mupt5	707677	841	3795	61	0	0	99	9	00	00	00	00	000	000	000	000		
qcdpt170mupt5	211917	460	1106	33	6	2	61	7	00	00	00	00	000	000	000	000		
qcdpt300mupt5	17606	132	104	10	0	0	5	2	00	00	0	4	0	7	000	000		
qcdpt470mupt5	1665	40	14	3	0	0	0	0	00	00	00	00	000	000	000	000		
qcdpt600mupt5	526	22	4	2	0	0	0	0	00	00	00	0	1	000	000	000		
qcdpt800mupt5	101	10	0	0	0	0	0	0	00	00	00	0	1	000	000	000		
qcdpt1000mupt5	36	6	0	0	0	0	0	0	00	00	00	00	000	000	000	000		
total	695163934	26365	959384	979	2036	45	46455	215	4	0	2	0	6840	2	82	7	000	000

Table 5.22: Yields of 1-vertex and 2-vertex events for various track multiplicities in Run-2 simulated background samples for the displacement triggers vetoed lepton events. All samples have been normalized to their expected cross-section.

Preselected			3-track				4-track				5-track			
			1-vertex		2-vertex		1-vertex		2-vertex		1-vertex		2-vertex	
qcdht0100	981561	990	12281	110	0	0	0	0	0 0	0 0	0 0	0 0	0 00	0 00
qcdht0200	5915793	2432	78029	279	0	0	0	0	0 0	0 0	1408 4	37 5	0 00	0 00
qcdht0300	41423371	6436	787352	887	5068	71	50606	224	0 0	0 0	4491 6	67 0	0 00	0 00
qcdht0500	62551612	7908	1095478	1046	7299	85	81190	284	0 0	0 0	6868 5	82 9	0 00	0 00
qcdht0700	29011307	5386	541766	736	3577	59	43518	208	18 1	4 2	3709 2	60 9	0 00	0 00
qcdht1000	4947388	2224	108008	328	834	28	9646	98	2 7	1 7	839 7	29 0	0 00	0 00
qcdht1500	50639	225	808	28	2	1	77	8	0 4	0 6	6 8	2 6	0 00	0 00
qcdht2000	11333	106	174	13	1	1	20	4	0 0	0 0	2 2	1 5	0 00	0 00
ttbar	4434822	2105	181945	426	1508	38	13661	116	9 1	3 0	1092 5	33 1	0 00	0 00
total	149327830	12219	2805845	1675	18292	135	198721	445	30 3	5 5	18418 9	135 7	0 00	0 00

data and simulation is quantified as the uncertainty of track reconstruction. If the chance to reconstruct a displaced track differs in simulated signals from what is supposed to be in data, the success of reconstructing a displaced vertex can alter. This is especially important because the vertex selection requires at least five total tracks per vertex. For instance, if a displaced vertex is expected to have five associated tracks in simulation, but poorer tracking efficiency in data results in the reconstruction of a vertex with fewer tracks, the signal yield becomes overestimated. Therefore, tracking efficiency is the first source of systematic uncertainty for a signal yield to consider.

The displaced analysis relies on a data-driven method to measure the tracking efficiency uncertainty. The method uses samples of K_S^0 mesons or short-lived Kaons in data and simulation, in which the K_S^0 mesons decay far from the primary interaction point. Their decay products, two charged pions, are studied further, although the K_S^0 mesons can also decay into a pair of neutral pions.

Two charged pions in the chosen decay correspond to a positively and negatively charged tracks, that are originated at the K_S^0 production point, analogous to seed tracks in Sec. 5.3.1.

The event selection criteria for this tracking efficiency study are as follows. We trigger on Z boson decays to a pair of muons. Selected muons must satisfy the requirements outlined in Sec. 5.2. The reason we trigger on Z bosons decaying to two muons is that jets containing Z bosons have a good probability of also containing K_S^0 mesons. K_S^0 meson is a Standard Model particle with displaced tracks, corresponding to a candidate K_S^0 decay vertex that can be reconstructed as a K_S^0 meson invariant mass. Such a vertex is required to pass $d_{BV} < 0.2$ cm, a minimum K_S^0 transverse momentum of 2 GeV, and a minimum value of 0.99975 for the square of the cosine of the angle between the K_S^0 momentum vector and its displacement vector to reduce backgrounds. Finally, the K_S^0 vertex is required to have a $\chi^2/\text{dof} < 7$.

The peak of the K_S^0 mass distribution is expected to be around 0.498 GeV. The invariant mass window is chosen to be 0.40 GeV to 0.69 GeV to subtract background from other physics processes. Background subtraction is performed by removing background events below the fitted function (red) in Figure 5.29. The remaining events, therefore, are used to derive K_S^0 vertex reconstruction efficiencies in data and simulation. The discrepancy between them is attributed to both tracking resolutions and tracking efficiencies. A plot of the data/MC track reconstruction efficiency ratios of the extracted signal events is found in Figure 5.30 before binning by d_{xy} , p_T . A clear discrepancy between the track reconstruction efficiency in data and MC can be seen that increases to $\sim 10\%$ at 0.3 cm. The correction for d_{xy} resolution is in progress. Work to date suggests

that resolution differences between data and simulation account for most of the observed deficit of large d_{xy} tracks in simulation. The remaining difference will provide the systematic uncertainty due to tracking reconstruction inefficiencies for tracks with large displacements.

Figure 5.31 shows the simultaneously-fitted functions from the ratios of normalized K_S^0 events in the data and simulation after performing the background subtraction by d_{xy} binning. There are the total 105 bins of d_{xy} in the range of 0 to 0.3 cm, varying by row-wise and p_T column-wise of the K_S^0 mesons. The goodness of the fitting result of $\chi^2/\text{ndof} = 158.89/177$.

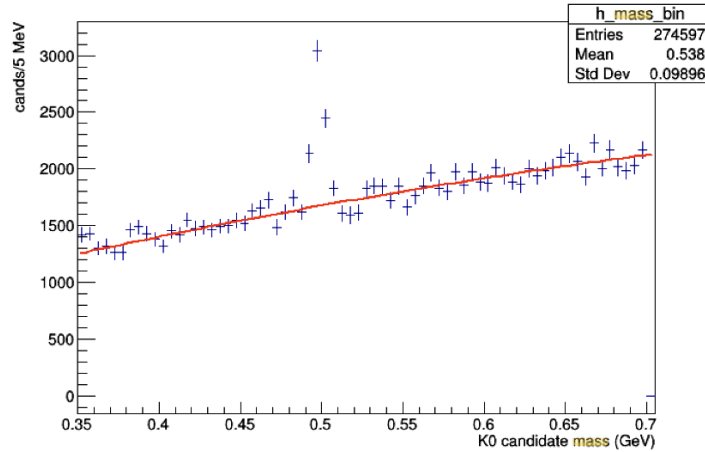


Figure 5.29: The distribution of K_S^0 invariant mass in a chosen window from one of d_{xy} and p_T bins of a simulated sample. K_S^0 background events are lying below the red fitted function. After subtracting these background events, the remaining events are K_S^0 meson decays. These decays are used for determining vertex reconstruction efficiency. Figure credit: Alec Duquette.

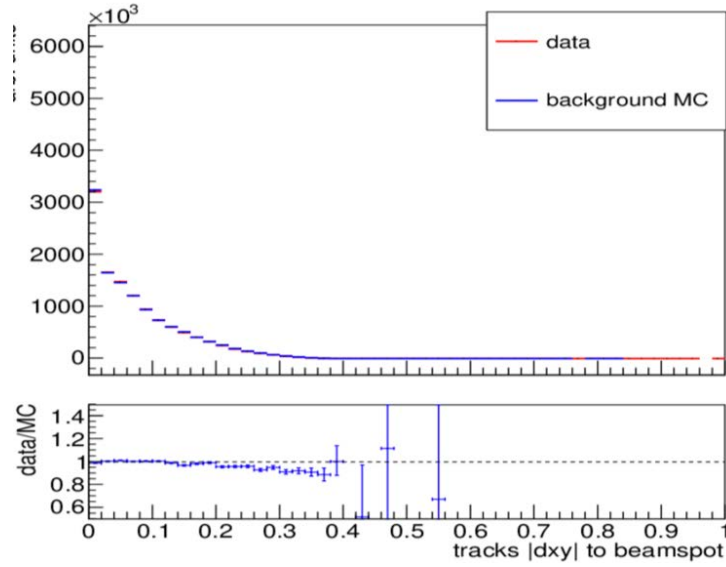


Figure 5.30: The distribution of the absolute value of the track impact parameter (d_{xy}) of the charged daughter pion with the largest value in a K_S^0 decay candidate vertex that is reconstructed within 1.9 cm of the beam spot, after background subtraction. Clear deviation from unity can be seen in the data/MC plot. Figure credit: Alec Duquette.

Vertex reconstruction

Differences in the vertex reconstruction efficiencies of data and simulation are an important source of systematic uncertainty. To assess this uncertainty, we have developed a data-driven method, “TrackMover” (TM), in which we move tracks in SM jets from the primary vertex (PV) to create a displaced vertex, and then determine the efficiency for reconstructing that vertex. To ensure that the results are applicable to our signal, we select the moved jets and weight the TM events so that the moved vertices replicate the important features of the signal. Since the efficiency of finding the vertex depends on the selection of the selected tracks, the TM study addresses the uncertainty of finding the vertex that is also dependent on the selection. This section presents detailed results for H → SS where S is an LLP with

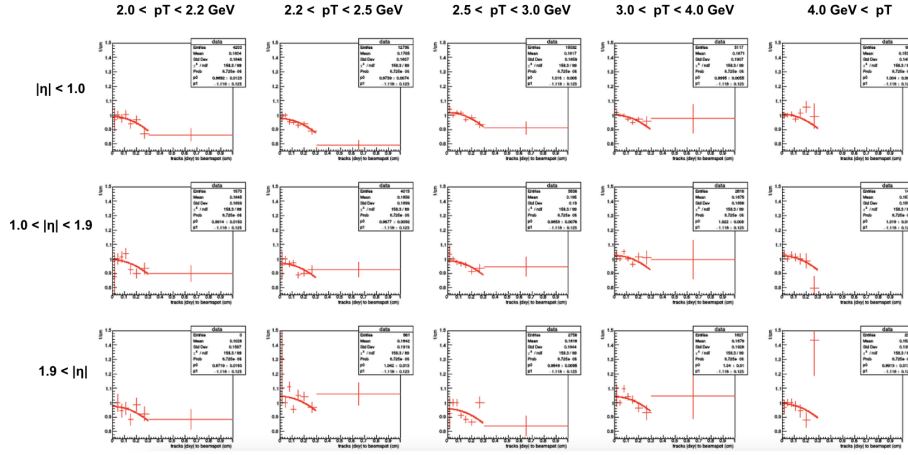


Figure 5.31: After subtracting background events from the K_S^0 mass peak as in Figure 5.29, the ratios of the d_{xy} distributions in data over normalized simulation are derived. These ratios are calculated for the charged tracks in each bin of d_{xy} and p_T . A simultaneous fit function is applied to the bins by d_{xy} , d_{xy} , and p_T , except the last d_{xy} -bin of each p_T binning. Figure credit: Alec Duquette.

mass 55 GeV and $c = 1$ mm and the Higgs has been produced in association with a W or Z; the results for other modes and parameters are summarized in the Appendix C. Because track characteristics such as impact parameter uncertainties are dataset dependent, we separately evaluate the vertexing efficiency 2016 and the later data sets.

This study utilizes events chosen using the triggers and offline selection criteria described in Sec. 5.2. In addition, for electrons, if $d_{xybs} < 0.05$ cm and $d_{zpv} < 0.1$ cm and otherwise, we require $d_{xybs} < 0.1$ cm, and $d_{zpv} < 0.2$ cm. Here, d_{xybs} refers to the electron miss distance in the x-y plane relative to the beam spot and d_{zpv} refers to the miss distance in z relative to the primary vertex. Offline muons must satisfy the additional requirements $d_{xybs} < 0.02$ cm, and $d_{zpv} < 0.5$ cm.

In detail, the steps are as follows:

- **Step 1:** In simulated background and data events, select light jets at random. Each selected jet must have at least two tracks. For signals with a two-body decay, such as exotic Higgs and RPV dijet, select two light jets. For signals with a three-body decay, such as RPV multijet, select three light jets.
- **Step 2:** Select tracks in the jets that pass all track quality criteria (Sec. 5.3.1) except $d_{xy} < 4$. Translate these tracks to an exponentially distributed *artificial vertex* position by shifting their d_{xy} . The artificial vertex positions are later reweighted to replicate various signal modes and lifetimes. Because the LLP momentum is aligned with its displacement, the direction of the artificial vertex is aligned with the net jet momentum after smearing by up to 0.2 radians in ϕ and θ , where the smearing approximately replicates mismeasurements of the jet momentum.
- **Step 3:** Impose online and offline trigger selection (from Sec. 5.2). Artificial vertices in TrackMover events, as well as LLP decay points in signal events, must have a radial displacement less than 2.4 cm, measured with respect to the primary vertex.
- **Step 4:** Reweight the TM events based on the jet distributions to replicate signal MC (see below). For the exotic Higgs models, we translate only about half of the tracks, and select them at random to properly replicate the very low p_T jets in the signal events.
- **Step 5:** Select seed tracks and reconstruct vertices as usual.

Importantly, TM emulates isolated LLP decays, but not pairs of vertices that may overlap. For comparison of TM with signal MC, we look only at

signal events in which the LLP decays that are well-separated. To enforce this, we impose the separation between LLP decay points greater than 360 m , and $R = 0.4$ between quarks in signal MC, and for parallelism, we impose $R = 0.4$ between moved jets in TM MC and data. At the end of this Section, we address cases in which the two LLP decays are close together.

Because tracks are constrained by the tracker acceptance, requirements are imposed on the quarks from the LLP decays. Both quarks must satisfy $\Delta\eta > 2.5$ (signal MC). This reduces the signal efficiency at the sub-percent level.

Emulating signal in TM events

By default, the event topology and jet kinematics in TM events differ from those in signal events. For instance, in exotic Higgs signals, the quarks are often too soft to produce “jets” by the CMS definition, which requires jets to have a transverse momentum (p_T) greater than 20 GeV . In signals, there is a clump of displaced tracks near a decay point with total momenta of less than 20 GeV . We find moving about half of tracks in reco jets approximately replicates the signal kinematics.

So that TM events better echo signal events, we reweight the TM MC and TM data based on event kinematics and topology. With the decision to move only half of the tracks, key kinematic variables between TrackMover and signal events are distributed with similar shapes. At that point, they can be reweighted to match one another, using weights that are of order unity.

Specifically, we reweight the TM events based on the opening angle between jets (ΔR) and the kinematic variable p_{LLP} . The variable p_{LLP} is defined as the

sum of p of all quality tracks that have been moved (in TM) or that pass within 10° of the LLP decay point and lie within a cone of radius $R = 0.4$ of a quark produced in the LLP decay. We also include in the sum any other tracks that pass within 5° of the artificial vertex or LLP decay point. Other benchmark samples, as well as the artificially displaced TrackMover events, do not have to use quality tracks clustered around daughter quarks of an LLP. When a pair of reconstructed jets is always found and matched with a decay, these events rely entirely on tracks in reconstructed jets. These distributions are shown in Figure 5.33. The same weight map is used to reweight TM events from all and all years.

