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Search for lepton-flavour violation in high-mass dilepton final states using 139 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

The ATLAS Collaboration

A search is performed for a heavy particle decaying into different-flavour, dilepton final states, using 139 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13 \text{ TeV}$ collected in 2015–2018 by the ATLAS detector at the Large Hadron Collider. Final states with electrons, muons and hadronically decaying tau leptons are considered ($e\mu$, $e\tau$ or $\mu\tau$). No significant excess over the Standard Model predictions is observed. Upper limits on the production cross-section are set as a function of the mass of a Z' boson, a supersymmetric τ -sneutrino, and a quantum black-hole. The observed 95% CL lower mass limits obtained on a typical benchmark model Z' boson are 5.0 TeV ($e\mu$), 4.0 TeV ($e\tau$), and 3.9 TeV ($\mu\tau$), respectively.

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1 Introduction

Lepton-flavour-violation (LFV) is forbidden in the Standard Model (SM) theory of particle physics. However, the observation of flavour oscillations among neutrinos has shown that lepton flavour is not a conserved symmetry of nature [1]. The search for charged LFV (CLFV) remains an area of active interest, motivating many experimental searches for the CLFV decays, such as the MEG experiment for $\mu \rightarrow e\gamma$ [2], $\mu \rightarrow 3e$ with the SINDRUM spectrometer [3] and also many searches of LFV τ -lepton decay [4]. So far, there is no experimental evidence that LFV also occurs in interactions between charged leptons and, any observation of LFV would be a clear signature of new physics.

Many extensions of the SM predict LFV couplings, such as models with Z' bosons [5], scalar neutrinos in R -parity-violating (RPV) [6, 7] supersymmetry (SUSY) and quantum black holes (QBH) in low-scale gravity [8]. These dilepton LFV processes are usually produced at TeV energy scale, with a clear detector signature of a prompt, different-flavour lepton pair, which decreases the contribution from SM background processes.

A common extension of the SM is the addition of an extra $U(1)$ gauge symmetry resulting in a massive neutral vector boson known as a Z' boson. The Sequential Standard Model (SSM) [5] is used as a benchmark in this paper, where the Z' boson is assumed to have the same quark couplings and chiral structure as the SM Z boson, but allowing for lepton flavour violating couplings. Additional LFV coupling parameters Q_{ij} are assigned for $Z' \rightarrow \ell_i \ell_j$ processes, where $i, j = 1 \dots 3$ represent the three lepton generations. It is assumed that the Q_{ij} parameters equal to the SM Z boson coupling for $i = j$. The latest ATLAS Collaboration study placed lower limits of 4.5, 3.7, and 3.5 TeV on the mass of a Z' boson decaying into $e\mu$, $e\tau$, and $\mu\tau$ pairs, respectively, using 36.1 fb^{-1} of the 13 TeV data sample [9]. The CMS Collaboration has placed limits up to 4.4 TeV on a Z' boson decaying into an $e\mu$ final state using 35.9 fb^{-1} [10]. Following the same methodology as in Ref. [11], the polarisation of τ -leptons is not included in the model, but its impact on the sensitivity to a possible signature is found to be negligible.

In the RPV SUSY model, the Lagrangian terms allowing LFV can be expressed as

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k,$$

where L and Q are the $SU(2)$ doublet superfields of leptons and quarks, e and d are the $SU(2)$ singlet superfields of charged leptons and down-type quarks, λ and λ' are Yukawa couplings, and the indices i, j , and k denote generations. A τ -sneutrino ($\tilde{\nu}_\tau$) may be produced in proton–proton (pp) collisions by $d\bar{d}$ annihilation and later decay into $e\mu$, $e\tau$, or $\mu\tau$. Although only $\tilde{\nu}_\tau$ is considered in this paper, results apply to any sneutrino flavour. For the theoretical prediction of the cross-section times branching ratio, the $\tilde{\nu}_\tau$ coupling to first-generation quarks (λ'_{311}) is assumed to be 0.11 for all channels. As in the Z' model, each lepton-flavour-violating final state is considered separately. It is assumed that $\lambda_{312} = \lambda_{321} = 0.07$ for the $e\mu$ final state, $\lambda_{313} = \lambda_{331} = 0.07$ for the $e\tau$ final state, and $\lambda_{323} = \lambda_{332} = 0.07$ for the $\mu\tau$ final state. These values are chosen for easy comparisons with previous ATLAS and CMS searches [11–13]. Note that in the signal model, the superpotential term corresponds to $-1/2\lambda_{ijk}(\tilde{\nu}_i\bar{l}_k l_j)$, and the gauge invariance enforces antisymmetry of the λ_{ijk} couplings with respect to their first two indices. As the signal is $\tilde{\nu}_\tau$ where $i = 3$, both λ_{331} and λ_{332} are set to be zero for $e\tau$ and $\mu\tau$ channel respectively. However, the $e\mu$ channel is not affected and both λ_{321} and λ_{312} are kept, resulting in the $\tilde{\nu}_\tau$ cross-section times branching ratio in the $e\mu$ channel being twice as large as in the $e\tau$ or $\mu\tau$ channel. The latest ATLAS results with 36.1 fb^{-1} using the 13 TeV data [9] have excluded RPV SUSY models below the $\tilde{\nu}_\tau$ masses 3.4 TeV, 2.6 TeV and below 2.3 TeV for $e\mu$, $e\tau$ and $\mu\tau$ channels respectively with exactly the same parameters mentioned above. The

CMS Collaboration has recently excluded RPV SUSY models below 1.7 TeV for $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$ [10].

Various models introduce extra spatial dimensions to reduce the value of the Planck mass and resolve the hierarchy problem. The search described in this paper presents interpretations based on two models: the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [14], assuming $n = 6$, where n is the number of extra dimensions, and on the Randall–Sundrum (RS) model [15] with one extra dimension. Due to the increased strength of gravity at short distances, in these models pp collisions at the LHC could produce states exceeding the threshold mass (m_{th}) to form black holes. In this paper, m_{th} is assumed to be equivalent to the extra-dimensional Planck scale. The quantum gravity regime [16–18] is applied only when considering the mass region below 3–5 m_{th} , since for masses beyond this region it is expected that thermal black holes would be produced. The non-thermal (or quantum) black holes could decay into two-particle final states, producing the topology investigated in this paper. QBHs would have a continuum mass distribution from m_{th} up to the beginning of the thermal regime which for the models considered in this paper is assumed to start at $3m_{\text{th}}$. This approach is consistent with the previous ATLAS analyses, such as Ref.[9]. The decay of the QBH would be governed by a yet unknown theory of quantum gravity. The two main assumptions of the extra-dimension models considered in this paper [8] are that (a) gravity couples with equal strength to all SM particle degrees of freedom and (b) gravity conserves local symmetries (colour and electric charge), but can violate global symmetries such as lepton-flavour and baryon-number conservation. Following these assumptions, the branching ratio to each final state can be calculated. QBHs decaying into different-flavour, opposite-charge lepton pairs are created via $q\bar{q}$ (gg) with a branching ratio to $\ell\ell'$ of 0.87% (0.34%) [8]. As in the Z' model, each lepton-flavour-violating final state is considered separately. These models were used in previous ATLAS and CMS searches for QBH in dijet [19–21], lepton+jet [22], photon+jet [23], $e\mu$ [10], and same-flavour dilepton [24] final states. The latest ATLAS Collaboration study placed lower limits of 5.5 (3.4), 4.9 (2.9), and 4.5 (2.6) TeV on m_{th} of QBH with ADD (RS) model decaying into $e\mu$, $e\tau$, and $\mu\tau$ pairs, respectively, using 36.1 fb^{-1} of the 13 TeV data sample [9].

This paper describes a search for new phenomena in final states with two leptons of different flavour using 139 fb^{-1} of data from pp collisions at $\sqrt{s} = 13 \text{ TeV}$ at the Large Hadron Collider (LHC). The dilepton signal final states consisting of $e\mu$, $e\tau$, or $\mu\tau$ pairs are considered, where the τ -lepton decays hadronically. This analysis is looking for a localised excess in the distribution of dilepton invariant mass in TeV range. There are three signal regions defined, one for each decay mode. Corresponding control regions are also designed to extract a normalisation of the most prominent SM backgrounds: production of top quarks and dibosons. The contributions from fake leptons are calculated from the data. The final simultaneous fit, with the signal and control regions, is performed separately in each decay mode. Four benchmark models (Z' , RPV SUSY $\tilde{\nu}_\tau$ and QBH: ADD $n=6$; RS $n=1$) are used to interpret the results. Compared with the previous ATLAS search with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ [9], this analysis benefits from a factor of four increase in integrated luminosity, improvements in object reconstruction (such as electron and tau lepton identification) the use of a more robust background estimation method (e.g. the 4×4 matrix method in $e\mu$ channel), and the application of a simultaneous fit with both signal region and control regions to constrain systematic uncertainties.

