



Search for pair production of heavy particles decaying to a top quark and a gluon in the lepton+jets final state in proton–proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration*

CERN, Geneva, Switzerland

Received: 27 October 2024 / Accepted: 15 December 2024
© CERN for the benefit of the CMS Collaboration 2025

Abstract A search is presented for the pair production of new heavy resonances, each decaying into a top quark (t) or antiquark and a gluon (g). The analysis uses data recorded with the CMS detector from proton–proton collisions at a center-of-mass energy of 13 TeV at the LHC, corresponding to an integrated luminosity of 138 fb^{-1} . Events with one muon or electron, multiple jets, and missing transverse momentum are selected. After using a deep neural network to enrich the data sample with signal-like events, distributions in the scalar sum of the transverse momenta of all reconstructed objects are analyzed in the search for a signal. No significant deviations from the standard model prediction are found. Upper limits at 95% confidence level are set on the product of cross section and branching fraction squared for the pair production of excited top quarks in the $t^* \rightarrow tg$ decay channel. The upper limits range from 120 to 0.8 fb for a t^* with spin-1/2 and from 15 to 1.0 fb for a t^* with spin-3/2. These correspond to mass exclusion limits up to 1050 and 1700 GeV for spin-1/2 and spin-3/2 t^* particles, respectively. These are the most stringent limits to date on the existence of $t^* \rightarrow tg$ resonances.

1 Introduction

The standard model (SM) of particle physics has proven to be a highly accurate and successful theory. It describes the properties of all elementary particles and their interactions with a small number of free parameters. However, several observations indicate that it is not a complete theory and has to be extended. For example, the naturalness problem arises because of quadratically divergent contributions to the Higgs boson mass from the top quark and the W and Z bosons. In the SM, an unnaturally large fine-tuning is required to explain the measured Higgs boson mass of around 125 GeV

[1–3]. This motivates searches for possible extensions of the SM, particularly for theoretical models proposing that the top quark is not a fundamental but a composite particle [4–10]. A composite top quark would result in excited states that could be observed at the CERN LHC, providing a way to confirm or exclude these models. Excited top quarks t^* are predicted to decay instantly after their production into a top quark by the radiation of excess energy in the form of a gluon or a photon, $t^* \rightarrow tg$ or $t^* \rightarrow t\gamma$. Other models of physics beyond the SM propose the existence of vector-like fermionic top quark partners, for example little Higgs models [11–14], models with extra dimensions [15–17], or composite Higgs models [18]. Usually, searches for these types of models are performed targeting decays including W , Z , or Higgs bosons [19–25]. However, in the case of a small mixing between the top quark partner and the top quark, these decay modes are suppressed and the quantum loop induced decays $t^* \rightarrow tg$ and $t^* \rightarrow t\gamma$ become dominant [26]. Top quark partners can provide an elegant solution to the naturalness problem, introducing additional terms cancelling out the quadratic divergences [27].

In this article, we present a search for the pair production of heavy excited top quarks or top quark partners, generically labeled t^* in the following. We target the $t^*\bar{t}^* \rightarrow t\bar{t}g$ channel with an experimental signature that is independent of which underlying theory is predicting it. The t^* is predicted to carry the same weak isospin, color and weak hypercharge as the top quark, but could exist with different spins: spin-1/2 or spin-3/2 [26]. For a spin-1/2 t^* , the field can be described in a similar way to those of heavy SM quarks. The spin-3/2 case is described by a Rarita–Schwinger Lagrangian [28], adapting the Dirac equation to a spin-3/2 particle. Assuming equal couplings to the strong and electroweak sectors compared with the SM top quark leads to a branching fraction $\mathcal{B}$ of 97% for the decay $t^* \rightarrow tg$ in both spin scenarios [26]. This motivates a search where both t^* decay into a top quark and a gluon.

* e-mail: cms-publication-committee-chair@cern.ch (corresponding author)

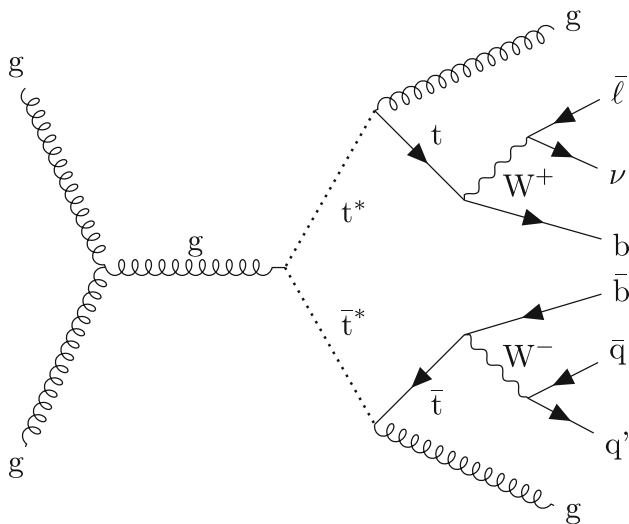


Fig. 1 Representative Feynman diagram of the signal process at leading order

We search for the $t^* \bar{t}^* \rightarrow t \bar{t} g$ process in final states containing a single lepton, a neutrino, four light jets from two gluons and two light quarks, and two jets originating from b quarks. A representative Feynman diagram of a signal process is shown in Fig. 1. Data collected between 2016 and 2018 with the CMS detector in proton–proton (pp) collisions at a center-of-mass energy of 13 TeV at the LHC are used in this analysis, corresponding to an integrated luminosity of 138 fb^{-1} . Previous searches in the same final state have been performed by the CMS Collaboration using 8 TeV [29] and 13 TeV [30] pp data. In comparison to the previous 13 TeV result, which is based on data corresponding to an integrated luminosity of 35.9 fb^{-1} , the analysis presented in this article achieves a substantial increase in sensitivity from the larger data set and from improved analysis techniques. In particular, machine-learning techniques are used to suppress backgrounds from known SM processes, and a more inclusive observable for the signal extraction results in an improved signal efficiency compared to the previous 13 TeV analysis [30].

Tabulated results are provided in the HEPData record for this analysis [31].

2 The CMS detector and simulated samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapid-

ity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [32,33].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of $4 \mu\text{s}$ [34]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [35].

Considering both the spin-1/2 and spin-3/2 scenarios, we produce Monte Carlo (MC) simulated samples of the $pp \rightarrow t^* \bar{t}^*$ signal process at leading order (LO) in perturbative quantum chromodynamics (QCD), using MADGRAPH5_aMC@NLO 2.6.5 [36]. We consider different values of resonance masses m_{t^*} between 700 and 3000 GeV, in steps of 100 GeV below 2000 GeV and in steps of 250 GeV above. The interactions with the SM particles are simulated using an effective field theory (EFT) [26,37], with the assumption that the t^* couplings in the strong and electroweak sectors are identical to the top quark couplings. The predicted production cross sections for the pair production of spin-3/2 t^* particles is larger than for spin-1/2 particles of the same mass, as the cross section for spin-3/2 grows with energy as $\hat{s}^3$ [37], where $\hat{s}$ is the partonic center-of-mass energy squared. This violates unitarity at high energies, but is regulated by some large scale of new physics $\Lambda \gg m_{t^*}$ at which the EFT approach becomes invalid. Differences in the kinematic distributions of t^* systems with different spins are observed in angular correlations, as well as in the t^* momenta and the invariant mass of the $t^* \bar{t}^*$ system, where the momenta and mass are larger on average for spin-3/2 compared to spin-1/2 fermions. These spin-dependent differences become smaller with increasing m_{t^*} .

Relevant SM background processes for this search are top quark pair ($t\bar{t}$) and single top quark production, as well as the production of a W boson in association with jets (W+jets). Less important background processes include the production of two weak gauge bosons (diboson), the production of multiple jets from the strong interaction (QCD multi-jet) and the Drell–Yan process. The $t\bar{t}$ production is simulated at next-to-LO (NLO) with POWHEG v2 [38–42]. The cross section of the $t\bar{t}$ process is corrected to a prediction at next-to-NLO (NNLO) precision, using a next-to-next-to-leading-logarithmic soft-gluon approximation, obtained with the TOP++ 2.0 program [43]. The production of single top quarks is simulated at NLO using POWHEG for the tW and

t channels, and MADGRAPH5_aMC@NLO for the s channel. The W +jets production is simulated at LO with four additional partons with MADGRAPH5_aMC@NLO. Diboson, QCD multijet production, and the Drell–Yan process are simulated at LO with PYTHIA 8.240 [44]. For all generated samples, the NNPDF 3.1 [45] NNLO parton distribution function (PDF) sets are used.

For all generated collision events, parton shower and hadronization are simulated using PYTHIA with the CP5 tune [46]. The CMS detector response is simulated using GEANT4 [47]. Additional inelastic pp collision events are simulated using PYTHIA and superimposed on simulated events to model the effect of additional pp collisions within the same or adjacent bunch crossings (pileup). We use a total inelastic cross section of 69.2 mb [48] to estimate the expected number of pp interactions per bunch crossing and correct the simulation to match the corresponding distribution to that observed in data.

3 Event reconstruction

A particle-flow (PF) algorithm [49] aims to reconstruct and identify each particle in an event, with an optimized combination of information from the various elements of the CMS detector.

The energy of muons is obtained from the curvature of the corresponding track. These are measured with a reconstruction and identification efficiency greater than 96%. For muons with transverse momentum p_T up to 100 GeV, a relative transverse momentum resolution of 1% in the barrel and 3% in the endcaps is obtained. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [50]. A set of selection criteria, different for low- p_T [51] and high- p_T [52] muons, is used to select prompt muons. Scale factors are used to correct for observed differences between data and simulation in the muon reconstruction and selection efficiencies.

The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track [53]. The momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \rightarrow ee$ decays ranges from 1.6 to 5%. It is generally better in the barrel region than in the endcaps, and also depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [53, 54]. A multivariate selection with a 90% efficiency to identify prompt electrons is used. Correction scale factors ensure that the electron reconstruction and selection efficiency is well modeled in MC simulation.

For both muons and electrons, we define an isolation variable I_{rel} as the p_T sum of nearby PF candidates relative to the

lepton p_T , after accounting for pileup contributions [50, 53]. For the calculation of I_{rel} , PF candidates within $\Delta R < 0.4$ and 0.3 for muons and electrons, respectively, are considered. The angular distance ΔR between two PF candidates i and j is defined as $\Delta R = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$, where $\Delta\eta_{i,j}$ and $\Delta\phi_{i,j}$ denote the distances in pseudorapidity and azimuth, respectively.

The energy of photons is obtained from the ECAL measurement [53]. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Two different types of hadron jets are reconstructed from PF candidates, referred to as small-radius and variable-radius jets.

Small-radius jets are clustered using the anti- k_T algorithm [55] as implemented in the FASTJET package [56] with an angular distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire p_T spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy deposits, increasing the apparent jet momentum. The pileup-per-particle identification (PUPPI) algorithm [57, 58] is used to mitigate the effect of pileup at the reconstructed-particle level, using local shape information, event pileup properties, and tracking information. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to the truth information from the simulation. In situ measurements of the momentum balance in dijet, γ +jet, Z +jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [59]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [58].

The second jet reconstruction algorithm, used to reconstruct variable-radius jets, is the Heavy Object Tagger with Variable R (HOTVR) algorithm [60], which is also implemented in FASTJET. It combines jet clustering with subjet finding and a soft-cluster rejection. Resulting jets have an angular size between 0.1 and 1.5 in the jet distance parameter, where the active jet area [61] decreases with increasing momentum. This jet reconstruction algorithm has been developed for the reconstruction of fully hadronic decays of Lorentz-boosted top quarks, where each decay results in a single jet reconstructed with an optimal jet size [62]. The top quark momentum, and therefore its Lorentz boost, varies depending on m_{t^*} in this search. Variable-radius jets are thus

better suited to capture the kinematic properties of the top quarks with reduced dependence on the assumed signal mass [63]. Jets originating from gluons of the t^* decay are reconstructed with the HOTVR algorithm as well, where the variable size of these jets helps to capture wide-angle radiation, which would result in out-of-cone effects for small-radius jets. The substructure of variable-radius jets is analyzed using the N -subjettiness variables τ_N , which provide a measure of the degree to which jets contain N or fewer localized regions of high energy density [64,65]. Pileup is accounted for using the PUPPI algorithm, following a similar procedure to that used for the small-radius jets. Momentum corrections are applied to the individual subjets of each HOTVR jet. Recombination of the corrected subjets gives the corrected variable-radius jet. This procedure was first applied in Ref. [66] and has been validated again for this analysis.

Jets originating from the fragmentation of b quarks are identified using the multiclassification algorithm DEEPJET [67–69], based on a deep neural network (DNN). It uses information from jet constituents, charged and neutral particles, secondary vertices, and global event variables to define a score for each jet. This score quantifies how likely the jet is to have originated from the decay of a b quark. Small-radius jets with a DEEPJET score above a certain threshold, corresponding to a 1% misidentification probability of light-quark and gluon jets, are referred to as b jets. This working point has an efficiency between 70 and 80% for correctly identifying b jets, depending on the data-taking era. Differences between data and simulation in the shape of the DEEPJET score distribution are accounted for by applying correction factors, and a secondary correction ensures that no change in normalization is introduced.

The missing transverse momentum vector $\mathbf{p}_T^{\text{miss}}$ is computed as the negative vector sum of the transverse momenta of all PF candidates in an event, and its magnitude is denoted as p_T^{miss} [70]. The PUPPI algorithm is applied to reduce the pileup dependence of the $\mathbf{p}_T^{\text{miss}}$ observable. The $\mathbf{p}_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the jets in the event.

