



The experimental status of direct searches for exotic physics beyond the standard model at the Large Hadron Collider

Salvatore Rappoccio

University at Buffalo, State University of New York, 239 Fronczak Hall, Amherst, NY 14260, USA

ARTICLE INFO

Keywords:

Beyond standard model
BSM
Exotica
EXO
B2G
LHC
CERN,

ABSTRACT

The standard model of particle physics is an extremely successful theory of fundamental interactions, but it has many known limitations. It is therefore widely believed to be an effective field theory that describes interactions near the TeV scale. A plethora of strategies exist to extend the standard model, many of which contain predictions of new particles or dynamics that could manifest in proton-proton collisions at the Large Hadron Collider (LHC). As of now, none have been observed, and much of the available phase space for natural solutions to outstanding problems is excluded. If new physics exists, it is therefore either heavy (i.e. above the reach of current searches) or hidden (i.e. currently indistinguishable from standard model backgrounds). We summarize the existing searches, and discuss future directions at the LHC.

1. Introduction

A man said to the universe:

“Sir, I exist!”

“However,” replied the universe,

“The fact has not created in me

A sense of obligation.”

– Stephen Crane

Particle physics is at a crossroads. The standard model (SM) explains a wide range of phenomena spanning interactions over many orders of magnitude, yet no demonstrated explanation exists for a variety of fundamental questions. Most recently, the discovery of the Higgs boson [1–9] at the ATLAS [10] and CMS [11] detectors has addressed the mechanism of electroweak symmetry breaking, but there is no explanation for why the scale of its mass is so much different from naive quantum-mechanical expectations (the “hierarchy problem”) [12–20]. Dark matter (DM) remains an enigma, despite extensive astronomical confirmation of its existence [21–23]. Neutrino masses are observed to be nonzero [24–27], and elements of the Pontecorvo–Maki–Nakagawa–Sakata matrix [28,29] have been measured, but these masses are not easily accounted for in the SM [30]. Unification of the strong and electroweak forces is expected, but not yet observed nor understood [31–44]; such models often predict the existence of yet-to-be-observed leptoquarks (LQs) or proton decay [45]. Furthermore, there are unexpected observations that are not explained in the SM, such as the baryon asymmetry [46], anomalies in the decays of bottom-quark hadrons [47], a discrepancy in the anomalous magnetic moment of the muon ($g-2$) [48], and the strong CP problem [49–51]. Even further, there are open questions about long-standing observations, such as whether or not there is an extended Higgs sector [52], why there are multiple generations of fermions with a large mass hierarchy [32,53–55], and why no magnetic monopoles are observed to exist [56]. For these reasons, the SM is considered

E-mail address: salvatore.rappoccio@cern.ch.

<https://doi.org/10.1016/j.revip.2018.100027>

Received 24 October 2018; Received in revised form 7 December 2018; Accepted 12 December 2018

Available online 13 December 2018

2405-4283/ © 2018 The Author. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

to be an effective field theory, and that physics beyond the SM (BSM) should exist.

There is no shortage of models to explain these elusive phenomenon, with varying degrees of complexity and explanatory power. One very popular group of theories to explain several of these phenomena involve supersymmetric (SUSY) extensions to the SM [12,13]. Many SUSY models contain a particle that only interacts very weakly with ordinary matter (the “lightest SUSY particle”, or LSP), providing a simple DM candidate. At the same time, SUSY also attempts to address questions about the hierarchy problem, the nature of space-time, grand unified theories, and even string theory. For this reason, SUSY has long been held as a very attractive BSM physics model, because it can explain a wide range of phenomena with simple assumptions.

Unfortunately, as of yet, no easily detectable signals have been observed at the LHC. This, in and of itself, is not necessarily a problem, because the scale of SUSY could always either be heavier than we can currently access, or exists in a region where the signals are hidden among SM backgrounds. The former case, however, limits the ability for SUSY to mitigate the hierarchy problem. The infrared divergences of the mass of the Higgs boson are only canceled if the masses of the SUSY particles are very close to their SM counterparts. This raises questions of whether or not the models themselves “naturally” explain the hierarchy problem. For the case of subtle signatures, of course, such questions of naturalness are less pressing, and can still preserve solutions to the hierarchy problem with a DM candidate.

Despite those attractive theoretical features, there is really no *a priori* reason (other than our personal aesthetic) that one model should address all of these open questions simultaneously. For these reasons, in this Review, we will discuss a subset of these questions that have been investigated recently at the LHC with 13 TeV proton-proton collisions by the ATLAS, CMS, and LHCb [57] experiments. From a collider standpoint, we will discuss the solution to the hierarchy problem, dark matter, the origins of neutrino masses, unification, and compositeness. We will also discuss the possibilities for improvements of these searches at the High-Luminosity LHC (HL-LHC) or other future colliders.

With a few exceptions, this Review will focus on answers to the above questions that do not involve SUSY, although it remains a theoretically attractive solution. This Review will also primarily not focus on solutions that involve an extended Higgs sector, nor open anomalies in hadron spectroscopy. All of these topics merit their own separate reviews.

Many models of BSM physics that can be tested at the LHC often involve spectacular signatures that distinguish them from SM backgrounds. It is therefore worthwhile to discuss the searches for new physics with their unique signatures in mind. As such, we will first broadly discuss the signatures used for LHC BSM searches, and then discuss the implications on various scenarios.

The rest of this Review will be structured as follows. We discuss novel reconstruction techniques that are used extensively in searches in Section 2, solutions to the hierarchy problem in Section 3, searches for DM in Section 4, understanding the neutrino mass in Section 5, the unification of the forces (including leptoquarks) in Section 6, and finally the compositeness of the fundamental particles in Section 7. As a guide, Figs. 2–8 show the summaries of the searches for non-SUSY BSM physics at ATLAS and CMS performed with the various techniques outlined in Section 2.

2. Tools of searches for BSM physics

Overall, the major signatures of the searches for BSM physics will include: (1) traditional signatures involving leptons, jets, and photons with high transverse momentum (p_T), or missing transverse momentum ($p_{T/}$); (2) signatures involving particles that have lifetimes long enough to detect their decays (“long-lived particles”); (3) signatures with highly Lorentz-boosted SM particles that result in collimated, massive jets (“boosted hadronic jets”); and (4) signatures involving resonances that decay to lower-mass states, which must be Lorentz-boosted via initial-state radiation (ISR) to be detected (“ISR boosted”).

2.1. Traditional signatures

The ATLAS and CMS experiments have been designed primarily with traditional signatures for particle collisions in mind, with relatively prompt signals containing hadrons and isolated leptons or photons. The LHCb experiment has slightly different goals, i.e. to precisely measure bottom and charm hadron production, decays, and properties, as well as other particles with long lifetimes. Of course, many models of new physics manifest in SM-like signatures with different kinematic decays, or at different rates, compared with their SM counterparts. Considerable effort must occur to ensure optimal performance of the detectors, triggers, object reconstruction, calibration, etc. A thorough discussion of the experimental challenges facing the LHC experiments is beyond the scope of this paper, however we will highlight a few key ideas that are used in searches for BSM physics that look qualitatively similar to SM production.

Hadronic jets are the result of fragmentation and hadronization of the underlying quarks and gluons in the LHC interactions. Due to the confinement and asymptotic freedom of the quantum chromodynamic (QCD) interaction, the fragmentation and hadronization occur primarily in a collimated spray of particles called “jets” [58]. They are reconstructed from different inputs (depending on the detector) using the FASTJET software package [59,60]. The ATLAS collaboration utilizes primarily topological clustering of their calorimeter deposits (TC) [61], or occasionally a full reconstruction of the particle flow throughout the detectors (PF) [62], while CMS utilizes PF almost exclusively except where noted [63]. The typical momentum resolutions and scale uncertainties achieved for both experiments are $\sim 10\%$ and $\sim 0.5\text{--}1.0\%$, respectively, for $p_T = 100$ GeV [62,64,65]. Jets containing bottom or charm hadrons can have some displaced particles within them, and ATLAS, CMS, and LHCb are able to discern very small displacements (a few tens of microns) with respect to the beam axis with dedicated tagging algorithms [66,67]. This allows the reconstruction of vertices a few hundred microns from the beam axis. Such information can be used to efficiently discriminate jets that originate from bottom or charm quarks from those that originate from lighter quarks or gluons.

Electrons and photons are reconstructed in both experiments accounting for interactions with the material of the detector using dedicated algorithms [68–71], and using both the electromagnetic calorimeter and tracking information. Muons are reconstructed using dedicated detectors outside of the calorimeter structures [72,73], as well as information about the muon track and the ionization deposits in the calorimeters. The performance is dependent on the purity of the signal in question, but a good benchmark is the performance in reconstructing electrons from Z bosons, where the experiments achieve electron momentum resolutions and scale uncertainties around 1.5–5.0% and $< 1\%$, respectively, and muon momentum resolutions and scale uncertainties around 1% and 1–2.0%, respectively.

The reconstruction of τ leptons is performed by first reconstructing jets, then applying selection criteria consistent with individual particle signatures that take advantage of the unique decays of the τ lepton either hadronically to one or three pions, or semileptonically to lighter leptons and neutrinos [74,75]. There is an additional challenge in τ reconstruction, in that there are neutrinos produced in their decay that escape detection, which causes difficulties in reconstruction of the four-vector. The momentum resolutions and scale uncertainties are around 15% and 0.5–1.0% for τ leptons decaying from Z bosons, respectively.

Neutrinos are produced at the LHC primarily through weak interactions of the W boson. They can be produced directly through on-shell W decays, or indirectly via weak decays of bottom or charm quarks, or τ leptons. Neutrinos are not directly detected. Their presence is inferred by taking advantage of the fact that, since the proton beams carry minimal transverse momentum, the vector sum of the transverse momenta of all of the observed particles should cancel. This is referred to as a “transverse momentum imbalance” or “missing transverse momentum” $p_T/$. This technique can also be used to signal the presence of other particles that are not directly detected, such as DM or other exotic particles. A critical feature of this method of detection is to have nearly hermetic coverage of the phase space, but perfect coverage is unrealistic. This incomplete coverage in part contributes to the $p_T/$ resolution, which is around 10–15% in control samples involving Z boson decays to e^+e^- and $\mu^+\mu^-$.

2.2. Long-lived particles

It is possible for some particles that are produced in the collision to decay after traveling a relatively long distance. The most colloquially well-known particles in this category are muons and pions, as produced copiously via interactions of cosmic rays with the upper atmosphere. The mechanics behind such long decay times can differ, but broadly, there is either a massive force mediator (such as the W boson) that weakens the interaction strength, or the masses of the parent and child particles in the decay are so close that the kinematic phase space for the decay is restricted. In either of these cases, the probability for the particle to decay at a given time is reduced, causing a longer lifetime.

The LHC detectors were not originally intended to detect particles that decay further than a few centimeters from the beamline. The focus has traditionally been on detecting jets containing bottom or charm quarks, which decay a few hundred micrometers from the beam axis. Most other particles are considered to be effectively stable on the timescales via which they traverse the detectors. For instance, accounting for their Lorentz boosts, both pions and muons are long-lived enough to avoid decaying within the detector itself.

However, considerable progress has also been made to detect particles with intermediate lifetimes (longer than bottom and charm hadrons, shorter than pions and muons, from millimeters to meters). There are several strategies that can be employed here, and we discuss some of the most popular. Firstly, the same strategy as the bottom and charm hadron detection can be used, whereby particles with long lifetimes will have large impact parameters with respect to the beam axis. For instance, in Refs. [76,77], the detectors can discern particles that decay tens of millimeters away from the beam axis. Secondly, signals of events in the calorimeters that occur outside the beam crossing can be used as in Ref. [78]. In this case, particles may be produced with long enough lifetimes to escape the inner detectors, becoming trapped by the nuclear material of the hadronic calorimeter, to decay some time later. Thirdly, the particles may be heavy and quasi-stable, leaving large amounts of ionizing radiation in the tracking detectors.

Newer ideas include proposals of dedicated satellite experiments outside of the detector collision halls, such as the “MAssive Timing Hodoscope for Ultra Stable neutraL pArticles” (MATHUSLA) [79,80] and “ForwArd Search ExpeRiment at the LHC” (FASER) [81] detectors. The former will be able to detect particles produced in LHC collisions that decay several hundred meters from the interaction point, which is the same scale as allowed values from constraints imposed by Big Bang Nucleosynthesis (BBN) [82,83]. The latter will be situated close to the beamline, downstream from LHC collisions, to detect long-lived particles that subsequently decay to lepton pairs. Such satellite experiments show strong promise in extending the reach of discovery of new particles with long lifetimes.

2.3. Boosted hadronic jets

Particles with masses above the scale of the SM are widely expected in many BSM scenarios. If these particles have couplings to the heavier SM particles (and they must, if we are to produce them at the LHC), then often they contain couplings to top quarks and $W/Z/H$ bosons. In these cases, due to the large difference in masses between the BSM particle and the SM particles, the latter will be produced with large Lorentz boosts. This causes the decay products of the unstable SM particles to be highly collimated. We refer to these as “boosted objects” [84–89].

In the case of particles that decay fully leptonically such as $Z \rightarrow \ell^+\ell^-$, there are some modest adjustments to identification criteria that distinguish this case from traditional reconstruction techniques in Section 2.1. These involve nonstandard reconstruction techniques with relaxed isolation requirements, since the resulting leptons typically appear geometrically close to other objects.

Particles that decay hadronically (such as $H \rightarrow b\bar{b}$ or $t \rightarrow Wb \rightarrow q\bar{q}b$) or semileptonically (such as $t \rightarrow Wb \rightarrow lb$) pose more of a

challenge. The reason is that hadronic particles, as mentioned in Section 2.1, already tend to fragment and hadronize in regions with small spatial extent. As such, the signatures of boosted hadronically decaying particles can look quite similar to traditional jets. Special techniques involving the substructure of jets have been developed to distinguish boosted hadronically decaying particles from standard jets.