To successfully emulate the LLPs using our artificial displacement procedure, we must also mimic the LLP displacement distributions. Due to the LLP boost, the simple exponential decay distribution that we artificially displace tracks by (mentioned in the previous section) provides us with a starting point, but is insufficient to fully capture the physics. To do so, we simultaneously reweight the 2D displacement (in the r plane) and 3D displacement of the artificial vertices in TrackMover (TM) events to match the signal, accounting for the signal lifetime, transverse boost, and overall boost, all at once. Both the 2D and 3D displacements are calculated with respect to the primary vertex, and the maximum 2D displacement is 2.4 cm. Figure 5.32 shows an example weight map, derived by taking ratios of the target signal events with respect to the corresponding distributions in the TrackMover data (left) and TrackMover simulation (right) events. We note that these distributions are normalized to unity before deriving the maps.

Figure 5.34 compares variables used in reweighting before and after

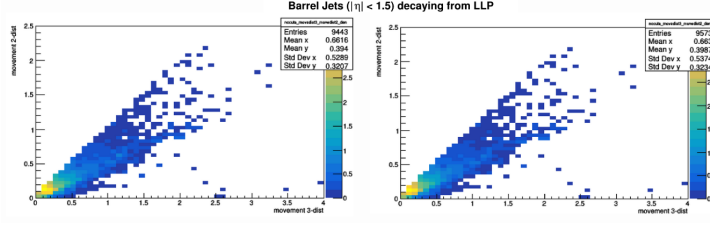


Figure 5.32: The 2D weight maps of artificial (or true decay, for signal) vertex displacement in 2D (r-phi plane) and 3D (3D space). The left map is applied to TM data, and the right map is applied to TM MC. The weight in each bin is determined by dividing the normalized 2D distributions of isolated LLPs in VH signal events with $c = 1$ mm and mass = 55 GeV by those of TM data events (left) or TM MC events (right). TM MC, TM data, and signal MC samples are derived from combining 2017-2018 datasets with barrel jets (quarks).

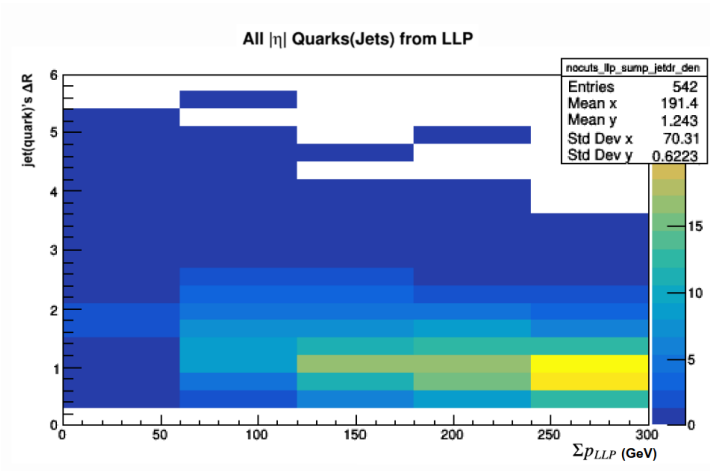


Figure 5.33: The 2D weight map of p_{LLP} and the R of a pair of jets(quarks) for the VH signal with $c = 1$ mm and mass = 55 GeV. The weight in each bin is determined by dividing the normalized 2D distribution of signal MC events by that of TM MC. Both samples are derived from combining 2016-2018 datasets with all bins of jets(quarks).

reweighting using the separate MC and data maps in Figure 5.32, and the common map in Figure 5.33 for $H \rightarrow SS$ (from VH) with $c_s = 1$ mm and $m_s = 55$ GeV. The discontinuity in the reweighted distributions of p_{LLP} is due to coarse binning of the 2D weight map (Figure 5.33) necessitated by low statistics. After reweighting, agreement between TM and signal MC is good.

TrackMover results for isolated LLPs

For isolated vertices, the vertex finding efficiency is a strong function of the number of close seed tracks (or $N_{\text{closeseedtks}}$). A close seed track is a seed track that passes within $d_{xy} \leq 5$ of the LLP decay point (for signal) or artificial vertex position (for TM events). As shown in Figure 5.35 (right), the vertexing efficiency rapidly approaches unity when there are five or more close seed tracks. In the remainder of this section “turn-on curve (TOC)” refers to this plot.

Our method is to predict the vertex finding efficiency for signal events in data by correcting the vertex finding efficiency in signal MC based on sources of variations found between data and simulation. The fractional change of the corrected efficiency by each source with respect to the original one quantifies a systematic uncertainty of vertex finding.

A vertex is successfully reconstructed if it satisfies $n_{\text{track}} \geq 5$, $d_{BV} \leq 50$ m, and $d_{BV} \leq 0.01$ cm as described in Sec. 5.3.4. In addition, it must lie within 400 m to the true decay point. The vertex selection variables are shown in Figure 5.36.

The first contribution to the uncertainty in the vertex reconstruction efficiency comes from the simulation of the number of close seed tracks. As shown in Figure 5.35 for the low p_{LLP} bin, the number of close seed tracks is higher in TM

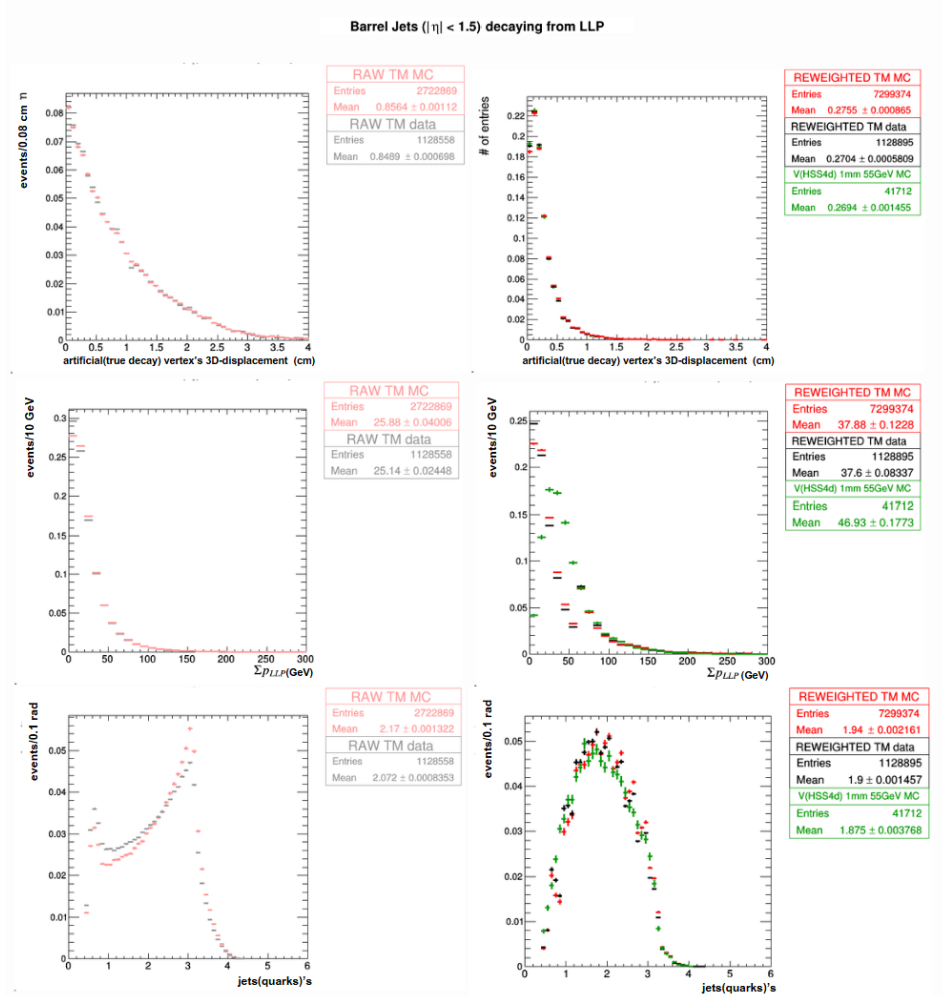


Figure 5.34: Distributions used to reweight TM before reweighting (left) and after reweighting (right), for 2017 and 2018. Samples shown are TM MC (red), TM data (black), and $VH \rightarrow SS$ with $m_S = 55$ GeV and $c_S = 1$ mm (green). Variables shown are the 3D displacement of the artificial vertex (TM) or generated decay point (signal) (top row); $p_{T,LLP}$ (middle row); and the opening angle between LLP daughters $R_{T,LLP}$ (bottom). Plots are for jets (quarks) in the barrel.

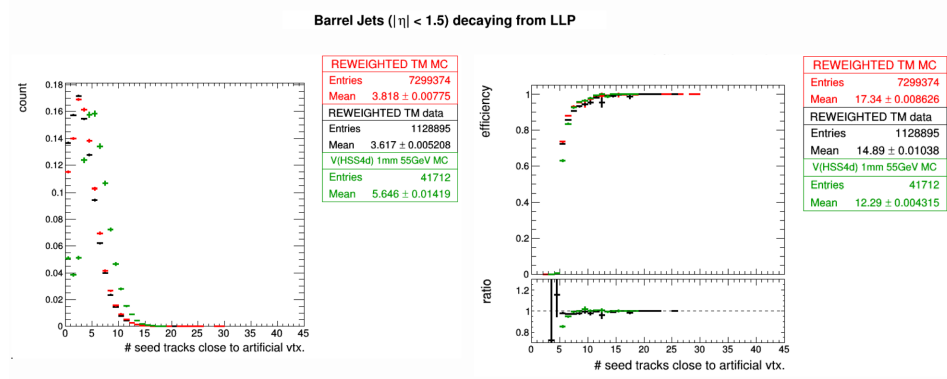


Figure 5.35: The number of “close” seed tracks within $5_{d_{xy}}$ of their expected decay point in 2017 and 2018 for reweighted TM MC (red), reweighted TM data (black), and isolated LLPs (green) from the VH signal MC with $c = 1$ mm and LLP mass of 55 GeV (left). The vertexing efficiency after applying the vertex selection cuts from Figure 5.36, shown as a function of the number of close seed tracks (right).

MC than in TM data by 0.2 tracks, so we shift the close seed tracks distribution of the signal MC downward by 0.2 and convolute the shifted distribution with the TOC in order to assess the impact on the efficiency. The fractional change in the efficiency is 6.2%. For other regions in η , the numbers of close seed tracks is shifted down by 0.25 and 0.28 tracks respectively, corresponding to uncertainties of 11.6% (mixed) and 12.6% (endcap).

A second uncertainty arises from a slight shift in the turn-on curves (TOCs) of TM data and TM MC, shown in Figure 5.35 (right). If we correct the TOC in signal MC by this difference and convolute the resulting TOC with the close seed track distribution, we see a fractional shift in the efficiency of 2.1% (barrel), 0.1% (mixed) and 5.8% (endcap) respectively.

We also assign an uncertainty for mismodeling of the signal MC by track mover. Imperfect modeling is indicated by a small, but noticeable, shift in the

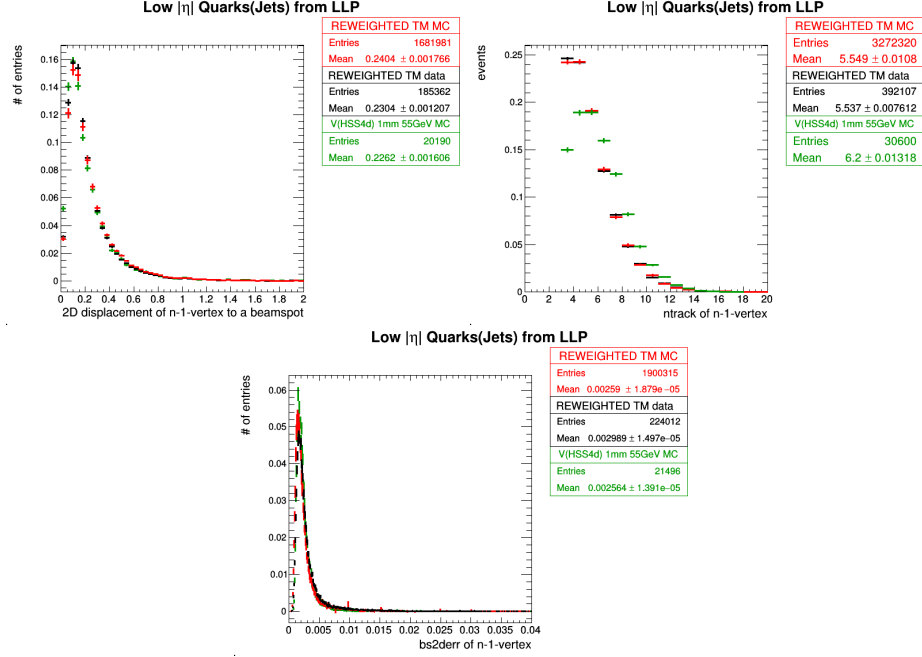


Figure 5.36: Variables used for vertex selection for the combined 2017 and 2018 samples of reweighted TM MC (red), reweighted TM data (black) and exotic Higgs decays with $c = 1$ mm and mass of 55 GeV (green). The variables are d_{BV} (Top-left), the number of tracks in the vertex (Top-right), and $bs2derr$ (Bottom). In all cases, the jets have $|\eta| < 1.5$ and all vertex selection cuts have been applied except the plotted variable.

TOCs in TM MC and signal MC as shown in Figure 5.35. The signal MC TOC turns on more slowly than that in TM MC for reasons that are not understood. To quantify the impact of this difference, we scale the TOC in signal MC to match TM MC. Figure 5.37 (left) shows the unscaled (blue) and scaled (purple) TOC of signal as a function of the number of close seed tracks for isolated LLPs in the same signal events as in Figure 5.35. Figure 5.37 (right) shows the close seed track distribution after convolution with the TOCs of TM MC and signal MC. The change in the efficiency is 4.5% (barrel), 7.8% (mixed) and 4.4% (end-cap). We take this as a systematic uncertainty.

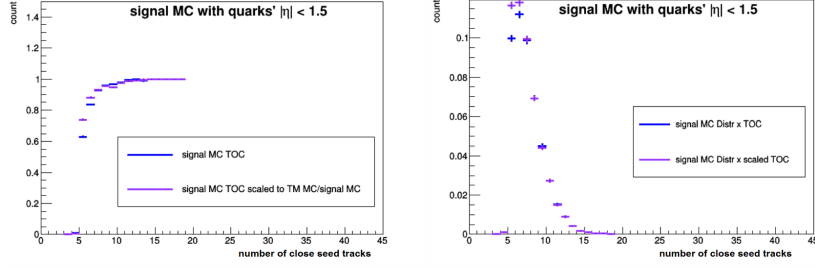


Figure 5.37: (Left) scaled signal TOC of the number of close seed tracks (purple) via scaling TOC of signal to be identical to TOC of TM MC is compared with the original TOC of signal (blue). (Right) the convoluted distributions of the modified TOC is shown in purple to compare against the uncorrected convoluted distribution of the signal MC in blue. The signal MC has 1 mm c and 55-GeV mass for isolated LLP decays and quarks in the barrel.

Table 5.23 summarizes the vertexing uncertainties for each decay vertex as a function of the $|\eta|$ of quarks from the decays in an exotic Higgs signal with 1 mm c and 55-GeV mass. The first three rows apply to LLP decay vertices that are well-separated from other LLPs. The next subsection addresses the case in which the two LLP decays are in proximity.

Overlapping vertices

While TrackMover quantifies the systematic data/MC shifts for isolated vertices, it does not address the additional uncertainty that arises when two LLPs decay near one another. These two types of LLP decays are defined by the separation between LLP decays, based on the truth information. The split-vertex merging algorithm from Sec. 5.3.3 merges pairs of vertices when they are separated by less than 300 μ m. This suggests that an LLP decay is impacted by another LLP decay when they are 300 μ m apart.