4 Event selection

We use HLT algorithms requiring the presence of a single muon, electron, or photon. These select events with at least one muon having p_T above 50 GeV or an electron with p_T above 115 GeV, with no isolation requirements. Complementary triggers requiring an isolated lepton extend the reach of the analysis to lower p_T , requiring a muon with p_T of at least 24 or 27 GeV in 2016 or 2017–2018, or an electron with p_T of at least 27, 35, or 32 GeV in the years 2016, 2017, and 2018, respectively. The different p_T thresholds were intro-

duced because of different instantaneous luminosities during the three years of data taking. To recover inefficiencies at high electron p_T , events selected using photon triggers with a photon with p_T larger than 175 or 200 GeV in 2016 or 2017–2018, respectively, are considered as well. The muon trigger efficiency exceeds 90% over the full momentum range, and the electron trigger efficiency is greater than 80% and increases with momentum. The same trigger selection criteria are applied to simulated events, and scale factors ensure that the trigger efficiency in simulation matches that in data.

A further correction factor is applied to simulated events to account for a trigger inefficiency in 2016 and 2017, caused by a timing shift in the ECAL. An issue in some HCAL modules during 2018 resulted in a loss of efficiency in a specific η - ϕ region of the detector. Therefore, any event in data that has a muon, electron, or jet in the affected region during this period in time is rejected. The effect is accounted for in MC simulations using event weights.

To select events matching the expected topology of the signal process, we require events to have a single lepton ℓ (muon or electron) within $|\eta| < 2.4$, and $p_T > 30$ or 40 GeV for muons or electrons, respectively. Events are assigned to a muon or an electron channel based on the flavor of the selected lepton. Muons or electrons with p_T smaller than 55 or 120 GeV, respectively, are referred to as low- p_T leptons. Low- p_T muons need to fulfill $I_{\text{rel}} < 0.15$. For low- p_T electrons, isolation is ensured by including relevant variables in the multivariate electron selection. High- p_T leptons with p_T above these thresholds are required to satisfy one of two looser isolation criteria: either $\Delta R(\ell, \text{jet}) > 0.4$ or $p_{T,\text{rel}} > 25$ GeV, to suppress contributions from QCD multi-jet production [71]. The angular distance $\Delta R(\ell, \text{jet})$ is calculated between the selected lepton and the closest small-radius jet in the η - ϕ plane, and $p_{T,\text{rel}}$ is the p_T component of the lepton perpendicular to the axis of the closest small-radius jet.

For a hadronically decaying top quark, we require at least one variable-radius jet with $p_T > 200$ GeV and $|\eta| < 2.4$, aiming to reconstruct the decay products in a single jet. Additionally, events must contain at least four small-radius jets with $p_T > 30$ GeV and $|\eta| < 2.4$, at least one of which must be a b jet. In this selection, the variable-radius jets and small-radius jets are treated separately and are independent of each other. We do not test for a potential overlap between the small-radius and variable-radius jets in an event. Furthermore, $p_T^{\text{miss}} > 50$ GeV is required to account for the neutrino from the W boson decay.

A scalar momentum sum variable S_T is defined as

$$S_T = p_T^\ell + p_T^{\text{miss}} + \sum_i p_{T,i}^{\text{jet}}, \quad (1)$$

where the sum runs over all variable-radius jets with $p_T > 200$ GeV and $|\eta| < 2.4$. This variable is useful for discrim-

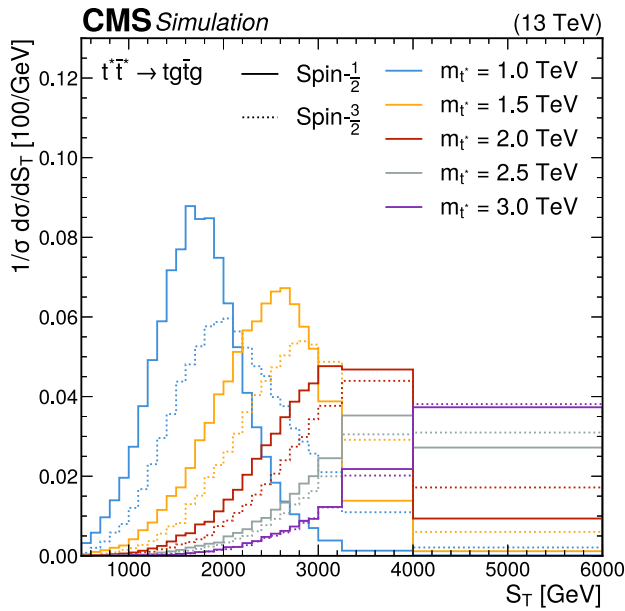


Fig. 2 Distributions in S_T for $t^* \bar{t}^*$ signal samples with different simulated values of m_{t^*} , for spin-1/2 (solid lines) and spin-3/2 (dashed lines) resonances. Each signal distribution is normalized to 100

inating signal from SM background events, as $t^* \bar{t}^*$ production results in a higher value of S_T on average. In Sect. 8, we use the measured distribution in S_T for the statistical interpretation of the results. All events are required to have $S_T > 500$ GeV to further reduce trigger inefficiency effects from events with low- p_T leptons and jets.

Depending on the spin and mass of the t^* , around 50% of signal events remain after the above requirements, with higher efficiency for spin-3/2 compared to spin-1/2 t^* , and increasing efficiency towards higher m_{t^*} . In contrast, the contribution of SM background processes is substantially reduced, with efficiencies below 1%. In Fig. 2 we show the S_T distributions of various simulated signal samples. The spin-3/2 signals feature a peak in S_T around $2m_{t^*}$, shifted to smaller values for spin-1/2 signals. The spin-3/2 signals have higher S_T on average, a difference that is more pronounced at lower t^* masses. This behavior results from higher t^* momentum and invariant mass of the $t^* \bar{t}^*$ system for spin-3/2 signals compared to spin-1/2. Because the SM background contributions monotonically decrease with increasing S_T , we expect better sensitivity for spin-3/2 signals compared to spin-1/2. These differences become smaller for higher t^* masses.

5 Event classification

We use a DNN to classify events as signal like and background like. It is designed to output a single DNN score s_{DNN} , where signal-like events are given a high score and background-like events a low score. We pass 33 input fea-

tures to the DNN, which are derived from the reconstructed PF candidates in signal events:

- p_T , η , ϕ , and I_{rel} of the lepton,
- p_T , η , ϕ , the number of subjets, τ_1 , τ_2 , and τ_3 of the three p_T -leading variable-radius jets,
- p_T , η , ϕ and the DEEJET score of the small-radius jet with the highest DEEJET score,
- p_T^{miss} and ϕ of $\mathbf{p}_T^{\text{miss}}$, and
- the multiplicities of the small-radius and variable-radius jets in the event.

Zero padding is used in case features cannot be defined, for example for events containing less than three variable-radius jets. We find that jet multiplicity and substructure variables are especially relevant for the DNN performance, together with information on the variable-radius jet that is third in the p_T hierarchy. The DNN uses a fully connected feed-forward architecture with four hidden layers and 25 nodes each. We trained it on simulated $t\bar{t}$ events and a balanced mixture of spin-1/2 signal events with m_{t^*} between 700 and 3000 GeV. We verified that no m_{t^*} bias arises, by investigating the effect of repeating the training with one m_{t^*} sample removed. The DNN is used for both spin scenarios, as we observe no substantial sensitivity increase when testing a separate, dedicated DNN for the spin-3/2 signals.

Some of the DNN input variables are used to calculate S_T , which results in an output strongly correlated with S_T . To prevent this and coerce the network to learn auxiliary features that differ between signal and background events, background events are reweighted to have an S_T distribution identical to that of the signal events used in the training. Aside from ensuring balance of the signal and background classes during training, this reduces the correlation between S_T and s_{DNN} . At the same time, it facilitates the exploitation of information other than the p_T , such as angular correlations, jet multiplicity, and the substructure of variable-radius jets. The importance of these features for the network decision increases after the S_T reweighting. However, some correlation between S_T and s_{DNN} remains, which is alleviated in a second decorrelation step. We use the “designing decorrelated taggers” (DDT) technique [72], where we shift s_{DNN} by an S_T -dependent value $f(S_T, \epsilon_{t\bar{t}})$ for each event,

$$s_{\text{DDT}} = s_{\text{DNN}} - f(S_T, \epsilon_{t\bar{t}}). \quad (2)$$

To determine the function $f(S_T, \epsilon_{t\bar{t}})$, a set of s_{DNN} selection thresholds are found in intervals of 100 GeV in S_T . In each interval, the threshold value corresponds to a given efficiency $\epsilon_{t\bar{t}}$ for selecting $t\bar{t}$ background events. To obtain the continuous function $f(S_T, \epsilon_{t\bar{t}})$, we fit the selection thresholds using an analytic function. The two-dimensional distribution in S_T versus $1 - s_{\text{DNN}}$ and the resulting function $f(S_T, \epsilon_{t\bar{t}})$ are shown in Fig. 3 for $\epsilon_{t\bar{t}} = 30\%$.

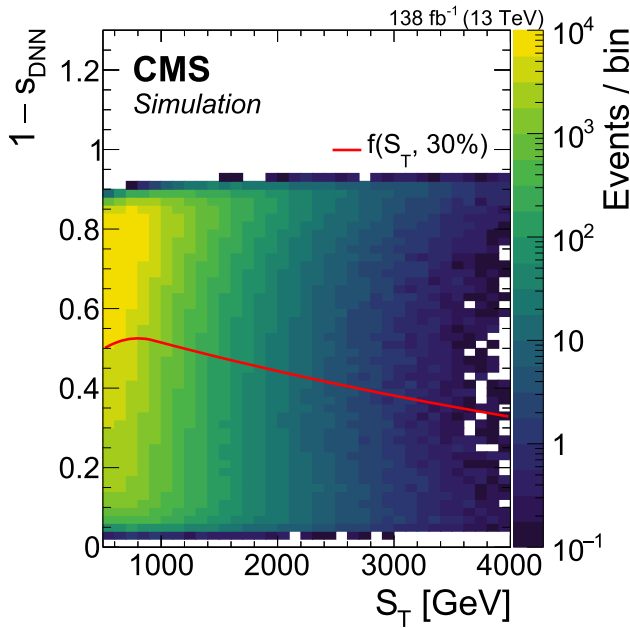


Fig. 3 Two-dimensional distribution in $1 - s_{\text{DNN}}$ versus S_T for simulated $t\bar{t}$ events. The function $f(S_T, 30\%)$ (red line) is determined by specifying a 30% selection efficiency for $t\bar{t}$ events, i.e., 30% of the $t\bar{t}$ events are below this function in each bin of S_T

The resulting score s_{DDT} is uncorrelated with S_T , i.e., a selection based on s_{DDT} results in a constant $t\bar{t}$ background efficiency as a function of S_T . This is crucial for the background estimation described below. We define a signal region (SR) with $s_{\text{DDT}} > 0$ and a validation region (VR) with $s_{\text{DDT}} < 0$. While the SR is used in the statistical analysis in the search for a signal, the VR is only used to validate the background estimation presented below. We find that a $t\bar{t}$ selection efficiency $\epsilon_{t\bar{t}} = 30\%$ results in the best sensitivity of this analysis, while ensuring that the split of events between the SR and VR only minimally changes the shape of the S_T distributions for the SM backgrounds. By construction, the SR contains 30% of all $t\bar{t}$ events after the analysis selection and the VR contains 70%. The efficiency for signal events to enter the SR varies between 55 and 75%, depending on the spin and m_{t^*} .

6 Background estimation

The SM processes that can result in a final state similar to the one expected from signal events can be divided into two classes: backgrounds containing top quarks, $t\bar{t}$ and single top quark events, and backgrounds without on-shell top quarks (non- t backgrounds), mostly consisting of events from W +jets, Drell–Yan, QCD multijet, and diboson production.

We estimate backgrounds with top quarks using simulation, for which the correction factors described in Sect. 3 ensure a good description of the data. In addition to these corrections, a reweighting as a function of the parton-level p_T of the top quark is applied to background events. These weights correct for a top quark p_T -dependent mismodeling in simulations at NLO precision [73,74].

We estimate the contribution from backgrounds without top quarks with a method based on control samples in data, because the production of weak vector bosons with multiple jets and QCD multijet production are not modeled with sufficient accuracy. We define a control region (CR) that contains events passing all the requirements described in Sect. 4, except for the b jet selection. Only events without a b jet enter the CR. No requirement on s_{DDT} is imposed in the CR. The CR is enriched in non- t backgrounds, with top quark background contaminations amounting to 10–20%, and is statistically independent of the SR. We use simulated events to construct an S_T -dependent ratio between the non- t background contributions in the CR and SR. We fit the ratio with two functions, a Landau distribution and a Gaussian distribution with a constant offset. The average of these two functions then defines a transfer function $g_{\text{TF}}(S_T)$. The ratios between the S_T distributions in the SR and CR are shown in Fig. 4, together with the fits of the transfer functions.

The function $g_{\text{TF}}(S_T)$ is used to estimate the non- t background contribution in the SR as

$$N_{\text{SR}}(\text{non-}t \text{ bkg}) = g_{\text{TF}}(S_T) (N_{\text{CR}}(\text{data}) - N_{\text{CR}}(\text{top bkg})), \quad (3)$$

where $N_{\text{CR}}(\text{data})$ and $N_{\text{CR}}(\text{top bkg})$ are the event counts in the CR for data and for the simulated samples with on-shell top quarks, respectively. The event counts are obtained in intervals of S_T . For the muon and electron channels, the number of events in the CR is multiplied by $g_{\text{TF}}(S_T)$, after subtracting contributions of simulated top quark backgrounds. Since the composition of non- t backgrounds differs between the muon and electron channels, the method is applied to each channel individually. We verify the estimation of the background in the SR using the VR. Results from the background estimation for the VR are shown in Fig. 5 for the muon and electron channels. The bin widths increase with increasing S_T so that each bin is appropriately populated in data and simulation. The uncertainty arising from the limited size of the simulated background samples becomes non-negligible towards high S_T , but its impact on the sensitivity of the analysis is small compared to other uncertainties. The predicted backgrounds describe the measured data within the uncertainties in both channels.