Since these techniques are somewhat new, the full phase space of possibility has not yet been explored for performance improvements. Some advances can come from better theoretical understanding of the underlying radiation patterns of jets, and/or from new advances in machine learning to better distinguish various types of jets [89].

2.4. ISR-boosted particles

Oftentimes, particles can be produced that create no detector signature (such as neutrinos or DM) or signatures that are completely overwhelmed by SM backgrounds (such as hadronic decays of the W or Z bosons). Reconstruction of such particles is impossible with standard techniques at the LHC.

In order to solve this problem, one clever idea is to look for signatures that recoil against initial-state radiation particles such as gluons. With sufficient Lorentz boosts, the previously undetectable or undiscernible particles become accessible again. This is the strategy behind most of the searches for DM outlined below, as well as searches for hadronically decaying BSM particles with masses below the $W/Z/H$ boson masses. This is also the strategy behind the recent observation of $H \rightarrow b\bar{b}$ [90,91], and the observation of hadronic decays of the W and Z bosons while searching for lower-mass vector resonances in Ref. [92].

3. The hierarchy problem

The hierarchy problem is, in its simplest form, a question about why the electroweak scale (100 GeV) is so much different from the Planck scale (10^{18} GeV). There are many references that describe this in detail (for instance, Refs. [12,93]), so here we discuss only the broadest overview.

The Higgs potential can be written as

$$V = m_H^2 |H|^2 + \lambda |H|^4. \quad (1)$$

where V is the Higgs potential, H is the Higgs field, m_H is the MS mass of the Higgs boson, and λ is a free parameter, experimentally determined by the vacuum expectation value (vev). The vev is nonzero if $\lambda > 0$ and $m_H^2 < 0$, resulting in $\langle H \rangle = \sqrt{-m_H^2/2\lambda}$, where $\langle H \rangle = 174$ GeV and the observed Higgs mass is around 125 GeV, yielding $m_H^2 = -(92.9 \text{ GeV})^2$.

The issue arises when one considers couplings of the Higgs field to SM fermions such as the top quark, in Fig. 1. These diagrams result in higher-order corrections to m_H such as

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \dots, \quad (2)$$

where λ_f is the Yukawa coupling of the fermion f to the Higgs field, and Λ_{UV} is some upper cutoff of the matrix-element integral to yield a finite result. There is no physical mechanism within the SM itself to yield a small value of Λ_{UV} to arrive at the observed Higgs boson mass, so either the SM is valid up to the Planck scale (resulting in $\Lambda_{UV} = \Lambda_{\text{Planck}}$, necessitating extremely fine-tuned higher-order corrections, or a new physical scale exists, Λ_{BSM} , between the electroweak and Planck scales, interpreted as the scale of BSM physics.

There are several proposals for the nature of BSM physics to solve the hierarchy problem, including SUSY [12,13], new strong dynamics or technicolor [14,15], and extra dimensions, either large [16,19] or warped [17,18]. Production of signatures involving “prompt” SUSY (i.e., SUSY without long-lived particles) will not be discussed in this Review, although signatures of SUSY with large lifetimes are discussed as they overlap significantly with signatures from other models [95,96]. Large extra dimensions (LED) are discussed below. Strong dynamics and warped extra dimensions are linked by an AdS/CFT correspondence [97], and are discussed together using the language of extra dimensions.

The solutions to the hierarchy problem and unification (see below) often predict additional gauge bosons. It is often convenient to simply assume SM-like couplings in the “sequential” SM (SSM). These are usually taken as benchmark scenarios and overlap with signatures from other models.

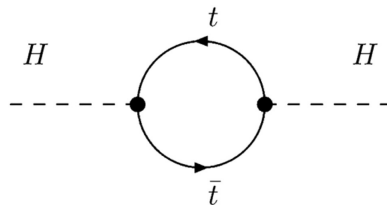
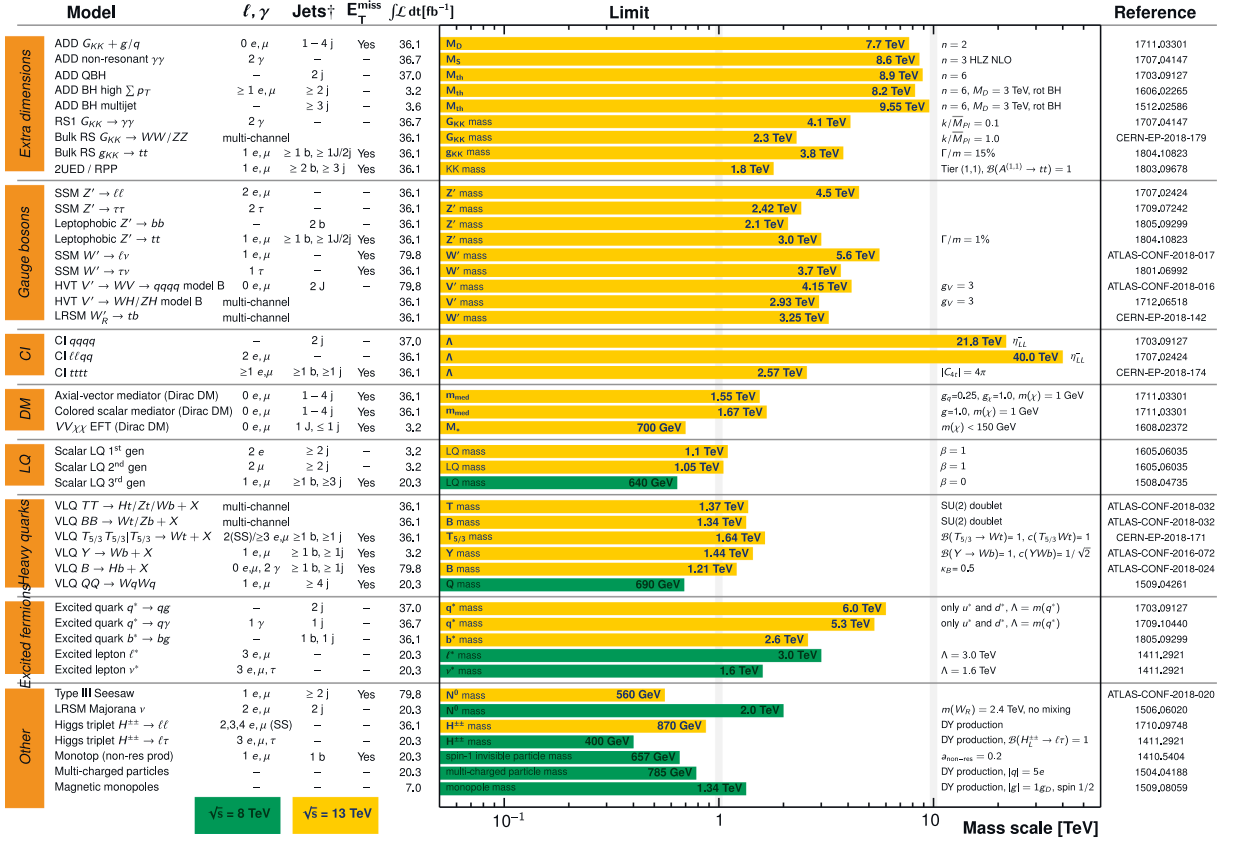


Fig. 1. Contributions to the Higgs boson mass from quantum mechanical effects. (Taken from Ref. [94]).

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

 $\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$ 

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Fig. 2. Summary of exotica searches at ATLAS with traditional, boosted, and ISR-boosted reconstructed techniques from Ref. [230]. These are interpreted in terms of limits on the mass of new particles in models containing extra dimensions, extra gauge bosons, new contact interactions (CI), dark matter (DM), leptoquarks (LQ), heavy quarks, excited fermions or miscellaneous others. Yellow (green) bands indicate 13 TeV (8 TeV) data results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Large extra dimensions

The existence of large extra dimensions (LED) [16,19] solves the hierarchy problem by positing that gravity is distributed through a higher-dimensional space (the “bulk”) whereas the SM particles are confined to a subspace (the “SM brane”). This results in a natural value for Λ_{UV} , much smaller than 10^{18} GeV . The relevant parameters are the number of extra dimensions n , the corresponding fundamental Planck scale M_D , and the mass threshold M_{th} , above which black holes are formed (where $M_{th} \geq M_D$). The relationship between M_D and the 3-dimensional Planck mass M_{pl} is given by

$$M_D = \frac{1}{r} \left(\frac{r M_{pl}}{\sqrt{8\pi}} \right)^{\frac{2}{n+2}} \quad (3)$$

where r is the compactification radius.

There are many signatures for LED models, including copious production of microscopic black holes [98–100]. These black holes decay almost instantly into one or more particles at high p_T , including signatures with photons, leptons, jets, or p_T . This provides a very unique signature at the LHC. For black hole masses far above M_{th} (for instance, $\sim 4M_{th}$ for $n = 6$) [101], the semiclassical approximation holds where quantum effects of individual gravitons can be neglected, and the black hole will decay uniformly to all SM particles (with quarks and gluons obtaining an enhancement from their 3 colors). The signature of such models contains a large number of high- p_T particles, and so the sensitive variable will be the scalar sum of the p_T of all of the jets, leptons, photons, and p_T . For black hole masses near M_{th} , however, the semiclassical approximation is invalid, and quantum-mechanical decay to a few highly energetic particles is the dominant decay mode.

At 13 TeV, there have been a large number of searches for such particles at both ATLAS [102–105] and CMS [106–108]. Figs. 2,3,4 show the results of many searches involving high-multiplicity events or events with significant p_T . The mass limits

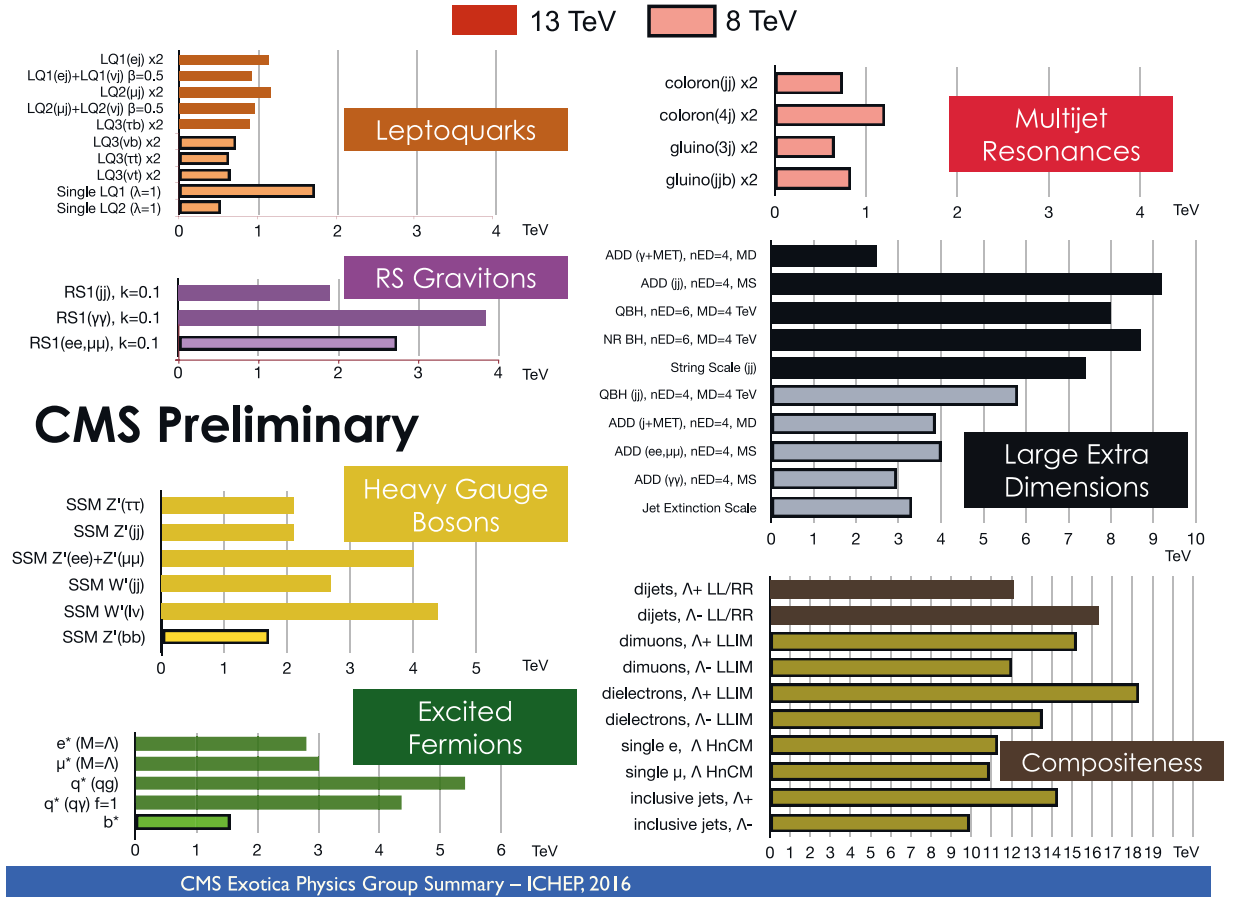


Fig. 3. Summary of exotica searches at CMS with traditional and ISR-boosted reconstructed techniques from Ref. [231]. These are presented in terms of limits on the mass of new particles in models containing leptoquarks, RS gravitons, heavy gauge bosons, excited fermions, multijet resonances, large extra dimensions, and compositeness. Boxed (open) bands indicate 13 TeV (8 TeV) data results.

depend on the signature, the model, and the number of extra dimensions, but are typically between 2–10 TeV. This covers a significant dynamic range of interest for these models for the case of $n = 4$ spatial dimensions, since models with considerably higher masses would be less likely to solve the hierarchy problem naturally.

The energy range of LED models is very large. As such, increases in the center-of-mass energy will provide the strongest improvements in sensitivity. However, better estimation of SM backgrounds or improved analysis techniques can also lead to improvements with more data at the HL-LHC.