2 The ATLAS detector

The ATLAS detector [25] is a general-purpose particle detector with approximately forward–backward symmetric cylindrical geometry. It covers nearly the entire solid angle around the collision point.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadron calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range of $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B-layer (IBL) installed before Run 2 [26, 27]. It is followed by the silicon microstrip tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region of $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

Interesting events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [28]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record events to disk at about 1 kHz.

An extensive software suite [29] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations and in the trigger and data acquisition systems of the experiment.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

3 Data and simulated event samples

The data sample used for this analysis was collected during 2015 to 2018 from pp collisions at a centre-of-mass energy of 13 TeV. After selecting periods with stable beams and applying data-quality requirements, the total integrated luminosity is 139 fb^{-1} with an uncertainty of 1.7% [30, 31].

The $pp \rightarrow Z' \rightarrow \ell\ell'$ Monte Carlo (MC) simulated samples were generated at leading order (LO) using the generator PYTHIA 8.186 [32] with the NNPDF2.3LO [33] parton distribution function (PDF) set and the A14 [34] set of tuned parameters. The signal samples were generated for the SSM, including fifteen mass points ranging from 1 TeV to 8 TeV in steps of 500 GeV. The cross-section of the Z' signal was corrected from LO to next-to-next-to-leading order (NNLO) in the strong coupling constant with a rescaling, which was computed with VRAP 0.9 [35] and the CT14NNLO PDF [36] set. The NNLO QCD correction was applied as a multiplicative factor from 1.44 to 0.29 for different Z' masses on total cross-section. No mixing of the Z' boson with the Z and γ^* bosons is included.

The $d\bar{d} \rightarrow \tilde{\nu}_\tau \rightarrow \ell\ell'$ samples were generated at LO with MADGRAPH5_AMC@NLO v2.3.3 [37] interfaced to the PYTHIA 8.186 parton shower model with the NNPDF2.3LO PDF set and the A14 tune. The signal samples were generated with the same mass values as for the Z' model described above. The cross-section was calculated at LO with the same generator used for simulation and corrected to next-to-leading-order (NLO) using LOOPTOOLS v2.2 [38]. The NLO correction factor ranges from 1.1 to 1.4, depending on different $\tilde{\nu}_\tau$ masses.

The $pp \rightarrow \text{QBH} \rightarrow \ell\ell'$ samples were generated with the program QBH 3.00 [39] using the CTEQ6L1 [40] PDF set and the A14 tune, for which PYTHIA 8.205 [41] provides showering and hadronisation. For each extra-dimensional model, eleven m_{th} points in 500 GeV steps were produced: from 4 TeV to 9 TeV for the ADD $n = 6$ model and from 2 TeV to 7 TeV for the RS $n = 1$ model. These two models differ in the number and nature of the additional extra dimensions (large extra dimensions for ADD and one highly warped extra dimension for RS). In particular, the ADD model predicts black holes with a larger gravitational radius and hence the parton–parton cross-section for this model is larger than for the RS model. Therefore, the m_{th} range of the generated samples differs for the two models.

The SM background in the LFV dilepton search is due to several processes which produce a final state with two different-flavour leptons. For the $e\mu$ mode, the dominant background contributions originate from $t\bar{t}$ and single-top tW production with the subsequent decay of both of the W bosons (including those from top quark decays) in the event into leptons, and diboson (WW , WZ , and ZZ) production. Other backgrounds originate from τ -lepton pair production ($q\bar{q} \rightarrow Z/\gamma^* \rightarrow \tau\tau$). Both diboson and τ -lepton pair production produce different-flavour final states, through the leptonic decays of the W and Z bosons or the τ -leptons. For the $e\tau$ and $\mu\tau$ modes, multijet and W +jets processes are the dominant backgrounds. They contribute due to the misidentification of jets as leptons.

Backgrounds from top quark production include $t\bar{t}$ and tW production. The production of $t\bar{t}$ events was modelled using the POWHEG-BOX v2 [42–45] generator at NLO with the NNPDF3.0NLO PDF set [46] and the h_{damp} parameter² set to $1.5 m_{\text{top}}$ [47]. The events were interfaced to PYTHIA 8.230 [41] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune and using the NNPDF2.3LO set of PDFs. The decays of bottom and charm hadrons were performed by EVTGEN 1.6.0 [48]. The tW backgrounds were modelled by the POWHEG-BOX v2 generator at NLO in QCD

² The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high- p_T radiation against which the $t\bar{t}$ system recoils.

using the five-flavour scheme and the NNPDF3.0NLO set of PDFs. The diagram removal scheme [49] was used to remove interference and overlap with $t\bar{t}$ production. The events were interfaced to PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO set of PDFs.

For diboson samples, final states were simulated with SHERPA 2.2.12 [50, 51], including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were simulated using matrix elements (ME) at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions.

The SM Drell–Yan process was generated at NLO using POWHEG-BOX v1 MC generator which is used for the simulation at NLO accuracy of the hard-scattering processes of Z-boson production and decay in the e , μ , and τ -lepton final states. It was interfaced to PYTHIA 8.186 with parameters set according to the AZNLO [52] tune. The CT10 PDF set [53] was used for the hard-scattering processes, whereas the CTEQ6L1 PDF set was used for the parton shower.

Processes such as W +jets and multijet production with jets that are misidentified as leptons were estimated through a combination of data-driven methods and simulation, detailed in Section 5. The W +jets contribution was estimated with the aid of the SHERPA 2.2.2 simulated samples using NLO MEs for up to two partons, and LO matrix elements for up to four partons calculated with the Comix [54] and OPENLOOPS libraries. They are matched with the SHERPA parton shower using the MEPS@NLO [55] prescription using the set of tuned parameters developed by the SHERPA authors [50].

For all samples used in this analysis, the effects of multiple proton–proton interactions per bunch crossing (pileup) were included by overlaying minimum-bias events simulated with PYTHIA 8.186 and reweighting the simulated events to reproduce the distribution of the number of interactions per bunch crossing observed in the data. The generated events were processed with the ATLAS simulation infrastructure [56], based on GEANT4 [57], and passed through the trigger simulation and the same reconstruction software used for the data.

4 Event reconstruction and selection

The search for new phenomena presented here is aimed at the high mass range, thus event selections are optimised accordingly. Events are kept only if they can satisfy a single-muon or single-electron trigger. The trigger p_T threshold is different for different data-taking periods. For 2015 data runs, a p_T threshold of 20 or 50 GeV for muons is applied, and the value for electrons is 24, 60 or 120 GeV. For 2016 - 2018 data runs, the p_T threshold is 26 or 50 GeV for muons, and 26, 60 or 140 GeV for electrons. This analysis relies on triggers with p_T threshold above 50 (60) GeV for muons (electrons). The single-electron trigger with higher p_T threshold has a looser identification requirement, resulting in an increased trigger efficiency in the high p_T region which is especially important for a high mass resonance search. In addition to the trigger selection, events are required to have at least one offline reconstructed signal lepton matched to the object that fired the trigger.

Electron candidates are formed by associating the energy in clusters of cells in the electromagnetic calorimeter with a track in the ID [58]. Candidate electrons are identified using a likelihood-based method. The likelihood discriminant utilises lateral and longitudinal calorimeter shower shapes together with tracking and cluster–track matching quantities. The discriminant criterion is a function of the p_T and $|\eta|$ of the electron candidate. Two operating points are used in this analysis, as defined in Ref. [59, 60]: *Medium*

and *Tight*, which correspond to an efficiency of 88% and 80% for a prompt electron with $E_T = 40$ GeV respectively. The *Tight* working point is required for electrons in signal events while the *Medium* working point is required in order to define an electron used for the reducible background estimates. Electron candidates must have $p_T > 65$ GeV and $|\eta| < 2.47$, excluding the region $1.37 < |\eta| < 1.52$, where the electron performance is degraded due to the presence of extra inactive material. Further requirements are made on their tracks: the transverse and longitudinal impact parameters relative to the primary vertex of the event (d_0 and Δz_0) must satisfy $|d_0/\sigma_{d_0}| < 5$ and $|\Delta z_0 \sin \theta| < 0.5$ mm. Candidates are required to satisfy relative track-based and calorimeter-based isolation requirements with an efficiency of 99% to suppress background from non-prompt electrons [61].