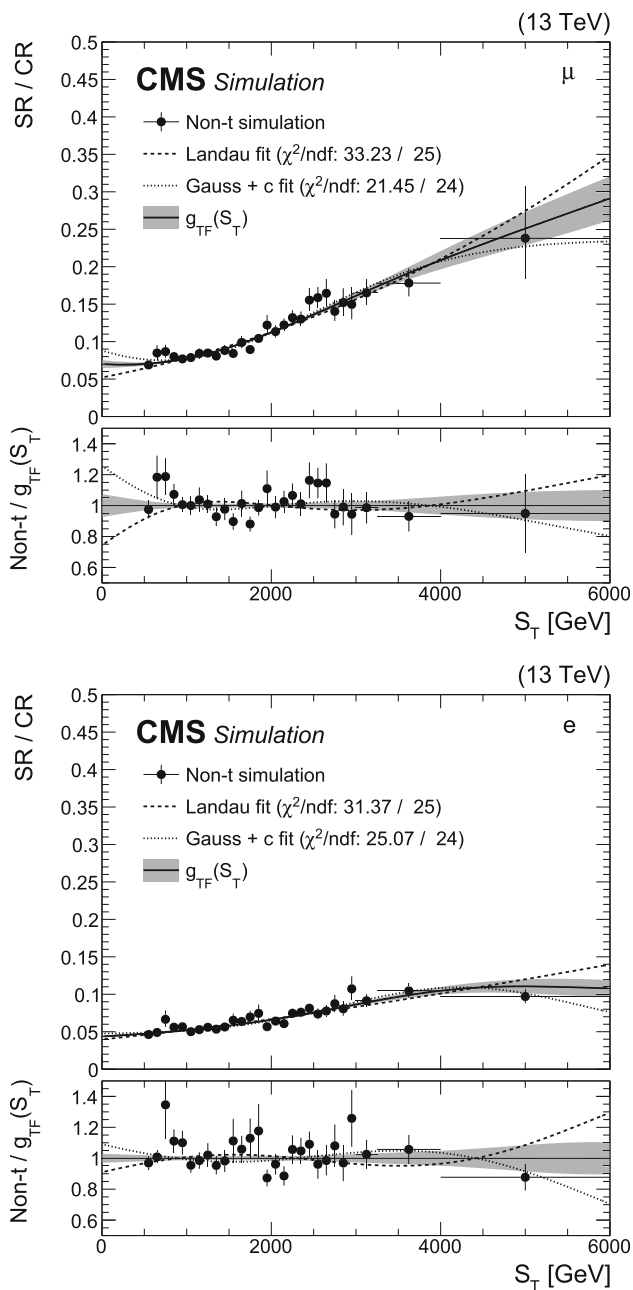


Fig. 4 The simulation-based ratios between the S_T distributions in the SRs and CRs for the muon (upper) and electron (lower) channels. Two functions are fit to each ratio, and the final transfer function used for the non-t background estimation is taken to be their average. The statistical uncertainties in the transfer functions are shown as grey bands. In the lower panels, the simulation-based ratios, fit functions, and statistical uncertainties are shown relative to the final transfer function

7 Systematic uncertainties

Several systematic effects introduce uncertainties affecting the normalization and shape of distributions in S_T . We summarize these in the following, split into experimental and theoretical uncertainties. All uncertainties, which can affect

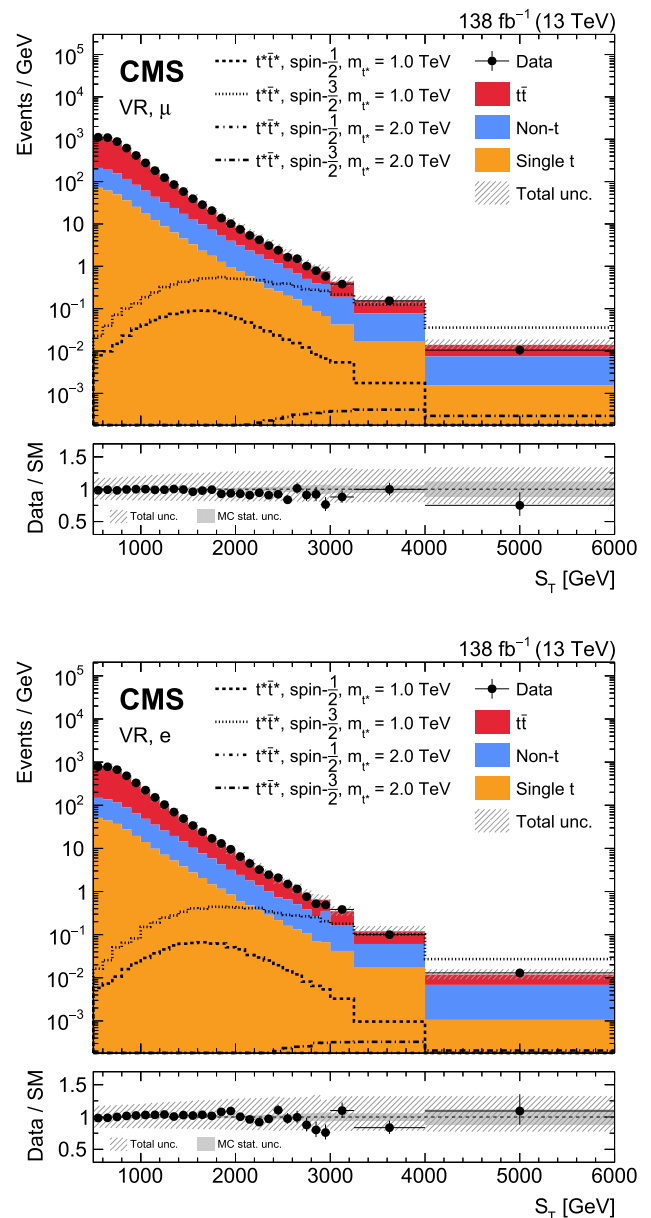


Fig. 5 Distributions of S_T in the VR for the muon (upper) and electron (lower) channels. The total uncertainties are shown as hatched bands. The signal distributions are scaled to the cross sections predicted by theory. Ratios of data to the expected backgrounds are shown in the lower panels

either the rate or both the rate and the shape of S_T , are included as nuisance parameters in the statistical analysis presented below. Details on the implementation of nuisance parameters are provided in Ref. [75]. To give an estimate of the relevance of the systematic uncertainties, we provide an approximate size of each source for the largest SM contribution it affects.

7.1 Experimental uncertainties

Systematic uncertainties arise from the selection of b jets and the corresponding efficiencies. The b jet selection uncertainties are split into different sources, depending on the jets they affect: jets originating from b quarks, c quarks, or light jets. Furthermore, these are split into statistical and systematic components, where the former are not correlated between eras of data taking, but the latter are. The uncertainty from each source corresponds to variations of up to 10% for $t\bar{t}$ events. An additional b tagging related uncertainty is connected to normalization differences before and after applying the b tagging correction factors. Separate corrections to the normalization are derived for the electron and muon channels. The differences between these and the correction obtained for a combination of the two channels is taken to be the associated uncertainty. This uncertainty can reach up to 5% for simulated $t\bar{t}$ events and is correlated between the years of data taking.

The impact of uncertainties associated with the jet energy scale and jet energy resolution corrections on small radius jets, variable-radius jets and $\mathbf{p}_T^{\text{miss}}$ is estimated by varying the corresponding corrections within their uncertainties. The resulting uncertainty is correlated between all affected objects and treated as uncorrelated between years. This uncertainty has an impact of up to 4% in $t\bar{t}$ events.

Uncertainties connected to correction factors for the lepton reconstruction, identification, isolation, and triggers are of the order of 1% or smaller for $t\bar{t}$ events, and are not correlated between years of data taking. An uncertainty in the correction factor accounting for the 2016 and 2017 trigger inefficiency is considered as well.

The total inelastic cross section of 69.2 mb, used to correct the pileup distribution in simulation, is varied by $\pm 4.6\%$ [48], resulting in an uncertainty of around 2% for $t\bar{t}$ events.

A total uncertainty of 1.6% in the integrated luminosity of 138 fb^{-1} is considered [76–78]. This uncertainty affects only the normalization of simulated samples.

Another source of uncertainty, specific to this analysis, arises from the DNN decorrelation procedure. We take the residual differences between the shapes of the S_T distributions in the SR and VR for top quark backgrounds as an estimate of the associated uncertainty. The resultant impact corresponds to variations of up to 10% for $t\bar{t}$ events.

Separate uncertainties are considered on the results of the data-driven background estimation. The procedure is repeated for each of the two functions used to construct $g_{\text{TF}}(S_T)$. The resulting distributions are used as a systematic variation around the nominal non- t background prediction. The effect is treated as fully correlated between years and is below 8% for the non- t background. The effect of the statistical uncertainty in $g_{\text{TF}}(S_T)$ amounts to around 5%. We estimate the systematic uncertainty connected to the b tagging

veto in the definition of the CR by repeating the background estimation for variations of the b tagging corrections, where the individual sources are combined. The resulting uncertainty can reach up to 15% for the non- t background and is treated as fully correlated between years.

In summary, the dominant experimental systematic uncertainties in this analysis are from the b tagging corrections and the decorrelation procedure for the background estimation.

7.2 Theoretical uncertainties

The largest systematic uncertainty in the modeling of SM background processes results from missing higher-order effects in the simulation. We estimate this effect by varying the renormalization and factorization scales in the simulation by factors of 2 and 1/2. An envelope is constructed from the possible variations, except for variations where one scale is varied by 2 and the other by 1/2. This uncertainty is taken to be fully correlated between data-taking years. It includes a normalization effect covering uncertainties in the production cross sections of the SM background processes and varies between 20 and 60% for $t\bar{t}$ events, with the larger values at high S_T . For signal samples, we remove uncertainties in the normalization from scale variations and consider only acceptance and shape effects.

The uncertainty in the correction of the p_T of the parton-level top quark is estimated from the difference in the S_T distribution before and after applying this correction. For $t\bar{t}$ events, it amounts to below 20%.

An uncertainty resulting from the choice of PDFs is obtained using the standard deviation of 100 different MC replicas, following the procedure described in Ref. [79]. The uncertainty has an unimportant effect on the analysis. For signal samples, only the acceptance and shape effects are considered for the PDF uncertainties.

Other sources of uncertainties related to the modelling of background processes, like uncertainties in the simulation of initial and final state radiation, the matching of matrix elements to the parton shower, or the modelling of hadronization, are small compared to the ones considered here.

8 Results

The S_T distribution in the SR, measured in the muon and electron channels, is the main observable of this analysis. The backgrounds from $t\bar{t}$ and single top quark production are taken from simulation, with the appropriate correction factors applied. The S_T distributions of the non- t backgrounds are extrapolated from the CR. Signal distributions are taken from simulations. We combine all years of data and include the uncertainties described in Sect. 7 as nuisance parameters.

A statistical analysis is performed to probe for the existence of $t^*\bar{t}^*$ production with a binned maximum likelihood fit. The modified frequentist approach [80–82], known as the CL_s criterion with the profile likelihood ratio as the test statistic, is used in this search to set 95% confidence level (CL) upper limits on the product of the production cross section for $pp \rightarrow t^*\bar{t}^*$ and the branching fraction squared $\mathcal{B}^2(t^* \rightarrow t\bar{g})$. We use the asymptotic approximation to the profile likelihood test statistic [83]. The statistical analysis is performed using the CMS statistical analysis tool COMBINE [75], which is based on the ROOFIT [84] and ROOSTATS [85] frameworks.

We show the S_T distributions in the SR for the muon and electron channels in Fig. 6 after the background-only maximum likelihood fit to the data. No significant deviation from the SM predictions is observed. The resulting upper limits on the product of the production cross section and the branching fraction squared are presented in Figs. 7 and 8 for spin-1/2 and spin-3/2 resonances, respectively. For the spin-1/2 case, the limits are found to be between 120 fb (190 fb expected) for $m_{t^*} = 700$ GeV, and 0.8 fb (0.8 fb expected) for $m_{t^*} = 3000$ GeV. For the spin-3/2 case, the upper limits are between 15 fb (18 fb expected) at 700 GeV and 1.0 fb (0.9 fb expected) at 2750 GeV.

As expected from the differences in the S_T distributions between spin-1/2 and spin-3/2 t^* signals, the analysis is more sensitive to spin-3/2 signals at low m_{t^*} . At high m_{t^*} , the sensitivity is comparable, with the analysis being slightly more sensitive to spin-1/2 signals. This is a result of the efficiency of the DNN-based SR definition, which decreases with increasing m_{t^*} . This effect is more pronounced for spin-3/2 than for spin-1/2 t^* signals.

For both spin scenarios, we compare the results to theory predictions of the $t^*\bar{t}^*$ pair production cross section. These are determined as described in Sect. 2, using an EFT approach to describe the interaction of the t^* and SM particles. We assume a branching fraction of 100% for the $t^* \rightarrow t\bar{g}$ decay.

The existence of a spin-1/2 t^* is excluded up to m_{t^*} values of 1050 GeV, with 990 GeV expected. These are the first mass exclusion limits on a spin-1/2 t^* in the $t^* \rightarrow t\bar{g}$ decay channel at 13 TeV, made possible by the improvements in this analysis compared to the previous analysis [30]. For the spin-3/2 case, the lower mass limit is considerably higher because of the higher predicted cross section and the better sensitivity of the analysis to spin-3/2 t^* resonances below 2 TeV. The existence of a spin-3/2 t^* is excluded below m_{t^*} of 1700 GeV, with 1690 GeV expected.