3.2. Warped extra dimensions

Extra-dimensional alternatives to LED include the “RS1” [17] and “RS2” models [18]. The RS1 model hypothesizes compact extra dimensions with two branes, one at the Planck scale and the other at the TeV scale. The SM particles are presumed to exist primarily on the TeV brane, and have Kaluza-Klein (KK) excitations around the TeV scale, which behave similarly to their SM counterparts and hence can be detected at colliders like the LHC. The RS2 model is similar to RS1, but omits the brane at the TeV scale, and also yield a KK tower of particles corresponding to the existing SM particles.

RS1 models can produce black holes as in Section 3.1, with masses larger than

$$M_D = \frac{M_{Pl}}{\sqrt{8\pi}} e^{-\pi k r} \quad (4)$$

where r and M_{Pl} are defined in Eq. 3, and k is a warp factor. These models also result in KK excitations of the graviton [109] and gluon [110,111], which can yield signatures in many final states such as dibosons, diquarks, di-Higgs, diphotons, and many others. One common feature is the high masses of the KK excitations, which often subsequently decay to highly Lorentz-boosted SM particles, necessitating the usage of the techniques outlined in Section 2.3. Such models also can result in additional quarks and/or leptons that transform as vectors under the ordinary symmetry of the SM, referred to as “vector-like” quarks (VLQs) or leptons (VLLs) [112].

Typically, the simplest signatures involving RS models (or the SSM) are resonances that decay to two objects. There are

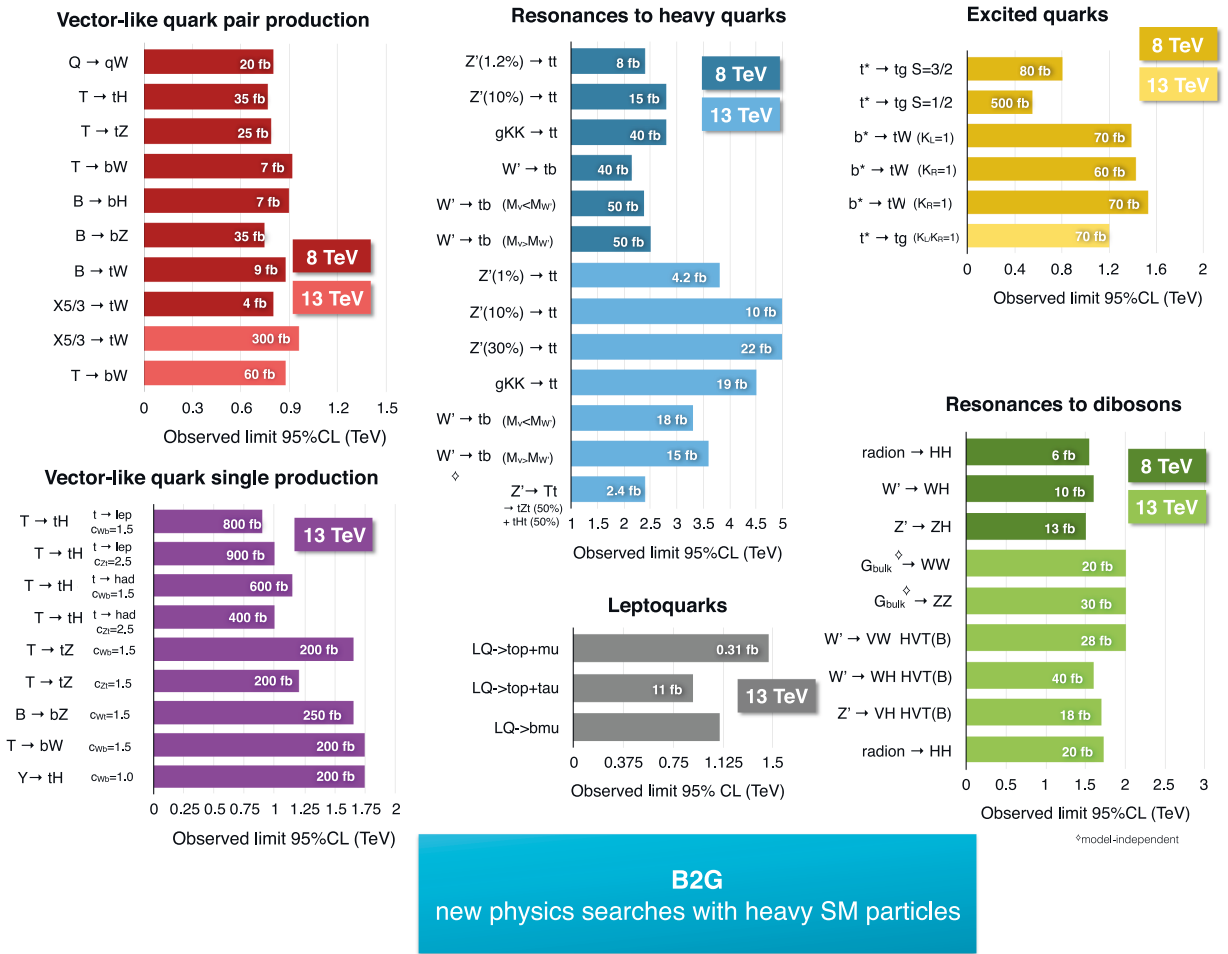


Fig. 4. Summary of exotica searches at CMS with boosted reconstructed techniques from Ref. [232]. These are interpreted in terms of limits on the mass of new particles in models containing vector-like quarks, resonances decaying to heavy quarks, leptoquarks, excited quarks, and resonances decaying to dibosons.

dilepton [113–119], diphoton [120–124], jet + boson or diboson [108,114,125–127,127–148], and diquark/dijet [149,149–155] analyses. There are also specialized diquark/dijet analyses in resonant production of $b\bar{b}$ [156,157], $t\bar{t}$ [128,158,159], $t\bar{b}$ [160–162], and resonances decaying to VLQs [163]. Overall, the benchmarks used in these searches are RS1 KK gravitons, RS1 KK gluons (for $t\bar{t}$ resonances), or W' bosons (for $t\bar{b}$ resonances). There are also other models that are probed with the dijet and $b\bar{b}$ resonance papers. The limits on these models are already quite stringent, effectively saturating the available parton luminosity at high masses in the multiple TeV range. There are also analyses that manifest as a combination of ISR boosts as in Section 2.4 and boosted hadronic jets as in Section 2.3, shown in Ref. [92]. There are also many analyses searching for direct production of VLQs [116,164–174].

Updates to these analyses will need to predominantly start focusing on reducing the SM background and its uncertainty, until a new collider is built at a significantly higher energy. In many cases, the resonances at higher masses are so broad that they are predominantly produced away from the resonant peak (“off-shell”), and manifest like a contact interaction above the SM backgrounds. In the case of a signal at lower mass, it will be difficult to interpret the precise mass of the new physics signals because of this off-shell effect. There is still sensitivity in the lower-mass states with increasing luminosity, so the HL-LHC will continue to provide useful improvements in these searches.

4. Dark matter

Dark matter comprises 4–5 times as much of the universe as ordinary matter [175]. It is natural to suppose that DM is comprised of particles that interact very seldomly, i.e. that it is due to “weakly interacting massive particles,” or WIMP. The relic density of DM hints at particle DM at the electroweak scale (the “WIMP miracle”) [21–23]. However, as of now, we have no candidate particle to explain the evidence. This remains one of the major open questions in physics.

As mentioned above, this review will not discuss the overall state of the search for SUSY, leaving this to other reviews, but instead we will focus on specific SUSY-inspired final states that include signatures that are difficult to detect (“hidden”).

While SUSY does provide a single natural DM candidate, there is nothing constraining the particle content of the dark sector. There may be a family of dark particles, even with their own interactions, that comprise the dark sector. The only real constraint we have is that if WIMPs exist, they interact weakly with SM particles. For this reason, more model-agnostic searches have become popular, with the help of effective field theories (EFTs) or simplified models of DM interactions [176]. These focus more on the signatures involving DM and place constraints simultaneously on the masses of the DM, and the mediator via which they interact with the SM particles. An exhaustive list of final states with spin hypotheses of the mediator can thus be made, and an extensive program has been undertaken to investigate these models.

We will now investigate the phenomenology of hidden signatures, as well as that of EFTs/simplified models in detail.

4.1. Hidden sectors and RPV SUSY

The postulation of a hidden sector [20,177,178] can explain DM, and arises in many solutions to the hierarchy problem. Some models postulate a non-abelian sector of light particles that interacts with the SM via a heavy mediator, thus becoming “hidden” or “dark”. These particles could form complex bound states since they are strongly interacting, thus forming “valley hadrons” or “v-hadrons” analogous to QCD. The LHC could in principle produce these v-hadrons, which would subsequently decay to detectable SM particles through the massive mediators after a long time [179], resulting in observable SM particles that are displaced from the interaction point, analogous to a charged pion that decays to a muon and neutrino via a massive W boson. This necessitates utilizing the detection techniques outlined in Section 2.2. Furthermore, the decay products may also potentially be collimated, necessitating the techniques outlined in Section 2.3. The Higgs boson could in principle couple with the hidden sector, providing a “Higgs portal” [180]. The latter signature would be a Higgs boson produced and decaying into long-lived v-hadrons, which may or may not decay to SM particles within the detector acceptance.

In addition to model-agnostic hidden sectors, SUSY can result in signatures that are quite similar, if they violate R-parity [95,96], i.e. RPV SUSY. In these cases, the LSP will often be sufficiently long-lived to decay centimeters or meters away from the LHC collisions. The methodologies for detection can range from detection of particles that decay within the tracker volume, possibly with other distinguishing features like p_T [76,77,181], those that contain extensive ionizing radiation in the tracker [182], particles that decay into hadronizing particles far from the interaction region (“emerging” jets) [183], particles that get trapped in the nuclear material and subsequently decay [78], particles that decay to unobservable particles in flight (“disappearing” tracks”) [184], and others not discussed here.

Figs. 5 and 6 show summary plots from ATLAS and CMS of searches for long-lived signatures from various models. An impressive array of models has been investigated at a wide range of distances over 15 orders of magnitude, ranging from millimeters to many meters at very long times.

Future directions of these searches will predominantly involve extending the baseline of detection or searches. Projects such as MATHUSLA and FASER are extremely promising ways to extend the reach and capability of these types of searches. It is still quite possible that natural SUSY models (RPV or not) could be found in these difficult signatures, and it should be a major part of the HEP program in the future.

4.2. EFTs And simplified models of DM

The overall construction of an EFT involving DM postulates a very massive mediator of the interaction between DM and SM particles, and hence can be modeled as a contact interaction. Simplified models, on the other hand, postulate various DM–SM mediators, as well as a DM particle, all with varying spins and couplings to the SM particles. Broadly speaking, these can both result in similar signatures. Overall, since any DM particles that are produced in LHC collisions will not interact with the detectors at all, detection techniques focus primarily on ISR-boosted detection techniques as in Section 2.4, and reconstruct the observable interaction from ISR with traditional techniques as in Section 2.1 or with boosted hadronic jets as in Section 2.3. Depending on the final state, flavor tagging techniques to detect bottom or top quarks can also be used. As such, existing analyses include a dizzying array of final states [137,152,154,155,185–196]. These are usually colloquially referred to as “mono-X” searches, since the signature in the detector is a single particle (X) recoiling against the DM particle. The particle X can be any SM particle. There are therefore searches with signatures of mono-jet, mono-bottom-jet, mono-top-jet, mono-photon, mono- W , mono- Z , mono-Higgs, etc. The mediators can also interact with a pair of particles, so signatures can also involve $q\bar{q}$, $\ell^+\ell^-$, $b\bar{b}$, $t\bar{t}$, etc.

Various interaction hypotheses are investigated for the DM–SM mediators. They can be vectors, axial-vectors, scalars, or pseudoscalars. The coupling constants for the DM–SM interaction are also unconstrained, so results must be framed in terms of these parameters. For instance, Ref. [108] present limits on the masses of a vector mediator and DM (with couplings to SM quarks equal to 0.25) of 1.8 and 0.7 TeV, respectively, in signatures containing Lorentz-boosted mono- $V \rightarrow q\bar{q}$. Another example is Ref. [191], which presents limits on the masses of an axial-vector mediator and DM of 1.5 and 0.4 TeV, respectively, using a mono-jet signature.