Candidate muon tracks are reconstructed independently in the ID and the MS which are then used in a combined fit. To ensure optimal muon momentum resolution to very high p_T region ($\sim 10\%$ at 1 TeV), the *High- p_T* operating point [62] is used in this analysis. Only tracks with hits in each of the three stations of the muon spectrometer are considered. Moreover, muon candidates are required to be within a pseudorapidity of $|\eta| < 2.5$, satisfy $|d_0/\sigma_{d_0}| < 3$ and $|\Delta z_0 \sin \theta| < 0.5$ mm, $p_T > 65$ GeV, and satisfy a track-based isolation criterion with an efficiency of 99% to further reduce contamination from non-prompt muons. The track isolation is similar to the one defined for electrons. Muon candidates fulfilling all selection except the isolation criterion are called “Loose muons” which are used in the reducible background estimates. An additional upper cut on μ p_T at 6 TeV is applied to remove poorly calibrated muons. This only affects the very high-mass signals, and no events fail this requirement in either the data or the background MC.

Jets are reconstructed using the anti- k_r algorithm [63] with a radius parameter of 0.4. The inputs to the jet clustering are built by combining the information from both the calorimeters and the ID using a particle-flow algorithm [64]. The cluster energies are calibrated according to in situ measurements of the jet energy scale [65]. Jets with $p_T < 60$ GeV and with $|\eta| < 2.4$ are further required to satisfy the jet vertex tagger [66], which is a likelihood discriminant that uses a combination of track and vertex information to suppress jets originating from pile-up activity.

Hadronic decays of τ -leptons are composed of a neutrino and a set of visible decay products (τ_{had}), typically one or three charged pions and up to two neutral pions. The reconstruction of τ_{had} starts with jets reconstructed from topological clusters [67, 68]. The τ_{had} candidates must have $|\eta| < 2.5$ with the transition region ($1.37 < |\eta| < 1.52$) excluded, a transverse momentum $p_T > 65$ GeV, one or three associated tracks with ± 1 total electric charge. To discriminate against jets, τ_{had} candidates are identified with a multivariate algorithm that employs a Recurrent Neural Network (RNN) using shower shape and tracking information [68]. All τ_{had} candidates are required to satisfy the *Medium* operating point which corresponds to an efficiency of 75% (60%) for 1-prong (3-prong) τ -leptons, and a jet background rejection of 35 (240) for 1-prong (3-prong) τ -lepton candidates. Furthermore, a dedicated Boosted Decision Tree-based veto is applied to reduce the number of electrons misidentified as τ_{had} candidates.

Jets with $|\eta| < 2.5$ containing a b -hadrons are identified with a b -tagging algorithm based on a deep-learning neural network [69]. The information used includes distinctive features of b -hadron decays in terms of the impact parameters of the tracks and the displaced vertices reconstructed in the ID. The chosen operating point has an efficiency of 85%. In this study, a veto on b -tagged jets is applied to reject contributions from events containing top quarks.

The missing transverse momentum vector \vec{p}_T^{miss} , with magnitude E_T^{miss} , is defined as the negative vector sum of the transverse momenta of all identified physics objects and an additional soft term. The soft term is constructed from all tracks that are associated with the primary vertex, but not associated with any selected physics object [70].

Candidate signal events must have a reconstructed primary vertex with at least two associated tracks, defined as the vertex whose constituent tracks have the highest sum of p_T^2 . There should be exactly two different-flavour, opposite-sign leptons satisfying the previously mentioned criteria: $e\mu$, $e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$. Events with an additional electron, muon or τ_{had} fulfilling all the selections are vetoed. For the $e\mu$ channel only, events with an extra electron or muon fulfilling the “loose” criteria are also vetoed. For all three channels, the lepton candidates must be back-to-back in the transverse plane with $\Delta\phi(\ell, \ell') > 2.7$. The invariant mass of the dilepton pair larger than 600 GeV is used as the discriminant. To account for differences between data and simulation, corrections are applied to the lepton trigger, reconstruction, identification, and isolation efficiencies as well as to the lepton energy/momentum resolution and scale [58, 62, 67].

To avoid double counting among objects, a lepton-lepton and lepton-jet overlap removal is applied based on the ΔR distance metric. The p_T threshold of muons considered in the overlap removal with τ_{had} is lowered to 2 GeV. Further details can be found in Ref. [71].

After the event selection mentioned above, for a Z' boson with a mass of 1.5 TeV, the fractions of signal events that satisfy all of the selection requirements are approximately 45%, 20%, and 15% for the $e\mu$, $e\tau$, and $\mu\tau$ final states, respectively.

Because of the presence of a neutrino in the τ -leptons hadronic decay, for the $e\tau$ and $\mu\tau$ channels the dilepton invariant mass cannot be fully reconstructed, so an approximation is used. The mass of the BSM particle from the signals considered is much larger than the masses of the SM leptons, thus producing very high energy τ -leptons when it decays. The hadronic cascade decay of the high energy τ -lepton results in the neutrino and the resultant jet being nearly collinear. The neutrino four-momentum is reconstructed from the magnitude of the missing transverse momentum and the direction of the τ_{had} candidate. This technique significantly improves the dilepton mass resolution and search sensitivity [12]. For a simulated Z' boson with a mass of 2 TeV, the mass resolution improves from 8% (17%) to 4% (12%) in the $e\tau$ ($\mu\tau$) channel.

5 Background estimation

The background processes for this search can be divided into two categories: reducible and irreducible. The latter is composed of processes, which can produce two different-flavour opposite-sign prompt leptons, including diboson, $t\bar{t}$, single-top tW , and $Z/\gamma^* \rightarrow \tau\tau$ production. These processes are modelled with MC simulated event samples and normalised to their theoretical cross-sections before further adjustment. Reducible backgrounds originate from jets mis-reconstructed as leptons, such as W +jets and multijet production. These backgrounds are estimated from the data. The contribution from reducible backgrounds is small in the $e\mu$ channel—approximately 10% in the signal region (SR)—whereas in the $e\tau$ and $\mu\tau$ channels they are among the leading components and account for 20–30% of the total background in the SR. Table 1 shows the regions used in the final fit mentioned in Section 7 in different channels.

5.1 Irreducible backgrounds

Among the irreducible backgrounds, $t\bar{t}$ and WW are the dominant processes in all channels. Their contributions are evaluated with MC simulation, which are corrected by factors derived in the relevant control regions (CR). For the $t\bar{t}$ process, which is the dominant contribution in “Top Quarks” backgrounds, a CR is built with the same selection as signal events but reversing the b -jet veto cut in each of $e\mu$, $e\tau$

Table 1: Regions used in the final fit mentioned in Section 7 in $e\mu$, $e\tau$ and $\mu\tau$ channels. ‘‘SR’’ and ‘‘CR’’ refer to signal and control regions respectively.