When comparing the exclusion limits to the ones from the previous CMS result, based on 13 TeV data corresponding to an integrated luminosity of 35.9 fb^{-1} , a substantial improvement is visible. The increased size of the analyzed data set yields an improvement in sensitivity to the cross section limit of about a factor of two. In addition, the sensi-

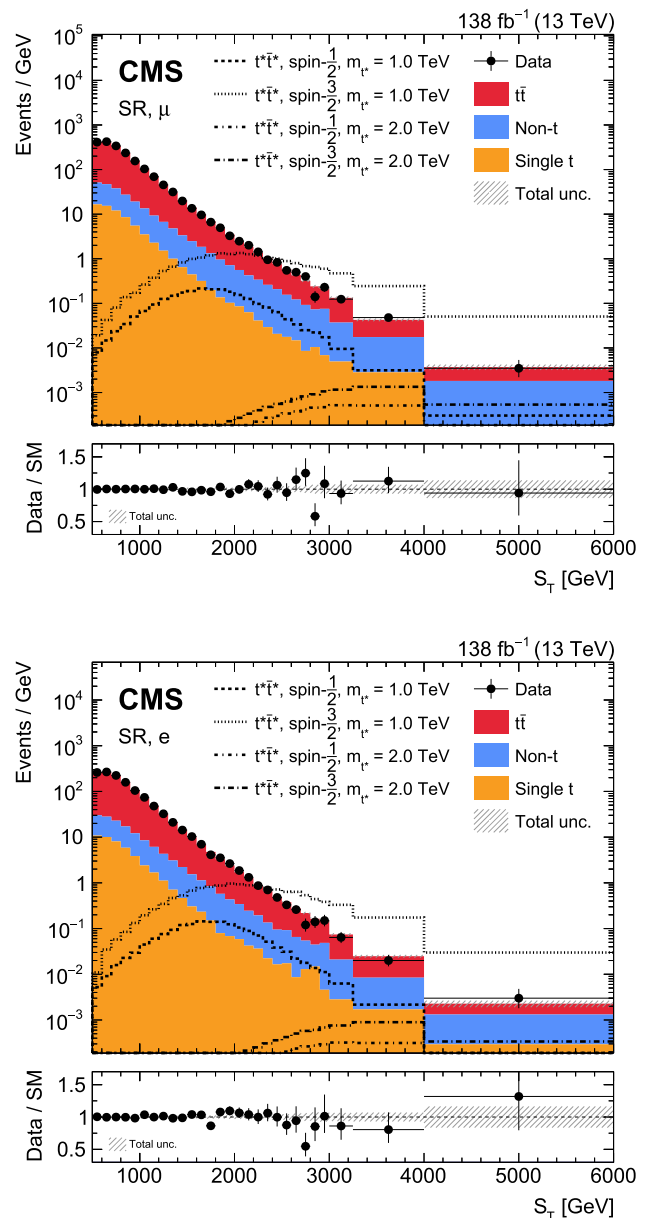


Fig. 6 Distributions in S_T in the SR for the muon (upper) and electron (lower) channels, after a background-only fit to the data. The signal distributions are scaled to the cross section predicted by the theory. The hatched bands show the post-fit uncertainty band, combining all sources of uncertainty. The ratio of data to the background predictions is shown in the panels below the distributions

tivity is increased by improvements of the analysis strategy. We impose looser lepton and jet multiplicity requirements and use variable-radius jets to access the Lorentz-boosted t^* decay products. This, combined with the addition of an event classification DNN and the usage of S_T instead of a reconstruction of the t^* system, leads to an increased signal efficiency: the fraction of signal events reaching the SR is about five times higher compared to the previous analysis. In contrast, background yields in the SR only increase by about

Fig. 7 Expected and observed 95% CL upper limits on the product of the $t^* \bar{t}^*$ production cross section and the branching fraction squared $\mathcal{B}^2(t^* \rightarrow t g)$ for a spin-1/2 t^* as a function of m_{t^*} . The inner (green) and outer (yellow) bands give the central probability intervals containing 68 and 95% of the expected upper limits under the background-only hypothesis. The cross section predicted by theory, following the EFT approach introduced in Ref. [26], is shown as a dotted line, assuming $\mathcal{B}(t^* \rightarrow t g) = 1$

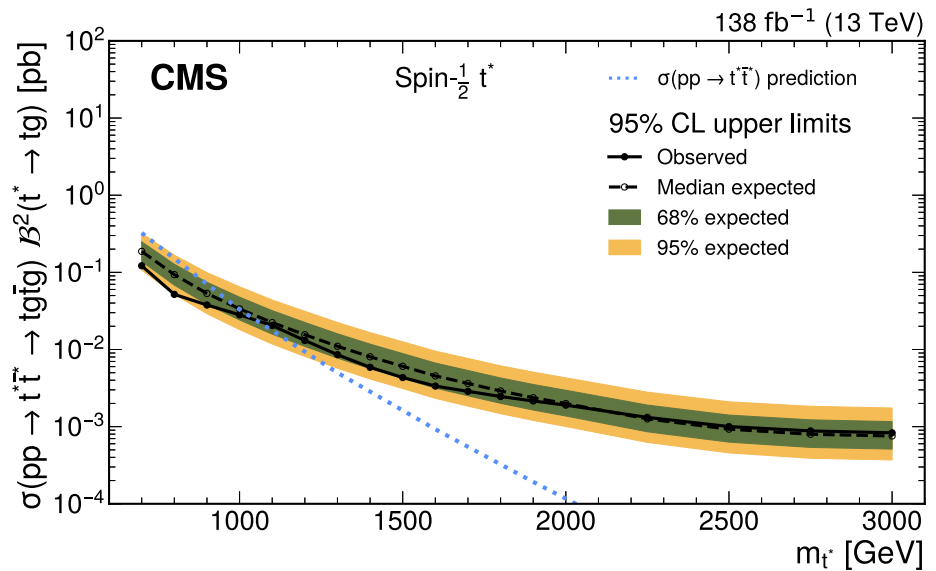
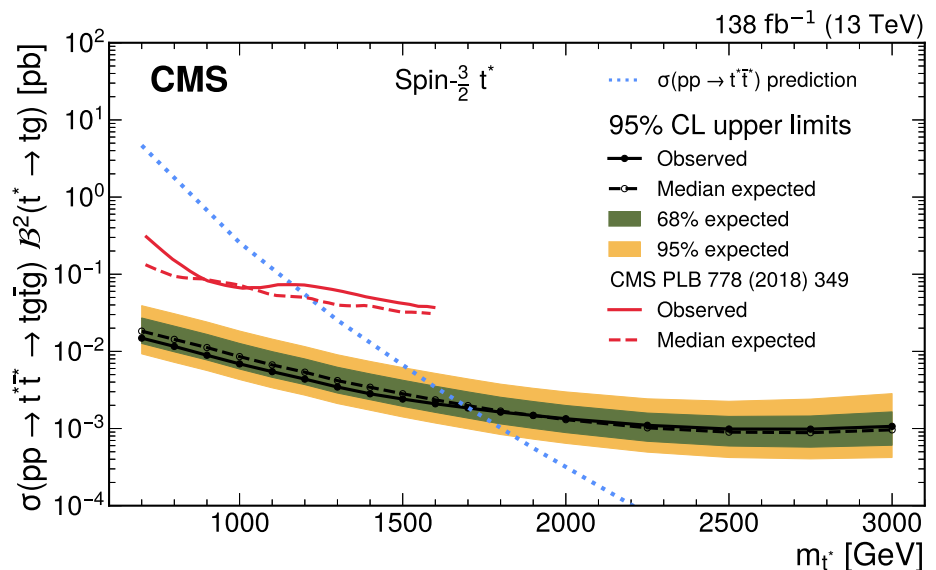


Fig. 8 Expected and observed 95% CL upper limits on the product of the $t^* \bar{t}^*$ production cross section and the branching fraction squared $\mathcal{B}^2(t^* \rightarrow t g)$ for a spin-3/2 t^* as a function of m_{t^*} . The inner (green) and outer (yellow) bands give the central probability intervals containing 68 and 95% of the expected upper limits under the background-only hypothesis. The cross section predicted by theory, following the EFT approach introduced in Ref. [26], is shown as a dotted line, assuming $\mathcal{B}(t^* \rightarrow t g) = 1$. The results of the previous CMS analysis [30], using data corresponding to an integrated luminosity of 35.9 fb^{-1} , are shown as well



10%. Overall, we achieve an increase in sensitivity by about a factor of five on top of the factor of two from the larger data set, resulting in a total improvement in sensitivity by about an order of magnitude compared to the previous analysis.

9 Summary

A search for the pair production of heavy top-quark partners t^* has been presented, where the t^* couples predominantly to gluons and decays to a top quark and a gluon, $t^* \rightarrow t g$. Both spin-1/2 and spin-3/2 resonances are considered. The analysis uses 13 TeV proton–proton collision data collected by the CMS experiment between 2016 and 2018, corresponding to an integrated luminosity of 138 fb^{-1} . The final state

analyzed consists of a lepton with high transverse momentum, missing transverse momentum and several jets. A deep neural network is used to identify potential signal events. With a two-step decorrelation procedure, independence of the deep neural network output from the main observable S_T has been achieved, where S_T is the scalar sum of the transverse momenta of the selected lepton and jets, and the missing transverse momentum. No statistically significant deviation from the background prediction was found. Upper limits at 95% confidence level are derived on the product of the $t^* \bar{t}^*$ production cross section and branching fraction squared for $t^* \rightarrow t g$. These are between 120 and 0.8 fb for a spin-1/2 t^* and between 15 and 1.0 fb for a spin-3/2 t^* , depending on the t^* mass. A comparison of these limits with the theory predictions results in mass limits for the t^* resonances, where

the existence of a spin- $1/2$ t^* is excluded below a mass of 1050 GeV and for a spin- $3/2$ t^* below a mass of 1700 GeV. These are the most stringent limits to date and the first exclusion limit for a spin- $1/2$ t^* resonance at 13 TeV. The results also substantially improve the spin- $3/2$ exclusion limits compared to previous results.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 – GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program – ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018

(Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the [CMS data preservation, re-use and open access policy](#).

Code Availability Statement The CMS core software is publicly available on GitHub (<https://github.com/cms-sw/cmssw>).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Funded by SCOAP³.

References

1. ATLAS Collaboration, 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**, 1 (2012). <https://doi.org/10.1016/j.physletb.2012.08.020>. arXiv:1207.7214
2. CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **716**, 30 (2012). <https://doi.org/10.1016/j.physletb.2012.08.021>. arXiv:1207.7235
3. CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV. *JHEP* **06**, 081 (2013). [https://doi.org/10.1007/JHEP06\(2013\)081](https://doi.org/10.1007/JHEP06(2013)081). arXiv:1303.4571
4. H. Georgi, L. Kaplan, D. Morin, A. Schenk, Effects of top compositeness. *Phys. Rev. D* **51**, 3888 (1995). <https://doi.org/10.1103/PhysRevD.51.3888>. arXiv:hep-ph/9410307
5. B. Lillie, J. Shu, T.M.P. Tait, Top compositeness at the Tevatron and LHC. *JHEP* **04**, 087 (2008). <https://doi.org/10.1088/1126-6708/2008/04/087>. arXiv:0712.3057
6. A. Pomarol, J. Serra, Top quark compositeness: feasibility and implications. *Phys. Rev. D* **78**, 074026 (2008). <https://doi.org/10.1103/PhysRevD.78.074026>. arXiv:0806.3247