The separation between two LLP decays required for successful reconstruction scales with the vertex position resolution. As shown in Figure 5.38, the 5-tk vertex position resolution is typically 40 to 90 μm , depending on η , and that resolution is on average 20% poorer in TM data (black) than MC (red). Therefore, if MC reliably resolves two vertices that are separated by 300 μm , then the data will require 360 μm separation for reliable reconstruction.

Therefore, we identify three regions based on the LLP decay separation in 3D (or d_{VV}^{GEN}): fully overlapping LLPs with $d_{VV}^{\text{GEN}} < 300 \mu\text{m}$, partially overlapping LLPs with $300 \mu\text{m} < d_{VV}^{\text{GEN}} < 360 \mu\text{m}$, and non-overlapping LLPs with $d_{VV}^{\text{GEN}} > 360 \mu\text{m}$.

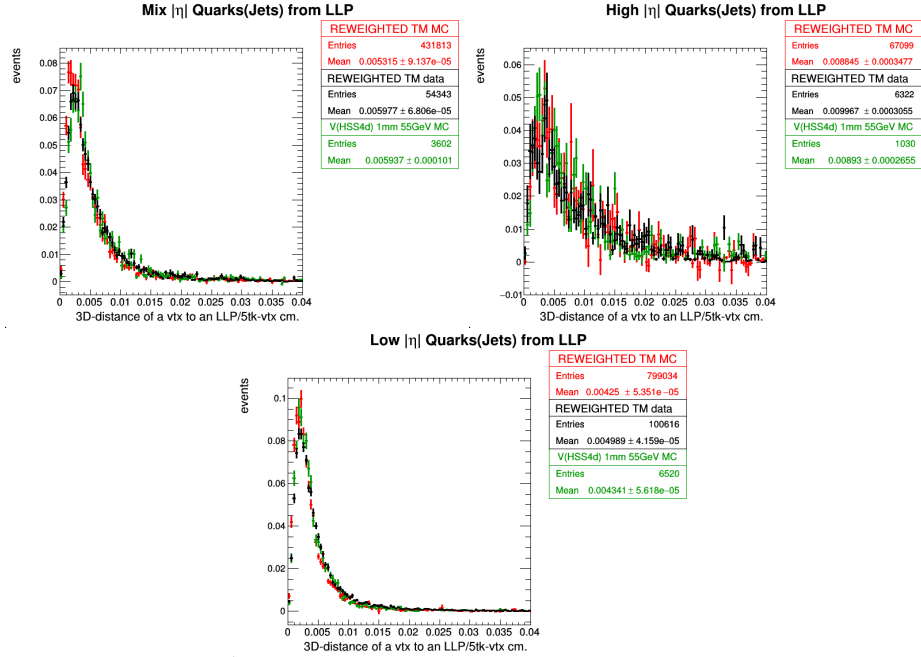


Figure 5.38: Comparison of the distributions of vertex position accuracy or the 3D displacement of a 5-tk reconstructed vertex to its expected decay point in TM data (black), TM MC (red), and signal MC (green). (Top-left) Mixed jets. (Top-right) Endcap jets. (Bottom) Low jets(quarks).

Given the signal MC example of 1-mm 55-GeV exotic Higgs decays in the barrel produced via associated production, the non-overlapping LLPs have the reconstruction efficiency in signal MC of 43%. The fractional vertexing uncertainty for non-overlapping LLPs is 7% from Sec. 5.8.1. In the fully overlapping region the reconstruction efficiency in signal MC is 12%, and we vary that by 50% of itself, resulting in a fractional vertexing uncertainty of 1.5%. In the partially overlapping region, we vary the reconstruction efficiency between that in the fully overlapping region (12%) and in the non-overlapping region (43%), resulting in a fractional vertexing uncertainty of 3%. Combining these two uncertainties gives a total fractional uncertainty due to overlaps of 3.4%. The expression for the fractional uncertainty in the vertex reconstruction efficiency is:

$$F_{\text{avg}} = F \frac{\max}{\text{avg}} \frac{\min}{\text{avg}} \quad (5.4)$$

where F is the fraction of LLP decays by the definition of d_{VV}^{GEN} in each region of the specific bin. While $\max$ (or $\min$) is the maximum (or minimum) possible vertexing efficiency in such a region, avg is the average vertexing efficiency of all LLP decays in the same bin.

Other LLP decays with mixed and endcap quarks(jets) have uncertainties of overlapping LLP decays, shown in Table 5.23, of 2.7% and 1.2%, respectively.

Summary of vertexing efficiency uncertainty

Finally, the uncertainties in the vertexing efficiency is the weighted average of the uncertainties for isolated and overlapping LLP decays. The vertexing efficiencies separated by decays and are summarized in Table 5.24. To determine

Table 5.23: Various sources of uncertainties in the vertexing efficiency in isolated LLPs and overlapping LLPs of 1-mm 55-GeV exotic Higgs decays in 2017-2018 data-taking periods from all associated vector boson production modes. Because signal events contain two vertices, the vertexing uncertainty per event is 2x the figures shown in the table.

Sources of uncertainties	Barrel quarks (%)	Mixed quarks (%)	Endcap quarks (%)	Average (%)
$N_{\text{closeseedtks}}$ distributions	6.2	11.6	12.6	9.0
Efficiency curves as a function of $N_{\text{closeseedtks}}$	2.1	0.1	5.8	2.4
TrackMover Mismodeling	4.5	7.8	4.4	5.8
overlapping LLPs	3.4	2.7	1.2	3.0
Total	8.6	14.2	14.6	11.3

Table 5.24: Vertexing efficiency in bins for 1-mm 55-GeV exotic Higgs decays produced via associated production in signal MC. Figures are based on run conditions from 2017-2018. Isolated-LLP signals are separated from other LLPs by more than 360 m; all others are overlapping.

	Barrel quarks (%)	Mixed quarks (%)	Endcap quarks (%)	Average (%)
Fraction of LLP decays	58	33	9	
Average vertex efficiency in signal MC	39.6	23.9	24.4	30.0
Vertex efficiency of isolated-LLPs in signal MC	43.5	25.8	25.2	36.0
Vertex efficiency of overlapping-LLPs in signal MC	11.6	5.1	6.9	9.0

the uncertainty per event (or per LLP decay pair), we assume that the efficiencies to reconstruct the two LLPs in a single event are fully-correlated, and so the uncertainty reported in Table 5.23 is doubled. The method is applied to other benchmark signal modes in Appendix C.

Trigger efficiency

Samples used to study the b-jet/displaced-jet triggers must pass `IsoMu27` trigger (`IsoMu24` for 2016 conditions) and have at least one selected muon with $p_T \geq 27$ GeV for the study of trigger efficiencies in order to avoid any biases. Each trigger path is composed of one or more online filters. The analysis applies some corresponding offline filters to echo these cuts as discussed in Sec. 5.2. The efficiency of each online filter is measured in data and simulation to quantify the systematic uncertainty of the trigger efficiency as a function of each offline filter. In the displaced-vertex analysis, there are two main types of filters in each trigger path. They are *kinematic filters* and *displaced filters*.

The kinematic filters pertain to jet variables used for triggering an event selection based on jet kinematics such as transverse momentum (p_T) and scalar sum of jets with certain p_T thresholds. The separation of kinematically-relevant jets is also considered a kinematic filter. Figure 5.39 shows the efficiency of kinematic filters of the *b-tagged di-jet* trigger path in 2017 as a function of the three offline filters in both data and background simulation. The offline variable cuts, shown in Table 5.17, are chosen to be the working point where the efficiency of the kinematic filters reaches 95% or slightly below to reduce the efficiency difference between data and simulation. The remaining efficiency difference at a chosen threshold of the offline kinematic filter is considered as a systematic uncertainty of the trigger efficiency. The same procedure is applied to other trigger paths in different years such as the *default displaced di-jet* trigger path in 2017 as shown in Figure 5.40.

Trigger efficiencies refer to the probability that an event passing offline selection criteria also passes the corresponding online trigger criteria. The systematic

uncertainty in signal yield due to trigger efficiencies is quantified by the ratio of the trigger efficiency at a chosen offline filter cut between data to simulation. It is found that the magnitude of this uncertainty is around 2% in the b-jet triggers and 0.5% in the displaced di-jet triggers.

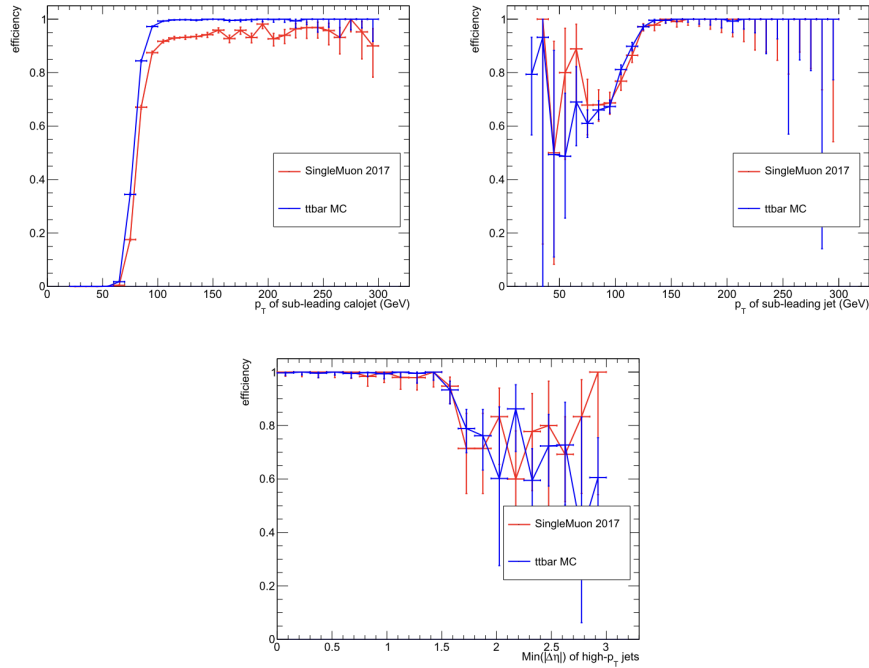


Figure 5.39: Comparison of the efficiency of the online kinematic filters in muon-triggered events. The events are from simulated $t\bar{t}$ (blue) and SingleMuon data (red) in 2017. The efficiency is shown as a function of an offline kinematic filter. These kinematic filters are those that make up *b-tagged di-jet* triggers in 2017. The differences of these efficiencies between data and simulation at a chosen offline cut of these filters shown in Table 5.17 are sources of the systematic uncertainty. Figure credit: Shaun Hogan.

The systematic uncertainty can arise from trigger paths that include *displaced filters*. They commonly require at least a certain number of displaced tracks or at most a certain number of prompt tracks. Since these filters include the selection cut on the number of b-jets, online b-tagging is part of systematic uncertainties.

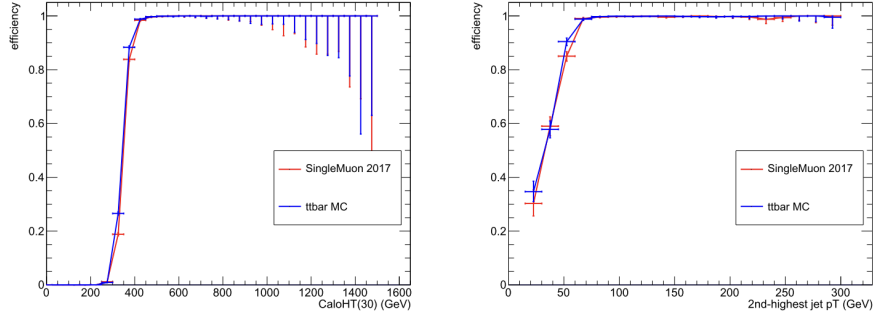


Figure 5.40: Comparison of the efficiency of the online kinematic filters in muon-triggered events of simulated $t\bar{t}$ (blue) and SingleMuon data (red) in 2017 as a function of an offline kinematic filter. These kinematic filters are those that make up *default displaced di-jet* triggers in 2017. The differences of these efficiencies between data and simulation at a chosen offline cut of these filters shown in Table 5.17 are sources of the systematic uncertainty. Figure credit: Shaun Hogan.

To evaluate this uncertainty, we consider the differences in b-tagging efficiencies between data and simulation. The following procedure was performed to derive this systematic uncertainty on a jet-by-jet basis and propagate it to a signal yield:

- **Tag-and-Probe:** Process di-leptonic $t\bar{t}$ MC events and data, for each event one jet is required to pass medium DeepJet working point, to be within 2.4 and to have $p_T \geq 30$ GeV.
- **Tagging Efficiency:** If other jets in the same event pass the same 2.4 and $p_T \geq 30$ GeV requirement, it enters the numerator for calculating b-tagging efficiencies.
- **Calculation of the Systematic Uncertainty via Scale Factors:** After the previous step, the online b-tagging efficiencies in data (ϵ_{dat}) and simulation (ϵ_{MC}) can be derived bin by bin of offline b-tagging scores. These b-tagging

efficiencies are translated to a scale factor (SF) equal to $\frac{data}{MC}$ if $MC > data$ per bin. Otherwise, the scale factor is written as $\frac{1}{1 - \frac{data}{MC}}$ if $MC < data$. In signals, a jet may satisfy an online b-tagging in simulation but may pass or fail a b-tagging working point in real data. To make a proper correction, a random number (x) is generated from a standard uniform distribution to artificially tag a jet in signals as failing the HLT b-tagging if $x < SF$ when $MC > data$ or as passing the HLT b-tagging if $x < SF$ when $MC < data$, respectively. The systematic uncertainty then is quantified by the difference from a unity of the ratio between the modified signal yield to the unmodified signal yield passing the b-tagged triggers.

The resulting systematic uncertainty from the b-tagging efficiency ranges from near zero in RPV SUSY models up to 10% in the exotic Higgs model, shown in Figure 5.41.

In addition to the b-tagging efficiency, the dominant contribution to the systematic uncertainty of displaced filters is the HLT tracking efficiency. At the online triggering level, prompt tracking efficiencies can be significantly different between data and simulation. This difference is more pronounced compared to displaced tracking efficiencies. Although the number of displaced tracks required for a *CaloJet* in the displaced di-jet trigger paths is part of displaced filters, the uncertainty associated with it is negligible. The uncertainty due to HLT prompt tracking can be determined from a modified signal yield with a similar technique to the one used for deriving the uncertainty due to online b-tagging. However, the preselection step relies on trigger paths with $H_T = 425$ GeV (or $H_T = 325$ GeV in 2016) instead of the *IsoMu27* (or *IsoMu24* for 2016 conditions). These kinematic filters are compatible with those of the inclusive

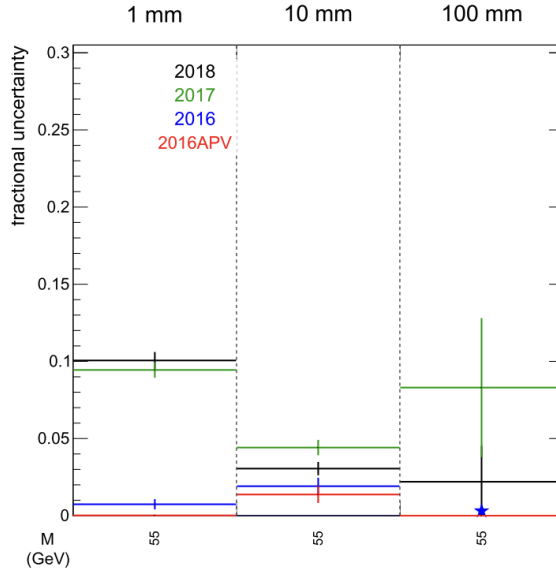


Figure 5.41: Systematic uncertainties due to the differences in HLT b tagging between data and simulation for all exotic Higgs signal points with mass of 55 GeV. The years are 2016APV (red), 2016 (blue), 2017 (green), and 2018 (black). Figure credit: Shaun Hogan.

displaced di-jet trigger paths. In fact, the online tracking uncertainty is poorer when a targeted long-lived particle has a low mass and a longer lifetime, especially in 2016APV shown in Figure 5.42. For the exotic Higgs signals not shown, the uncertainty is uniformly about 2% in 2016, 2017, and 2018. Nevertheless, the uncertainty is up to 21% in 2016APV.