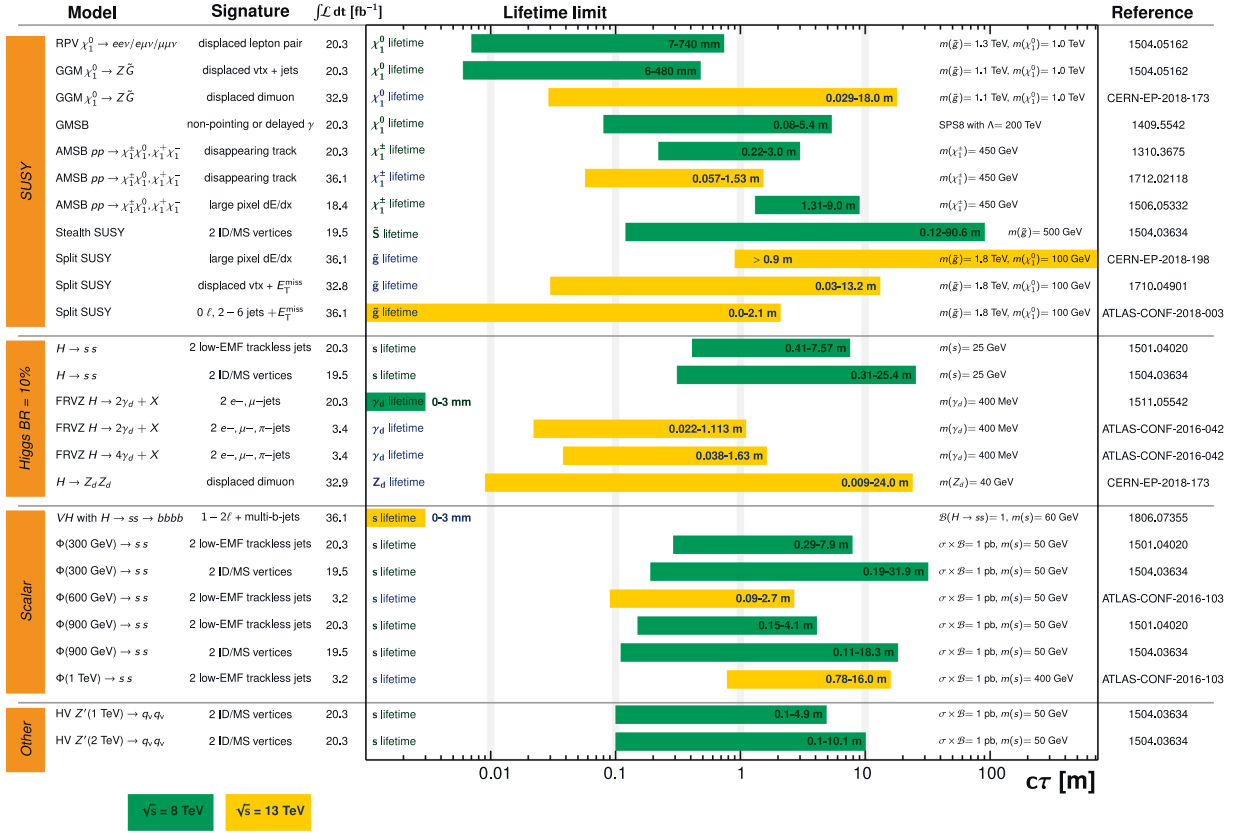
In simple interpretations of the DM–nucleon scattering cross section as a function of the DM mass, LHC searches complement direct detection (DD) and indirect detection (ID) searches [197]. Overall, LHC searches are more sensitive than ID/DD at very low mediator masses (below 5 GeV), as well as for axial-vector mediators, whereas ID/DD searches are more sensitive at higher masses if there are vector or scalar mediators. For instance, for a vector mediator, Refs. [108,191] show DM–nucleon cross-section limits of $\sim 10^{-42} \text{ cm}^2$ for a DM mass of 1 GeV, whereas there is no corresponding DD sensitivity, but the DD searches become more sensitive for DM masses around 30 GeV, with cross-section limits of $\sim 10^{-46} \text{ cm}^2$ from XENON1T [198]. Figs. 7 and 8 show limits of searches for axial-vector-mediated DM in multijet final states from ATLAS and CMS, respectively.

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2018

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 36.1) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}$$



*Only a selection of the available lifetime limits on new states is shown.

 $(\gamma\beta = 1)$

Fig. 5. Summary of long-lived exotic searches at ATLAS from Ref. [233]. These are interpreted in terms of limits on the lifetime of various models.

For much of the phase space, the limits can be improved with increased luminosity. As such, future prospects for DM detection are quite strong at the HL-LHC.

5. Neutrino mass

As of yet, the observation of non-zero neutrino masses is the strongest direct evidence for BSM particle physics. DM also strongly points to a new sector, but has not been directly observed nor produced in particle-particle interactions, and the effects are only observed at large distances, either in galaxial rotations or CMB observations. Neutrinos, on the other hand, have been directly shown to have individual masses, and an extensive research program exists to investigate this regime [199].

The LHC can play a role in the investigation of such anomalies by searching for possible heavy partners of the neutrino N , which are naturally predicted by the “seesaw” mechanism [200–203], where the neutrino masses m_ν are proportional to $y_\nu^2 v^2/m_N$, where v is the vacuum expectation value of the Higgs field, and y_ν is a Yukawa coupling. Very small neutrino masses m_ν could correspond to large masses for the heavy neutrinos. It is quite reasonable to expect that, should such a mechanism exist, the LHC would be able to observe these partners. There are, as such, many searches for BSM physics involving heavy neutrinos decaying into various final states, including leptons, jets, or bosons [142,166,204–206].

Overall, the exclusion depends on the relative mixing between the light and heavy neutrinos, $V_{\nu N}$. If this mixing is 0.1, the masses probed by existing searches are in the several hundred GeV range. If the mixing is 1, the masses probed are close to 1 TeV.

Production of heavy neutrinos is mostly limited by the available center-of-mass energy, so future colliders will be very effective at extending the reach of searches for heavy neutrinos. There will be, however, still available phase space to explore at the HL-LHC for lower masses.

6. Unification

Extensions to new gauge sectors that encompass the SM have long sought to find an overarching symmetry that couples the strong and electroweak forces. Fundamentally, any unification of the strong and electroweak forces will involve some BSM coupling

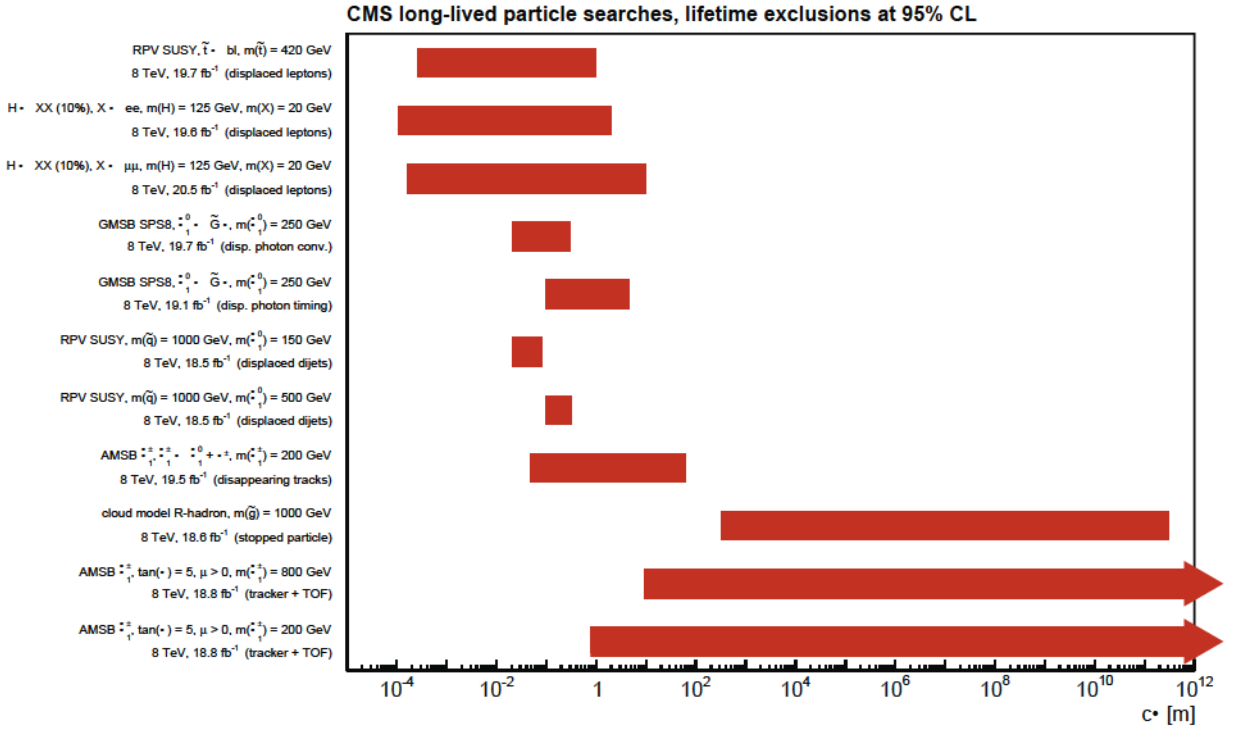


Fig. 6. Summary of long-lived exotica searches at CMS from Ref. [234]. These are interpreted in terms of limits on the lifetime of various models.

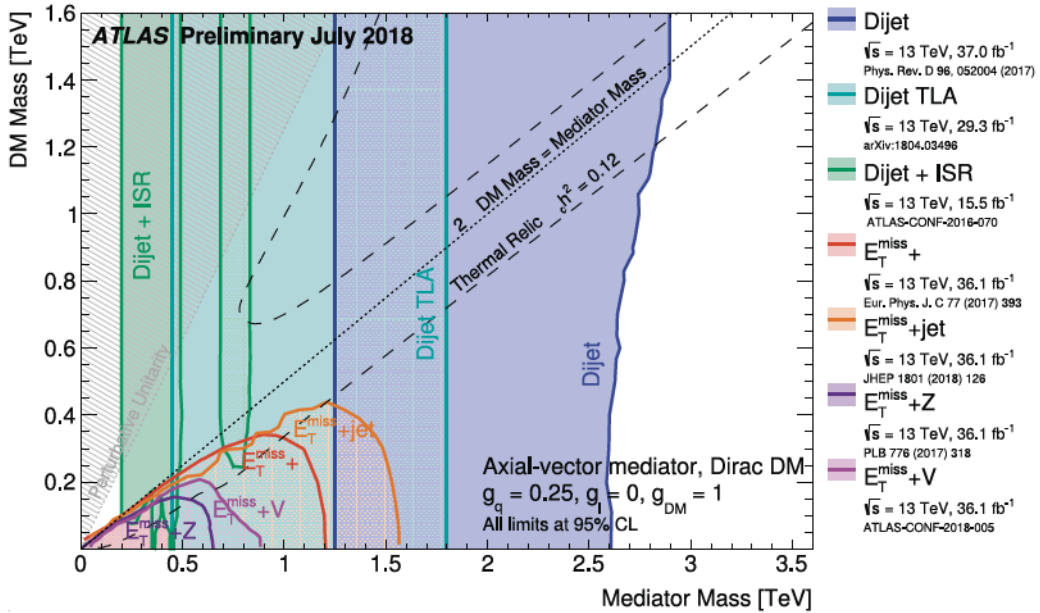


Fig. 7. Summary of searches for DM from multijet final states with an axial-vector mediator at ATLAS from Ref. [235]. These are interpreted in terms of limits on the masses of the mediator and dark matter candidate.

between quarks and leptons. One can think of this as lepton number being a fourth color. Oftentimes, such an interaction will contain new particles that contain quantum numbers for both the strong and electroweak forces. These are known as “leptoquarks” (LQs) [31–44]. Of course, such interactions would also contain predictions for unstable protons [45], where extremely stringent limits must be considered in building BSM physics models.

There is further recent interest in LQs because they have been proposed as solutions [207–215] to several outstanding hints of lepton flavor non-universality in heavy-flavor hadron observations from Belle [216] and LHCb [217–219]. Such particles have also

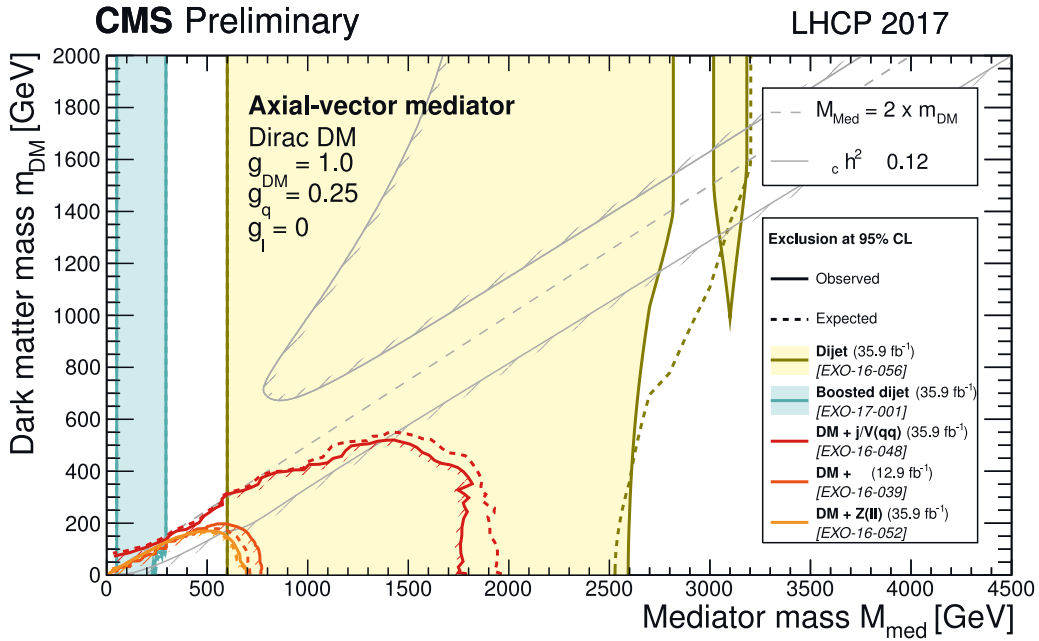


Fig. 8. Summary of searches for DM from multijet final states with an axial-vector mediator at CMS from Ref. [236]. These are interpreted in terms of limits on the masses of the mediator and dark matter candidate.

been hypothesized [220,221] to explain the $g - 2$ anomaly [48,222].

With those considerations in mind, many models of unification testable at the LHC will contain LQs. Broadly speaking, these will occur as an excess of events involving both leptons and hadrons. There are various strategies to deal with such signatures [142,168,205,223–225]. One example is to search for first- or second-generation LQs coupling to first- or second-generation quarks and leptons. In those cases, analyses can estimate the background for such searches using the known rates of electroweak production of W and Z bosons, as well as top quark pair production. Another strategy is to search for third-generation LQs in signatures involving τ leptons, bottom or top quarks. The SM backgrounds for such signatures are dominated by top quark pair production, which can be predicted. The limits for LQs are currently on the order of 800–1500 GeV depending on the channel.

Since the masses of the LQs the LHC is sensitive to are relatively modest, increases in luminosity at the HL-LHC can provide a good opportunity to continue these searches.

7. Compositeness

Ever since Rutherford began to probe the structure of the proton, the question of whether or not the particles we observe are fundamental or composite is a perennial question. Investigations of quark compositeness are not fundamentally different than the Rutherford experiment, and involve investigations of the number of high-mass quark-quark interactions. Since a massive mediator would often manifest as a contact interaction at lower energies (much like the W boson appears as a contact interaction in pion decay, etc), the searches often focus on such interactions. At its heart, the LHC is a QCD jet factory. As such, it can set extraordinarily sensitive limits on such fundamental interactions. The searches in Refs. [150,154,226], for instance, are able to set limits on composite scales between 10–20 TeV. The size of the quark is pointlike down to 10^{-18} m, and the scale of contact interactions manifesting in dijet samples must be larger than the scale of the LHC center-of-mass energy.