7. K. Kumar, T.M.P. Tait, R. Vega-Morales, Manifestations of top compositeness at colliders. *JHEP* **05**, 022 (2009). <https://doi.org/10.1088/1126-6708/2009/05/022>. [arXiv:0901.3808](https://arxiv.org/abs/0901.3808)
8. T.A. DeGrand et al., Towards partial compositeness on the lattice: Baryons with fermions in multiple representations, in *Proceedings of 34th annual International Symposium on Lattice Field Theory – PoS(LATTICE2016)* (2016), p. 219. [arXiv:1610.06465](https://arxiv.org/abs/1610.06465). <https://doi.org/10.22323/1.256.0219>
9. A. Pierce, Y. Zhao, Naturalness from a composite top? *JHEP* **01**, 054 (2017). [https://doi.org/10.1007/JHEP01\(2017\)054](https://doi.org/10.1007/JHEP01(2017)054). [arXiv:1607.01318](https://arxiv.org/abs/1607.01318)
10. D. Buarque Franzosi, A. Tonero, Top-quark partial compositeness beyond the effective field theory paradigm. *JHEP* **04**, 040 (2020). [https://doi.org/10.1007/JHEP04\(2020\)040](https://doi.org/10.1007/JHEP04(2020)040). [arXiv:1908.06996](https://arxiv.org/abs/1908.06996)
11. N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, The littlest Higgs. *JHEP* **07**, 034 (2002). <https://doi.org/10.1088/1126-6708/2002/07/034>. [arXiv:hep-ph/0206021](https://arxiv.org/abs/hep-ph/0206021)
12. N. Arkani-Hamed, A.G. Cohen, H. Georgi, Electroweak symmetry breaking from dimensional deconstruction. *Phys. Lett. B* **513**, 232 (2001). [https://doi.org/10.1016/S0370-2693\(01\)00741-9](https://doi.org/10.1016/S0370-2693(01)00741-9). [arXiv:hep-ph/0105239](https://arxiv.org/abs/hep-ph/0105239)
13. M. Perelstein, Little Higgs models and their phenomenology. *Prog. Part. Nucl. Phys.* **58**, 247 (2007). <https://doi.org/10.1016/j.pnpnp.2006.04.001>. [arXiv:hep-ph/0512128](https://arxiv.org/abs/hep-ph/0512128)
14. A. Ahmed, M. Lindner, P. Saake, Conformal little Higgs models. *Phys. Rev. D* **109**, 075041 (2024). <https://doi.org/10.1103/PhysRevD.109.075041>. [arXiv:2309.07845](https://arxiv.org/abs/2309.07845)
15. L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension. *Phys. Rev. Lett.* **83**, 3370 (1999). <https://doi.org/10.1103/PhysRevLett.83.3370>. [arXiv:hep-ph/9905221](https://arxiv.org/abs/hep-ph/9905221)
16. T. Gherghetta, A. Pomarol, Bulk fields and supersymmetry in a slice of AdS. *Nucl. Phys. B* **586**, 141 (2000). [https://doi.org/10.1016/S0550-3213\(00\)00392-8](https://doi.org/10.1016/S0550-3213(00)00392-8). [arXiv:hep-ph/0003129](https://arxiv.org/abs/hep-ph/0003129)
17. S.B. Giddings, S. Kachru, J. Polchinski, Hierarchies from fluxes in string compactifications. *Phys. Rev. D* **66**, 106006 (2002). <https://doi.org/10.1103/PhysRevD.66.106006>. [arXiv:hep-th/0105097](https://arxiv.org/abs/hep-th/0105097)
18. K. Agashe, R. Contino, A. Pomarol, The minimal composite Higgs model. *Nucl. Phys. B* **719**, 165 (2005). <https://doi.org/10.1016/j.nuclphysb.2005.04.035>. [arXiv:hep-ph/0412089](https://arxiv.org/abs/hep-ph/0412089)
19. CMS Collaboration, Search for pair production of vector-like quarks in the $b W \bar{b} W$ channel from proton–proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B* **779**, 82 (2018). <https://doi.org/10.1016/j.physletb.2018.01.077>. [arXiv:1710.01539](https://arxiv.org/abs/1710.01539)
20. CMS Collaboration, Search for electroweak production of a vector-like T quark using fully hadronic final states. *JHEP* **01**, 036 (2020). [https://doi.org/10.1007/JHEP01\(2020\)036](https://doi.org/10.1007/JHEP01(2020)036). [arXiv:1909.04721](https://arxiv.org/abs/1909.04721)
21. CMS Collaboration, Search for single production of a vector-like T quark decaying to a top quark and a Z boson in the final state with jets and missing transverse momentum at $\sqrt{s} = 13$ TeV. *JHEP* **05**, 093 (2022). [https://doi.org/10.1007/JHEP05\(2022\)093](https://doi.org/10.1007/JHEP05(2022)093). [arXiv:2201.02227](https://arxiv.org/abs/2201.02227)
22. CMS Collaboration, Search for pair production of vector-like quarks in leptonic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP* **07**, 020 (2023). [https://doi.org/10.1007/JHEP07\(2023\)020](https://doi.org/10.1007/JHEP07(2023)020). [arXiv:2209.07327](https://arxiv.org/abs/2209.07327)
23. ATLAS Collaboration, Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector. *Eur. Phys. J. C* **83**, 719 (2023). <https://doi.org/10.1140/epjc/s10052-023-11790-7>. [arXiv:2212.05263](https://arxiv.org/abs/2212.05263)
24. ATLAS Collaboration, Search for pair-production of vector-like quarks in pp collision events at $\sqrt{s} = 13$ TeV with at least one leptonically decaying Z boson and a third-generation quark with the ATLAS detector. *Phys. Lett. B* **843**, 138019 (2023). <https://doi.org/10.1016/j.physletb.2023.138019>. [arXiv:2210.15413](https://arxiv.org/abs/2210.15413)
25. ATLAS Collaboration, Search for singly produced vector-like top partners in multilepton final states with 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Rev. D* **109**, 112012 (2024). <https://doi.org/10.1103/PhysRevD.109.112012>. [arXiv:2307.07584](https://arxiv.org/abs/2307.07584)
26. H. Alhazmi, J.H. Kim, K. Kong, I.M. Lewis, Shedding light on top partner at the LHC. *JHEP* **01**, 139 (2019). [https://doi.org/10.1007/JHEP01\(2019\)139](https://doi.org/10.1007/JHEP01(2019)139). [arXiv:1808.03649](https://arxiv.org/abs/1808.03649)
27. J. Berger, J. Hubisz, M. Perelstein, A fermionic top partner: naturalness and the LHC. *JHEP* **07**, 016 (2012). [https://doi.org/10.1007/JHEP07\(2012\)016](https://doi.org/10.1007/JHEP07(2012)016). [arXiv:1205.0013](https://arxiv.org/abs/1205.0013)
28. W. Rarita, J. Schwinger, On a theory of particles with half integral spin. *Phys. Rev.* **60**, 61 (1941). <https://doi.org/10.1103/PhysRev.60.61>
29. C.M.S. Collaboration, Search for pair production of excited top quarks in the lepton+jets final state. *JHEP* **06**, 125 (2014). [https://doi.org/10.1007/JHEP06\(2014\)125](https://doi.org/10.1007/JHEP06(2014)125). [arXiv:1311.5357](https://arxiv.org/abs/1311.5357)
30. CMS Collaboration, Search for pair production of excited top quarks in the lepton+jets final state. *Phys. Lett. B* **778**, 349 (2018). <https://doi.org/10.1016/j.physletb.2018.01.049>. [arXiv:1711.10949](https://arxiv.org/abs/1711.10949)
31. HEPData record for this analysis, 2024. <https://doi.org/10.17182/hepdata.153717>
32. CMS Collaboration, The CMS experiment at the CERN LHC. *JINST* **3**, S08004 (2008). <https://doi.org/10.1088/1748-0221/3/08/S08004>
33. CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3. *JINST* **19**, P05064 (2024). <https://doi.org/10.1088/1748-0221/19/05/P05064>. [arXiv:2309.05466](https://arxiv.org/abs/2309.05466)
34. CMS Collaboration, Performance of the CMS level-1 trigger in proton–proton collisions at $\sqrt{s} = 13$ TeV. *JINST* **15**, P10017 (2020). <https://doi.org/10.1088/1748-0221/15/10/P10017>. [arXiv:2006.10165](https://arxiv.org/abs/2006.10165)
35. CMS Collaboration, The CMS trigger system. *JINST* **12**, P01020 (2017). <https://doi.org/10.1088/1748-0221/12/01/P01020>. [arXiv:1609.02366](https://arxiv.org/abs/1609.02366)
36. J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP* **07**, 079 (2014). [https://doi.org/10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079). [arXiv:1405.0301](https://arxiv.org/abs/1405.0301)
37. D.A. Dicus, D. Karabacak, S. Nandi, S.K. Rai, Search for spin-3/2 quarks at the Large Hadron Collider. *Phys. Rev. D* **87**, 015023 (2013). <https://doi.org/10.1103/PhysRevD.87.015023>. [arXiv:1208.5811](https://arxiv.org/abs/1208.5811)
38. P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms. *JHEP* **11**, 040 (2004). <https://doi.org/10.1088/1126-6708/2004/11/040>. [arXiv:hep-ph/0409146](https://arxiv.org/abs/hep-ph/0409146)
39. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. *JHEP* **11**, 070 (2007). <https://doi.org/10.1088/1126-6708/2007/11/070>. [arXiv:0709.2092](https://arxiv.org/abs/0709.2092)
40. S. Frixione, P. Nason, G. Ridolfi, A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction. *JHEP* **09**, 126 (2007). <https://doi.org/10.1088/1126-6708/2007/09/126>. [arXiv:0707.3088](https://arxiv.org/abs/0707.3088)
41. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *JHEP* **06**, 043 (2010). [https://doi.org/10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043). [arXiv:1002.2581](https://arxiv.org/abs/1002.2581)
42. E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method. *Eur. Phys. J. C* **71**, 1547 (2011). <https://doi.org/10.1140/epjc/s10052-011-1547-z>. [arXiv:1009.2450](https://arxiv.org/abs/1009.2450)
43. M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders. *Comput. Phys. Com-*

- mun. **185**, 2930 (2014). <https://doi.org/10.1016/j.cpc.2014.06.021>. arXiv:1112.5675
44. T. Sjöstrand et al., An introduction to PYTHIA 8.2. *Comput. Phys. Commun.* **191**, 159 (2015). <https://doi.org/10.1016/j.cpc.2015.01.024>. arXiv:1410.3012
 45. NNPDF Collaboration, Parton distributions from high-precision collider data. *Eur. Phys. J. C* **77**, 663 (2017). <https://doi.org/10.1140/epjc/s10052-017-5199-5>. arXiv:1706.00428
 46. CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements. *Eur. Phys. J. C* **76**, 155 (2016). <https://doi.org/10.1140/epjc/s10052-016-3988-x>. arXiv:1512.00815
 47. GEANT4 Collaboration, Geant4-a simulation toolkit. *Nucl. Instrum. Methods A* **506**, 250 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
 48. CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV. *JHEP* **07**, 161 (2018). [https://doi.org/10.1007/JHEP07\(2018\)161](https://doi.org/10.1007/JHEP07(2018)161). arXiv:1802.02613
 49. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. *JINST* **12**, P10003 (2017). <https://doi.org/10.1088/1748-0221/12/10/P10003>. arXiv:1706.04965
 50. CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST* **13**, P06015 (2018). <https://doi.org/10.1088/1748-0221/13/06/P06015>. arXiv:1804.04528
 51. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV. *JINST* **7**, P10002 (2012). <https://doi.org/10.1088/1748-0221/7/10/P10002>. arXiv:1206.4071
 52. CMS Collaboration, Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST* **15**, P02027 (2020). <https://doi.org/10.1088/1748-0221/15/02/P02027>. arXiv:1912.03516
 53. CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC. *JINST* **16**, P05014 (2021). <https://doi.org/10.1088/1748-0221/16/05/P05014>. arXiv:2012.06888
 54. CMS Collaboration, ECAL 2016 refined calibration and Run2 summary plots, CMS Detector Performance Summary CMS-DP-2020-021 (2020)
 55. M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm. *JHEP* **04**, 063 (2008). <https://doi.org/10.1088/1126-6708/2008/04/063>. arXiv:0802.1189
 56. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. *Eur. Phys. J. C* **72**, 1896 (2012). <https://doi.org/10.1140/epjc/s10052-012-1896-2>. arXiv:1111.6097
 57. D. Bertolini, P. Harris, M. Low, N. Tran, Pileup per particle identification. *JHEP* **10**, 059 (2014). [https://doi.org/10.1007/JHEP10\(2014\)059](https://doi.org/10.1007/JHEP10(2014)059). arXiv:1407.6013
 58. CMS Collaboration, Pileup mitigation at CMS in 13 TeV data. *JINST* **15**, P09018 (2020). <https://doi.org/10.1088/1748-0221/15/09/P09018>. arXiv:2003.00503
 59. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV. *JINST* **12**, P02014 (2017). <https://doi.org/10.1088/1748-0221/12/02/P02014>. arXiv:1607.03663
 60. T. Lapsien, R. Kogler, J. Haller, A new tagger for hadronically decaying heavy particles at the LHC. *Eur. Phys. J. C* **76**, 600 (2016). <https://doi.org/10.1140/epjc/s10052-016-4443-8>. arXiv:1606.04961
 61. M. Cacciari, G.P. Salam, G. Soyez, The catchment area of jets. *JHEP* **04**, 005 (2008). <https://doi.org/10.1088/1126-6708/2008/04/005>. arXiv:0802.1188
 62. CMS Collaboration, Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques. *JINST* **15**, P06005 (2020). <https://doi.org/10.1088/1748-0221/15/06/P06005>. arXiv:2004.08262
 63. R. Kogler, Advances in jet substructure at the LHC: Algorithms, measurements and searches for new physical phenomena, volume 284 of Springer Tracts Mod. Phys. Springer (2021). <https://doi.org/10.1007/978-3-030-72858-8> (ISBN 978-3-030-72857-1, 978-3-030-72858-8)
 64. J. Thaler, K. Van Tilburg, Identifying boosted objects with N -subjettiness. *JHEP* **03**, 015 (2011). [https://doi.org/10.1007/JHEP03\(2011\)015](https://doi.org/10.1007/JHEP03(2011)015). arXiv:1011.2268
 65. J. Thaler, K. Van Tilburg, Maximizing boosted top identification by minimizing N -subjettiness. *JHEP* **02**, 093 (2012). [https://doi.org/10.1007/JHEP02\(2012\)093](https://doi.org/10.1007/JHEP02(2012)093). arXiv:1108.2701
 66. CMS Collaboration, Search for a heavy resonance decaying into a top quark and a W boson in the lepton+jets final state at $\sqrt{s} = 13$ TeV. *JHEP* **04**, 048 (2022). [https://doi.org/10.1007/JHEP04\(2022\)048](https://doi.org/10.1007/JHEP04(2022)048). arXiv:2111.10216
 67. CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV. *JINST* **13**, P05011 (2018). <https://doi.org/10.1088/1748-0221/13/05/P05011>. arXiv:1712.07158
 68. E. Bols et al., Jet flavour classification using DeepJet. *JINST* **15**, P12012 (2020). <https://doi.org/10.1088/1748-0221/15/12/P12012>. arXiv:2008.10519
 69. CMS Collaboration, Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector, Technical Report CMS-DP-2023-005 (2023)
 70. CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector. *JINST* **14**, P07004 (2019). <https://doi.org/10.1088/1748-0221/14/07/P07004>. arXiv:1903.06078
 71. CMS Collaboration, Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP* **04**, 031 (2019). [https://doi.org/10.1007/JHEP04\(2019\)031](https://doi.org/10.1007/JHEP04(2019)031). arXiv:1810.05905
 72. J. Dolen et al., Thinking outside the ROCs: Designing decorrelated taggers (DDT) for jet substructure. *JHEP* **05**, 156 (2016). [https://doi.org/10.1007/JHEP05\(2016\)156](https://doi.org/10.1007/JHEP05(2016)156). arXiv:1603.00027
 73. CMS Collaboration, Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV. *Eur. Phys. J. C* **75**, 542 (2015). <https://doi.org/10.1140/epjc/s10052-015-3709-x>. arXiv:1505.04480
 74. CMS Collaboration, Measurement of the $t\bar{t}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8$ TeV. *Eur. Phys. J. C* **76**, 128 (2016). <https://doi.org/10.1140/epjc/s10052-016-3956-5>. arXiv:1509.06076
 75. CMS Collaboration, The CMS statistical analysis and combination tool: COMBINE. 2024. arXiv:2404.06614. Accepted by *Comput. Softw. Big Sci.*
 76. CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS. *Eur. Phys. J. C* **81**, 800 (2021). <https://doi.org/10.1140/epjc/s10052-021-09538-2>. arXiv:2104.01927
 77. CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-17-004 (2018)
 78. CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-18-002, (2019)
 79. J. Butterworth et al., PDF4LHC recommendations for LHC Run II. *J. Phys. G* **43**, 023001 (2016). <https://doi.org/10.1088/0954-3899/43/2/023001>. arXiv:1510.03865
 80. ATLAS and CMS Collaborations, and LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, CMS Note CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11 (2011)