Energy and resolution scale factor of b-jet and/or displaced jets

Events that are selected by the b-jet triggers and displaced-jet triggers are required to pass offline selection. Any kinematic differences between data and simulation due to jet energy scaling or jet energy resolution can impact signal yield. Unlike displaced filters, kinematic filters are required in all trigger paths.

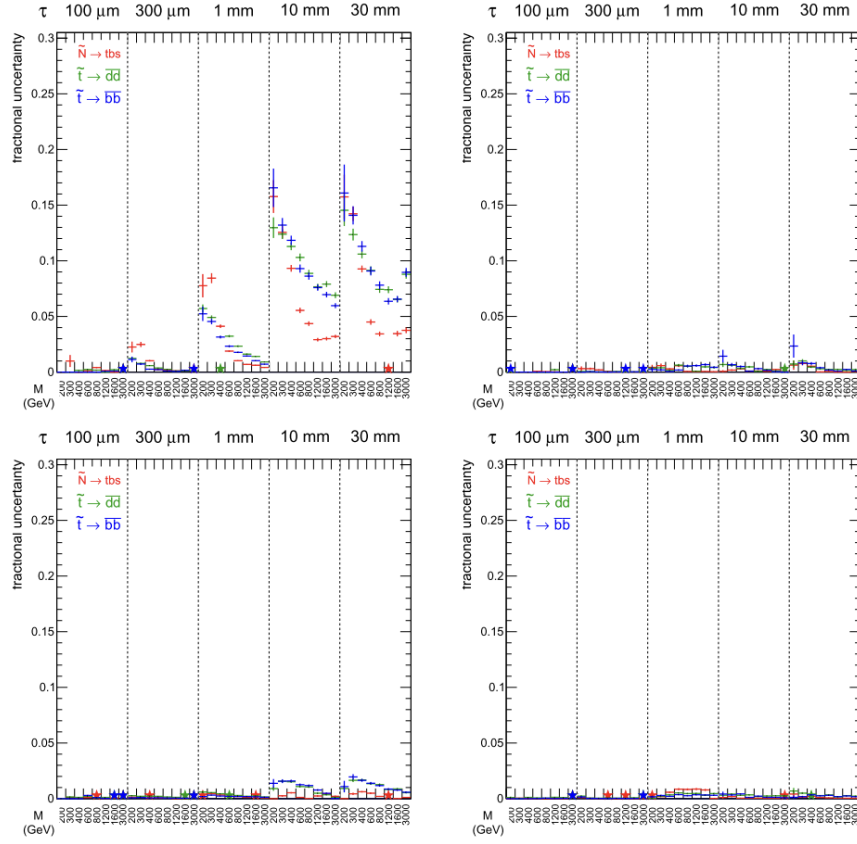


Figure 5.42: Systematic uncertainties due to the differences in HLT prompt tracking between data and simulation for all RPV SUSY signal points. The years are 2016APV (top left), 2016 (top right), 2017 (bottom left), and 2018 (bottom right). Figure credit: Shaun Hogan.

Energy and resolution scale factors are obtained to apply to b-jets and displaced-jets in simulation. Since the b-jet and displaced-jet triggers are correlated, some sources of the signal uncertainty are also correlated. In order to understand them better, they are classified into three categories:

- **Exclusive uncertainties from displaced-jet triggers:** relevant kinematic filters, HLT tracking efficiency, and the number of offline prompt tracks.
- **Exclusive uncertainties from b-jet triggers:** relevant kinematic filters, b-

tagging efficiency, and the offline b-tag scale factors.

- **Inclusive uncertainties from both triggers:** *jet energy scaling* (JES) and *jet energy resolution* (JER) scale factors.

Note that the uncertainties due to JES and JER scale factors are derived with a similar technique as in [27], as well as the b-tagging and HLT tracking as mentioned before. This procedure involves randomly removing a b-tag or lowering the jet energy/resolution scale of a signal MC jet based on a probability determined by the corresponding scale factor. This in turn results in a modified signal yield of each signal point. The systematic uncertainty of each aforementioned scale factor is calculated by the ratio of a modified signal yield to a nominal signal yield. Since the effect on event yield is unbiased toward upward or downward fluctuations, the total uncertainty of each scale factor is calculated from the averaged magnitude of the upward and downward fluctuations.

Finally, the two exclusive categories are assumed to be fully-correlated, but the sources of the uncertainty within each category are assumed to be uncorrelated. Therefore, uncertainties in the same category are added in quadrature to derive an uncertainty per category.

For each signal point, there are three sets of events satisfying: only the displaced-jet triggers, only the b-jet triggers, and both triggers inclusively. The systematic uncertainty per each signal point is determined by adding the signal yield fluctuations from the *primary set* and the *secondary set* of events, assuming a full correlation. To explain further, the primary set is derived from one of the exclusive categories with lower uncertainty, making it orthogonal to the secondary set. The secondary set contains the remaining events, excluding those in the primary set, and must satisfy other trigger paths as well. The uncertainty of

this secondary set then can be combined with the inclusive uncertainties from events passing both triggers, which include the uncertainties of JES and JER scale factors, by summing them in quadrature to derive the total systematic uncertainty, shown in Figure 5.43 for exotic Higgs signals and in Figure 5.44 for RPV SUSY signals. In this manner, the total trigger-related systematic uncertainty for a signal point is accounted for any correlations between trigger filters.

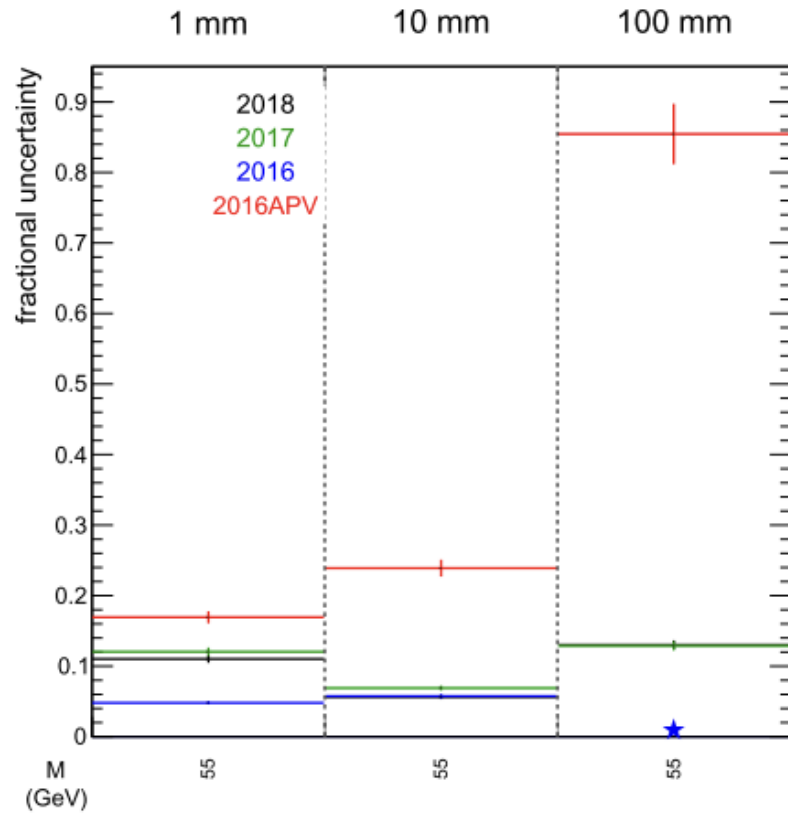


Figure 5.43: Systematic uncertainties due to the combined uncertainties from *secondary-set* trigger filters, JES, and JER for all exotic Higgs signal points with mass of 55 GeV. The figure shows the uncertainties for different data-taking periods: 2016APV (red), 2016 (blue), 2017 (green), and 2018 (black). These uncertainties are crucial for understanding the impact of kinematic filters on the signal yield. Figure credit: Shaun Hogan.

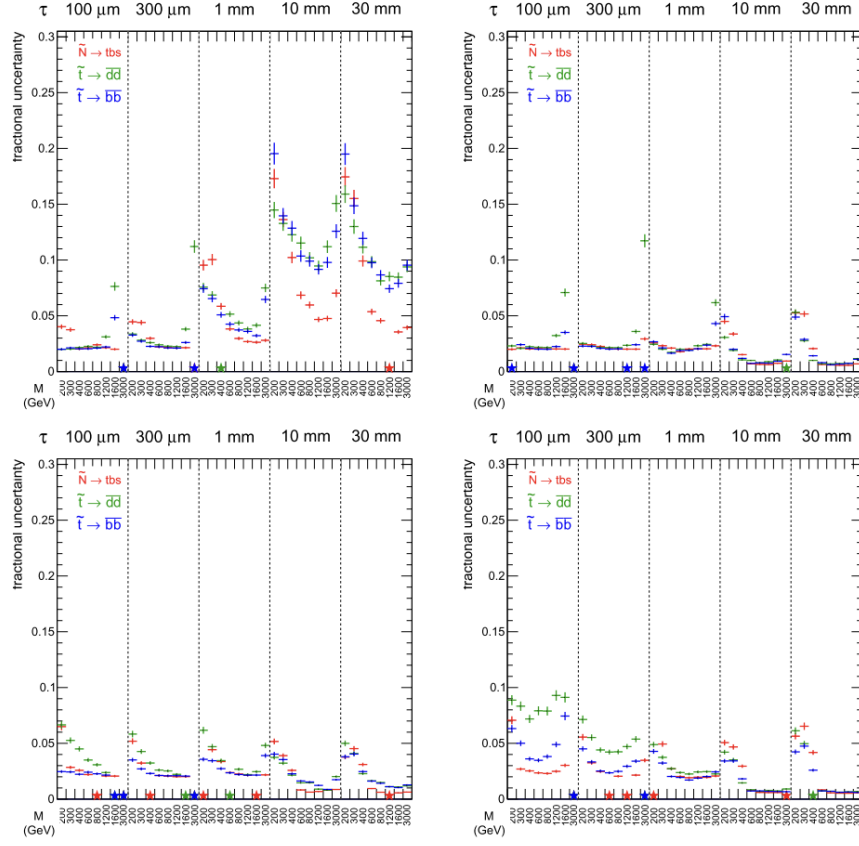


Figure 5.44: Systematic uncertainties due to the combined uncertainties from *secondary-set* trigger filters, JES, and JER for all RPV SUSY signal points. The figure shows the uncertainties for different years: 2016APV (top left), 2016 (top right), 2017 (bottom left), and 2018 (bottom right). These uncertainties are crucial for understanding the impact of kinematic filters on the signal yield. Figure credit: Shaun Hogan.

Pileup

The amount of *pileup* or inelastic collisions of protons in an event can be another source of the uncertainty on signal yield. Pileup does not only affect the vertexing efficiency, but also determines the number of tracks and jet variables such as p_T and H_T . In this analysis, the pileup uncertainty is quantified by the ratio of the signal yield in the pileup condition with the number of pileup vertices

shifted by 5% from the nominal condition to the nominal signal yield. Similar to other uncertainties, the final pileup uncertainty is calculated from the average of the magnitudes of the upward and downward fluctuations.

Integrated luminosity

Since signal yields are directly related to the amount of data collected by the LHC, the integrated luminosity recorded by the CMS detector is another source of systematic uncertainties. The following uncertainties from the luminosity per era are reported by the CMS collaboration. They are 2.5% for 2016 [23], 2.3% for 2017 [24], and 2.5% for 2018 [25].

Calorimeter inefficiencies

Since the displaced-jet triggers rely on *calorimeter jets* (or CaloJets) for selecting events in real-time. Any failures of the calorimeter systems during Run-2 that had not been propagated to the simulation could be another source of systematic uncertainty. To be specific, there are two calorimeter inefficiencies that need to be quantified. The first is the timing inconsistency in the EE region of the detector during data-taking periods in 2016 and 2017. The second is the issue of power supply in the HCAL system in 2018.

For the timing inconsistency, the calorimeter inefficiency is quantified by evaluating the trigger and preselection efficiency in the signal-like events after jets with 2.25 have been artificially removed to replicate the condition in real data. These inefficiencies are then compared to the nominal efficiencies in the signal-like events to derive the systematic uncertainty of the calorimeter

inefficiency. The result of the calorimeter inefficiency is almost undetectable in 2017, but is up to 5% in low-mass and high-lifetime samples in 2016.

Next, the power-supply issue only affects a subset of the data samples in 2018. This inefficiency in 2018 is also evaluated analogously as the timing inconsistency in the EE region across years. Jets in 2018 are removed when their momentum vectors lie in the problematic region of the detector. The result also shows that the signal yield, after this modification has made, is rarely changed.

Hence, the calorimeter inefficiency is taken as a flat 1% uncertainty for 2017 and 2018 data-taking periods. Nevertheless, it is higher in 2016. For example, the uncertainty for RPV SUSY samples with LLP mass points less than or equal to 300 GeV and a lifetime of 10 mm or more is approximately 5%. The rest of RPV SUSY samples under the 2016 conditions are assigned the flat 1% uncertainty.

5.8.2 Systematic uncertainties on background templates

Uncertainties in the constructed d_{BV}^C distribution

The technique discussed in Sec. 5.4.2 for constructing background d_{BV}^C templates requires various input from background events. These inputs include:

- Distributions of angles between jets, which serve as a proxy for angles between displaced vertices
- Information about the likelihood that pairs of vertices survive the main track-arbitration step of the vertex reconstruction

- Information about the likelihood that pairs of vertices survive the vertex-refinement steps of the vertex reconstruction

Each of these inputs could affect the shape of the d_{BV}^C templates. While these uncertainty studies have yet to be carried out, a brief discussion of how we will approach the study of them follows.

First, to obtain an uncertainty in the d_{BV}^C template relating to the angular separation between vertices: we replace the flat d_{BV}^C distribution with one taken from d_{JJ} . The d_{JJ} construction is motivated because misreconstructed tracks tend to be displaced perpendicular to their direction of travel, and therefore perpendicular to the direction of jets. Thus, the angular separation between two misreconstructed vertices is influenced by the angular separation between jets, or d_{JJ} . We now use the d_{JJ} method as a systematic check. We plan to rerun the background template reconstruction procedure and take the change in the resulting distributions as an uncertainty.

The next two inputs pertain to vertex pair efficiency curves used to punish toy two-vertex events where the vertices have small values for their vertex separation or d_{VV} . The first of these curves, which provides the efficiency for pairs of vertices to survive the track-arbitration steps of vertexing, is made by counting all possible pairs of vertices (starting with two-track *seed* vertices) throughout all loops of the vertexing algorithm using the combined 2017 and 2018 background simulation. Figure 5.45 shows this curve and the variations used to assess the systematic uncertainty in the d_{BV}^C templates.