There are also searches for signals of compositeness that search for excited states of fermions, which then radiate either photons or gluons with specific characteristics. For example, excited quarks are investigated in Refs. [150,155,157,227,228], and dedicated searches for excited top quarks are shown in Ref. [229]. Excited top quarks are excluded below 1 TeV, and excited light quarks are excluded below 3–5 TeV.

Generally speaking, compositeness is probed by increases in center-of-mass energy more than by collecting more data. As such, the HL-LHC prospects for such searches for BSM physics are somewhat limited. New colliders at a higher center-of-mass energy would drastically increase the sensitivity.

8. Discussion

As of yet, there are no substantive signals of BSM physics at the LHC. However, it is unwise to conclude that none exist. There is, a priori, no particularly better region of phase space aside from arguments about how much tuning we are psychologically comfortable with in nature. It is indeed true that a great portion of the available kinematic phase space of the LHC has been ruled out for strongly

produced BSM signatures (with picobarn-level cross sections), but the new particles may simply have larger masses than we have excluded at the LHC (i.e. are heavy), may have cross sections that are below our current sensitivity, decay outside our detector volume, or we have not looked explicitly in the correct signatures (i.e. are hidden). There are multiple strategies to deal with increasing sensitivity to these signatures, based on new detection and reconstruction techniques.

Of course, for heavy signatures, there is nothing better than building a new proton-proton collider at a much higher center-of-mass energy. However, better reconstruction and background rejection techniques can improve sensitivity considerably. In addition, there are a plethora of targeted signatures that are not difficult to investigate, but the LHC experiments have simply not addressed them.

Hidden signatures require several approaches. If a particle is strongly produced, but decays outside of the region where our traditional techniques are efficient, new strategies must be employed to be sensitive to them. This includes detection of long-lived particles via extensions to the CMS and ATLAS detectors such as MATHUSLA and FASER. Alternatively, there may be direct signatures that are produced with smaller cross sections than we are currently sensitive to. Such searches will improve with more accumulated luminosity at the HL-LHC. These are typically extremely time-consuming searches, because they require extensive understanding of the background and subtle systematic effects. A long, arduous program of measurements and signal characterization is necessary to investigate these BSM signals. Such signatures could also be produced indirectly via interactions with the electroweak bosons, or the Higgs. In this case, such signatures will have much lower cross sections, and again require rigorous understanding of the SM background.

Overall, the LHC search program has an extensive future in the HL-LHC era and beyond. We should not give up hope only because our preferred ideas do not correspond to what actually exists in the universe.

Acknowledgments

This work has been supported under NSF grant 1806573, “High Energy Physics Research at the CMS Experiment”. SR would also like to thank Patrick Meade for helpful discussions about black hole semiclassical approximations.

References

- [1] F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons, *Phys. Rev. Lett.* 13 (1964) 321–323, <https://doi.org/10.1103/PhysRevLett.13.321>. 157(1964)
- [2] P.W. Higgs, Broken symmetries, massless particles and gauge fields, *Phys. Lett.* 12 (1964) 132–133, [https://doi.org/10.1016/0031-9163\(64\)91136-9](https://doi.org/10.1016/0031-9163(64)91136-9).
- [3] P.W. Higgs, Broken symmetries and the masses of gauge bosons, *Phys. Rev. Lett.* 13 (1964) 508–509, <https://doi.org/10.1103/PhysRevLett.13.508>. 160(1964)
- [4] G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles, *Phys. Rev. Lett.* 13 (1964) 585–587, <https://doi.org/10.1103/PhysRevLett.13.585>. 162(1964)
- [5] P.W. Higgs, Spontaneous symmetry breakdown without massless bosons, *Phys. Rev.* 145 (1966) 1156–1163, <https://doi.org/10.1103/PhysRev.145.1156>.
- [6] T.W.B. Kibble, Symmetry breaking in nonabelian gauge theories, *Phys. Rev.* 155 (1967) 1554–1561, <https://doi.org/10.1103/PhysRev.155.1554>. 165(1967)
- [7] G. Aad, et al., Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* 716 (2012) 1–29, <https://doi.org/10.1016/j.physletb.2012.08.020>.
- [8] S. Chatrchyan, et al., Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* 716 (2012) 30–61, <https://doi.org/10.1016/j.physletb.2012.08.021>.
- [9] G. Aad, et al., Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, *Phys. Rev. Lett.* 114 (2015) 191803, <https://doi.org/10.1103/PhysRevLett.114.191803>.
- [10] G. Aad, et al., The ATLAS experiment at the CERN large hadron collider, *JINST* 3 (2008) S08003, <https://doi.org/10.1088/1748-0221/3/08/S08003>.
- [11] S. Chatrchyan, et al., The CMS experiment at the CERN LHC, *JINST* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [12] S.P. Martin, A Supersymmetry primer (1997) 1–98. [Adv. Ser. Direct. High Energy Phys. 18,1(1998)]. 10.1142/9789812839657_0001.
- [13] J.D. Lykken, Introduction to supersymmetry, Fields, strings and duality. Proceedings, Summer School, Theoretical Advanced Study Institute in Elementary Particle Physics, TASI’96, Boulder, USA, June 2–28, 1996, (1996), pp. 85–153. http://lss.fnal.gov/cgi-bin/find_paper.pl?pub-96-445-T
- [14] K. Lane, Two lectures on technicolor(2002).
- [15] C.T. Hill, E.H. Simmons, Strong dynamics and electroweak symmetry breaking, *Phys. Rept.* 381 (2003) 235–402, [https://doi.org/10.1016/S0370-1573\(03\)00140-6](https://doi.org/10.1016/S0370-1573(03)00140-6). [Erratum: *Phys. Rept.* 390,553(2004)]
- [16] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, The hierarchy problem and new dimensions at a millimeter, *Phys. Lett. B* 429 (1998) 263–272, [https://doi.org/10.1016/S0370-2693\(98\)00466-3](https://doi.org/10.1016/S0370-2693(98)00466-3).
- [17] L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension, *Phys. Rev. Lett.* 83 (1999) 3370–3373, <https://doi.org/10.1103/PhysRevLett.83.3370>.
- [18] L. Randall, R. Sundrum, An alternative to compactification, *Phys. Rev. Lett.* 83 (1999) 4690–4693, <https://doi.org/10.1103/PhysRevLett.83.4690>.
- [19] N. Arkani-Hamed, A.G. Cohen, H. Georgi, Electroweak symmetry breaking from dimensional deconstruction, *Phys. Lett. B* 513 (2001) 232–240, [https://doi.org/10.1016/S0370-2693\(01\)00741-9](https://doi.org/10.1016/S0370-2693(01)00741-9).
- [20] M.J. Strassler, K.M. Zurek, Echoes of a hidden valley at Hadron colliders, *Phys. Lett. B* 651 (2007) 374–379, <https://doi.org/10.1016/j.physletb.2007.06.055>.
- [21] G. Bertone, D. Hooper, J. Silk, Particle dark matter: evidence, candidates and constraints, *Phys. Rept.* 405 (2005) 279–390, <https://doi.org/10.1016/j.physrep.2004.08.031>.
- [22] J.L. Feng, Dark matter candidates from particle physics and methods of detection, *Ann. Rev. Astron. Astrophys.* 48 (2010) 495–545, <https://doi.org/10.1146/annurev-astro-082708-101659>.
- [23] T.A. Porter, R.P. Johnson, P.W. Graham, Dark matter searches with astroparticle data, *Ann. Rev. Astron. Astrophys.* 49 (2011) 155–194, <https://doi.org/10.1146/annurev-astro-081710-102528>.
- [24] Q.R. Ahmad, et al., Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^8B solar neutrinos at the Sudbury neutrino observatory, *Phys. Rev. Lett.* 87 (2001) 071301, <https://doi.org/10.1103/PhysRevLett.87.071301>.
- [25] Y. Fukuda, et al., Evidence for oscillation of atmospheric neutrinos, *Phys. Rev. Lett.* 81 (1998) 1562–1567, <https://doi.org/10.1103/PhysRevLett.81.1562>.
- [26] J.K. Ahn, et al., Observation of reactor electron antineutrino disappearance in the RENO experiment, *Phys. Rev. Lett.* 108 (2012) 191802, <https://doi.org/10.1103/PhysRevLett.108.191802>.
- [27] K. Abe, et al., Evidence of electron neutrino appearance in a muon neutrino beam, *Phys. Rev. D* 88 (3) (2013) 032002, <https://doi.org/10.1103/PhysRevD.88.032002>.
- [28] B. Pontecorvo, Inverse beta processes and nonconservation of lepton charge, *Sov. Phys. JETP* 7 (1958) 172–173. [*Zh. Eksp. Teor. Fiz.* 34,247(1957)]