81. A.L. Read, Presentation of search results: the CL_s technique. *J. Phys. G* **28**, 2693 (2002). <https://doi.org/10.1088/0954-3899/28/10/313>
82. T. Junk, Confidence level computation for combining searches with small statistics. *Nucl. Instrum. Methods A* **434**, 435 (1999). [https://doi.org/10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2). [arXiv:hep-ex/9902006](https://arxiv.org/abs/hep-ex/9902006)
83. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J. C* **71**, 1554 (2011). (Erratum: 10.1140/epjc/s10052-013-2501-z). <https://doi.org/10.1140/epjc/s10052-011-1554-0>. [arXiv:1007.1727](https://arxiv.org/abs/1007.1727)
84. W. Verkerke, D.P. Kirkby, The RooFit toolkit for data modeling, in *Proc. Int. Conf on Computing in High Energy and Nuclear Physics (CHEP03)*, ed. by L. Lyons, M. Karagoz, p. MOLT007 (2003). [arXiv:physics/0306116](https://arxiv.org/abs/physics/0306116)
85. L. Moneta et al., The RooStats project, in *Proc. 13th Int. Workshop on Advanced Computing and Analysis Techniques in Physics Research*, ed. by T. Speer et al., volume ACAT2010 (2010), p. 057. <https://doi.org/10.22323/1.093.0057>. [arXiv:1009.1003](https://arxiv.org/abs/1009.1003)

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan ¹

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J. W. Andrejkovic , L. Benato , T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P. S. Hussain , M. Jeitler ², N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck ², R. Schöfbeck ², D. Schwarz , M. Sonawane , W. Waltenberger , C.-E. Wulz ²

Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , T. Van Laer, P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat ³, G. P. Van Onsem , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A. K. Das, I. De Bruyn , G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F. A. Khan , K. Lee , A. Malara , S. Paredes , M. A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 

Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I. S. Donertas , A. Giammanco , A. O. Guzel , Sa. Jain , V. Lemaître, J. Lidrych , P. Mastrapasqua , T. T. Tran , S. Turkcapar 

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G. A. Alves , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera ⁴, P. Rebello Teles , M. Soeiro, E. J. Tonelli Manganote ⁵, A. Vilela Pereira ⁴

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato ⁶, E. M. Da Costa , G. G. Da Silveira ⁷, D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, T. Laux Kuhn ⁷, M. Macedo , J. Martins , L. Mundim , H. Nogima , J. P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C. A. Bernardes ⁷, L. Calligaris , T. R. Fernandez Perez Tomei , E. M. Gregores , I. Masetto Silverio , P. G. Mercadante , S. F. Novaes , B. Orzari , Sandra S. Padula 

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. Shopova , G. Sultanov 

University of Sofia, Sofia, BulgariaA. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka **Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**S. Keshri , D. Laroze , S. Thakur **Beihang University, Beijing, China**T. Cheng , T. Javaid , L. Yuan **Department of Physics, Tsinghua University, Beijing, China**Z. Hu , Z. Liang, J. Liu**Institute of High Energy Physics, Beijing, China**G. M. Chen ⁸, H. S. Chen ⁸, M. Chen ⁸, F. Iemmi , C. H. Jiang, A. Kapoor ⁹, H. Liao , Z.-A. Liu ¹⁰, R. Sharma ¹¹, J. N. Song ¹⁰, J. Tao , C. Wang ⁸, J. Wang , Z. Wang ⁸, H. Zhang , J. Zhao **State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S. J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou **Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**S. Yang **Sun Yat-Sen University, Guangzhou, China**Z. You **University of Science and Technology of China, Hefei, China**K. Jaffel , N. Lu **Nanjing Normal University, Nanjing, China**G. Bauer ¹², B. Li ¹³, K. Yi ¹⁴, J. Zhang **Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)-Fudan University, Shanghai, China**

Y. Li

Zhejiang University, Hangzhou, Zhejiang, ChinaZ. Lin , C. Lu , M. Xiao **Universidad de Los Andes, Bogota, Colombia**C. Avila , D. A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J. A. Reyes Vega**Universidad de Antioquia, Medellin, Colombia**F. Ramirez , C. Rendón, M. Rodriguez , A. A. Ruales Barbosa , J. D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac **University of Split, Faculty of Science, Split, Croatia**M. Kovac , A. Petkovic, T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**P. Bargassa , V. Brigljevic , B. K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov ¹⁵, T. Susa **University of Cyprus, Nicosia, Cyprus**A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P. A. Razis , H. Rykaczewski, H. Saka , A. Stepenov **Charles University, Prague, Czech Republic**M. Finger , M. Finger Jr , A. Kveton 

Escuela Politecnica Nacional, Quito, EcuadorE. Ayala **Universidad San Francisco de Quito, Quito, Ecuador**E. Carrera Jarrin **Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**H. Abdalla ¹⁶, Y. Assran ^{17,18}, B. El-mahdy**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M. Abdullah Al-Mashad , M. A. Mahmoud **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K. T. S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow **IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J. L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M. Ö. Sahin , A. Savoy-Navarro ¹⁹, P. Simkina , M. Titov , M. Tornago **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , T. D. Cuisset , F. Damas , O. Davignon , A. De Wit , I. T. Ehle , B. A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J. B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram ²⁰, J. Andrea , D. Apparu , D. Bloch , J.-M. Brom , E. C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M. A. Sessini , P. Van Hove , P. Vaucelle **Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**A. Di Florio **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen ²¹, H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourdain, I. B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao **Georgian Technical University, Tbilisi, Georgia**A. Khvedelidze ¹⁵, I. Lomidze , Z. Tsamalaidze ¹⁵**I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany**V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 

III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , C. Seth, A. Sharma , J. L. Spah , A. Stein , F. Torres Da Silva De Araujo ²², S. Wiedenbeck , S. Zaleski

III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman ²³, K. Borras ²⁴, A. Campbell , A. Cardini , C. Cheng, F. Colombina , G. Eckerlin, D. Eckstein , L. I. Estevez Banos , E. Gallo ²³, A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka ²⁵, W. Lohmann ²⁶, F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A. B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L. P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham ^{24,27}, S. Schnake ²⁴, P. Schütze , C. Schwanenberger ²³, D. Selivanova , K. Shariko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , K. Wichmann, L. Wiens ²⁴, C. Wissing , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , D. Hundhausen, H. R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcar , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K. J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , E. Butz , T. Chwalek , A. Dierlamm , A. Droll, U. Elicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann ²⁸, R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , O. Lavoryk, J. M. Lawhorn , M. Link, A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H. J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R. F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos ²⁸, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos

National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsipolitis , A. Zacharopoulou

University of Ioánnina, Ioannina, Greece

I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas , P. G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu , D. Horvath ^{29,30}, K. Márton, A. J. Rádl ³¹, F. Sikler , V. Veszpremi 

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanád , K. Farkas , A. Fehérkuti ³², M. M. A. Gadallah ³³, Á. Kadlecsek , P. Major , G. Pásztor , G. I. Veres 

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

L. Olah , B. Ujvari 

HUN-REN ATOMKI-Institute of Nuclear Research, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo ³², F. Nemes ³², T. Novak 

Panjab University, Chandigarh, India

S. Bansal , S. B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra ³⁴, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J. B. Singh , A. Singla 

University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , A. Chhetri , B. C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M. K. Saini, S. Saumya 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman ³⁵, S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India

M. M. Ameen , P. K. Behera , S. C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J. R. Komaragiri ³⁶, D. Kumar ³⁶, T. Mishra , B. Parida ³⁷, P. R. Pujahari , N. R. Saha , A. Sharma , A. K. Sikdar , R. K. Singh, P. Verma, S. Verma , A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, G. B. Mohanty , M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R. M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati ³⁸, C. Kar , D. Maity ³⁹, P. Mal , K. Naskar ³⁹, A. Nayak ³⁹, S. Nayak, K. Pal, P. Sadangi, S. K. Swain ³⁹, S. Varghese ³⁹, D. Vats ³⁹

Indian Institute of Science Education and Research (IISER), Pune, India

S. Acharya ⁴⁰, A. Alpana , S. Dube , B. Gomber ⁴⁰, P. Hazarika , B. Kansal , A. Laha , B. Sahu ⁴⁰, S. Sharma , K. Y. Vaish 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi ⁴¹, A. Jafari ⁴², M. Zeinali ⁴³

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Bashiri, S. Chenarani ⁴⁴, S. M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi ⁴⁵, S. Tizchang 

University College Dublin, Dublin, Ireland

M. Felcini , M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia ^{a,b}, A. Colaleo ^{a,b}, D. Creanza ^{a,c}, B. D'Anzi ^{a,b}, N. De Filippis ^{a,c}, M. De Palma ^{a,b}, W. Elmetenawee ^{a,b,46}, N. Ferrara ^{a,b}, L. Fiore ^a, G. Iaselli ^{a,c}, L. Longo ^a, M. Louka ^{a,b}, G. Maggi ^{a,c}, M. Maggi ^a, I. Margjeka ^a, V. Mastrapasqua ^{a,b}, S. My ^{a,b}, S. Nuzzo ^{a,b}, A. Pellecchia ^{a,b}, A. Pompili ^{a,b}

G. Pugliese ^{a,c}, R. Radogna ^{a,b}, D. Ramos ^a, A. Ranieri ^a, L. Silvestris ^a, F. M. Simone ^{a,c}, Ü. Sözbilir ^a, A. Stamerra ^{a,b}, D. Troiano ^{a,b}, R. Venditti ^{a,b}, P. Verwilligen ^a, A. Zaza ^{a,b}

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi ^a, C. Battilana ^{a,b}, D. Bonacorsi ^{a,b}, P. Capiluppi ^{a,b}, A. Castro ^{a,b}, F. R. Cavallo ^a, M. Cuffiani ^{a,b}, G. M. Dallavalle ^a, T. Diotallevi ^{a,b}, F. Fabbri ^a, A. Fanfani ^{a,b}, D. Fasanella ^a, P. Giacomelli ^a, L. Giommi ^{a,b}, C. Grandi ^a, L. Guiducci ^{a,b}, S. Lo Meo ^{a,47}, M. Lorusso ^{a,b}, L. Lunerti ^a, S. Marcellini ^a, G. Masetti ^a, F. L. Navarria ^{a,b}, G. Paggi ^{a,b}, A. Perrotta ^a, F. Primavera ^{a,b}, A. M. Rossi ^{a,b}, S. Rossi Tisbeni ^{a,b}, T. Rovelli ^{a,b}, G. P. Siroli ^{a,b}

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Costa ^{a,b,48}, A. Di Mattia ^a, A. Lapertosa ^a, R. Potenza ^{a,b}, A. Tricomi ^{a,b,48}, C. Tuve ^{a,b}

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

P. Assiouras ^a, G. Barbagli ^a, G. Bardelli ^{a,b}, B. Camaiani ^{a,b}, A. Cassese ^a, R. Ceccarelli ^a, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, E. Focardi ^{a,b}, T. Kello ^a, G. Latino ^{a,b}, P. Lenzi ^{a,b}, M. Lizzo ^a, M. Meschini ^a, S. Paoletti ^a, A. Papanastassiou ^{a,b}, G. Sguazzoni ^a, L. Viliani ^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi ^a, S. Bianco ^a, S. Meola ^{a,49}, D. Piccolo ^a

INFN Sezione di Genova^a, Università di Genova^b, Genoa, Italy

M. Alves Gallo Pereira ^a, F. Ferro ^a, E. Robutti ^a, S. Tosi ^{a,b}, F. Cetorelli ^{a,b}, F. De Guio ^{a,b}, M. E. Dinardo ^{a,b}

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milan, Italy

A. Benaglia ^a, F. Brivio ^a, P. Dini ^a, S. Gennai ^a, R. Gerosa ^{a,b}, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, L. Guzzi ^a, M. T. Lucchini ^{a,b}, M. Malberti ^a, S. Malvezzi ^a, A. Massironi ^a, D. Menasce ^a, L. Moroni ^a, M. Paganoni ^{a,b}, S. Palluotto ^{a,b}, D. Pedrini ^a, A. Perego ^{a,b}, B. S. Pinolini ^a, G. Pizzati ^{a,b}, S. Ragazzi ^{a,b}, T. Tabarelli de Fatis ^{a,b}

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Naples, Italy

S. Buontempo ^a, A. Cagnotta ^{a,b}, F. Carnevali ^{a,b}, N. Cavallo ^{a,c}, F. Fabozzi ^{a,c}, A. O. M. Iorio ^{a,b}, L. Lista ^{a,b,50}, P. Paolucci ^{a,28}, B. Rossi ^a

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

R. Ardino ^a, P. Azzi ^a, N. Bacchetta ^{a,51}, P. Bortignon ^a, G. Bortolato ^{a,b}, A. Bragagnolo ^{a,b}, A. C. M. Bulla ^a, R. Carlin ^{a,b}, P. Checchia ^a, T. Dorigo ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, S. Giorgetti ^a, E. Lusiani ^a, M. Margoni ^{a,b}, G. Maron ^{a,52}, A. T. Meneguzzo ^{a,b}, M. Migliorini ^{a,b}, J. Pazzini ^{a,b}, P. Ronchese ^{a,b}, R. Rossin ^{a,b}, F. Simonetto ^{a,b}, M. Tosi ^{a,b}, A. Triossi ^{a,b}, S. Ventura ^a, M. Zanetti ^{a,b}, P. Zotto ^{a,b}, A. Zucchetta ^{a,b}, G. Zumerle ^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

A. Braghieri ^a, S. Calzaferri ^a, D. Fiorina ^a, P. Montagna ^{a,b}, V. Re ^a, C. Riccardi ^{a,b}, P. Salvini ^a, I. Vai ^{a,b}, P. Vitulo ^{a,c}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

S. Ajmal ^{a,b}, M. E. Ascioti ^{a,b}, G. M. Bilei ^a, C. Carrivale ^{a,b}, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, M. Magherini ^{a,b}, V. Mariani ^{a,b}, M. Menichelli ^a, F. Moscatelli ^{a,53}, A. Rossi ^{a,b}, A. Santocchia ^{a,b}, D. Spiga ^a, T. Tedeschi ^{a,b}