A similar source of uncertainty arises from the behavior of the vertex pair efficiency curves for the vertex refinement steps. As mentioned in Sec. 5.4.2,

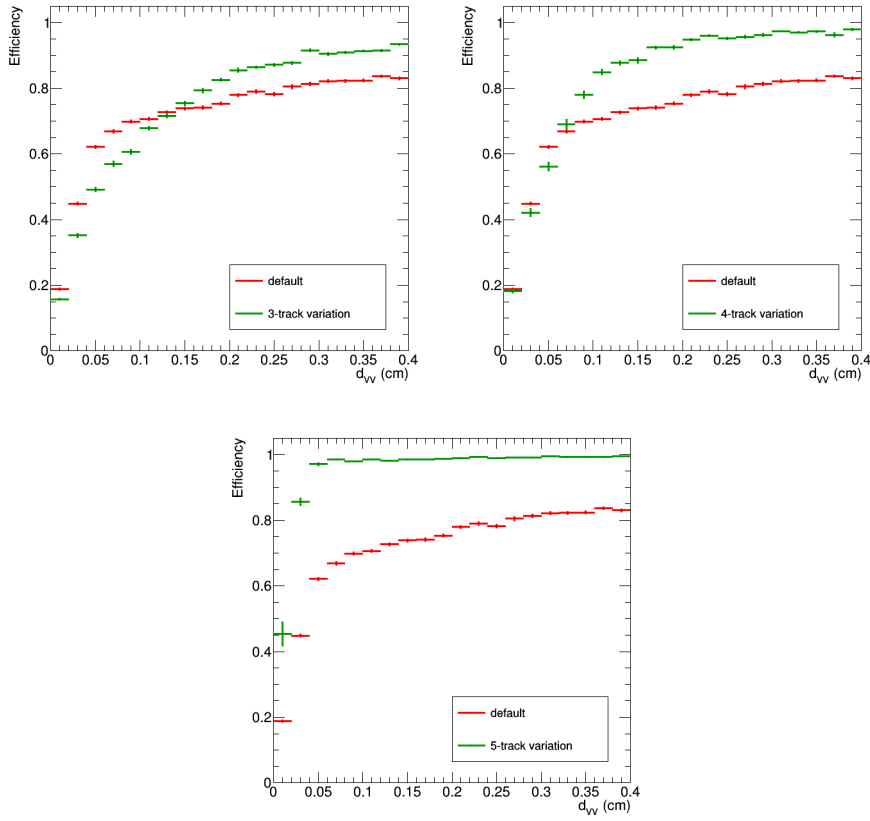


Figure 5.45: The efficiency for pairs of vertices to survive the track arbitration steps of the vertexing algorithm for combined 2017 and 2018 background simulation. The default curve (red) is common to all plots and is determined from seed vertices formed from track pairs, while the others show variations in which seed vertices are formed from track triplets (top left), track quadruplets (top right), and track quintuplets (bottom) (all in green). Figure credit: Shaun Hogan.

these efficiency curves are produced using 3-track vertices which are outputs of the arbitration steps. Statistics are too poor to make the same plots for 4-track or 5-track vertices, so we will instead replace the overlap curve with one from simulation to assess our sensitivity to this effect.

Pile-up effects

As the true number of pileup interactions increases, the fraction of events with vertices increases slightly, but the tail of the d_{BV} distribution is expected to decrease unnoticeably. Since the background template is constructed from data (Sec. 5.4.2), pileup is reflected; however, the small correlation resulting from pairing events with the same pileup conditions is not accounted for. This effect is small, so no systematic uncertainty is assigned.

Signal Contamination

Signal contamination can in principle affect both the normalization of the background in Sec. 5.4.3 and the shape of the background template in Sec. 5.4.2.

Consider $H \rightarrow SS$ with a 10% branching fraction, to which we are sensitive through associated production and the lepton trigger. In that case, the signal contamination in the one-vertex sample would be 2% (230 signal events in 82,000 background events in 2017). That would change the predicted background in two-vertex events by 0.6%, or ~ 0.02 event.

Essentially, the signal can be large enough to affect the background template only if it is far larger than the expected background level.

CHAPTER 6

BROADER CONTEXTS AND FUTURE DIRECTIONS

The focus of this section is on a broader context and a future direction of the LHC physics program for long-lived particle (LLP) searches. Previous efforts, as well as ongoing ones, that rely on displaced vertices to search for new physics are highlighted. LLP analyses using other signatures such as displaced jets and displaced muons for different decay modes of LLPs are briefly mentioned. Lastly, prospects on future techniques for LLP searches in the upcoming High-Luminosity LHC (HL-LHC) program are discussed.

6.1 Other analyses

6.1.1 Displaced vertices + X

Given that many physics beyond the Standard Model (BSM) predict the existence of lightest supersymmetric particles (LSPs) for dark matter candidates, they can be long-lived particles. These particles are accompanied by a lot of possibilities to decay. In the context of R-parity violation (RPV) (discussed in Sec. 2.4.1), stop LSPs can decay into a pair of quarks (Figure 5.1 (right)), as well as a quark and a lepton shown in Figure 6.1, while neutralino/gluino LSPs can decay into top, bottom, and strange quarks via virtual top squarks (Figure 5.1 (left)).

On the other hands, if R-parity number is conserving, an LSP may decay to a pair of SM particles and another supersymmetric particle. Such an LSP is long-lived because its decay is suppressed by the SUSY breaking scale (m_{SUSY}).

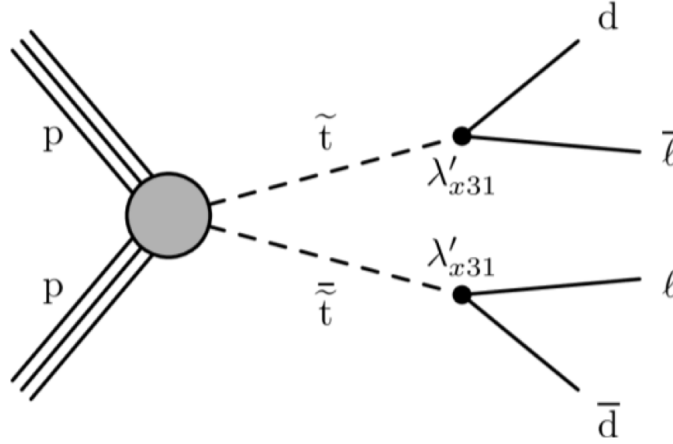


Figure 6.1: Another possible decay of stop LSPs. The simplified model of the decay of a stop LSP to a quark (e.g. a down quark) and a lepton, appearing as a displaced vertex reconstructed by tracks from a jet and a lepton. The signature is a displaced vertex (DV), plus a lepton.

In particular, such a model generally assumes $m_{\text{SUSY}} \sim 10^6 \text{ TeV}$ [49] for all scalars to acquire masses, except the Higgs mass that needs to be fine-tuned. The simplified model of the decay of a long-lived gluino LSP to a pair of quarks and a stable neutralino is shown in Figure 6.2. This model is called *split SUSY* [6].

These theoretical models motivate the search for displaced vertices (DV). Additionally, searches can include either a lepton (*DV+lepton*) or a MET (*DV+MET*). Specifically, the DV+lepton search expects a lepton in a reconstructed vertex. An ongoing effort within the CMS collaboration utilizes single lepton triggers to select targeted events. This approach is similar to this search for discovering exotic Higgs decays with an associated vector boson. In terms of the vertex reconstruction, the DV+lepton reconstruction not only relies on selected tracks, similar to the DV reconstruction, but also requires a selected lepton be part of a reconstructed vertex. Although this requirement can be implemented with an existing analysis tool, the discrimination between sig-

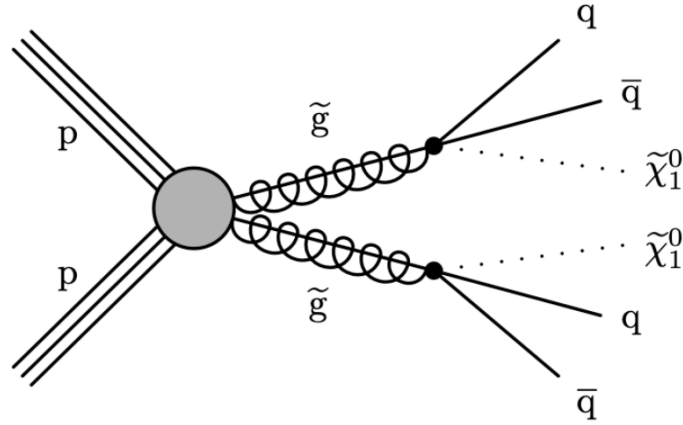


Figure 6.2: RPC-conserving model of LSPs so-called *split SUSY*. A long-lived gluino decays to a pair of SM quarks and a stable neutralino. The signature is a displaced vertex (DV), plus a missing transverse energy (MET).

nals and background in the DV+lepton analysis is more challenging. A lepton can randomly cross a b-hadron vertex, causing background events to remain even after applying a similar set of vertex selection. To be sensitive to the RPV stop model (Figure 6.1), a machine learning tool such as a boosted decision tree (BDT) is used in the analysis to classify signals and backgrounds. This analysis technique proves to be more promising than a traditional approach of using a cut-based method.

Another DV search at the CMS experiment is the DV+MET search, with a public result available at [49]. This search aims to select signals in real-time using MET triggers primarily. MET (Sec. 4.6) is a signature of a stable neutralino in the split SUSY model, shown in Figure 6.2. The challenge in this analysis, however, is a reconstruction of a displaced vertex with a missing particle. Because of this missing particle, the number of tracks per vertex is no longer a powerful discriminator between signals and background. Nonetheless, the search

was achieved by using a combination of our customized displaced vertex reconstruction and an interactive Neural Network (NN) tool to probe the first-ever signal sensitivity in the split SUSY model (Figure 6.2).

In addition to the searches for displaced vertices and alike at the CMS experiment, as mentioned previously, the ATLAS experiment has also been conducting a search for displaced vertices both in the context of RPV SUSY [20] and exotic Higgs decays [19] [21]. The ATLAS searches rely on an excellent performance of their inner tracking system, which is similar to the CMS pixel detector, to reconstruct displaced vertices. Although tracking performances are quite similar between the two experiments, the ATLAS searches not only select tracks from a standard algorithm but also run a second algorithm with more relaxed impact parameter criteria to reconstruct and select displaced tracks from any remaining hits. This second algorithm is called *Large Radius Tracking or (LRT)*. It has provided an outstanding performance compared to the standard algorithm alone, shown in Figure 6.3 (left). Additionally, the selected tracks in these ATLAS DV analyses are not restricted to come from charged particles originated within the beampipe, but include those that decay 30 cm away from the beam axis.

In addition, the displaced-vertex reconstruction algorithm by ATLAS also takes an advantage of the LRT tracking by recovering those unselected and "attaching" them to a reconstructed vertex that is compatible as much as $^2 \text{ndof} \approx 20$ [19]. Although this track attachment technique shows a significant improvement in the signal efficiency as in Figure 6.3 (right) for ATLAS, the same technique was studied in this CMS search, but did not outperform the current DV-reconstruction technique. Our result shown in Figure 6.4 demon-

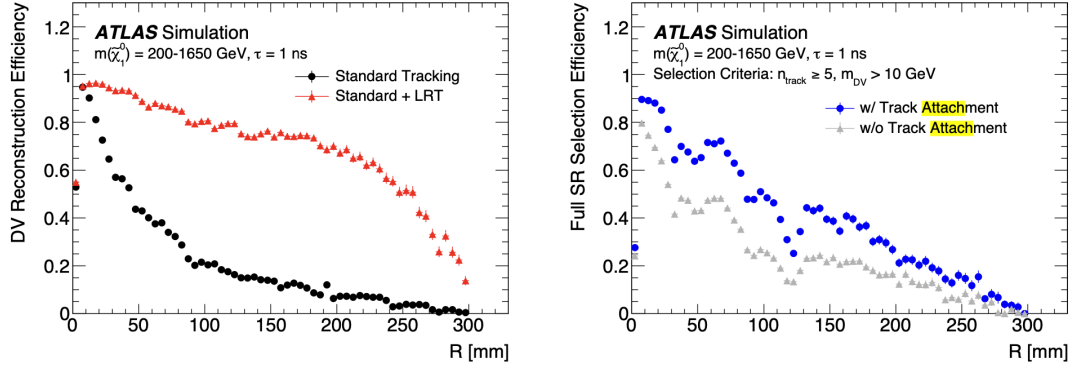


Figure 6.3: (Left) The efficiency in reconstructing a displaced vertex for a neutralino LSP based on a strong RPV SUSY model with masses between 200-1650 GeV and a proper lifetime of 100 mm with (red) and without (black) the LRT tracks as a function of the tracking radius. (Right) The full signal selection efficiency in the ATLAS displaced-vertex search without (gray) and with (blue) missing tracks from the standard + LRT selection attached to a reconstructed vertex as a function of the tracking radius of the same neutralino signals [19].

strates that by relaxing a displaced criterion (from $d_{xy} \geq 4$ to $d_{xy} \geq 2$) and attach tracks with a slightly-tighter displaced criterion ($d_{xy} \geq 3.5$) to reconstructed vertices, the alternative (red) finds no improvement compared with the current reconstruction (green), based on the sensitivity value or Z_0 (Eq. 40.82 [33]) across benchmark signals. Nevertheless, this technique is more suitable for attaching ATLAS's LTR tracks with large impact parameters since it allow ATLAS searches to be most sensitive to LLP lifetimes between 10-30 mm.

6.1.2 Displaced jets

Although the focus of this analysis is on the displaced-vertex signature of long-lived particles (LLPs), a companion analysis exists and looks for displaced jets.

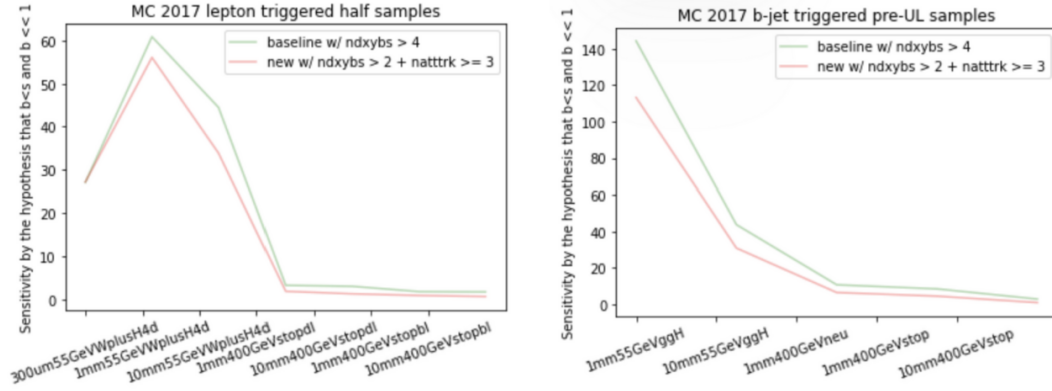


Figure 6.4: Signal sensitivities (Z_0) of various signals from the CMS-DV reconstruction are compared. The comparison includes a procedure of relaxing the displaced criterion and attaching selected tracks to a vertex (red) and the default procedure (green). (Left) The x-axis shows lepton-triggered signals. These include exotic Higgs with LLP mass of 55 GeV and proper lifetimes ranging from 300 μ m to 10 mm. It also includes stop LSP with mass of 400 GeV decaying to a lepton and a quark with proper lifetimes from 1 mm to 10 mm. (Right) B-jet triggered signals on the x-axis are exotic Higgs with LLP mass of 55 GeV, and RPV SUSY LSPs with mass of 400 GeV decaying hadronically to jets, with 1-10 mm proper lifetimes.