| Region | Channels | Requirements |
|--|--------------------------------|---|
| Nominal $\Delta\phi_{\ell\ell'}$ | | |
| SR | $e\mu$, $e\tau$ and $\mu\tau$ | $\Delta\phi_{\ell\ell'} > 2.7$, no b -jet, $m_{\ell\ell'} > 600$ GeV |
| $t\bar{t}$ CR | $e\mu$, $e\tau$ and $\mu\tau$ | $\Delta\phi_{\ell\ell'} > 2.7$, at least one b -jet, $m_{\ell\ell'} > 600$ GeV |
| Reversed $\Delta\phi_{\ell\ell'}$ | | |
| Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR | $e\mu$ | $\Delta\phi_{\ell\ell'} < 2.7$, at least one b -jet, $m_{\ell\ell'} > 600$ GeV |
| WW CR | $e\mu$ | $\Delta\phi_{\ell\ell'} < 2.7$, no b -jet, $m_{\ell\ell'} > 600$ GeV |

and $\mu\tau$ channels. In the $e\mu$ channel, a WW CR is built with the SR selection, but reversing the $\Delta\phi_{\ell\ell'}$ cut. In this WW CR, as the $t\bar{t}$ contamination is significant ($\sim 40\%$), a dedicated $t\bar{t}$ CR is defined in the $\Delta\phi_{\ell\ell'} < 2.7$ region to control the $t\bar{t}$ contamination. For the $e\tau$ and $\mu\tau$ channels, WW CRs are not defined due to non-negligible contributions from fake backgrounds. However, due to lepton flavour universality, the correction factor ratios between the $t\bar{t}$ and WW processes are assumed to be the same in the $e\mu$ and τ -lepton channels:

$$\frac{k_{WW}^{e(\mu)\tau}}{k_{WW}^{e\mu}} = \frac{k_{t\bar{t}}^{e(\mu)\tau}}{k_{t\bar{t}}^{e\mu}}, \quad (1)$$

where $k_{WW}^{e(\mu)\tau}$ is the correction factor for the WW process in the $e\tau$ or $\mu\tau$ channel, $k_{WW}^{e\mu}$ is the correction factor for the WW process in the $e\mu$ channel. The $k_{t\bar{t}}^{e(\mu)\tau}$ is the correction factor for the $t\bar{t}$ process in the $e\tau$ or $\mu\tau$ channel, and $k_{t\bar{t}}^{e\mu}$ is the correction factor for the $t\bar{t}$ process in the $e\mu$ channel. The correction factor for the WW process in the $e\mu$ channel can be extrapolated to the $e\tau$ or $\mu\tau$ channel with a factor equal to the ratio of the $t\bar{t}$ correction factors between the $e\mu$ channel and τ channels:

$$k_{WW}^{e(\mu)\tau} = k_{WW}^{e\mu} \times \frac{k_{t\bar{t}}^{e(\mu)\tau}}{k_{t\bar{t}}^{e\mu}}. \quad (2)$$

From the simultaneous fit in all CRs for the $e\mu$ channel, the fitted uncertainty of $k_{WW}^{e\mu}$ is 12% and it is highly correlated with $k_{t\bar{t}}^{e\mu}$. The same uncertainty is assigned to $k_{WW}^{e(\mu)\tau}$. Conservatively, it is treated as uncorrelated to $k_{t\bar{t}}^{e\mu}$, thus leading to an over-estimate in the final fit uncertainties. The 12% uncertainty on the WW correction is also much larger than the correction effect itself in the $e\tau$ and $\mu\tau$ channels, which is less than 5% on the diboson background.

The $t\bar{t}$ and WW correction factors are used to correct the total yields of ‘‘Top Quarks’’ and ‘‘Diboson’’ backgrounds respectively. Other irreducible background processes, such as $Z \rightarrow \ell\ell'$ are evaluated directly with MC simulation.

5.2 Reducible backgrounds

The dominant reducible backgrounds, W +jets and multijet production, are estimated by using data-driven techniques. In the $e\mu$ channel, the matrix method [24] is used, while in the $e\tau$ and $\mu\tau$ channels, the fake-lepton background is extrapolated from dedicated CRs to SR with the method described in Ref. [12].

5.2.1 Fake backgrounds in $e\mu$ channel

The goal of the matrix method is to estimate the fraction of events in the data sample with a “real” electron and a “real” muon (N_{RR}), events with a jet faking an electron (“fake” electron) and a “fake” muon (N_{FF}), and events with one “real” lepton and one “fake” lepton (N_{RF} and N_{FR}).

Two selection criteria are defined: “Tight” and “Loose” for muons (electrons) based on their lepton quality (identification and isolation) respectively. As the selection efficiency is different between a “real” lepton and a “fake” lepton, the contribution of “fake” leptons is estimated by the number of data events passing each selection criteria.

Four data samples are constructed based on the lepton quality:

- a sample where both the electrons and muons pass the “Tight” quality cut, with number of events N_{TT} ;
- a sample where the electrons pass the “Loose” but failed the “Tight” selection, and the muons pass the “Tight” selection, with event number N_{LT} ;
- a sample where the muons pass the “Loose” but failed the “Tight” selection, and the electrons pass the “Tight” selection, with event number N_{TL} ;
- a sample where both the electrons and muons pass the “Loose” but fail the “Tight” selection, with event number N_{LL} .

By solving a system of linear equations involving the numbers of events for these four data samples, the reducible background contributions can be evaluated.

$$\begin{bmatrix} N_{TT} \\ N_{LT} \\ N_{TL} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_e r_\mu & f_e r_\mu & r_e f_\mu & f_e f_\mu \\ (1-r_e)r_\mu & (1-f_e)r_\mu & (1-r_e)f_\mu & (1-f_e)f_\mu \\ r_e(1-r_\mu) & f_e(1-r_\mu) & r_e(1-f_\mu) & f_e(1-f_\mu) \\ (1-r_e)(1-r_\mu) & (1-f_e)(1-r_\mu) & (1-r_e)(1-f_\mu) & (1-f_e)(1-f_\mu) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{FR} \\ N_{RF} \\ N_{FF} \end{bmatrix} \quad (3)$$

Among these equations, “ r ” is the probability of a “Loose” lepton matched to a true lepton to satisfy the “Tight” quality selection, defined as the “real efficiency.” It is evaluated from $Z \rightarrow \ell\ell'$ simulated events. The “ f ” refers to the probability that a jet is misidentified as a “Tight” quality lepton, so called “fake rate” which is determined in a multijet-enriched data sample. The creation of this sample starts with the selection of a “Loose” lepton back-to-back with a jet. To suppress the W +jets contamination to the multijet-enriched sample, the events are required to have $E_T^{\text{miss}} < 25$ GeV and the transverse mass $m_T < 50$ GeV. Transverse mass is defined as $m_T = \sqrt{2E_T^{\ell^\pm} E_T^{\text{miss}} (1 - \cos \Delta\phi)}$, where $E_T^{\ell^\pm}$ and E_T^{miss} denote the transverse energies of the final state charged lepton and neutrino with $\Delta\phi$ as the azimuthal angle difference. Since most of the “fake” muons are from heavy flavour jets decays in the muon fake rate measurement, the requirements on both of the impact parameters d_0 and z_0 are reversed in order to further suppress the W +jets contamination. Remaining contamination are subtracted relying on simulations from W +jets and other SM background processes (top, diboson and $Z \rightarrow \ell\ell$). Both the real efficiency and the fake rate are determined as a function of p_T .

The uncertainties associated with the matrix method are evaluated by considering systematic effects on the lepton fake rate measurement and uncertainties in the real lepton efficiency. The latter is considered to be the difference in the lepton η distribution between SR and $Z \rightarrow \ell\ell$ MC [71]. It is assigned by comparing

the real lepton efficiency measured with $Z \rightarrow \ell\ell$ plus zero jet events and inclusive $Z \rightarrow \ell\ell$ events. The systematic uncertainties in the fake rate include:

- the choice of multijet-enriched region;
- the impact of reversing d_0 and z_0 on muons;
- the difference in the fake rates between the SR and multijet-enriched region due to the difference in the jet flavour components.

The overall uncertainty on the $e\mu$ reducible background is about 30% in the SR. Given that in the $e\mu$ channel SR, this contribution is about 10% of the total background over the invariant mass range considered, the uncertainties in the fake-lepton background estimates have little impact on the results.

5.2.2 Fake backgrounds in $e\tau$ and $\mu\tau$ channels

One of the major backgrounds for the $e\tau$ and $\mu\tau$ channels is the W +jets process, where a jet is misidentified as a lepton candidate. As it is difficult to model misidentification of jets as leptons, particularly in the high p_T region, the W +jets backgrounds are determined from dedicated CRs. They are built from events selected with the same criteria as used in the signal selection except for requiring $E_T^{\text{miss}} > 30$ GeV to enhance the W +jets contribution and suppress the $Z \rightarrow \ell\ell'$ contamination. The dilepton mass requirement is also lowered to 130 GeV to reduce the statistical uncertainty in these control regions. Furthermore, the $\Delta\phi_{\ell\ell'}$ requirement is reversed ($\Delta\phi_{\ell\ell'} < 2.7$) to ensure orthogonality with the SR. Simulation studies indicate that the multijet background is negligible in this CR. Contributions from other SM background processes are estimated by using MC simulation. The W +jet MC samples are used to calculate the ratio of events in the CR to events in the SR. Then the total W +jet backgrounds yields are extrapolated from CR to SR with this ratio. Kinematic distributions of the W +jets background are derived by relying on MC simulation. The uncertainties considered in this method include

- the construction of the W +jets CR,
- uncertainties in the estimates of other SM background processes in the W +jets CR,
- and the W +jets MC shape uncertainty which is assigned based on the data versus prediction agreement in the W +jet CR.