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

C. Aimè ^a, C. A. Alexe ^{a,c}, P. Asenov ^{a,b}, P. Azzurri ^b, G. Bagliesi ^a, R. Bhattacharya ^a, L. Bianchini ^{a,b}, T. Boccali ^a, E. Bossini ^a, D. Bruschini ^{a,c}, R. Castaldi ^a, M. A. Ciocci ^{a,b}, M. Cipriani ^{a,b}, V. D'Amante ^{a,d}, R. Dell'Orso ^a, S. Donato ^a, A. Giassi ^a, F. Ligabue ^{a,c}, A. C. Marini ^a, D. Matos Figueiredo ^a, A. Messineo ^{a,b}, S. Mishra ^a, V. K. Muraleedharan Nair Bindhu ^{a,b,39}, M. Musich ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}

G. Rolandi ^{a,c}, S. Roy Chowdhury ^a, T. Sarkar ^a, A. Scribano ^a, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, N. Turini ^{a,d}, F. Vaselli ^{a,c}, A. Venturi ^a, P. G. Verdini ^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Rome, Italy

C. Baldenegro Barrera ^{a,b}, P. Barria ^a, C. Basile ^{a,b}, F. Cavallari ^a, L. Cunqueiro Mendez ^{a,b}, D. Del Re ^{a,b}, E. Di Marco ^{a,b}, M. Diemoz ^a, F. Errico ^{a,b}, R. Gargiulo ^{a,b}, E. Longo ^{a,b}, L. Martikainen ^{a,b}, J. Mijuskovic ^{a,b}, G. Organtini ^{a,b}, F. Pandolfi ^a, R. Paramatti ^{a,b}, C. Quaranta ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^a, V. Vladimirov ^{a,b}

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, N. Bartosik ^a, R. Bellan ^{a,b}, A. Bellora ^{a,b}, C. Biino ^a, C. Borca ^{a,b}, N. Cartiglia ^a, M. Costa ^{a,b}, R. Covarelli ^{a,b}, N. Demaria ^a, L. Finco ^a, M. Grippo ^{a,b}, B. Kiani ^{a,b}, F. Legger ^a, F. Luongo ^{a,b}, C. Mariotti ^a, L. Markovic ^{a,b}, S. Maselli ^a, A. Mecca ^{a,b}, L. Menzio ^{a,b}, P. Meridiani ^b, E. Migliore ^{a,b}, M. Monteno ^a, R. Mulargia ^a, M. M. Obertino ^{a,b}, G. Ortona ^a, L. Pacher ^a, N. Pastrone ^a, M. Pelliccioni ^a, M. Ruspa ^{a,c}, F. Siviero ^{a,b}, V. Sola ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a, C. Tarricone ^{a,b}, D. Trocino ^a, G. Umoret ^{a,b}, R. White ^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

J. Babbar ^{a,b}, S. Belforte ^a, V. Candelise ^{a,b}, M. Casarsa ^a, F. Cossutti ^a, K. De Leo ^a, G. Della Ricca ^{a,b}

Kyungpook National University, Daegu, Korea

S. Dogra ^a, J. Hong ^a, B. Kim ^a, J. Kim ^a, D. Lee ^a, H. Lee ^a, S. W. Lee ^a, C. S. Moon ^a, Y. D. Oh ^a, M. S. Ryu ^a, S. Sekmen ^a, B. Tae ^a, Y. C. Yang ^a

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M. S. Kim ^a

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

G. Bak ^a, P. Gwak ^a, H. Kim ^a, D. H. Moon ^a

Hanyang University, Seoul, Korea

E. Asilar ^a, J. Choi ^a, D. Kim ^a, T. J. Kim ^a, J. A. Merlin ^a, Y. Ryu ^a

Korea University, Seoul, Korea

S. Choi ^a, S. Han ^a, B. Hong ^a, K. Lee ^a, K. S. Lee ^a, S. Lee ^a, J. Yoo ^a

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh ^a, S. Yang ^a

Sejong University, Seoul, Korea

H. S. Kim ^a, Y. Kim ^a, S. Lee ^a

Seoul National University, Seoul, Korea

J. Almond ^a, J. H. Bhyun ^a, J. Choi ^a, J. Choi ^a, W. Jun ^a, J. Kim ^a, Y. W. Kim ^a, S. Ko ^a, H. Kwon ^a, H. Lee ^a, J. Lee ^a, J. Lee ^a, B. H. Oh ^a, S. B. Oh ^a, H. Seo ^a, U. K. Yang ^a, I. Yoon ^a

University of Seoul, Seoul, Korea

W. Jang ^a, D. Y. Kang ^a, Y. Kang ^a, S. Kim ^a, B. Ko ^a, J. S. H. Lee ^a, Y. Lee ^a, I. C. Park ^a, Y. Roh ^a, I. J. Watson ^a

Yonsei University, Department of Physics, Seoul, Korea

S. Ha ^a, K. Hwang ^a, H. D. Yoo ^a

Sungkyunkwan University, Suwon, Korea

M. Choi ^a, M. R. Kim ^a, H. Lee ^a, Y. Lee ^a, I. Yu ^a

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy ^a, Y. Gharbia ^a

Department of Physics, Kuwait University-College of Science, Safat, Kuwait

F. Alazemi ^a

Riga Technical University, Riga, LatviaK. Dreimanis , A. Gaile , C. Munoz Diaz, D. Osite , G. Pikurs, A. Potrebko , M. Seidel , D. Sidiropoulos Kontos**University of Latvia (LU), Riga, Latvia**N. R. Strautnieks **Vilnius University, Vilnius, Lithuania**M. Ambrozias , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis **National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**I. Yusuff ⁵⁴, Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**J. F. Benitez , A. Castaneda Hernandez , H. A. Encinas Acosta, L. G. Gallegos Maríñez, M. León Coello , J. A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz ⁵⁵, R. Lopez-Fernandez , J. Mejia Guisao , C. A. Mondragon Herrera, A. Sánchez Hernández **Universidad Iberoamericana, Mexico City, Mexico**C. Oropeza Barrera , D. L. Ramirez Guadarrama, M. Ramírez García **Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**I. Bautista , I. Pedraza , H. A. Salazar Ibarguen , C. Uribe Estrada **University of Montenegro, Podgorica, Montenegro**I. Bubanja , N. Raicevic **University of Canterbury, Christchurch, New Zealand**P. H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad , M. I. Asghar, A. Awais , M. I. M. Awan, H. R. Hoorani , W. A. Khan **AGH University of Krakow, Kraków, Poland**V. Avati, L. Grzanka , M. Malawski **National Centre for Nuclear Research, Swierk, Poland**H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szleper , P. Zalewski **Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolkowski , A. Muhammad **Warsaw University of Technology, Warsaw, Poland**P. Fokow , K. Pozniak , W. Zabolotny **Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , G. B. Marozzo, A. Petrilli , M. Pisano , J. Seixas , J. Varela , J. W. Wulff**Faculty of Physics, University of Belgrade, Belgrade, Serbia**P. Adzic , P. Milenovic **VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**D. Devetak, M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**J. Alcaraz Maestre , Cristina F. Bedoya , J. A. Brochero Cifuentes , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J. P. Fernández Ramos , J. Flix , M. C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J. M. Hernandez 

M. I. Josa , J. Llorente Merino , C. Martin Perez , E. Martin Viscasillas , D. Moran , C. M. Morcillo Perez ,
 Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo ,
 S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 

Universidad Autónoma de Madrid, Madrid, Spain

J. F. de Trocóniz 

Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Universidad de Oviedo, Oviedo, Spain

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina ,
 E. Palencia Cortezon , J. Prado Pico, C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote ,
 C. Vico Villalba , P. Vischia 

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

S. Bhowmik , S. Blanco Fernández , I. J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez ,
 G. Gomez , C. Lasasa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras ,
 P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J. M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

B. Kailasapathy ⁵⁶, D. D. C. Wickramaratna 

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W. G. D. Dharmaratna ⁵⁷, K. Liyanage , N. Perera 

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez ,
 M. Bianco , A. A. Bin Anuar , A. Bocci , L. Borgonovi , C. Botta , E. Brondolin , C. Caillol , G. Cerminara ,
 N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M. M. Defranchis , M. Deile ,
 M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , J. Hegeman , J. K. Heikkilä ,
 B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban ²⁶, S. Laurila , P. Lecoq ,
 E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi ,
 E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo ,
 G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabady , B. Ribeiro Lopes , F. Riti , M. Rovere ,
 H. Sakulin , R. Salvatico , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina ,
 P. Silva , P. Sphicas ⁵⁸, A. G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter ,
 J. Wanczyk ⁵⁹, J. Wang, K. A. Wozniak ⁶⁰, S. Wuchterl , P. Zehetner , P. Zejd , W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua ⁶¹, L. Caminada ⁶¹, A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H. C. Kaestli ,
 D. Kotlinski , C. Lange , M. Missiroli ⁶¹, L. Noehte ⁶¹, T. Rohe , A. Samalan

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T. K. Aarrestad , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazzaniga , K. Datta ,
 P. De Bryas Dexmiers D'archiac ⁵⁹, A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli ,
 K. Gedia , F. Glessgen , C. Grab , N. Härringer , T. G. Harte, D. Hits , W. Lustermann , A.-M. Lyon ,
 R. A. Manzoni , M. Marchegiani , L. Marchese , A. Mascellani ⁵⁹, F. Nessi-Tedaldi , F. Pauss , V. Perovic ,
 S. Pigazzini , B. Ristic , R. Seidita , J. Steggemann ⁵⁹, A. Tarabini , D. Valsecchi , R. Wallny 

Universität Zürich, Zurich, Switzerland

C. Amsler ⁶², P. Bärtzchi , M. F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster ,
 S. Leontsinis , S. P. Liehti , A. Macchiolo , P. Meiring , F. Meng , J. Motta , A. Reimers , P. Robmann,
 M. Senger , E. Shokr, F. Stäger , R. Tramontano 

National Central University, Chung-Li, Taiwan

C. Adloff ⁶³, D. Bhowmik, C. M. Kuo, W. Lin, P. K. Rout , P. C. Tiwari ³⁶

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K. F. Chen , Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan 

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi 

Physics Department Science and Art Faculty, Çukurova University, Adana, Turkey

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu ⁶⁴, E. Eskut , Y. Guler ⁶⁵, E. Gurpinar Guler ⁶⁵, C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , Y. Komurcu , G. Onengut , K. Ozdemir ⁶⁶, A. Polatoz , B. Tali ⁶⁷, U. G. Tok , E. Uslan , I. S. Zorbakir 

Physics Department, Middle East Technical University, Ankara, Turkey

G. Sokmen, M. Yalvac ⁶⁸

Bogazici University, Istanbul, Turkey

B. Akgun , I. O. Atakisi , E. Gülmez , M. Kaya ⁶⁹, O. Kaya ⁷⁰, S. Tekten ⁷¹

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak ^{64,72}, G. G. Dincer ⁶⁴, S. Sen ⁷³

Istanbul University, Istanbul, Turkey

O. Aydilek ⁷⁴, B. Hacisahinoglu , I. Hos ⁷⁵, B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 

Yildiz Technical University, Istanbul, Turkey

S. Cerci , B. Isildak ⁷⁶, D. Sunar Cerci , T. Yetkin 

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

A. Boyaryntsev , B. Grynyov 

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 

University of Bristol, Bristol, UK

D. Anthony , J. J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , H. F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw, V. J. Smith , K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, UK

A. H. Ball, K. W. Bell , A. Belyaev ⁷⁷, C. Brew , R. M. Brown , D. J. A. Cockerill , C. Cooke , A. Elliot , K. V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos, D. M. Newbold , E. Olaiya, D. Petyt , T. Reis , A. R. Sahasransu , G. Salvi , T. Schuh, C. H. Shepherd-Themistocleous , I. R. Tomalin , K. C. Whalen , T. Williams 

Imperial College, London, UK

I. Andreou , R. Bainbridge , P. Bloch , C. E. Brown , O. Buchmuller, C. A. Carrillo Montoya , G. S. Chahal ⁷⁸, D. Colling , J. S. Dancu, I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , A. Howard, G. Iles , C. R. Knight , P. Krueper, J. Langford , K. H. Law , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios, M. Mieskolainen , J. Nash ⁷⁹, M. Pesaresi , P. B. Pradeep, B. C. Radburn-Smith , A. Richards, A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G. P. Uttley , T. Virdee ²⁸, M. Vojinovic , N. Wardle , D. Winterbottom 

Brunel University, Uxbridge, UK

J. E. Cole , A. Khan, P. Kyberd , I. D. Reid 

Baylor University, Waco, TX, USA

S. Abdullin , A. Brinkerhoff , E. Collins , M. R. Darwish , J. Dittmann , K. Hatakeyama , V. Hegde , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 

Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , A. E. Simsek , S. S. Yu 

The University of Alabama, Tuscaloosa, AL, USA

B. Bam , A. Buchot Perraguin , R. Chudasama , S. I. Cooper , C. Crovella , S. V. Gleyzer , E. Pearson, C. U. Perez , P. Rumerio ⁸⁰, E. Usai , R. Yi 

Boston University, Boston, MA, USA

A. Akpinar , C. Cosby , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A. G. Zecchinelli 

Brown University, Providence, RI, USA

G. Barone , G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , K. W. Ho , J. M. Hogan ⁸¹, T. Kwon , G. Landsberg , K. T. Lau , J. Luo , S. Mondal , T. Russell, S. Sagir ⁸², X. Shen, F. Simpson , M. Stamenkovic , N. Venkatasubramanian

University of California, Davis, Davis, CA, USA

S. Abbott , B. Barton , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P. T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo , F. Zhang 

University of California, Los Angeles, CA, USA

K. Adamidis, M. Bachtis , D. Campos, R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M. A. Iqbal , T. Lam , Y.f. Lo, E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

University of California, Riverside, Riverside, CA, USA

R. Clare , J. W. Gary , G. Hanson 

University of California, San Diego, La Jolla, CA, USA

A. Aportela, A. Arora , J. G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch, M. Quinnan , B. V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 

Department of Physics, University of California, Santa Barbara, Santa Barbara, CA, USA