Such search is sensitive to LLP lifetimes between 1-550 mm. By the name suggested, the analysis is called the *displaced-jets* search, which is also a part of the CMS LLP group. In particular, the displaced-jets search is designed to select events with a pair of jets (called dijet events) that are displaced from the primary vertex, while the dijet must be associated with at least one displaced vertex. However, the reconstructed vertex does not necessarily need to be reconstructed by tracks from both jets, allowing for inclusivity to models with a single displaced jet. With their analysis on Run-2 data, the displaced-jets analysis demonstrates the world's most competitive exclusion limits on several BSM models with LLP lifetimes between 1-10 mm, including the exotic Higgs with

LLPs decaying hadronically (discussed in Sec. 2.5.2), the mini-split SUSY model, as well as RPV SUSY models [71].

To achieve such an outstanding performance, the displaced-jets analysis includes several key improvements to its analysis strategies. The first improvement is the use of two displaced-jet triggers, one requiring at least one displaced track and another only minimizing prompt tracks, to cover both low-mass and high-mass LLPs, respectively. The two displaced triggers are also used in the current search for displaced vertices, as described in Sec. 5.2. Another key improvement is on the use of machine learning for increasing signal-to-background discrimination and background rejection. In Run-2, the displaced-jets analysis uses the gradient boosted decision tree (GBDT) algorithm to classify signals and backgrounds. Particularly, the algorithm takes an input from a reconstructed vertex and leading tracks associated with the dijet to output a discriminating score, or so-called *GBDT score*. This variable along with the number of prompt tracks of the dijet system are used to define a signal region, which is a region of high GBDT score and low prompt tracks.

Similarly, they carry out some of these techniques to the search for light LLPs using the first year of the Run-3 dataset. Instead of probing a multitude of BSM models, the displaced-jets analysis improves the exclusion limit on the exotic Higgs decay, especially for $\text{LLP} \rightarrow b\bar{b}$. The machine learning in this work is a graph neural network (GNN) that gains popular attention recently. The GNN learns from the existence of tracks and displaced vertices and their relations. With this improvement along with others, the displaced-jets analysis excludes $\text{Br}(H \rightarrow \text{SS})$ greater than 1% at 95% CL of an SM Higgs decaying to LLPs with a mass greater than 40 GeV and a proper lifetime between 1.5-370 mm for $S \rightarrow b\bar{b}$

or 1.3-380 mm for $S \rightarrow d\bar{d}$ [32].

6.1.3 Displaced muons

As mentioned in Sec. 2.5.2, the displaced dimuon [48] has set the most stringent exclusion limit on $\text{Br}(H \rightarrow XX)$ for the new long-lived scalar particle. This particle has a mass greater than 40 GeV and decays leptonically across a wide range of lifetimes. In fact, the dataset used in the analysis was collected solely from the 2022 data-taking period, which is the first year of Run-3 LHC program. With the goal of the analysis being a search for a pair of displaced muons with a common vertex, it gains advantages from a new displaced-muon reconstruction algorithm as well as a new trigger scheme. For a new displaced-muon reconstruction, the analysis is aware that three main types of muons are reconstructed at the CMS experiment, namely *global muons*, *tracker muons*, and *standalone muons*, as explained in Sec. 4.3. Fortunately, the standalone muon algorithm used in the analysis has been developed recently to eliminate the constraint and improve spatial and momentum resolutions of standalone muons, that used to be their disadvantages.

After the reconstruction of muons is completed, a dimuon is used as an object for triggering and selecting events from the hardware level (or the L1 trigger) onward to higher selection levels. A pair of muons classified by the aforementioned categories of muon reconstruction with the highest $\min(d_0, -d_0)$, or the minimum impact parameter significance of a muon pair, in an event is selected to estimate a di-muon mass. As expected, SM processes in this search tend to have a small impact parameter significance and a low di-muon

mass. With these analysis strategies, the analysis excludes $\text{Br}(H \rightarrow Z_D Z_D)$ as low as 0.01% at 95% CL, based on the hidden Abelian Higgs model (or HAHM) [40] [29], in the $c(Z_D)$ range of 0.3 mm to 0.5 m, and the m_{Z_D} range of 20-60 GeV.

6.2 Future prospects

As of this writing, the LHC program has been continued to Run-3, shown in Figure 6.5. However, the physics analysis in this work is based on data collected during Run-2, between 2016 and 2018. In the near future, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC) program, which is expected to start in 2029 and last for about 10 years. The HL-LHC program will provide an integrated luminosity of 3000 fb^{-1} , which is ten times more than the current LHC program. This upgrade will allow the CMS experiment to probe a wider range of new physics, including the search for LLPs. With more particles colliding in the HL-LHC program, the chance to be sensitive to rare physics processes is higher. The number of pile-up events is expected to be around 200, which is significantly higher than 30-40 pile-up events of the current Run-3 condition. The demand to achieve this run condition while operating physics detectors under a similar level of computational constraints is a challenge.

On one hand, new technologies for powerful magnets and beam collimation are being upgraded to satisfy such a run condition. For instance, twelve quadrupole magnets will be installed close to the ATLAS and CMS experiments to squeeze the beam size for more intense and more concentrated particle bunches than ever. Another upgrade is on electrical transmission lines that can

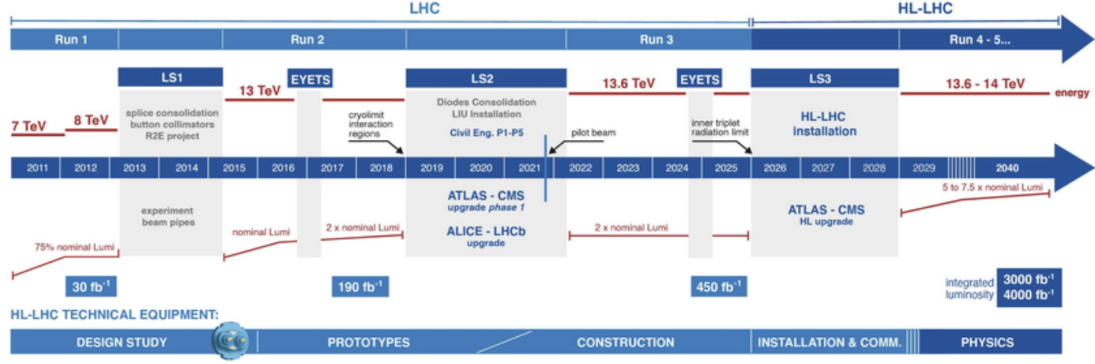


Figure 6.5: Timeline of the LHC and HL-LHC programs, showing key milestones and upgrades [83].

deliver current to magnets of up to 100 kA, based on the novel high-temperature superconducting material. Apart from these, machine protection systems for beam losses as well as on-site infrastructures are being developed to ensure the safety and effectiveness of the HL-LHC operation [83].

On the other hand, physics experiments such as the CMS experiment have major upgrades to their detectors. The CMS experiment will have a new tracker system, called the Phase-2 tracker, which is designed to have a better resolution and a higher granularity and extends the coverage up to $\eta = 3.8$. More importantly, the new tracker, especially the outer tracker, will accommodate a new *track-trigger* system. Particularly, the track-trigger system will operate in real-time to select events based on tracks' p_T . Instead of limiting this L1 hardware trigger rate to 100 kHz, the new system will be able to filter events from 40 MHz collision rate to 750 kHz. However, the track-trigger latency is limited to 12.5 μ s, with only 4 μ s allocated for running track-finding algorithms. Other subdetectors, including HLT systems, calorimeters, and muon chambers, are also being upgraded to cope with a demanding run condition at the HL-LHC [1].

6.2.1 The Phase-II Upgrade of the CMS L1 Trigger

The L1 trigger works together with the outer tracker or strip tracker (Sec. 3.2.7) at the CMS experiment. This collaboration aims to achieve the goal of the HL-LHC program. Outer tracker modules are redesigned to deliver track hit information to the L1 trigger. Specifically, the concept of estimating p_T of a track before reading an event out is a game changer in this upgrade. It is implemented by “ p_T modules”, consisting of two silicon layers. Whenever two hits are found in two consecutive sensor layers and are compatible within a small angular separation ($\Delta\eta$), they form a “stub.” Stubs corresponding to a particle trajectory with $p_T > 2$, based on the track-finding algorithm, are read out for further processing. It should be emphasized that the track-finding algorithm is designed to be fast and efficient. In addition to the geometric consideration of a high- p_T track during the stub formation, it also performs a road search to find matched stubs for the formation of a track in a narrow region of $\Delta\eta$, as ‘Virtual Modules’ (VMs), as illustrated in Figure 6.6. Given that VMs are segmented by $\Delta\eta$ and $\Delta\phi$, track-finding algorithms are divided into several processing steps. The algorithm manages these resources in a pipeline-like manner with a fixed latency for each step to process different events in parallel [8].

The track-trigger system relies on several FPGA-based modules to perform track-finding algorithms simultaneously. These modules are interconnected by high-speed optical links to exchange data and control signals on TFP boards based on the Apollo platform [3]. These FPGA-based modules are key components of the track-trigger system and are constrained by a 4-ns latency budget. The solution is to develop FPGA-based firmware using a high-level synthesis (HLS) tool, called Vivado HLS, to convert C++ code to VHDL code, as well as

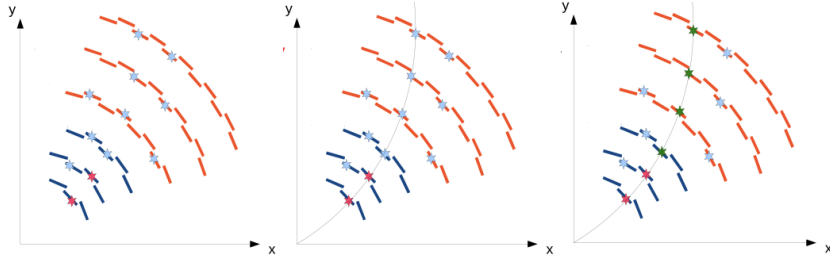


Figure 6.6: (Left) Stubs are formed in different p_T modules by hit information. (Middle) a pair of stubs (red) forms a seed or tracklet and is projected to other layers with a constraint at the origin. (Right) Matched stubs (green) are included in a track trajectory and fitted by a linearized χ^2 -fit to determine a set of track parameters [8].

the VHDL code in combination. Most of the hardware and firmware development have been carried out by the CMS collaboration at Cornell University, in which the author has been involved.

6.2.2 Prospects on long-lived particle physics at HL-LHC era

With a larger dataset exceeding the technical design of the LHC program by a factor of ten, along with the intelligence of a track-trigger system, the HL-LHC program will provide a unique opportunity to search for long-lived particles (LLPs) in a wider range of masses, lifetimes and physics models. In fact, the search for exotic Higgs decaying to LLPs with a displaced-vertex signature will not only take the full advantage of the larger Higgs samples in an order of $O(10^8)$, but will also potentially benefit from the track-trigger system to select events with a displaced vertex in real-time. As a matter of fact, the concept of current track finding that targets only prompt tracks is applicable to displaced tracks, as well as the track-trigger system that can be adapted to select events

with displaced tracks or displaced vertices at the L1 trigger level. However, the challenge for an L1 displaced-vertex trigger is the latency cost of reconstructing displaced vertices and the fake rate of SM backgrounds with displaced decays. Although the L1 displaced-vertex trigger is still in its infancy, it has proven to be more sensitive to exotic Higgs decays with LLPs by an order of magnitude than current hardware-based trigger systems [46]. Figure 6.7 shows the L1 trigger efficiency as a function of proper lifetimes ($c\tau$) of LLPs from various ways of triggering. The L1 displaced-vertex trigger (solid blue) is more competitive select LLPs with $c\tau$ between 1-100 mm than the L1 displaced-jet trigger (dashed blue), regardless of whether the LLP mass is 5 GeV (left) or 15 GeV (right). With this promising result, the HL-LHC program will be a golden opportunity to discover and constrain the exotic Higgs decays with long-lived particles (LLPs), especially in the context of LLPs with proper lifetimes of a few mm studied in this analysis.

Moreover, the HL-LHC program will allow the ATLAS and CMS experiments to exclude extensive ranges of LSP masses from some supersymmetric models. For example, the ATLAS experiment conducted a study on the prospective exclusion limits at 95% confidence level of a specific model of RPC SUSY with a gluino decaying to a pair of quarks and an unstable sparticle (appearing as MET). The study shows that the ATLAS experiment can exclude the gluino mass up to 3.4 TeV for proper lifetimes between 10 mm to 1 m, compared to the current exclusion limit of up to 2.4 TeV at 95% confidence level, shown in Figure 6.8. Nevertheless, this comparison is under the assumption of no signals observed and with different scenarios for a background yield of $1.8^{+1.8}_{-0.9}$ events (left) and of $0.02^{+0.02}_{-0.01}$ events (right). If the signal is present, the 3 σ and 5 σ observation reaches are also shown in the same figure. Since the search such as

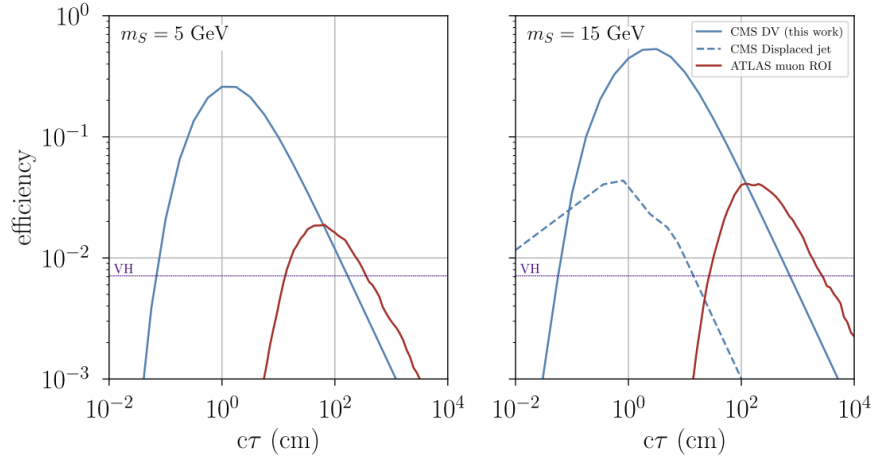


Figure 6.7: A simulation study of the CMS L1 displaced-vertex trigger in the scenario of exotic Higgs decays to LLPs with a mass of 5 GeV (left) or 15 GeV (right). The L1 trigger efficiency on the y-axis is normalized to the gluon fusion cross-section as a function of LLP proper lifetimes on the x-axis. The projected performances of the CMS displaced-vertex trigger (solid blue), the CMS L1 track-jet trigger for displaced jets, assuming 5 kHz rate, (dashed blue), the CMS single-lepton trigger on an associated lepton in VH production (purple) and the existing ATLAS muon region of interest trigger (solid red) are compared [46].

displaced-jets (Sec. 6.1.2) is sensitive competitively in this lifetime range, the same amount of delivered luminosity from the HL-LHC is expected to allow the CMS experiment to push the exclusion limits stringently in this mini-split SUSY model as well.