The overall uncertainty of W +jets in $e\tau$ and $\mu\tau$ channels is approximately 20%.

The contribution from multijets production is estimated also from a CR with the same selection as the SR except that the leptons are required to have the same electric charge, assuming that the probability of misidentifying a jet as a lepton is independent of the charge. The dilepton mass requirement is also lowered to 130 GeV to estimate the low mass multijets contribution used in the high mass extrapolation. The contamination from processes with prompt leptons is subtracted from data in the same-sign CR using MC simulation, while the contamination from W +jets is subtracted using the previously mentioned procedure. The assumption of charge independence of the jet misidentification rates is tested in a multijet-enriched region with two non-isolated leptons. After subtraction of other SM backgrounds, the ratio of opposite-sign to same-sign events is found to be in reasonable agreement in the range of 10% to 20% up to the TeV dilepton invariant mass range. The remaining lack of closure is taken as an uncertainty. Besides this charge independence assumption uncertainty, the uncertainties in multijets estimates mainly come from uncertainties in the W +jets subtraction and other MC irreducible background subtractions. As the

uncertainty in W +jets is quite significant, they are also propagated to the multijets estimate through the W +jets subtraction. In this way, the yield of the multijets background is highly anti-correlated with the W +jets background, and they are combined together as “fake” background. The overall uncertainty in the “fake” background is approximately 25% in the $e\tau$ and $\mu\tau$ channels.

Considering the lack of “fake” background event numbers at high dilepton invariant mass values in the signal region, a function of the form $f(m_{l\tau}) = Am_{l\tau}^{B+C\log(m_{l\tau})}$ with free parameters A , B and C is fitted to the dilepton invariant mass distribution in the range $340 < m_{l\tau} < 3000$ GeV. This function is used to extrapolate the fake background estimate for the whole signal region ($m_{l\tau} > 600$ GeV). The statistical uncertainty of the fitted function is determined by the propagation of the statistical uncertainties on the fitted parameters. The uncertainty due to the extrapolation is dominated by the fit function choice uncertainty, and it is evaluated by comparing the nominal estimate with the one obtained when changing the fit function ($f(m_{l\tau}) = Am_{l\tau}^B$, with the free parameters A and B). The difference of these two function is more than 100% above 2 TeV. The same functions have been previously used to model the jet backgrounds in other analyses [72]. Both the data-driven uncertainties and the fit related uncertainties are taken into account as independent sources for the fake estimation uncertainty.

6 Systematic uncertainties

Systematic uncertainties affect the event yields and the shape of the invariant mass distribution in the signal and control regions. They are grouped into two types: theoretical and experimental uncertainties. The systematic uncertainties related to the estimates of fake backgrounds are discussed in Section 5.

Experimental uncertainties considered include those from the trigger, reconstruction, identification and isolation requirements of the final-state particles, such as electrons [58], muons [62], τ -leptons [67], jets [65], E_T^{miss} [73], and b-tagging [74]. Their energy scale and resolution uncertainties are also taken into account. An additional uncertainty (1.7%) from the measurement of the integrated luminosity is included. Sources of uncertainty are considered for both the simulated background and signal processes. Experimental uncertainties affect the event yields of background and the signal cross-section through their effects on the acceptance and the event migration between different analysis regions.

Theoretical uncertainties are considered for the renormalisation (μ_r) and factorisation (μ_f) scales, the choice of PDF, the choice of the value of the strong coupling constant α_s , and the modelling of the $t\bar{t}$ and diboson backgrounds. The strategy used in the same analysis with partial data sample at $\sqrt{s} = 13$ TeV [9] is followed in this search.

Variation of the renormalisation and factorisation scales is used to estimate the uncertainty due to missing higher order corrections. Pairwise variations of μ_r and μ_f are considered to find the maximum and minimum variations. The PDF uncertainty consists of the contribution from the PDF set used in the matrix element calculation. It is estimated using different PDF sets and eigenvector variations within a particular PDF set for the top-quark, diboson, and W +jets backgrounds. The α_s uncertainty is evaluated by using the same PDF set evaluated with two different α_s values. The uncertainty in the modelling of the $t\bar{t}$ background is assessed by evaluating two MC samples which are generated by POWHEG-BOX+PYTHIA8 and AMC@NLO+PYTHIA8 as sources of modelling uncertainty. The uncertainty in the modelling of the diboson background is assessed by evaluating two MC samples which are generated by SHERPA 2.2.12 and POWHEG-BOX+PYTHIA8.

Experimental systematic uncertainties common to signal and background processes are assumed to be correlated. For signal processes, only experimental systematic uncertainties and uncertainties due to the limited statistical precision of simulated samples are considered. All uncertainties are evaluated as a function of $m_{\ell\ell'}$.

For illustration, Table 2 lists the post-fit impact of uncertainties in the RPV SUSY $\tilde{\nu}_\tau$ model for each measurement grouped by their respective sources. The Z' and QBH models have similar results. The sources of the largest systematic uncertainties are the statistical uncertainties associated with the background estimate and background modelling uncertainties in the $e\mu$ channel. In the τ -lepton channels, the uncertainties are dominated by the statistical precision of the background estimate and experimental uncertainties related to τ -leptons and the estimate of fake backgrounds. The total uncertainties are dominated by the statistical precision in all three channels.

Table 2: Summary of the different sources of relative uncertainty (post-fit) in percentage on the observed signal strength of the RPV SUSY $\tilde{\nu}_\tau$ model with a mass of 3 TeV in the $e\mu$, $e\tau$, and $\mu\tau$ channels. “Other” refers to luminosity, jet-vertex-tagger (JVT) and pile-up weight uncertainties. “NA” stands for not applicable.

| Source of uncertainty (in percent) | Impact on observed $\mu_{\text{RPV}}^{e\mu}$ | Impact on observed $\mu_{\text{RPV}}^{e\tau}$ | Impact on observed $\mu_{\text{RPV}}^{\mu\tau}$ |
|---------------------------------------|--|---|---|
| Electrons | 2.2 | 0.85 | NA |
| Muons | 2.8 | NA | 4.4 |
| τ -leptons | NA | 9.7 | 11 |
| Jets and $E_{\text{T}}^{\text{miss}}$ | 2.1 | 0.8 | 0.8 |
| Flavour tagging | 2.1 | <0.1 | 0.1 |
| Other (luminosity, JVT, pile-up) | 0.6 | 0.4 | 0.7 |
| Fake backgrounds | 0.6 | 3.2 | 9.7 |
| Background modelling | 9.6 | 2.1 | 7.3 |
| Top and Diboson normalisations | 8.7 | 1.6 | 1.8 |
| Simulation statistical uncertainty | 28 | 9.6 | 15 |
| Total systematic uncertainty | 32 | 14 | 23 |
| Data statistical uncertainty | 53 | 48 | 71 |
| Total uncertainty | 62 | 50 | 74 |

7 Statistical analysis

The dilepton invariant mass distribution in the SR and CRs are fitted simultaneously to test for the presence of a signal. For hypothesis testing, binned profile-likelihood fits are performed, following a modified frequentist method [75] implemented in RooStats [76]. The fits are performed for each decay channel separately. For the $e\mu$ channel, WW and low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CRs are included in the fit to extract the overall normalisation of the diboson background while keeping the normalisation of the top quark background uncorrelated in the high- and low- $\Delta\phi_{\ell\ell'}$ regions. Separate normalisation factors of the top quark background are used for the high- and low- $\Delta\phi_{\ell\ell'}$ regions in the simultaneous fit, by which their correlation is determined. For the $e\tau$ and $\mu\tau$ channels, only $t\bar{t}$ CRs are included in the fit and the diboson correction factors are calculated from the CR-only fit results and put into the final fit as fixed normalisation factors.