- [29] Z. Maki, M. Nakagawa, S. Sakata, Remarks on the unified model of elementary particles, *Prog. Theor. Phys.* 28 (1962) 870–880, <https://doi.org/10.1143/PTP.28.870>.
- [30] F. Capozzi, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, Neutrino masses and mixings: status of known and unknown 3ν parameters, *Nucl. Phys. B* 908 (2016) 218–234, <https://doi.org/10.1016/j.nuclphysb.2016.02.016>.
- [31] J.C. Pati, A. Salam, Unified lepton-Hadron symmetry and a gauge theory of the basic interactions, *Phys. Rev. D* 8 (1973) 1240–1251, <https://doi.org/10.1103/PhysRevD.8.1240>.
- [32] J.C. Pati, A. Salam, Lepton number as the fourth color, *Phys. Rev. D* 10 (1974) 275–289, <https://doi.org/10.1103/PhysRevD.10.275>, [10.1103/PhysRevD.11.703.2](https://doi.org/10.1103/PhysRevD.11.703.2) [Erratum: *Phys. Rev. D* 11, 703(1975)].
- [33] H. Georgi, S.L. Glashow, Unity of all elementary particle forces, *Phys. Rev. Lett.* 32 (1974) 438–441, <https://doi.org/10.1103/PhysRevLett.32.438>.
- [34] H. Murayama, T. Yanagida, A viable SU(5) GUT with light leptoquark bosons, *Mod. Phys. Lett. A* 7 (1992) 147–152, <https://doi.org/10.1142/S0217732392000070>.
- [35] H. Fritzsch, P. Minkowski, Unified interactions of leptons and hadrons, *Annals Phys.* 93 (1975) 193–266, [https://doi.org/10.1016/0003-4916\(75\)90211-0](https://doi.org/10.1016/0003-4916(75)90211-0).
- [36] G. Senjanovic, A. Sokorac, Light Leptoquarks in SO(10), *Z. Phys. C* 20 (1983) 255, <https://doi.org/10.1007/BF01574858>.
- [37] P.H. Frampton, B.-H. Lee, SU(15) Grand unification, *Phys. Rev. Lett.* 64 (1990) 619, <https://doi.org/10.1103/PhysRevLett.64.619>.
- [38] P.H. Frampton, T.W. Kephart, Higgs sector and proton decay in SU(15) grand unification, *Phys. Rev. D* 42 (1990) 3892–3894, <https://doi.org/10.1103/PhysRevD.42.3892>.
- [39] B. Schrempp, F. Schrempp, Light leptoquarks, *Phys. Lett.* 153B (1985) 101–107, [https://doi.org/10.1016/0370-2693\(85\)91450-9](https://doi.org/10.1016/0370-2693(85)91450-9).
- [40] S. Dimopoulos, L. Susskind, Mass without scalars, *Nucl. Phys. B* 155 (1979) 237–252, [https://doi.org/10.1016/0550-3213\(79\)90364-X](https://doi.org/10.1016/0550-3213(79)90364-X) [2,930(1979)].
- [41] S. Dimopoulos, Technicolored signatures, *Nucl. Phys. B* 168 (1980) 69–92, [https://doi.org/10.1016/0550-3213\(80\)90277-1](https://doi.org/10.1016/0550-3213(80)90277-1).
- [42] W. Buchmüller, R. Ruckl, D. Wyler, Leptoquarks in Lepton - Quark collisions, *Phys. Lett. B* 191 (1987) 442–448, [https://doi.org/10.1016/S0370-2693\(99\)00014-3](https://doi.org/10.1016/S0370-2693(99)00014-3), [10.1016/0370-2693\(87\)90637-X](https://doi.org/10.1016/0370-2693(87)90637-X) [Erratum: *Phys. Lett. B* 448, 320(1999)].
- [43] E. Eichten, K.D. Lane, Dynamical breaking of weak interaction symmetries, *Phys. Lett. B* 90B (1980) 125–130, [https://doi.org/10.1016/0370-2693\(80\)90065-9](https://doi.org/10.1016/0370-2693(80)90065-9).
- [44] J.L. Hewett, T.G. Rizzo, Low-Energy Phenomenology of Superstring Inspired E(6) Models, *Phys. Rept.* 183 (1989) 193, [https://doi.org/10.1016/0370-1573\(89\)90071-9](https://doi.org/10.1016/0370-1573(89)90071-9).
- [45] P. Nath, P. Fileviez Perez, Proton stability in grand unified theories, in strings and in branes, *Phys. Rept.* 441 (2007) 191–317, <https://doi.org/10.1016/j.physrep.2007.02.010>.
- [46] L. Canetti, M. Drewes, M. Shaposhnikov, Matter and antimatter in the universe, *New J. Phys.* 14 (2012) 095012, <https://doi.org/10.1088/1367-2630/14/9/095012>.
- [47] D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, B-Physics anomalies: a guide to combined explanations, *JHEP* 11 (2017) 044, [https://doi.org/10.1007/JHEP11\(2017\)044](https://doi.org/10.1007/JHEP11(2017)044).
- [48] J.L. Holzbauer, The muon G-2 experiment overview and status as of June 2016, *J. Phys. Conf. Ser.* 770 (1) (2016) 012038, <https://doi.org/10.1088/1742-6596/770/1/012038>.
- [49] R.D. Peccei, H.R. Quinn, Constraints imposed by CP conservation in the presence of instantons, *Phys. Rev. D* 16 (1977) 1791–1797, <https://doi.org/10.1103/PhysRevD.16.1791>.
- [50] R.D. Peccei, H.R. Quinn, CP Conservation in the Presence of Instantons, *Phys. Rev. Lett.* 38 (1977) 1440–1443, <https://doi.org/10.1103/PhysRevLett.38.1440>.
- [51] H. Banerjee, D. Chatterjee, P. Mitra, Is there still a strong CP problem? *Phys. Lett. B* 573 (2003) 109–114, <https://doi.org/10.1016/j.physletb.2003.08.058>, <http://www.sciencedirect.com/science/article/pii/S0370269303013212>.
- [52] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher, J.P. Silva, Theory and phenomenology of two-Higgs-doublet models, *Phys. Rept.* 516 (2012) 1–102, <https://doi.org/10.1016/j.physrep.2012.02.002>.
- [53] I.A. D'Souza, C.S. Kalman, Preons: Models of Leptons, Quarks and Gauge Bosons as Composite Objects, World Scientific Publishing Co, 1992, <https://doi.org/10.1142/1700>.
- [54] C.D. Froggatt, H.B. Nielsen, Hierarchy of quark masses, Cabibbo angles and CP violation, *Nucl. Phys. B* 147 (1979) 277–298, [https://doi.org/10.1016/0550-3213\(79\)90316-X](https://doi.org/10.1016/0550-3213(79)90316-X).
- [55] N. Arkani-Hamed, M. Schmaltz, Hierarchies without symmetries from extra dimensions, *Phys. Rev. D* 61 (2000) 033005, <https://doi.org/10.1103/PhysRevD.61.033005>.
- [56] A. Rajantie, The search for magnetic monopoles, *Phys. Today* 69 (10) (2016) 40–46, <https://doi.org/10.1063/PT.3.3328>.
- [57] A.A. Alves Jr. et al., The LHCb Detector at the LHC, *JINST* 3 (2008) S08005, <https://doi.org/10.1088/1748-0221/3/08/S08005>.
- [58] S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Tonnesmann, Jets in hadron-hadron collisions, *Prog. Part. Nucl. Phys.* 60 (2008) 484–551, <https://doi.org/10.1016/j.pnpnp.2007.12.002>.
- [59] M. Cacciari, G.P. Salam, Dispelling the N^3 myth for the k_t jet-finder, *Phys. Lett. B* 641 (2006) 57–61, <https://doi.org/10.1016/j.physletb.2006.08.037>.
- [60] M. Cacciari, G.P. Salam, G. Soyez, FastJet User Manual, *Eur. Phys. J. C* 72 (2012) 1896, <https://doi.org/10.1140/epjc/s10052-012-1896-2>.
- [61] G. Aad, et al., Topological cell clustering in the ATLAS calorimeters and its performance in LHC run 1, *Eur. Phys. J. C* 77 (2017) 490, <https://doi.org/10.1140/epjc/s10052-017-5004-5>.
- [62] M. Aaboud, et al., Jet reconstruction and performance using particle flow with the ATLAS detector, *Eur. Phys. J. C* 77 (7) (2017) 466, <https://doi.org/10.1140/epjc/s10052-017-5031-2>.
- [63] A.M. Sirunyan, et al., Particle-flow reconstruction and global event description with the CMS detector, *JINST* 12 (10) (2017) P10003, <https://doi.org/10.1088/1748-0221/12/10/P10003>.
- [64] M. Aaboud, et al., Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* 96 (7) (2017) 072002, <https://doi.org/10.1103/PhysRevD.96.072002>.
- [65] V. Khachatryan, et al., Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, *JINST* 12 (02) (2017) P02014, <https://doi.org/10.1088/1748-0221/12/02/P02014>.
- [66] M. Aaboud, et al., Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV, *JHEP* 08 (2018) 089, [https://doi.org/10.1007/JHEP08\(2018\)089](https://doi.org/10.1007/JHEP08(2018)089).
- [67] A.M. Sirunyan, et al., Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, *JINST* 13 (05) (2018) P05011, <https://doi.org/10.1088/1748-0221/13/05/P05011>.
- [68] Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach, Technical Report, CERN, Geneva, 2017. <http://cds.cern.ch/record/2298955>.
- [69] M. Aaboud, et al., Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016 (2018).
- [70] V. Khachatryan, et al., Performance of electron reconstruction and selection with the CMS detector in proton-Proton collisions at $\sqrt{s} = 8$ TeV, *JINST* 10 (06) (2015) P06005, <https://doi.org/10.1088/1748-0221/10/06/P06005>.
- [71] V. Khachatryan, et al., Performance of photon reconstruction and identification with the CMS detector in proton-Proton collisions at $\sqrt{s} = 8$ TeV, *JINST* 10 (08) (2015) P08010, <https://doi.org/10.1088/1748-0221/10/08/P08010>.
- [72] G. Aad, et al., Muon reconstruction performance of the ATLAS detector in proton proton collision data at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 76 (5) (2016) 292, <https://doi.org/10.1140/epjc/s10052-016-4120-y>.
- [73] S. Chatrchyan, et al., Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, *JINST* 7 (2012) P10002, <https://doi.org/10.1088/1748-0221/7/10/P10002>.
- [74] G. Aad, et al., Reconstruction of hadronic decay products of tau leptons with the ATLAS experiment, *Eur. Phys. J. C* 76 (5) (2016) 295, <https://doi.org/10.1140/epjc/s10052-016-4110-0>.

- [75] A.M. Sirunyan, et al., Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, JINST 13 (10) (2018) P10005, <https://doi.org/10.1088/1748-0221/13/10/P10005>.
- [76] M. Aaboud, et al., Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, Phys. Rev. D97 (5) (2018) 052012, <https://doi.org/10.1103/PhysRevD.97.052012>.
- [77] A.M. Sirunyan, et al., Search for new long-lived particles at $\sqrt{s} = 13$ TeV, Phys. Lett. B780 (2018) 432–454, <https://doi.org/10.1016/j.physletb.2018.03.019>.
- [78] A.M. Sirunyan, et al., Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 05 (2018) 127, [https://doi.org/10.1007/JHEP05\(2018\)127](https://doi.org/10.1007/JHEP05(2018)127).
- [79] J.P. Chou, D. Curtin, H.J. Lubatti, New detectors to explore the lifetime frontier, Phys. Lett. B767 (2017) 29–36, <https://doi.org/10.1016/j.physletb.2017.01.043>.
- [80] D. Curtin, et al., Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case (2018).
- [81] J.L. Feng, I. Galon, F. Kling, S. Trojanowski, ForwArd Search Experiment at the LHC, Phys. Rev. D97 (3) (2018) 035001, <https://doi.org/10.1103/PhysRevD.97.035001>.
- [82] M. Kawasaki, K. Kohri, T. Moroi, Big-Bang nucleosynthesis and hadronic decay of long-lived massive particles, Phys. Rev. D71 (2005) 083502, <https://doi.org/10.1103/PhysRevD.71.083502>.
- [83] K. Jedamzik, Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles, Phys. Rev. D74 (2006) 103509, <https://doi.org/10.1103/PhysRevD.74.103509>.
- [84] A. Abdesselam, et al., Boosted objects: A Probe of beyond the Standard Model physics, Eur. Phys. J. C71 (2011) 1661, <https://doi.org/10.1140/epjc/s10052-011-1661-y>.
- [85] A. Altheimer, et al., Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks, J. Phys. G39 (2012) 063001, <https://doi.org/10.1088/0954-3899/39/6/063001>.
- [86] A. Altheimer, et al., Boosted objects and jet substructure at the LHC. report of BOOST2012, held at IFIC valencia, 23rd-27th of july 2012, Eur. Phys. J. C74 (3) (2014) 2792, <https://doi.org/10.1140/epjc/s10052-014-2792-8>.
- [87] D. Adams, et al., Towards an Understanding of the Correlations in Jet Substructure, Eur. Phys. J. C75 (9) (2015) 409, <https://doi.org/10.1140/epjc/s10052-015-3587-2>.
- [88] A.J. Larkoski, I. Moult, B. Nachman, Jet Substructure at the Large Hadron Collider: A Review of Recent Advances in Theory and Machine Learning(2017).
- [89] L. Asquith, et al., Jet Substructure at the Large Hadron Collider : Experimental Review (2018).
- [90] M. Aaboud, et al., Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector, Phys. Lett. B786 (2018) 59–86, <https://doi.org/10.1016/j.physletb.2018.09.013>.
- [91] A.M. Sirunyan, et al., Observation of Higgs boson decay to bottom quarks, Phys. Rev. Lett. 121 (12) (2018) 121801, <https://doi.org/10.1103/PhysRevLett.121.121801>.
- [92] A.M. Sirunyan, et al., Search for low mass vector resonances decaying to Quark-Antiquark pairs in proton-Proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. 119 (11) (2017) 111802, <https://doi.org/10.1103/PhysRevLett.119.111802>.
- [93] M. Tanabashi, et al., Review of particle physics, Phys. Rev. D 98 (2018) 030001, <https://doi.org/10.1103/PhysRevD.98.030001>.
- [94] A. Arbey, et al., Physics at the e+ e- Linear Collider, Eur. Phys. J. C75 (8) (2015) 371, <https://doi.org/10.1140/epjc/s10052-015-3511-9>.
- [95] P.W. Graham, D.E. Kaplan, S. Rajendran, P. Saraswat, Displaced supersymmetry, JHEP 07 (2012) 149, [https://doi.org/10.1007/JHEP07\(2012\)149](https://doi.org/10.1007/JHEP07(2012)149).
- [96] G.R. Farrar, P. Fayet, Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry, Phys. Lett. B 76 (5) (1978) 575–579, [https://doi.org/10.1016/0370-2693\(78\)90858-4](https://doi.org/10.1016/0370-2693(78)90858-4). <http://www.sciencedirect.com/science/article/pii/0370269378908584>
- [97] J.M. Maldacena, The large n limit of superconformal field theories and supergravity, Int. J. Theor. Phys. 38 (1999) 1113–1133, <https://doi.org/10.1023/A:1026654312961>, 10.4310/ATMP.1998.v2.n2.a1. [Adv. Theor. Math. Phys.2,231(1998)]
- [98] T. Banks, W. Fischler, A Model for high-energy scattering in quantum gravity (1999).
- [99] S. Dimopoulos, G.L. Landsberg, Black holes at the LHC, Phys. Rev. Lett. 87 (2001) 161602, <https://doi.org/10.1103/PhysRevLett.87.161602>.
- [100] S.B. Giddings, S.D. Thomas, High-energy colliders as black hole factories: The End of short distance physics, Phys. Rev. D65 (2002) 056010, <https://doi.org/10.1103/PhysRevD.65.056010>.
- [101] P. Meade, L. Randall, Black Holes and Quantum Gravity at the LHC, JHEP 05 (2008) 003, <https://doi.org/10.1088/1126-6708/2008/05/003>.
- [102] G. Aad, et al., Search for strong gravity in multijet final states produced in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC, JHEP 03 (2016) 026, [https://doi.org/10.1007/JHEP03\(2016\)026](https://doi.org/10.1007/JHEP03(2016)026).
- [103] G. Aad, et al., Search for new phenomena with photon + jet events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 03 (2016) 041, [https://doi.org/10.1007/JHEP03\(2016\)041](https://doi.org/10.1007/JHEP03(2016)041).
- [104] M. Aaboud, et al., Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 06 (2016) 059, [https://doi.org/10.1007/JHEP06\(2016\)059](https://doi.org/10.1007/JHEP06(2016)059).
- [105] M. Aaboud, et al., Search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 13$ TeV, Phys. Lett. B760 (2016) 520–537, <https://doi.org/10.1016/j.physletb.2016.07.030>.
- [106] A.M. Sirunyan, et al., Search for black holes in high-multiplicity final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B774 (2017) 279–307, <https://doi.org/10.1016/j.physletb.2017.09.053>.
- [107] A.M. Sirunyan, et al., Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 10 (2017) 073, [https://doi.org/10.1007/JHEP10\(2017\)073](https://doi.org/10.1007/JHEP10(2017)073).
- [108] A.M. Sirunyan, et al., Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at $\sqrt{s} = 13$ TeV, Phys. Rev. D97 (9) (2018) 092005, <https://doi.org/10.1103/PhysRevD.97.092005>.
- [109] A.L. Fitzpatrick, J. Kaplan, L. Randall, L.-T. Wang, Searching for the Kaluza-Klein graviton in bulk RS models, JHEP 09 (2007) 013, <https://doi.org/10.1088/1126-6708/2007/09/013>.
- [110] K. Agashe, T. Belyaev, T. Krupovnickas, G. Perez, J. Virzi, LHC Signals from Warped Extra Dimensions, Phys. Rev. D77 (2008) 015003, <https://doi.org/10.1103/PhysRevD.77.015003>.
- [111] B. Lillie, L. Randall, L.-T. Wang, The bulk RS KK-gluon at the LHC, JHEP 09 (2007) 074, <https://doi.org/10.1088/1126-6708/2007/09/074>.
- [112] A. De Simone, O. Matsedonskyi, R. Rattazzi, A. Wulzer, A First Top Partner Hunter's Guide, JHEP 04 (2013) 004, [https://doi.org/10.1007/JHEP04\(2013\)004](https://doi.org/10.1007/JHEP04(2013)004).
- [113] V. Khachatryan, et al., Search for heavy resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 02 (2017) 048, [https://doi.org/10.1007/JHEP02\(2017\)048](https://doi.org/10.1007/JHEP02(2017)048).
- [114] M. Aaboud, et al., Combination of searches for heavy resonances decaying into bosonic and leptonic final states using 36 fb⁻¹ of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D98 (2018) 052008, <https://doi.org/10.1103/PhysRevD.98.052008>.
- [115] A.M. Sirunyan, et al., Search for high-mass resonances in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 06 (2018) 120, [https://doi.org/10.1007/JHEP06\(2018\)120](https://doi.org/10.1007/JHEP06(2018)120).
- [116] V. Khachatryan, et al., Search for heavy gauge W' boson in events with an energetic lepton and large missing transverse momentum at $\sqrt{s} = 13$ TeV, Phys. Lett. B770 (2017) 278–301, <https://doi.org/10.1016/j.physletb.2017.04.043>.
- [117] M. Aaboud, et al., Search for new resonances in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B762 (2016) 334–352, <https://doi.org/10.1016/j.physletb.2016.09.040>.
- [118] M. Aaboud, et al., Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in 36 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment, Eur. Phys. J. C78 (5) (2018) 401, <https://doi.org/10.1140/epjc/s10052-018-5877-y>.
- [119] M. Aaboud, et al., Search for high-mass resonances decaying to $\tau\nu$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. 120 (16) (2018) 161802, <https://doi.org/10.1103/PhysRevLett.120.161802>.
- [120] V. Khachatryan, et al., Search for resonant production of high-Mass photon pairs in proton-Proton collisions at $\sqrt{s} = 8$ and 13 TeV, Phys. Rev. Lett. 117 (5)