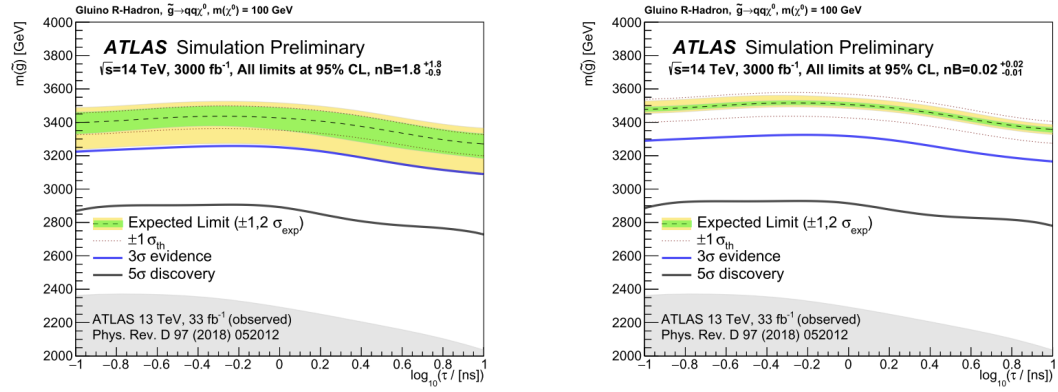


Figure 6.8: The projection on the sensitivity for the upper limit on the mass of a gluino R-hadron as a function of the gluino lifetime, assuming 3 ab^{-1} of collisions at $\sqrt{s} = 14 \text{ TeV}$ collected with the upgraded ATLAS detector. These results under no-signal hypothesis are compared with the observed ATLAS exclusion limits for a dataset of 33 fb^{-1} of collisions at $\sqrt{s} = 13 \text{ TeV}$ (gray). (Left) A background yield of $1.8^{+1.8}_{-0.9}$ events. (Right) A background yield of $0.02^{+0.02}_{-0.01}$ events. If the signal is present, the 3 (blue solid) and 5 (black solid) observation reaches are estimated [13].

CHAPTER 7

CONCLUSIONS AND SUMMARY

This thesis presents the current effort in a search for long-lived particles (LLPs) with proper lifetimes between 100 μm to 30 mm, corresponding to a displaced-vertex (DV) signature. The analysis on this DV signature of LLPs used data delivered by the LHC to the CMS experiment in Run-2, lasting from 2016 to 2018. The datasets in 2016 are divided into two periods because of the technical issue with the CMS silicon strip tracker. The dataset collected before resolving the issue is referred to as "2016APV", while the dataset collected after resolving the issue is referred to as "2016". In total, the amount of collected data is 136 fb⁻¹. Thanks to this large luminosity and the excellent performance of the CMS detector, the search for LLPs with a DV signature has probed a variety of physics beyond the Standard Model (BSM), including exotic Higgs decays and R-parity violation (RPV) supersymmetry (SUSY) models.

Although these models are driven by different theoretical frameworks and parameter spaces of new physics, all simplified models have a common feature of a pair production of LLPs that decay hadronically, appearing as at least two jets per decay. Furthermore, this feature motivates the search to define a signal region composed of two selected displaced vertices, reconstructed by an in-house vertex reconstruction algorithm. The number of tracks associated with each selected vertex must be at least five to ensure a good vertex position, as well as discriminating SM backgrounds.

In fact, the vertex selection criteria have not changed much from the previous iteration of the analysis [70], that used the high- H_T triggers in the same datasets. However, this iteration has improved significantly in three main ways. Firstly,

the analysis now probes not only the RPV SUSY model, as in the previous iteration, but also extends sensitivity to exotic Higgs models. This includes two main production modes of the SM Higgs boson: gluon-fusion production and associated vertex-boson production. Secondly, it is designed to be sensitive to low-mass LLPs by using a complementary set of triggers, including displaced-jet triggers, b-jet triggers, and single muon (electron) triggers. This approach covers the parameter space of LLPs that are beyond the reach of high- H_T triggers. Thirdly, the data-driven approach has been extended beyond the background estimation technique, which predicts two-vertex events from one-vertex events in data. It now includes other aspects of the search, such as vertex reconstruction algorithms and vertex-finding systematic uncertainties.

To elaborate on the third improvement over the high- H_T analysis, the vertex reconstruction algorithms have been studied in great detail. They have been optimized for all signal models. This is particularly challenging when including exotic Higgs signals with LLP mass points lower than LSP mass points in RPV SUSY by an order of magnitude. For instance, low-mass LLPs tend to be boosted with high momentum, while high-mass LLPs are slow-moving particles. Boosted LLPs generally have a lower vertexing efficiency because their decay is either intrinsically collimated, providing lower vertex position resolution, or located in a high pseudorapidity ($|\eta| > 2.5$) region undetected by the CMS tracker. To avoid these biases in real data, we decided to mitigate pile-up tracks by using a significant shift variable of a refitted vertex position along the z-axis instead of an absolute value. This approach is less biased in discarding genuine signal tracks with high p_T . Additionally, the vertex position accuracy variable, d_{BV} , has been relaxed from a maximum value of 25 μm to 50 μm . This change allows the vertex reconstruction algorithm to reject 2-vertex events in

backgrounds by a factor of about 2.5. Such an opportunity would be impossible without observing ‘shared-jets’ due to misreconstructed tracks. Resolving shared jets caused by misreconstructed tracks is highly sensitive to background vertices with fewer tracks migrating out of the signal region. This is key to the success of a model-independent vertex reconstruction.

The third improvement based on the data-driven principle also covers the systematic uncertainties on the vertex reconstruction algorithms. These uncertainties used to be the most dominant source of total systematic uncertainties of signal yield in the previous iteration, reaching up to 40% in the dijet signal model. This technique directly probes the systematic uncertainty from the real-data environment by comparing the vertexing efficiency difference between simulation and data. However, displaced vertices are rare in both samples. The technique called ‘TrackMover’ (TM) is used to artificially move tracks in both simulated and data events. To replicate each signal point’s characteristics in LLP decays by topology and kinematics, the TM data and TM simulated events are reweighted to exhibit decay characteristics. This includes moved tracks and their displacement, similar to isolated LLP decays of signals. Each signal efficiency is then corrected based on TM data and TM MC differences, such as the number of tracks close to an expected decay position and their efficiency curves. The fractional difference in the corrected signal efficiency compared to the original one is quantified as the systematic uncertainty for vertex finding. TrackMover’s procedures have been generalized to apply not only to signals with displaced vertices in all models considered but also to signals with other displaced objects. For instance, with all sources of uncertainties relevant to vertex finding, this uncertainty is found to be around 10% in the exotic Higgs model with an LLP mass point of 55 GeV and a proper lifetime of 1 mm.

By the time the analysis is completed and un-blinded, the search for LLPs with a DV signature is expected to fill in the gap of our knowledge in the exclusion limit of $\text{Br}(H \rightarrow SS)$ in the exotic Higgs model. It will also address the exclusion limit of stop and gluino/neutralino mass in the RPV SUSY model. Conclusively, with the search being sensitive to smaller proper lifetimes than 1 mm, it provides a complementary exclusion limit, as previously done in Figure 2.11, to other searches at ATLAS and CMS experiments when they start to degrade in their sensitivity.

APPENDIX A

IMPACT OF RELAXING A DISPLACED CRITERION OF TRACKS TO RECONSTRUCTED VERTICES AND YIELDS

As mentioned in Sec. 5.3.1 and Sec. 5.3.3, the current displaced criterion for selecting seed tracks could have been $d_{xy} \leq 2$ instead of $d_{xy} \leq 4$. This approach to increase signal yields does not significantly improve signal efficiency. Moreover, it introduces a significant amount of background to the signal region and even more to the control region.

In Figure A.1 (top), the impact on signal-like events is evident from the number of entries with at least two reconstructed vertices. The number of exotic Higgs MC events (orange) increases by 15% with respect to the baseline (light-blue). However, background MC events (brown) increase to nearly 4 events out of 7514 events, as opposed to zero (green). In addition to this observation in the discovery region, the number of events with at least two reconstructed vertices in the control region in which the vertices have exactly three tracks become 50 times more than before relaxing the displaced criterion, shown in Figure A.1 (bottom right). Therefore, the displaced criterion remains as $d_{xy} \leq 4$.

To explain further, Figure A.2 demonstrates the number of output vertices (right) and the number of tracks per vertex (left). This result shows that the number of vertices reconstructed by the main algorithm increases when relaxing the displaced criterion (red) compared to the current criterion (blue). Nevertheless, the majority of extra vertices have only two tracks per vertex. These output vertices that pass vertex selection cuts and have at least five tracks are shown in Figure A.3. The distributions between red and blue are similar. This implies that the relaxed criterion does not significantly increase the number of

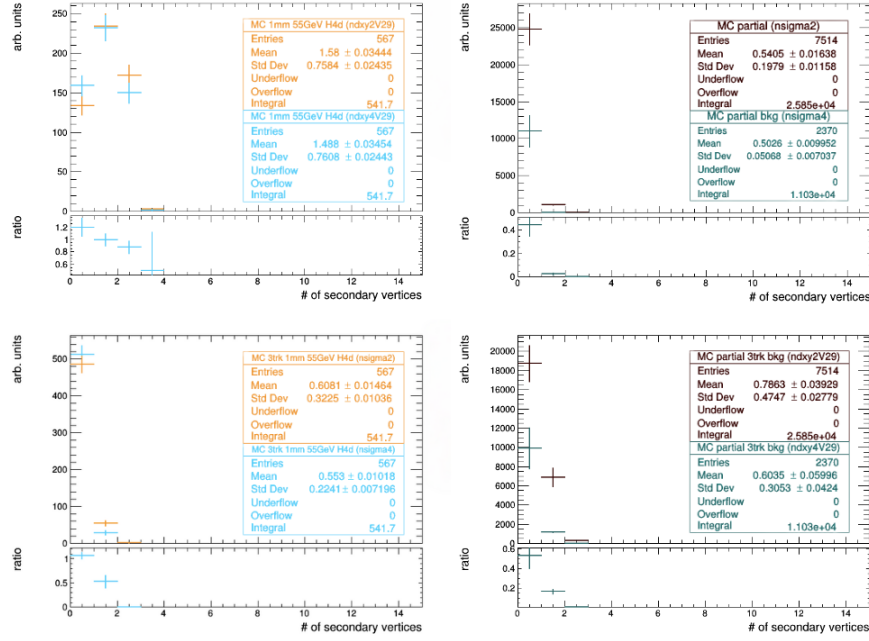


Figure A.1: The distributions of reconstructed vertices (i.e. secondary vertices) are compared between events with tracks satisfying the relaxed (labelled by "nsigma2") and the current (labelled by "nsigma4") displaced criterion in signal (left) or background simulation (right). (Top) reconstructed vertices have at least 5 tracks, meaning that bins with two or more vertices are in the signal-like region of the search. (Bottom) reconstructed vertices have exactly 3 tracks, meaning that bins with two or more vertices are in the control region of the search. Note that the signal is the exotic Higgs with LLP mass of 55 GeV and c of 1 mm.

signal-like vertices.

With the split-vertex merging algorithm included, the results before (light-blue) and after (orange) relaxing the displaced criterion of seed tracks are compared. The comparison shows that relaxing the displaced criterion does not assist the new algorithm. It does not help to pick up surplus 2-track vertices and merge them with split vertices.

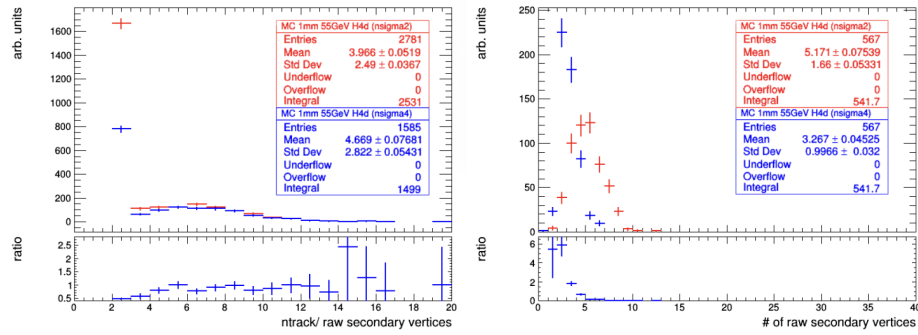


Figure A.2: (Right) The number of output vertices per event, with no vertex selection applied. (Left) The number of tracks per vertex on the right. The distributions derived after the main vertex reconstruction algorithm are compared with (red) and without (blue) the "relaxed" displaced criterion imposed to selected tracks in the exotic Higgs signal with c of 1 mm and LLP mass of 55 GeV.

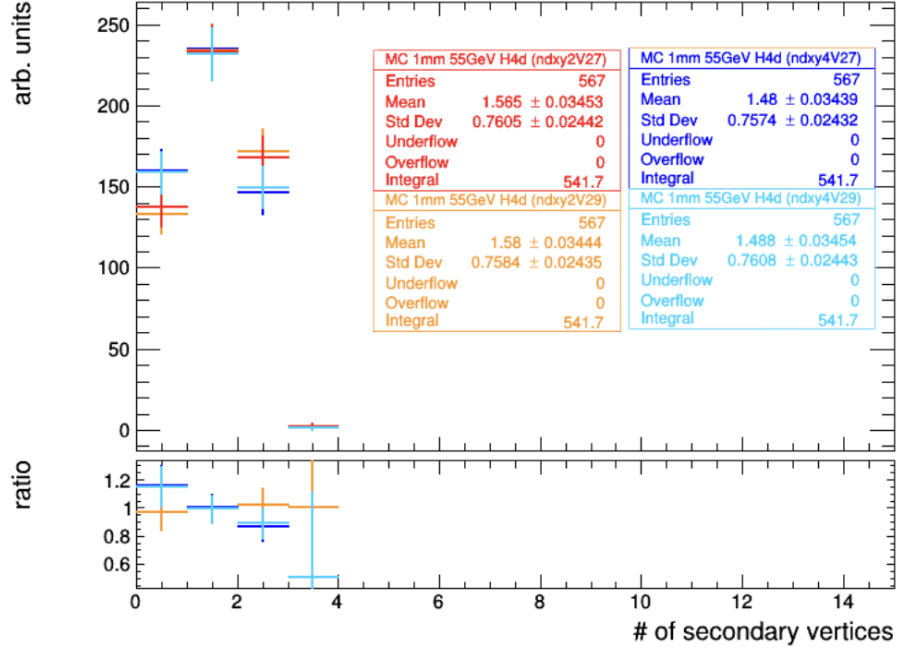


Figure A.3: Comparison of the distributions of signal-like vertices (i.e. secondary vertices) by various vertex reconstruction regimes in the exotic Higgs signal with c of 1 mm and LLP mass of 55 GeV. With the main reconstruction algorithm alone, the distributions with (red) and without (blue) the “relaxed” displaced criterion imposed to selected tracks are compared. By adding the split-vertex reconstruction and shared-jet mitigation, the distributions with (orange) and without (light-blue) the “relaxed” displaced criterion imposed to selected tracks are compared.

APPENDIX B

PREDICTING TWO-VERTEX YIELD FROM ONE-VERTEX EVENTS

This appendix presents our method for normalizing the two-vertex background and assesses its reliability.

The premise of the background estimate is that the probability of finding 2-vtx events is the product of the probability of finding each vertex in 1-vtx events, multiplied by the probability of finding the other vertex in 1-vtx events. That is, the yield of events with an n -track and an m -track vertex, $N_{n\ m\ n}$, is given by

$$N_{n\ m\ n} = N_{2v,tot} \frac{N_{1v,n}}{N_{1v,tot}} \frac{N_{1v,m}}{N_{1v,tot}} \quad (B.1)$$

Here, $N_{2v,tot}$ is the sum of 2-vtx events in all categories, and therefore accounts for factors such as vertex overlap and the impact of the shared-jet mitigation algorithm.