The binned likelihood function ($\mathcal{L}(\mu, \theta)$) is constructed as a product of Poisson probability terms over all

bins considered in the search. The likelihood function depends on the parameter of interest (POI), the signal strength parameter μ , a factor multiplying the theoretical signal production cross-section and a set of nuisance parameters θ that encode the effect of systematic uncertainties in the signal and background expectations. All nuisance parameters are implemented in the likelihood function as Gaussian constraints. Unconstrained normalisation factors are applied on the top quark and diboson background components in the $e\mu$ channel, and the top quark background in the τ -lepton channels. They are controlled by the previously mentioned CRs in the respective channels. The expected event yield in a bin depends on the normalisation factors and on the nuisance parameters. The nuisance parameters adjust the expected event yields for signal and background according to the best fit to data.

The likelihood function is fitted to the data to test for the presence of a signal. The test statistic q_μ is defined as the profile likelihood ratio, $q_\mu = -2 \ln \mathcal{L}(\mu, \hat{\theta}) / \mathcal{L}(\hat{\mu}, \hat{\theta})$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that simultaneously maximise the likelihood function, and $\hat{\theta}$ are the values of the nuisance parameters that maximise the likelihood function for a fixed value of μ . Compatibility of the observed data with the background-only hypothesis is tested by setting $\mu = 0$ in the test statistic q_0 . Upper limits on the signal production cross-section for each considered signal scenario are computed using q_μ in the CL_s method [75] with the asymptotic approximation [77]. A given signal scenario is considered to be excluded at the 95% confidence level (CL) if the value of the signal production cross-section (parameterised by μ) yields a CL_s value less than 0.05.

8 Results

Tables 3, 4 and 5 show the observed data event yields and the expected background event yields in the CRs and SRs for $e\mu$, $e\tau$ and $\mu\tau$ channels. The $e\mu$ background is dominated by $t\bar{t}$ and diboson events, while W+jets events are dominant for the $e\tau$ and $\mu\tau$ final states.

Binned profile-likelihood fits are performed on dilepton invariant mass spectra for each signal scenario in $e\mu$, $e\tau$ and $\mu\tau$ channels. Table 6 shows the fitted correction factors for ‘‘Top Quarks’’ and ‘‘Diboson’’ backgrounds applied to SR. Figures 1 and 2 show the post-fit dilepton invariant mass distributions of the background-only fit in the CRs for the $e\mu$, $e\tau$ and $\mu\tau$ channels. Figure 3 shows the post-fit dilepton invariant mass distributions of the background-only fit in the SR for the $e\mu$, $e\tau$ and $\mu\tau$ channels. The SM expectations agree well with the data in the SR of the $e\mu$ channel. Mild tension with the SM background estimates is observed between 2.0 TeV and 2.3 TeV in the SRs of the τ -lepton channels. Nevertheless, SM expectations are still statistically consistent with the data within 2σ .

Figures 4–6 show the observed and expected 95% CL upper limits on the production cross-section times branching ratio of the Z' , RPV SUSY $\tilde{\nu}_\tau$ and QBH models for each of the final states considered. The limits for signal masses above 3.0 TeV are dominated by the last bin in the dilepton invariant mass spectrum, thus the limit curve tends to be flat in the high mass region.

The extracted limits are not as strong for signal masses above about 2.5 TeV due to a decrease in acceptance at very high p_T and, specifically to the LFV Z' model, low-mass signal production due to PDF suppression at high masses. The observed limits are slightly more stringent than the expected limits above 2 TeV because of the small deficit observed in data in $e\mu$ channel. In the τ -lepton channels, the observed limits are less stringent than the expected limits above 2 TeV because of the mild excess above the background estimates between 2.0 TeV and 2.3 TeV. The acceptance times efficiency of the ADD and RS QBH models

agree with each other within 1%, and the same prediction is used for the limit extraction. The results are summarised in Table 7.

Table 3: Observed data event yields and the expected background event yields with their total uncertainties in the CRs in the $e\mu$ channel after applying all selection criteria and the background-only fit. The “Fake” background refers to “ W +jets” and “Multijet” events with fake leptons. The “Top Quarks” contains single top and $t\bar{t}$ events.

| Process | $t\bar{t}$ CR | WW CR | Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR |
|------------------|----------------|----------------|--|
| Top Quarks | 660 ± 27 | 55.4 ± 5.9 | 279 ± 18 |
| Diboson | 11.3 ± 2.4 | 54.3 ± 8.4 | 7.5 ± 2.3 |
| Fake | 29.3 ± 5.9 | 18.3 ± 3.8 | 16.6 ± 4.9 |
| Drell–Yan | 0.25 ± 0.03 | 0.26 ± 0.03 | 0 |
| Total background | 701 ± 26 | 128.2 ± 8.3 | 304 ± 17 |
| Data | 700 | 133 | 301 |

Table 4: Observed data event yields and the expected background event yields with their total uncertainties in the CRs in the $e\tau$ and $\mu\tau$ channels after applying all selection criteria and the background-only fit. The “Fake” background is estimated directly by W +jets MC, and the multijet contribution is not considered in the $t\bar{t}$ CRs. The “Top Quarks” contains single top and $t\bar{t}$ events.

| Process | $e\tau$ channel $t\bar{t}$ CR | $\mu\tau$ channel $t\bar{t}$ CR |
|------------------|-------------------------------|---------------------------------|
| Top Quarks | 406 ± 21 | 305 ± 17 |
| Diboson | 9.6 ± 2.8 | 6.1 ± 1.6 |
| Fake | 6.8 ± 1.2 | 8.6 ± 2.6 |
| Drell–Yan | 2.1 ± 0.1 | 3.6 ± 0.7 |
| Total background | 424 ± 20 | 324 ± 17 |
| Data | 422 | 324 |

Table 5: Observed data event yields and the expected background event yields with their total uncertainties in the SR ($m_{\ell\ell'} > 600$ GeV) in the $e\mu$, $e\tau$, and $\mu\tau$ channels after applying all selection criteria and the background-only fit. The “Fake” background refers to “ W +jets” and “Multijet” events with fake leptons. The “Top Quarks” contains single top and $t\bar{t}$ events.

| Process | $e\mu$ channel | $e\tau$ channel | $\mu\tau$ channel |
|------------------|----------------|-----------------|-------------------|
| Top Quarks | 151 ± 15 | 114 ± 10 | 79.4 ± 6.4 |
| Diboson | 246 ± 28 | 125 ± 27 | 94 ± 20 |
| Fake | 66 ± 11 | 172 ± 34 | 67 ± 25 |
| Drell–Yan | 8.6 ± 0.5 | 76.1 ± 8.9 | 78.0 ± 7.9 |
| Total background | 471 ± 21 | 488 ± 21 | 319 ± 16 |
| Data | 470 | 499 | 319 |

Table 6: The fitted correction factors of “Top Quarks” and “Diboson” backgrounds which are applied in the SR for the background-only fit in the $e\mu$, $e\tau$ and $\mu\tau$ channel. For the $e\tau$ and $\mu\tau$ channels, the diboson correction factors are calculated from the CR-only fit results and put into the final fit as fixed normalisation factors.

| Correction factor | $e\mu$ | $e\tau$ | $\mu\tau$ |
|-------------------|-----------------|-----------------|-----------------|
| Top Quarks | 0.89 ± 0.06 | 0.94 ± 0.11 | 0.97 ± 0.11 |
| Diboson | 0.94 ± 0.11 | 1.05 ± 0.12 | 1.00 ± 0.12 |

Table 7: Expected and observed 95% CL lower limits on the mass of a Z' boson with lepton-flavour-violating couplings, a supersymmetric τ -sneutrino ($\tilde{\nu}_\tau$) with R -parity-violating couplings, and the threshold mass for quantum black-hole production for the ADD $n = 6$ and RS $n = 1$ models.

| Model | Observed (expected) 95% CL lower limit [TeV] | | |
|-----------------------------|--|-----------------|-------------------|
| | $e\mu$ channel | $e\tau$ channel | $\mu\tau$ channel |
| LFV Z' | 5.0 (4.8) | 4.0 (4.3) | 3.9 (4.2) |
| RPV SUSY $\tilde{\nu}_\tau$ | 3.9 (3.7) | 2.8 (3.0) | 2.7 (2.9) |
| QBH ADD $n = 6$ | 5.9 (5.7) | 5.2 (5.5) | 5.1 (5.2) |
| QBH RS $n = 1$ | 3.8 (3.6) | 3.0 (3.3) | 3.0 (3.1) |