- (2016) 051802, <https://doi.org/10.1103/PhysRevLett.117.051802>.
- [121] V. Khachatryan, et al., Search for high-mass diphoton resonances in proton-proton collisions at 13 TeV and combination with 8 TeV search, *Phys. Lett. B* 767 (2017) 147–170, <https://doi.org/10.1016/j.physletb.2017.01.027>.
- [122] M. Aaboud, et al., Search for resonances in diphoton events at $\sqrt{s} = 13$ TeV with the ATLAS detector, *JHEP* 09 (2016) 001, [https://doi.org/10.1007/JHEP09\(2016\)001](https://doi.org/10.1007/JHEP09(2016)001).
- [123] M. Aaboud, et al., Search for new phenomena in high-mass diphoton final states using 37 fb⁻¹ of proton-proton collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 775 (2017) 105–125, <https://doi.org/10.1016/j.physletb.2017.10.039>.
- [124] A.M. Sirunyan, et al., Search for physics beyond the standard model in high-mass diphoton events from proton-proton collisions at $\sqrt{s} = 13$ TeV, Submitted to: *Phys. Rev.* (2018).
- [125] A.M. Sirunyan, et al., Search for high-mass $Z\gamma$ resonances in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV using jet substructure techniques, *Phys. Lett. B* 772 (2017) 363–387, <https://doi.org/10.1016/j.physletb.2017.06.062>.
- [126] V. Khachatryan, et al., Search for high-mass $Z\gamma$ resonances in $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ final states in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV, *JHEP* 01 (2017) 076, [https://doi.org/10.1007/JHEP01\(2017\)076](https://doi.org/10.1007/JHEP01(2017)076).
- [127] A.M. Sirunyan, et al., Search for $Z\gamma$ resonances using leptonic and hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 09 (2018) 148, [https://doi.org/10.1007/JHEP09\(2018\)148](https://doi.org/10.1007/JHEP09(2018)148).
- [128] A.M. Sirunyan, et al., Search for $t\bar{t}$ resonances in highly boosted lepton + jets and fully hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 07 (2017) 001, [https://doi.org/10.1007/JHEP07\(2017\)001](https://doi.org/10.1007/JHEP07(2017)001).
- [129] M. Aaboud, et al., Search for heavy resonances decaying to a photon and a hadronically decaying $Z/W/H$ boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (2018a).
- [130] M. Aaboud, et al., Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (2018b).
- [131] A.M. Sirunyan, et al., Search for a heavy resonance decaying into a Z boson and a Z or W boson in $22q$ final states at $\sqrt{s} = 13$ TeV, *JHEP* 09 (2018) 101, [https://doi.org/10.1007/JHEP09\(2018\)101](https://doi.org/10.1007/JHEP09(2018)101).
- [132] M. Aaboud, et al., Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b -jets in 36 fb⁻¹ of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *JHEP* 03 (2018) 174, [https://doi.org/10.1007/JHEP03\(2018\)174](https://doi.org/10.1007/JHEP03(2018)174).
- [133] M. Aaboud, et al., Search for WW/WZ resonance production in $\ell\ell q\bar{q}$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *JHEP* 03 (2018) 042, [https://doi.org/10.1007/JHEP03\(2018\)042](https://doi.org/10.1007/JHEP03(2018)042).
- [134] M. Aaboud, et al., Searches for heavy ZZ and ZW resonances in the $\ell\ell q\bar{q}$ and $\nu\ell q\bar{q}$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *JHEP* 03 (2018) 009, [https://doi.org/10.1007/JHEP03\(2018\)009](https://doi.org/10.1007/JHEP03(2018)009).
- [135] M. Aaboud, et al., Search for diboson resonances with boson-tagged jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 777 (2018) 91–113, <https://doi.org/10.1016/j.physletb.2017.12.011>.
- [136] M. Aaboud, et al., Search for heavy resonances decaying to a W or Z boson and a Higgs boson in the $q\bar{q}^{(\prime)}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 774 (2017) 494–515, <https://doi.org/10.1016/j.physletb.2017.09.066>.
- [137] M. Aaboud, et al., Search for dark matter at $\sqrt{s} = 13$ TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector, *Eur. Phys. J. C* 77 (6) (2017) 393, <https://doi.org/10.1140/epjc/s10052-017-4965-8>.
- [138] M. Aaboud, et al., Search for heavy resonances decaying to a Z boson and a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 764 (2017) 11–30, <https://doi.org/10.1016/j.physletb.2016.11.005>.
- [139] M. Aaboud, et al., Search for new resonances decaying to a W or Z boson and a Higgs boson in the $\ell^+\ell^--b\bar{b}$, $\ell\nu b\bar{b}$, and $\nu\bar{\nu}b\bar{b}$ channels with pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 765 (2017) 32–52, <https://doi.org/10.1016/j.physletb.2016.11.045>.
- [140] M. Aaboud, et al., Searches for heavy diboson resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *JHEP* 09 (2016) 173, [https://doi.org/10.1007/JHEP09\(2016\)173](https://doi.org/10.1007/JHEP09(2016)173).
- [141] A.M. Sirunyan, et al., Search for a heavy resonance decaying to a pair of vector bosons in the lepton plus merged jet final state at $\sqrt{s} = 13$ TeV, *JHEP* 05 (2018) 088, [https://doi.org/10.1007/JHEP05\(2018\)088](https://doi.org/10.1007/JHEP05(2018)088).
- [142] A.M. Sirunyan, et al., Search for third-generation scalar leptoquarks and heavy right-handed neutrinos in final states with two tau leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 07 (2017) 121, [https://doi.org/10.1007/JHEP07\(2017\)121](https://doi.org/10.1007/JHEP07(2017)121).
- [143] A.M. Sirunyan, et al., Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* 781 (2018) 244–269, <https://doi.org/10.1016/j.physletb.2018.03.084>.
- [144] A.M. Sirunyan, et al., Search for massive resonances decaying into WW , WZ , ZZ , qW , and qZ with dijet final states at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* 97 (7) (2018) 072006, <https://doi.org/10.1103/PhysRevD.97.072006>.
- [145] A.M. Sirunyan, et al., Search for heavy resonances that decay into a vector boson and a Higgs boson in hadronic final states at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 77 (9) (2017) 636, <https://doi.org/10.1140/epjc/s10052-017-5192-z>.
- [146] A.M. Sirunyan, et al., Combination of searches for heavy resonances decaying to WW , WZ , ZZ , WH , and ZH boson pairs in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV, *Phys. Lett. B* 774 (2017) 533–558, <https://doi.org/10.1016/j.physletb.2017.09.083>.
- [147] A.M. Sirunyan, et al., Search for massive resonances decaying into WW , WZ or ZZ bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 03 (2017) 162, [https://doi.org/10.1007/JHEP03\(2017\)162](https://doi.org/10.1007/JHEP03(2017)162).
- [148] M. Aaboud, et al., Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* 94 (5) (2016) 052002, <https://doi.org/10.1103/PhysRevD.94.052002>.
- [149] V. Khachatryan, et al., Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* 116 (7) (2016) 071801, <https://doi.org/10.1103/PhysRevLett.116.071801>.
- [150] M. Aaboud, et al., Search for new phenomena in dijet events using 37 fb⁻¹ of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* 96 (5) (2017) 052004, <https://doi.org/10.1103/PhysRevD.96.052004>.
- [151] M. Aaboud, et al., Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV (2018).
- [152] A.M. Sirunyan, et al., Search for dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter and other models, *Phys. Lett. B* 769 (2017) 520–542, <https://doi.org/10.1016/j.physletb.2017.09.029>, <https://doi.org/10.1016/j.physletb.2017.02.012>. [Erratum: *Phys. Lett. B* 772, 882 (2017)]
- [153] A.M. Sirunyan, et al., Search for new physics with dijet angular distributions in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 07 (2017) 013, [https://doi.org/10.1007/JHEP07\(2017\)013](https://doi.org/10.1007/JHEP07(2017)013).
- [154] A.M. Sirunyan, et al., Search for new physics in dijet angular distributions using proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter and other models, *Eur. Phys. J. C* 78 (9) (2018) 789, <https://doi.org/10.1140/epjc/s10052-018-6242-x>.
- [155] A.M. Sirunyan, et al., Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter mediators and other new particles, *JHEP* 08 (2018) 130, [https://doi.org/10.1007/JHEP08\(2018\)130](https://doi.org/10.1007/JHEP08(2018)130).
- [156] M. Aaboud, et al., Search for resonances in the mass distribution of jet pairs with one or two jets identified as b -jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 759 (2016) 229–246, <https://doi.org/10.1016/j.physletb.2016.05.064>.
- [157] M. Aaboud, et al., Search for resonances in the mass distribution of jet pairs with one or two jets identified as b -jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (2018a).
- [158] M. Aaboud, et al., Search for heavy particles decaying into top-quark pairs using lepton-plus-jets events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Submitted to: *Eur. Phys. J.* (2018).
- [159] A.M. Sirunyan, et al., Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV (2018).
- [160] M. Aaboud, et al., Search for $W' \rightarrow t\bar{b}$ decays in the hadronic final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 781 (2018) 327–348, <https://doi.org/10.1016/j.physletb.2018.03.036>.