The results of the background estimate are given in Table B.1–Table B.8.

Table B.1: Results of predicting the number of two-vertex events for different vertex track multiplicities background in 2016APV selected by single-lepton triggers.

Inputs		Yield	
N_{2v} tot		38	4
3-track 1-vtx (N_{1v3})		53140	3354
4-track 1-vtx (N_{1v4})		3974	1088
5-track 1-vtx (N_{1v5})		104	19
Two-vertex Category		Predicted Yield	Observed Yield
3-track	3-track	33 3	32 3
4-track	4-track	0 183 0 018	0 0
5-track	5-track	0 0	0 0

Table B.2: Results of predicting the number of two-vertex events for different vertex track multiplicities background in 2016 selected by single-lepton triggers.

Inputs		Yield	
N_{2v} tot		91	4
3-track 1-vtx (N_{1v3})		55745	3112
4-track 1-vtx (N_{1v4})		2735	459
5-track 1-vtx (N_{1v5})		603	457
Two-vertex Category		Predicted Yield	Observed Yield
3-track	3-track	81 4	78 4
4-track	4-track	0 195 0 011	0 3 0 2
5-track	5-track	0 009 0 001	0 0

Table B.3: Results of predicting the number of two-vertex events for different vertex track multiplicities background in 2017 selected by single-lepton triggers.

Inputs		Yield			
N_{2v} tot		350		30	
3-track 1-vtx (N_{1v3})		289493		8950	
4-track 1-vtx (N_{1v4})		12263		1555	
5-track 1-vtx (N_{1v5})		2641		1413	
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	317	27	309	26
4-track	4-track	0 568	0 049	2 3	2 2
5-track	5-track	0 026	0 002	0	0

Table B.4: Results of predicting the number of two-vertex events for different vertex track multiplicities background in 2018 selected by single-lepton triggers.

Inputs		Yield			
N_{2v} tot		1682		1091	
3-track 1-vtx (N_{1v3})		561007		19677	
4-track 1-vtx (N_{1v4})		27482		3632	
5-track 1-vtx (N_{1v5})		3493		1544	
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	1511	979	1618	1091
4-track	4-track	3 6	2 4	1 4	0 5
5-track	5-track	0 059	0 038	0	0

Table B.5: Results of predicting the number of two-vertex events for different vertex track multiplicities background 2016APV selected by displacement triggers vetoed lepton events.

Inputs		Yield			
N_{2v} tot		7878 850			
3-track 1-vtx (N_{1v3})		1103960 12446			
4-track 1-vtx (N_{1v4})		90310 2671			
5-track 1-vtx (N_{1v5})		39761 1646			
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	6623	714	6807	794
4-track	4-track	44	5	17	9
5-track	5-track	0 518	0 057	0	0

Table B.6: Results of predicting the number of two-vertex events for different vertex track multiplicities background 2016 selected by displacement triggers vetoed lepton events.

Inputs		Yield			
N_{2v} tot		3781 604			
3-track 1-vtx (N_{1v3})		598207 14579			
4-track 1-vtx (N_{1v4})		45932 1855			
5-track 1-vtx (N_{1v5})		3779 550			
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	3223	515	3342	599
4-track	4-track	19	3	10	6
5-track	5-track	0 129	0 021	0	0

Table B.7: Results of predicting the number of two-vertex events for different vertex track multiplicities background 2017 selected by displacement triggers vetoed lepton events.

Inputs		Yield			
N_{2v} tot		4606		1095	
3-track 1-vtx (N_{1v3})		498864		13191	
4-track 1-vtx (N_{1v4})		25355		2323	
5-track 1-vtx (N_{1v5})		2459		878	
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	4132	982	4167	1086
4-track	4-track	11	2	14	06
5-track	5-track	0100	0024	0	0

Table B.8: Results of predicting the number of two-vertex events for different vertex track multiplicities background 2018 selected by displacement triggers vetoed lepton events.

Inputs		Yield			
N_{2v} tot		4801		484	
3-track 1-vtx (N_{1v3})		604815		11471	
4-track 1-vtx (N_{1v4})		37124		2742	
5-track 1-vtx (N_{1v5})		2420		356	
Two-vertex Category		Predicted Yield		Observed Yield	
3-track	3-track	4230	427	3976	435
4-track	4-track	16	2	2	1
5-track	5-track	0 068	0 007	0	0

APPENDIX C

SYSTEMATICS UNCERTAINTIES OF VERTEXING EFFICIENCY

RESULTS FOR BENCHMARK MODELS

Sec. 5.8.1 analyzes the systematic uncertainties associated with vertex reconstruction for a particular exotic Higgs decay mode: $H \rightarrow SS$ where S has $c = 1$ mm and mass of 55 GeV and decays to a $d\bar{d}$ pair. The event uncertainty is the vertex uncertainty quoted here, multiplied by two. In this appendix, we apply the same method to other benchmark models. For each model, the sources of vertex uncertainty are:

- $N_{\text{closeseedtks}}$ distributions
- Curves of efficiency as a function of $N_{\text{closeseedtks}}$
- Mismodeling of TrackMover events
- Impact of a nearby LLP

The results for other models are summarized in Figures C.1 – C.12. For each one, two plots are shown. The first plot displays the vertexing efficiency as a function of lifetime and the second displays the associated systematic uncertainties.

Exotic Higgs signals from associated-boson production (lepton trigger)

In these modes, a Higgs produced via associated production decays via $H \rightarrow SS$, where S is an LLP that in turn decays to $d\bar{d}$. Results are shown for various S masses and lifetimes in Figures C.1 – C.4.

Exotic Higgs signals produced via gluon-fusion (displacement trigger)

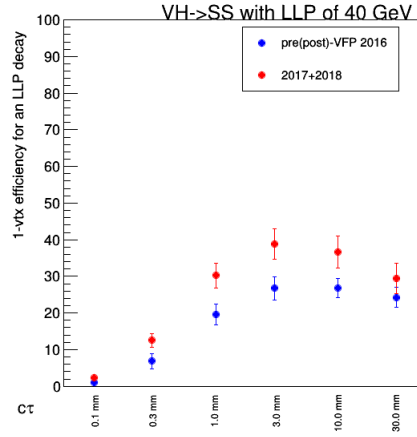


Figure C.1: Vertexing efficiency for exotic Higgs signals from associated-boson production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 40-GeV LLP. The error bars indicate the systematic uncertainty in the efficiency.

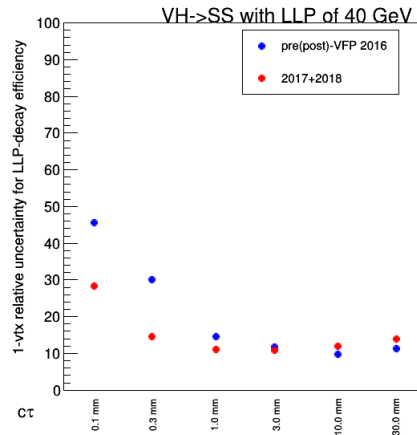


Figure C.2: Vertexing systematic uncertainty for exotic Higgs signals from associated-boson production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 40-GeV LLP

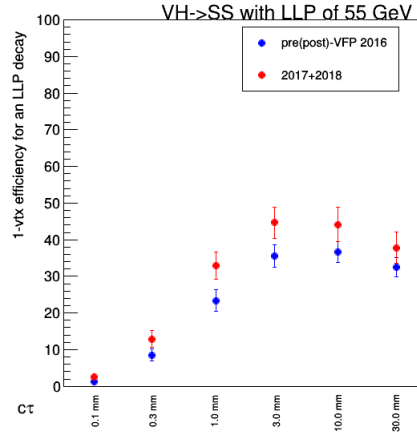


Figure C.3: Vertexing efficiency for exotic Higgs signals from associated-boson production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 55-GeV LLP. The error bars indicate the systematic uncertainty in the efficiency.

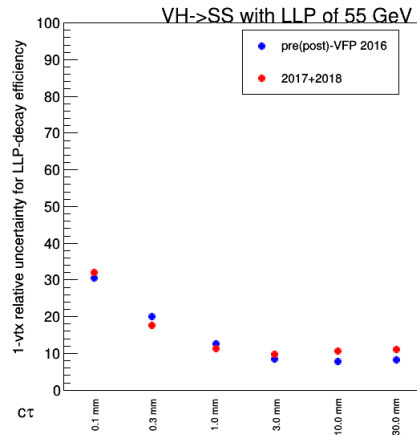


Figure C.4: Vertexing systematic uncertainty for exotic Higgs signals from associated-boson production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 55-GeV LLP.

In these modes, a Higgs produced via gluon-gluon fusion decays via $H \rightarrow S\bar{S}$, where S is an LLP that in turn decays to $d\bar{d}$. Results are shown for various S masses and lifetimes in Figures C.5 – C.8.

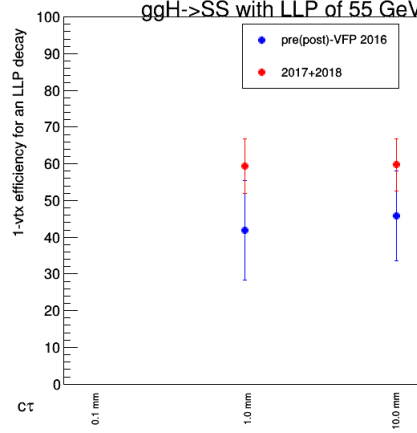


Figure C.5: Vertexing efficiency for exotic Higgs signals from gluon-fusion production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 55-GeV LLP. The error bars indicate the systematic uncertainty in the efficiency.

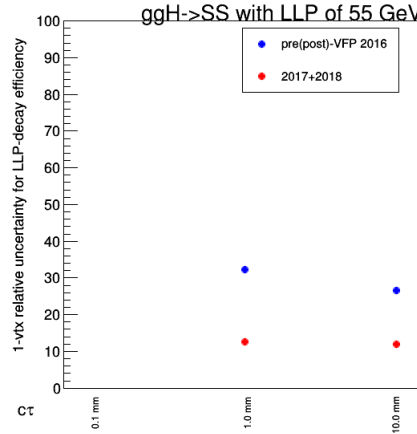


Figure C.6: Vertexing systematic uncertainty for exotic Higgs signals from gluon-fusion production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 55-GeV LLP

RPV SUSY stop

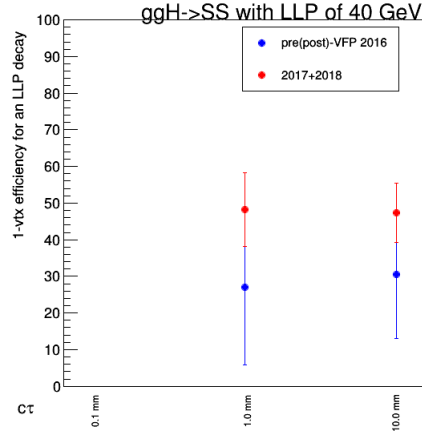


Figure C.7: Vertexing efficiency for exotic Higgs signals from gluon-fusion production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 40-GeV LLP. The error bars indicate the systematic uncertainty in the efficiency.

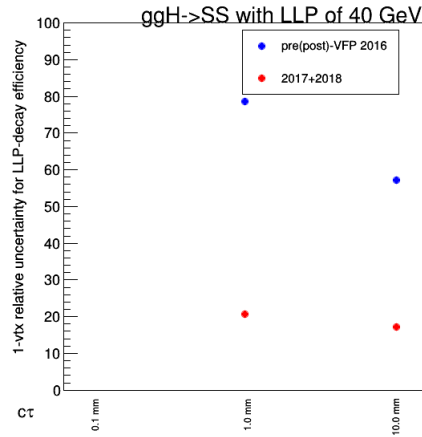


Figure C.8: Vertexing systematic uncertainty for exotic Higgs signals from gluon-fusion production in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for 40-GeV LLP

In these modes, a top squark decays to $\bar{d}\bar{d}$ or $\bar{b}\bar{b}$. Results are shown for various top squark masses and lifetimes in Figures C.9 – C.12.

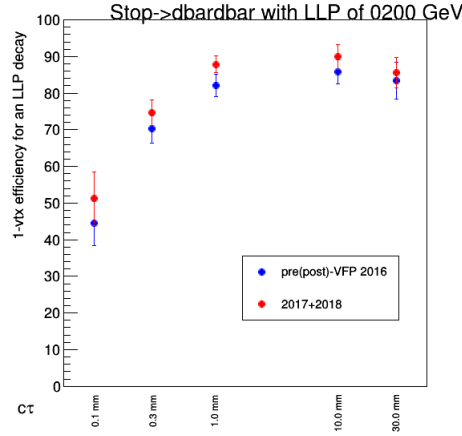


Figure C.9: Vertexing efficiency for RPV SUSY ($\tilde{t} \rightarrow \bar{d}\bar{d}$) signals in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for Stop with mass of 200 GeV. The error bars indicate the systematic uncertainty in the efficiency.

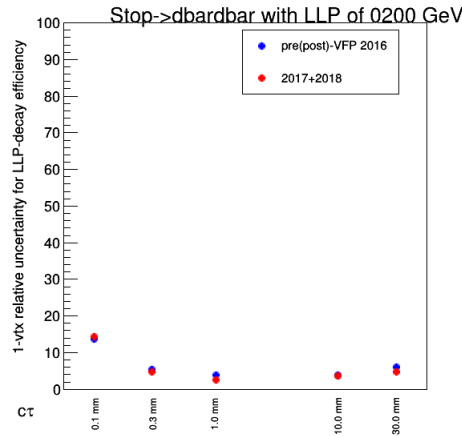


Figure C.10: Vertexing systematic uncertainty for RPV SUSY ($\tilde{t} \rightarrow \bar{d}\bar{d}$) signals in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for Stop with mass of 200 GeV.

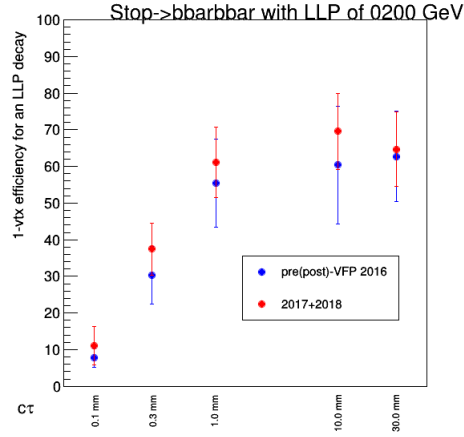


Figure C.11: Vertexing efficiency for RPV SUSY ($\tilde{t} \rightarrow b\bar{b}$) signals in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for Stop with mass of 200 GeV. The error bars indicate the systematic uncertainty in the efficiency.

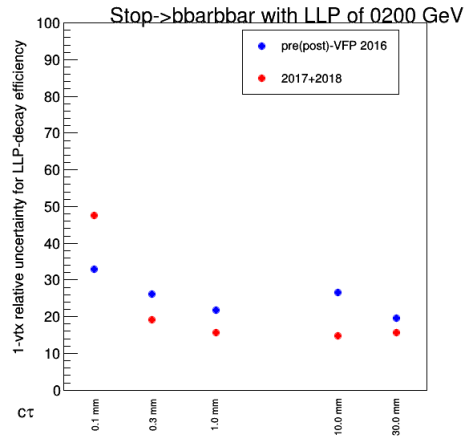


Figure C.12: Vertexing systematic uncertainty for RPV SUSY ($\tilde{t} \rightarrow b\bar{b}$) signals in 2016 data (blue) and 2017-2018 data (red) across LLP proper lifetimes for Stop with mass of 200 GeV.

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