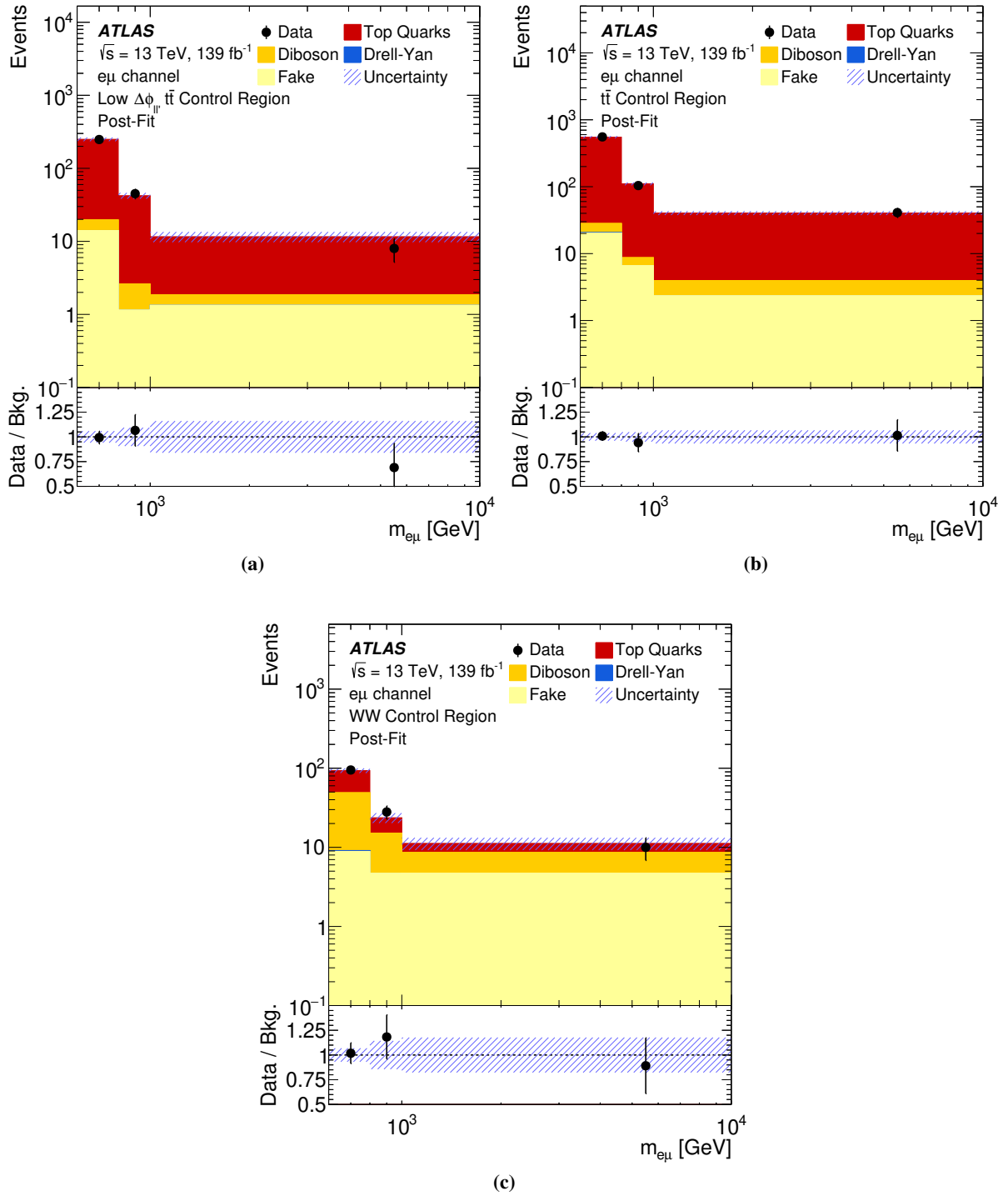


Figure 1: The background-only post-fit invariant mass distribution of (a) Low $\Delta\phi_{\ell\ell}$ $t\bar{t}$ CR, (b) $t\bar{t}$ CR and (c) WW CR for data and the SM background predictions in the $e\mu$ channel. The error bars show the statistical uncertainty of the observed yields, while the hashed band includes the post-fit total uncertainties taking into account all the correlations. The ratio of data to the best-fit prediction is shown in the bottom panels of the plots. The last bin contains the overflow events. The binning of the control regions was limited by the background statistics.

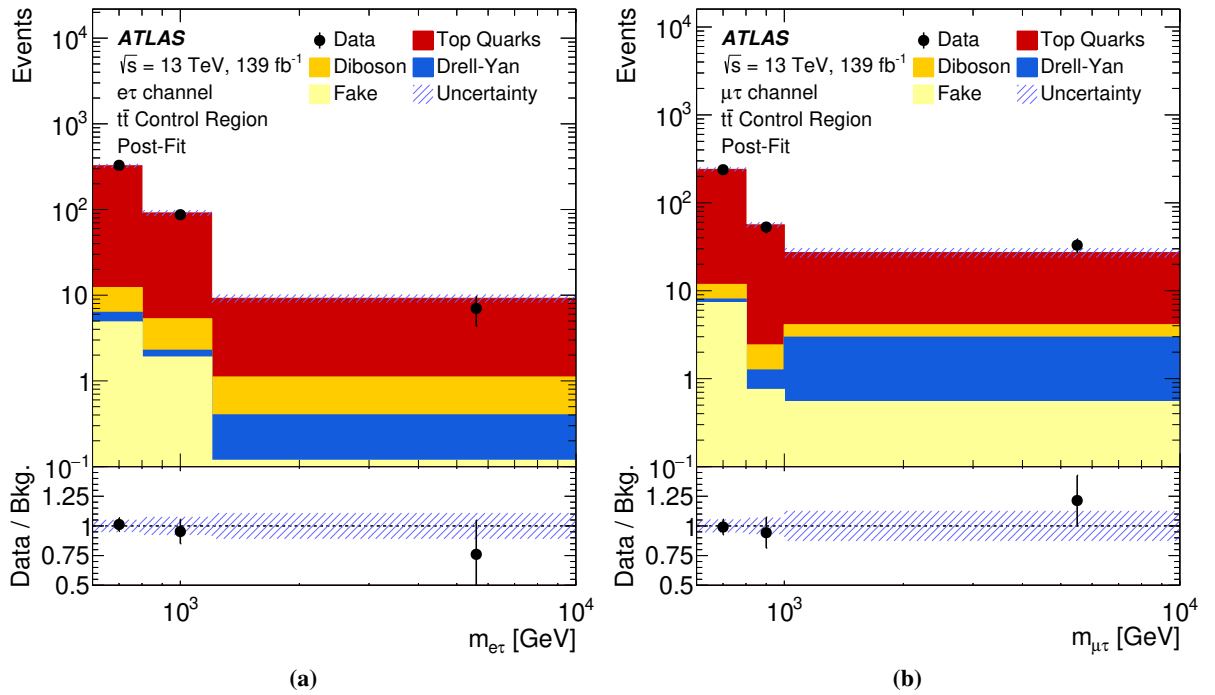


Figure 2: The background-only post-fit invariant mass distribution of (a) $e\tau$ and (b) $\mu\tau$ pairs for data and the SM background predictions in the $t\bar{t}$ CR. The error bars show the statistical uncertainty of the observed yields, while the hashed band includes the post-fit total uncertainties taking into account all the correlations. The ratio of data to the best-fit prediction is shown in the bottom panels of the plots. The last bin contains the overflow events.