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , M. M. Hussain, J. Incandela , J. Kim , A. J. Li , P. Masterson , H. Mei , J. Richman , S. N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , X. Yan , D. Zhang

California Institute of Technology, Pasadena, CA, USA

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H. B. Newman , G. Reales Gutiérrez, M. Spiropulu , J. R. Vlimant , C. Wang , S. Xie , R. Y. Zhu 

Carnegie Mellon University, Pittsburgh, PA, USA

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T. A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

University of Colorado Boulder, Boulder, CO, USA

J. P. Cumalat , W. T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Parkes , C. Savard , N. Schonbeck , K. Stenson , K. A. Ulmer , S. R. Wagner , N. Zipper , D. Zuolo 

Cornell University, Ithaca, NY, USA

J. Alexander , S. Bright-Thonney , X. Chen , D. J. Cranshaw , J. Dickinson , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J. R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, IL, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L. A. T. Bauerdick , D. Berry , J. Berryhill , P. C. Bhat , K. Burkett , J. N. Butler , A. Canepa , G. B. Cerati , H. W. K. Cheung , F. Chlebana , G. Cummings , I. Dutta , V. D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R. M. Harris , R. Heller , T. C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K. H. M. Kwok , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena ⁸³, F. Ravera , A. Reinsvold Hall ⁸⁴, L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N. V. Tran , L. Uplegger , E. W. Vaandering , I. Zoi 

University of Florida, Gainesville, FL, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R. D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 

Florida State University, Tallahassee, FL, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Hashmi , R. S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P. R. Prova, M. Wulansatiti , R. Yohay , J. Zhang

Florida Institute of Technology, Melbourne, FL, USA

B. Alsufyani, S. Butalla , S. Das , T. Elkafrawy ⁸⁵, M. Hohlmann , E. Yanes

University of Illinois Chicago, Chicago, IL, USA

M. R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C. E. Gerber , M. Hawksworth, A. Hingrajiya, D. J. Hofman , J. h. Lee , D. S. Lemos , A. H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , N. Singh, M. B. Tonjes , N. Varelas , M. A. Wadud , Z. Ye , J. Yoo 

The University of Iowa, Iowa City, IA, USA

M. Alhusseini , D. Blend, K. Dilsiz ⁸⁶, L. Emediato , G. Karaman , O. K. Köseyan , J.-P. Merlo, A. Mestvirishvili ⁸⁷, O. Neogi, H. Ogul ⁸⁸, Y. Onel , A. Penzo , C. Snyder, E. Tiras ⁸⁹

Johns Hopkins University, Baltimore, MD, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A. V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 

The University of Kansas, Lawrence, KS, USA

A. Abreu , L. F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu ⁹⁰, C. Rogan , C. Royon , S. Sanders , C. Smith , G. Wilson 

Kansas State University, Manhattan, KS, USA

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

University of Maryland, College Park, MD, USA

A. Baden , A. Belloni , J. Bistany-riebman, Y. M. Chen , S. C. Eno , N. J. Hadley , S. Jabeen , R. G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A. C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M. M. Paranjpe, E. Popova ⁹¹, A. Shevelev , L. Wang 

Massachusetts Institute of Technology, Cambridge, MA, USA

J. Bendavid , I. A. Cali , P. c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long 

C. McGinn, A. Novak , M. I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman ,
G. S. F. Stephens , Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, MN, USA

B. Crossman , B. M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering ,
R. Rusack , R. Saradhy , N. Strobbe

University of Nebraska-Lincoln, Lincoln, NE, USA

K. Bloom , D. R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , A. Rohilla , J. E. Siado , W. Tabb ,
A. Vagnerini , A. Wightman , F. Yan , D. Yu

State University of New York at Buffalo, Buffalo, NY, USA

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava , M. Morris ,
D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young

Northeastern University, Boston, MA, USA

G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan, Y. Haddad , Y. Han , I. Israr ,
A. Krishna , J. Li , M. Lu , G. Madigan , R. McCarthy , D. M. Morse , V. Nguyen , T. Orimoto , A. Parker ,
L. Skinnari , E. Tsai, D. Wood

Northwestern University, Evanston, IL, USA

J. Bueghly, S. Dittmer , K. A. Hahn , D. Li , Y. Liu , M. McGinnis , Y. Miao , D. G. Monk , M. H. Schmitt ,
A. Taliercio , M. Velasco

University of Notre Dame, Notre Dame, IN, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa ,
T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister,
T. McCauley , C. Mcgrady , C. Moore , Y. Musienko ¹⁵, H. Nelson , M. Osherson , A. Piccinelli ,
R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala

The Ohio State University, Columbus, OH, USA

A. Basnet , M. Carrigan , L. S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei, D. A. Wenzl,
B. L. Winer , B. R. Yates 

Princeton University, Princeton, NJ, USA

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich ,
K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland ,
C. Tully , L. H. Vage

University of Puerto Rico, Mayaguez, PR, USA

S. Malik , R. Sharma

Purdue University, West Lafayette, IN, USA

A. S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A. W. Jung , A. M. Koshy, M. Liu ,
G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , V. Scheurer, J. F. Schulte , M. Stojanovic , J. Thieman ,
A. K. Viridi , F. Wang , A. Wildridge , W. Xie , Y. Yao

Purdue University Northwest, Hammond, IN, USA

J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, TX, USA

D. Acosta , T. Carnahan , K. M. Ecklund , P. J. Fernández Manteca , S. Freed, P. Gardner, F. J. M. Geurts ,
I. Krommydas , W. Li , J. Lin , O. Miguel Colin , B. P. Padley , R. Redjimi, J. Rotter , E. Yigitbasi ,
Y. Zhang

University of Rochester, Rochester, NY, USA

A. Bodek , P. de Barbaro , R. Demina , J. L. Dulemba , A. Garcia-Bellido , O. Hindrichs ,
A. Khukhunaishvili , N. Parmar, P. Parygin ⁹¹, R. Taus 

Rutgers, The State University of New Jersey, Piscataway, NJ, USA

B. Chiarito , J. P. Chou , S. V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton ,
D. Jaroslawski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo , K. Nash , J. Reichert , H. Routray ,
P. Saha , S. Salur , S. Schnetzer , S. Somalwar , R. Stone , S. A. Thayil , S. Thomas , J. Vora , H. Wang 

University of Tennessee, Knoxville, TN, USA

D. Ally , A. G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A. R. Kanuganti , N. Karunarathna ,
L. Lee , E. Nibigira , S. Spanier

Texas A&M University, College Station, TX, USA

D. Aebi , M. Ahmad , T. Akhter , K. Androsov ⁵⁹, O. Bouhali ⁹², R. Eusebi , J. Gilmore , T. Huang ,
T. Kamon ⁹³, H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov

Texas Tech University, Lubbock, TX, USA

N. Akchurin , J. Damgov , N. Gogate , A. Hussain , Y. Kazhykarim , K. Lamichhane , S. W. Lee , A. Mankel ,
T. Peltola , I. Volobouev

Vanderbilt University, Nashville, TN, USA

E. Appelt , Y. Chen , S. Greene , A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo ,
P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen

University of Virginia, Charlottesville, VA, USA

B. Cardwell , H. Chung , B. Cox , J. Hakala , R. Hirosky , A. Ledovsky , C. Neu 

Wayne State University, Detroit, MI, USA

S. Bhattacharya , P. E. Karchin 

University of Wisconsin-Madison, Madison, WI, USA

A. Aravind , S. Banerjee , K. Black , T. Bose , E. Chavez , S. Dasu , P. Everaerts , C. Galloni , H. He ,
M. Herndon , A. Herve , C. K. Koraka , A. Lanaro , R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli ,
A. Mohammadi , S. Mondal , G. Parida , L. Pétré , D. Pinna , A. Savin , V. Shang , V. Sharma , W. H. Smith ,
D. Teague , H. F. Tsoi , W. Vetens , A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin , I. Gorbunov , V. Karjavine , V. Korenkov ,
A. Lanev , A. Malakhov , V. Matveev ⁹⁴, V. Palichik , V. Perelygin , M. Savina , V. Shalae , S. Shmatov ,
S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B. S. Yuldashev ⁹⁵, A. Zarubin , I. Zhizhin , G. Gavrillov ,
V. Golovtsov , Y. Ivanov , V. Kim ⁹⁴, P. Levchenko ⁹⁶, V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov ,
L. Uvarov , A. Vorobyev , Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu ,
D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin , T. Aushev , K. Ivanov , V. Gavrillov ,
N. Lychkovskaya , A. Nikitenko ^{97,98}, V. Popov , A. Zhokin , R. Chistov ⁹⁴, M. Danilov ⁹⁴, S. Polikarpov ⁹⁴,
V. Andreev , M. Azarkin , M. Kirakosyan , A. Terkulov , E. Boos , V. Bunichev , M. Dubinin ⁸³, L. Dudko ,
V. Klyukhin , O. Kodolova ⁹⁸, S. Obraztsov , M. Perfilov , S. Petrushanko , V. Savrin , P. Volkov ,
G. Vorotnikov , V. Blinov ⁹⁴, T. Dimova ⁹⁴, A. Kozyrev ⁹⁴, O. Radchenko ⁹⁴, Y. Skovpen ⁹⁴, V. Kachanov ,
D. Konstantinov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin ⁹⁹

- 1: Also at Yerevan State University, Yerevan, Armenia
- 2: Also at TU Wien, Vienna, Austria
- 3: Also at Ghent University, Ghent, Belgium
- 4: Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- 5: Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
- 6: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 7: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 8: Also at University of Chinese Academy of Sciences, Beijing, China
- 9: Also at China Center of Advanced Science and Technology, Beijing, China
- 10: Also at University of Chinese Academy of Sciences, Beijing, China

- 11: Also at China Spallation Neutron Source, Guangdong, China
- 12: Now at Henan Normal University, Xinxiang, China
- 13: Also at University of Shanghai for Science and Technology, Shanghai, China
- 14: Now at The University of Iowa, Iowa City, USA
- 15: Also at an institute or an international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
- 16: Also at Cairo University, Cairo, Egypt
- 17: Also at Suez University, Suez, Egypt
- 18: Now at British University in Egypt, Cairo, Egypt
- 19: Also at Purdue University, West Lafayette, IN, USA
- 20: Also at Université de Haute Alsace, Mulhouse, France
- 21: Also at Istinye University, Istanbul, Turkey
- 22: Also at The University of the State of Amazonas, Manaus, Brazil
- 23: Also at University of Hamburg, Hamburg, Germany
- 24: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 25: Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- 26: Also at Brandenburg University of Technology, Cottbus, Germany
- 27: Also at Forschungszentrum Jülich, Jülich, Germany
- 28: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 29: Also at HUN-REN ATOMKI-Institute of Nuclear Research, Debrecen, Hungary
- 30: Now at Universitatea Babes-Bolyai-Facultatea de Fizica, Cluj-Napoca, Romania
- 31: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 32: Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- 33: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 34: Also at Punjab Agricultural University, Ludhiana, India
- 35: Also at University of Visva-Bharati, Santiniketan, India
- 36: Also at Indian Institute of Science (IISc), Bangalore, India
- 37: Also at Amity University Uttar Pradesh, Noida, India
- 38: Also at IIT Bhubaneswar, Bhubaneswar, India
- 39: Also at Institute of Physics, Bhubaneswar, India
- 40: Also at University of Hyderabad, Hyderabad, India
- 41: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 42: Also at Isfahan University of Technology, Isfahan, Iran
- 43: Also at Sharif University of Technology, Tehran, Iran
- 44: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 45: Also at Department of Physics, Faculty of Science, Arak University, Arak, Iran
- 46: Also at Helwan University, Cairo, Egypt
- 47: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 48: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 49: Also at Università degli Studi Guglielmo Marconi, Rome, Italy
- 50: Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Naples, Italy
- 51: Also at Fermi National Accelerator Laboratory, Batavia, IL, USA
- 52: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- 53: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- 54: Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- 55: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 56: Also at Trincomalee Campus, Eastern University, Nilaveli, Sri Lanka
- 57: Also at Saegis Campus, Nugegoda, Sri Lanka
- 58: Also at National and Kapodistrian University of Athens, Athens, Greece
- 59: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 60: Also at University of Vienna, Vienna, Austria
- 61: Also at Universität Zürich, Zurich, Switzerland
- 62: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

- 63: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 64: Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- 65: Also at Konya Technical University, Konya, Turkey
- 66: Also at Izmir Bakircay University, Izmir, Turkey
- 67: Also at Adiyaman University, Adiyaman, Turkey
- 68: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 69: Also at Marmara University, Istanbul, Turkey
- 70: Also at Milli Savunma University, Istanbul, Turkey
- 71: Also at Kafkas University, Kars, Turkey
- 72: Now at Istanbul Okan University, Istanbul, Turkey
- 73: Also at Hacettepe University, Ankara, Turkey
- 74: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 75: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- 76: Also at Yildiz Technical University, Istanbul, Turkey
- 77: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 78: Also at IPPP Durham University, Durham, UK
- 79: Also at Monash University, Faculty of Science, Clayton, Australia
- 80: Also at Università di Torino, Turin, Italy
- 81: Also at Bethel University, St. Paul, MN, USA
- 82: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 83: Also at California Institute of Technology, Pasadena, CA, USA
- 84: Also at United States Naval Academy, Annapolis, MD, USA
- 85: Also at Ain Shams University, Cairo, Egypt
- 86: Also at Bingol University, Bingol, Turkey
- 87: Also at Georgian Technical University, Tbilisi, Georgia
- 88: Also at Sinop University, Sinop, Turkey
- 89: Also at Erciyes University, Kayseri, Turkey
- 90: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- 91: Now at another institute or international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
- 92: Also at Texas A&M University at Qatar, Doha, Qatar
- 93: Also at Kyungpook National University, Daegu, Korea
- 94: Also at another institute or international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
- 95: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 96: Also at Northeastern University, Boston, MA, USA
- 97: Also at Imperial College, London, UK
- 98: Now at Yerevan Physics Institute, Yerevan, Armenia
- 99: Also at Universiteit Antwerpen, Antwerpen, Belgium