- [161] A.M. Sirunyan, et al., Searches for W bosons decaying to a top quark and a bottom quark in proton-proton collisions at 13 TeV, JHEP 08 (2017) 029, [https://doi.org/10.1007/JHEP08\(2017\)029](https://doi.org/10.1007/JHEP08(2017)029).
- [162] A.M. Sirunyan, et al., Search for heavy resonances decaying to a top quark and a bottom quark in the lepton + jets final state in proton proton collisions at 13TeV, Phys. Lett. B777 (2018) 39–63, <https://doi.org/10.1016/j.physletb.2017.12.006>.
- [163] A.M. Sirunyan, et al., Search for a heavy resonance decaying to a top quark and a vector-like top quark at $\sqrt{s} = 13$ TeV, JHEP 09 (2017) 053, [https://doi.org/10.1007/JHEP09\(2017\)053](https://doi.org/10.1007/JHEP09(2017)053).
- [164] M. Aaboud, et al., Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector (2018).
- [165] M. Aaboud, et al., Search for pair production of vector-like top quarks in events with one lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, JHEP 08 (2017) 052, [https://doi.org/10.1007/JHEP08\(2017\)052](https://doi.org/10.1007/JHEP08(2017)052).
- [166] A.M. Sirunyan, et al., Search for vector-like T and B quark pairs in final states with leptons at $\sqrt{s} = 13$ TeV, JHEP 08 (2018) 177, [https://doi.org/10.1007/JHEP08\(2018\)177](https://doi.org/10.1007/JHEP08(2018)177).
- [167] A.M. Sirunyan, et al., Search for single production of vector-like quarks decaying to a b quark and a Higgs boson, JHEP 06 (2018) 031, [https://doi.org/10.1007/JHEP06\(2018\)031](https://doi.org/10.1007/JHEP06(2018)031).
- [168] A.M. Sirunyan, et al., Search for pair production of second-generation leptoquarks at $\sqrt{s} = 13$ TeV, Submitted to: Phys. Rev. (2018).
- [169] A.M. Sirunyan, et al., Search for single production of a vector-like T quark decaying to a Z boson and a top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B781 (2018) 574–600, <https://doi.org/10.1016/j.physletb.2018.04.036>.
- [170] A.M. Sirunyan, et al., Search for pair production of vector-like T and B quarks in single-lepton final states using boosted jet substructure in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 11 (2017) 085, [https://doi.org/10.1007/JHEP11\(2017\)085](https://doi.org/10.1007/JHEP11(2017)085).
- [171] A.M. Sirunyan, et al., Search for single production of vector-like quarks decaying into a b quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B772 (2017) 634–656, <https://doi.org/10.1016/j.physletb.2017.07.022>.
- [172] A.M. Sirunyan, et al., Search for single production of vector-like quarks decaying to a Z boson and a top or a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 05 (2017) 029, [https://doi.org/10.1007/JHEP05\(2017\)029](https://doi.org/10.1007/JHEP05(2017)029).
- [173] A.M. Sirunyan, et al., Search for electroweak production of a vector-like quark decaying to a top quark and a Higgs boson using boosted topologies in fully hadronic final states, JHEP 04 (2017) 136, [https://doi.org/10.1007/JHEP04\(2017\)136](https://doi.org/10.1007/JHEP04(2017)136).
- [174] V. Khachatryan, et al., Search for single production of a heavy vector-like t quark decaying to a higgs boson and a top quark with a lepton and jets in the final state, Phys. Lett. B771 (2017) 80–105, <https://doi.org/10.1016/j.physletb.2017.05.019>.
- [175] P.A.R. Ade, et al., Planck 2013 results. I. Overview of products and scientific results, Astron. Astrophys. 571 (2014) A1, <https://doi.org/10.1051/0004-6361/201321529>.
- [176] D. Abercrombie, et al., Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum(2015).
- [177] R. Barbieri, T. Gregoire, L.J. Hall, Mirror world at the Large Hadron Collider(2005).
- [178] R.M. Schabinger, J.D. Wells, A Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the large hadron collider, Phys. Rev. D72 (2005) 093007, <https://doi.org/10.1103/PhysRevD.72.093007>.
- [179] M.J. Strassler, K.M. Zurek, Discovering the Higgs through highly-displaced vertices, Phys. Lett. B661 (2008) 263–267, <https://doi.org/10.1016/j.physletb.2008.02.008>.
- [180] C. Englert, T. Plehn, D. Zerwas, P.M. Zerwas, Exploring the Higgs portal, Phys. Lett. B703 (2011) 298–305, <https://doi.org/10.1016/j.physletb.2011.08.002>.
- [181] R. Aaij, et al., Search for massive long-lived particles decaying semileptonically in the LHCb detector, Eur. Phys. J. C77 (4) (2017) 224, <https://doi.org/10.1140/epjc/s10052-017-4744-6>.
- [182] V. Khachatryan, et al., Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D94 (11) (2016) 112004, <https://doi.org/10.1103/PhysRevD.94.112004>.
- [183] R. Aaij, et al., Updated search for long-lived particles decaying to jet pairs, Eur. Phys. J. C77 (12) (2017) 812, <https://doi.org/10.1140/epjc/s10052-017-5178-x>.
- [184] M. Aaboud, et al., Search for long-lived charginos based on a disappearing-track signature in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 06 (2018) 022, [https://doi.org/10.1007/JHEP06\(2018\)022](https://doi.org/10.1007/JHEP06(2018)022).
- [185] M. Aaboud, et al., Search for dark matter produced in association with a Hadronically decaying vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B763 (2016) 251–268, <https://doi.org/10.1016/j.physletb.2016.10.042>.
- [186] M. Aaboud, et al., Search for dark matter in association with a Higgs boson decaying to b-quarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B765 (2017) 11–31, <https://doi.org/10.1016/j.physletb.2016.11.035>.
- [187] M. Aaboud, et al., Search for dark matter in association with a Higgs boson decaying to two photons at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D96 (11) (2017) 112004, <https://doi.org/10.1103/PhysRevD.96.112004>.
- [188] M. Aaboud, et al., Search for dark matter produced in association with a Higgs boson decaying to $b\bar{b}$ using 36 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. 119 (18) (2017) 181804, <https://doi.org/10.1103/PhysRevLett.119.181804>.
- [189] M. Aaboud, et al., Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B776 (2018) 318–337, <https://doi.org/10.1016/j.physletb.2017.11.049>.
- [190] M. Aaboud, et al., Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, Eur. Phys. J. C78 (1) (2018) 18, <https://doi.org/10.1140/epjc/s10052-017-5486-1>.
- [191] M. Aaboud, et al., Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector, JHEP 01 (2018) 126, [https://doi.org/10.1007/JHEP01\(2018\)126](https://doi.org/10.1007/JHEP01(2018)126).
- [192] A.M. Sirunyan, et al., Search for dark matter and unparticles in events with a z boson and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 03 (2017) 061, [https://doi.org/10.1007/JHEP03\(2017\)061](https://doi.org/10.1007/JHEP03(2017)061), [10.1007/JHEP09\(2017\)106](https://doi.org/10.1007/JHEP09(2017)106), [10.1007/JHEP03\(2017\)061](https://doi.org/10.1007/JHEP03(2017)061). [Erratum: JHEP09, 106(2017)]
- [193] A.M. Sirunyan, et al., Search for dark matter produced with an energetic jet or a hadronically decaying w or z boson at $\sqrt{s} = 13$ TeV, JHEP 07 (2017) 014, [https://doi.org/10.1007/JHEP07\(2017\)014](https://doi.org/10.1007/JHEP07(2017)014).
- [194] A.M. Sirunyan, et al., Search for associated production of dark matter with a higgs boson decaying to $b\bar{b}$ or $\gamma\gamma$ at $\sqrt{s} = 13$ TeV, JHEP 10 (2017) 180, [https://doi.org/10.1007/JHEP10\(2017\)180](https://doi.org/10.1007/JHEP10(2017)180).
- [195] A.M. Sirunyan, et al., Search for dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C77 (12) (2017) 845, <https://doi.org/10.1140/epjc/s10052-017-5317-4>.
- [196] A.M. Sirunyan, et al., Search for dark matter in events with energetic, hadronically decaying top quarks and missing transverse momentum at $\sqrt{s} = 13$ TeV, JHEP 06 (2018) 027, [https://doi.org/10.1007/JHEP06\(2018\)027](https://doi.org/10.1007/JHEP06(2018)027).
- [197] F. Kahlhoefer, Review of LHC dark matter searches, Int. J. Mod. Phys. A32 (13) (2017) 1730006, <https://doi.org/10.1142/S0217751X1730006X>.
- [198] E. Aprile, et al., Dark Matter Search Results from a One Ton-Year Exposure of XENON1T, Phys. Rev. Lett. 121 (11) (2018) 111302, <https://doi.org/10.1103/PhysRevLett.121.111302>.
- [199] D.V. Forero, M. Tortola, J.W.F. Valle, Global status of neutrino oscillation parameters after Neutrino-2012, Phys. Rev. D86 (2012) 073012, <https://doi.org/10.1103/PhysRevD.86.073012>.
- [200] P. Minkowski, $\mu \rightarrow e\gamma$ At a rate of one out of 10^9 muon decays? Phys. Lett. 67B (1977) 421–428, [https://doi.org/10.1016/0370-2693\(77\)90435-X](https://doi.org/10.1016/0370-2693(77)90435-X).
- [201] R.N. Mohapatra, G. Senjanovic, Neutrino mass and spontaneous parity violation, Phys. Rev. Lett. 44 (1980) 912, <https://doi.org/10.1103/PhysRevLett.44.912>.
- [202] R.N. Mohapatra, J.W.F. Valle, Neutrino mass and baryon number nonconservation in superstring models, Phys. Rev. D34 (1986) 1642, <https://doi.org/10.1103/PhysRevD.34.1642>, 235(1986)

- [203] H. An, P.S.B. Dev, Y. Cai, R.N. Mohapatra, Sneutrino dark matter in gauged inverse seesaw models for neutrinos, *Phys. Rev. Lett.* 108 (2012) 081806, <https://doi.org/10.1103/PhysRevLett.108.081806>.
- [204] A.M. Sirunyan, et al., Search for a heavy composite majorana neutrino in the final state with two leptons and two quarks at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* 775 (2017) 315–337, <https://doi.org/10.1016/j.physletb.2017.11.001>.
- [205] V. Khachatryan, et al., Search for heavy neutrinos or third-generation leptoquarks in final states with two hadronically decaying τ leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 03 (2017) 077, [https://doi.org/10.1007/JHEP03\(2017\)077](https://doi.org/10.1007/JHEP03(2017)077).
- [206] A.M. Sirunyan, et al., Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* 120 (22) (2018) 221801, <https://doi.org/10.1103/PhysRevLett.120.221801>.
- [207] S. Wehle, et al., Lepton-Flavor-Dependent angular analysis of $B \rightarrow K^* \ell^+ \ell^-$, *Phys. Rev. Lett.* 118 (11) (2017) 111801, <https://doi.org/10.1103/PhysRevLett.118.111801>.
- [208] W. Altmannshofer, D.M. Straub, New physics in $b \rightarrow s$ transitions after LHC run 1, *Eur. Phys. J. C* 75 (8) (2015) 382, <https://doi.org/10.1140/epjc/s10052-015-3602-7>.
- [209] S. Descotes-Genon, L. Hofer, J. Matias, J. Virto, Global analysis of $b \rightarrow s \ell \ell$ anomalies, *JHEP* 06 (2016) 092, [https://doi.org/10.1007/JHEP06\(2016\)092](https://doi.org/10.1007/JHEP06(2016)092).
- [210] T. Hurth, F. Mahmoudi, S. Neshatpour, On the anomalies in the latest LHCb data, *Nucl. Phys. B* 909 (2016) 737–777, <https://doi.org/10.1016/j.nuclphysb.2016.05.022>.
- [211] N. Assad, B. Fornal, B. Grinstein, Baryon number and lepton universality violation in leptoquark and diquark models, *Phys. Lett. B* 777 (2018) 324–331, <https://doi.org/10.1016/j.physletb.2017.12.042>.
- [212] W. Altmannshofer, C. Niehoff, P. Stangl, D.M. Straub, Status of the $B \rightarrow K^* \mu^+ \mu^-$ anomaly after moriond 2017, *Eur. Phys. J. C* 77 (6) (2017) 377, <https://doi.org/10.1140/epjc/s10052-017-4952-0>.
- [213] G. D'Amico, M. Narddecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, A. Urbano, Flavour anomalies after the R_{K^*} measurement, *JHEP* 09 (2017) 010, [https://doi.org/10.1007/JHEP09\(2017\)010](https://doi.org/10.1007/JHEP09(2017)010).
- [214] W. Altmannshofer, P. Stangl, D.M. Straub, Interpreting hints for lepton flavor universality violation, *Phys. Rev. D* 96 (5) (2017) 055008, <https://doi.org/10.1103/PhysRevD.96.055008>.
- [215] L. Calibbi, A. Crivellin, T. Li, A model of vector leptoquarks in view of the B -physics anomalies (2017).
- [216] A. Abashian, et al., The Belle detector, *Nucl. Instrum. Meth. A* 479 (2002) 117–232, [https://doi.org/10.1016/S0168-9002\(01\)02013-7](https://doi.org/10.1016/S0168-9002(01)02013-7).
- [217] R. Aaij, et al., Measurements of the S-wave fraction in $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ decays and the $B^0 \rightarrow K^* (892)^0 \mu^+ \mu^-$ differential branching fraction, *JHEP* 11 (2016) 047, [https://doi.org/10.1007/JHEP11\(2016\)047](https://doi.org/10.1007/JHEP11(2016)047), [https://doi.org/10.1007/JHEP04\(2017\)142](https://doi.org/10.1007/JHEP04(2017)142). [Erratum: *JHEP* 04, 142 (2017)]
- [218] R. Aaij, et al., Angular analysis and differential branching fraction of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$, *JHEP* 09 (2015) 179, [https://doi.org/10.1007/JHEP09\(2015\)179](https://doi.org/10.1007/JHEP09(2015)179).
- [219] R. Aaij, et al., Angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay using 3 fb⁻¹ of integrated luminosity, *JHEP* 02 (2016) 104, [https://doi.org/10.1007/JHEP02\(2016\)104](https://doi.org/10.1007/JHEP02(2016)104).
- [220] E. Coluccio Leskow, G. D'Ambrosio, A. Crivellin, D. Mller, ($g - 2$) _{μ} , Lepton flavor violation, and Z decays with leptoquarks: correlations and future prospects, *Phys. Rev. D* 95 (5) (2017) 055018, <https://doi.org/10.1103/PhysRevD.95.055018>.
- [221] C.-H. Chen, T. Nomura, H. Okada, Excesses of muon $g - 2$, $R_{D^{(*)}}$, and R_K in a leptoquark model, *Phys. Lett. B* 774 (2017) 456–464, <https://doi.org/10.1016/j.physletb.2017.10.005>.
- [222] G.W. Bennett, et al., Final report of the muon E821 anomalous magnetic moment measurement at BNL, *Phys. Rev. D* 73 (2006) 072003, <https://doi.org/10.1103/PhysRevD.73.072003>.
- [223] M. Aaboud, et al., Search for scalar leptoquarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment, *New J. Phys.* 18 (9) (2016) 093016, <https://doi.org/10.1088/1367-2630/18/9/093016>.
- [224] A.M. Sirunyan, et al., Search for a singly produced third-generation scalar leptoquark decaying to a τ lepton and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV, *JHEP* 07 (2018) 115, [https://doi.org/10.1007/JHEP07\(2018\)115](https://doi.org/10.1007/JHEP07(2018)115).
- [225] A.M. Sirunyan, et al., Search for third-generation scalar leptoquarks decaying to a top quark and a τ lepton at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 78 (9) (2018) 707, <https://doi.org/10.1140/epjc/s10052-018-6143-z>.
- [226] G. Aad, et al., Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 754 (2016) 302–322, <https://doi.org/10.1016/j.physletb.2016.01.032>.
- [227] A.M. Sirunyan, et al., Search for excited quarks of light and heavy flavor in γ -jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* 781 (2018) 390–411, <https://doi.org/10.1016/j.physletb.2018.04.007>.
- [228] M. Aaboud, et al., Search for new phenomena in high-mass final states with a photon and a jet from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Eur. Phys. J. C* 78 (2) (2018) 102, <https://doi.org/10.1140/epjc/s10052-018-5553-2>.
- [229] A.M. Sirunyan, et al., Search for pair production of excited top quarks in the lepton + jets final state, *Phys. Lett. B* 778 (2018) 349–370, <https://doi.org/10.1016/j.physletb.2018.01.049>.
- [230] Reach of ATLAS searches for new phenomena other than Supersymmetry., Technical Report, CERN, Geneva, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>.
- [231] CMS Exotica Physics Group Summary–ICHEP 2016, Technical Report, CERN, Geneva, <http://cms-results.web.cern.ch/cms-results/public-results/publications/>.
- [232] B2G: new physics searches with heavy SM particles, Technical Report, CERN, Geneva, <http://cms-results.web.cern.ch/cms-results/public-results/publications/>.
- [233] Reach in lifetime (τ) of ATLAS searches for new phenomena., Technical Report, CERN, Geneva, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>.
- [234] Long-lived particle searches, Technical Report, CERN, Geneva, <http://cms-results.web.cern.ch/cms-results/public-results/publications/>.
- [235] Regions in a dark matter mass-mediator mass plane, Technical Report, CERN, Geneva, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>.
- [236] Dark Matter Summary Plots from CMS for LHCP and EPS 2017, Technical Report, CERN, Geneva, <http://cms-results.web.cern.ch/cms-results/public-results/publications/>.