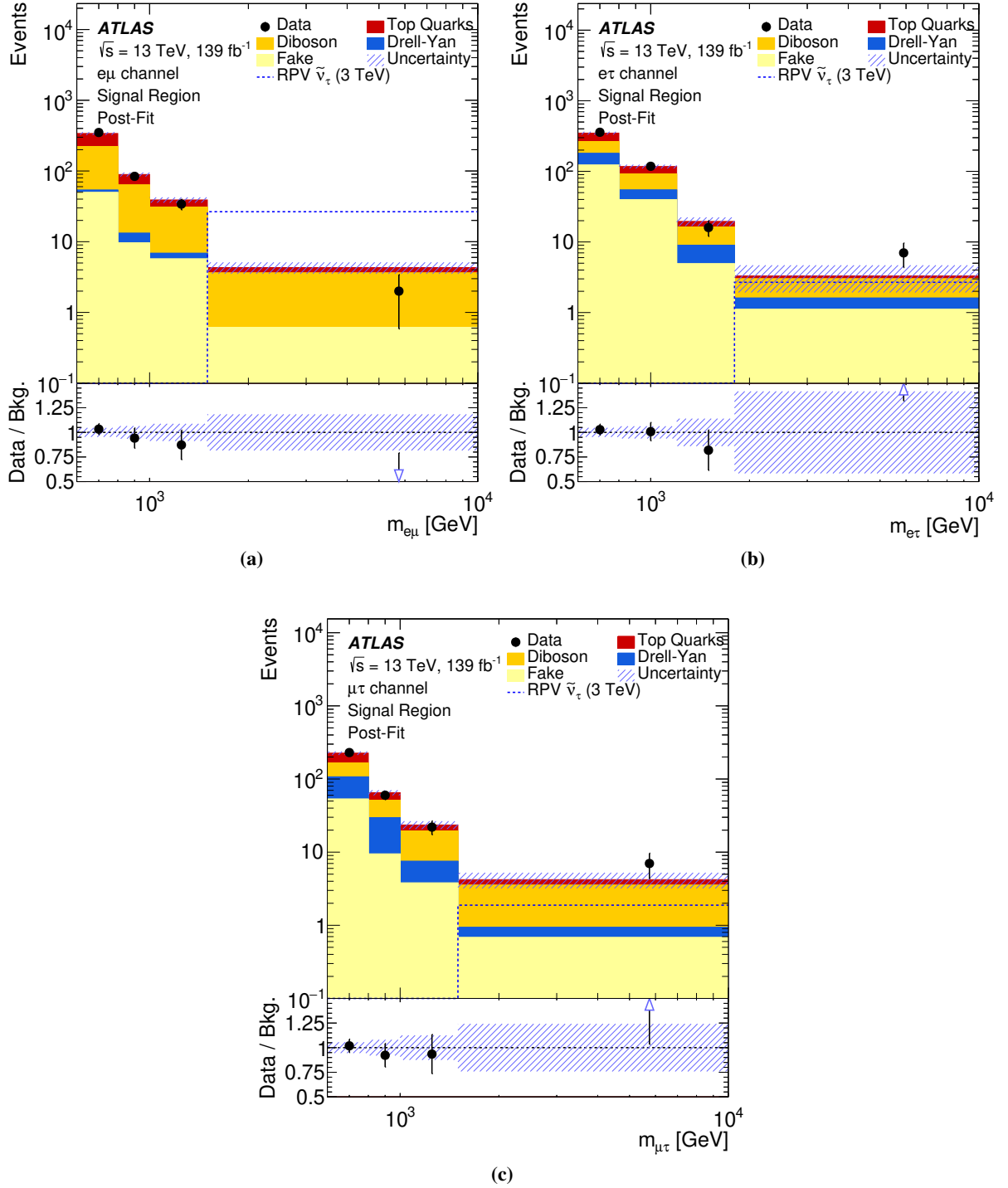


Figure 3: The background-only post-fit invariant mass distribution of (a) $e\mu$, (b) $e\tau$ and (c) $\mu\tau$ pairs for data and the SM background predictions in the SR. The error bars show the statistical uncertainty of the observed yields, while the hashed band includes the post-fit total uncertainties taking into account all the correlations. The dashed line shows a typical pre-fit signal mass distribution (RPV $\tilde{\nu}_\tau$ at 3 TeV). The ratio of data to the best-fit prediction is shown in the bottom panels of the plots. The arrow shows the difference between data and MC which exceeded the ratio range. The last bin contains the overflow events.

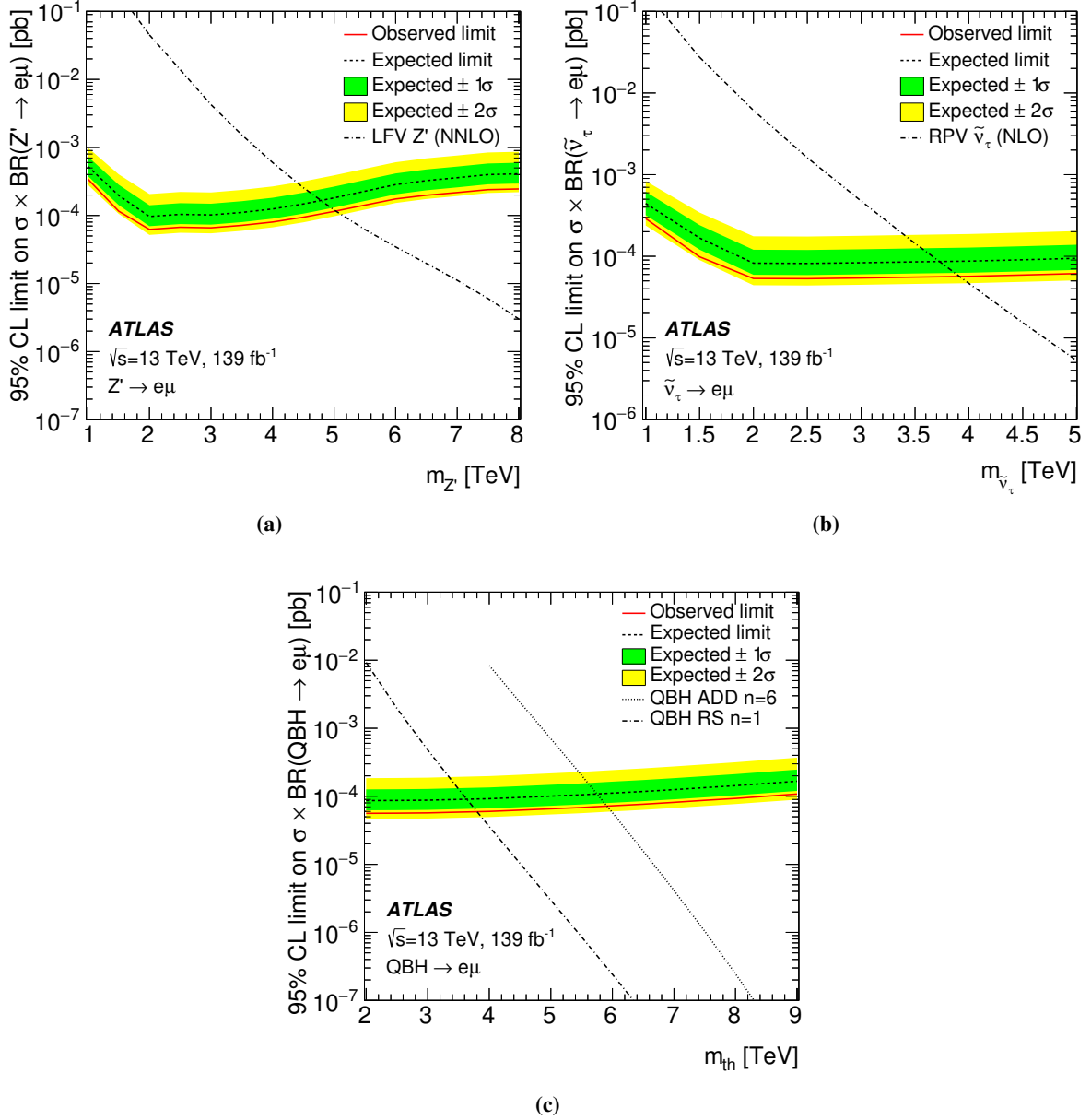


Figure 4: The observed and expected 95% CL upper limits on the (a) Z' boson, (b) RPV τ -sneutrino ($\tilde{\nu}_\tau$) and (c) QBH ADD and RS production cross-section times branching ratio for decays into an $e\mu$ final state. The signal theoretical cross-section times branching ratio lines for the Z' model, the QBH ADD model assuming six extra dimensions, and the RS model with one extra dimension are obtained from the simulation of each process, while the Z' is corrected to NNLO and the RPV $\tilde{\nu}_\tau$ is corrected to NLO. The theoretical uncertainties are not considered in the mass limit calculation. The acceptance times efficiency of the ADD and RS QBH models agree to within 1% and the same curve is used for limit extraction. The expected limits are shown with the ± 1 and ± 2 standard deviation uncertainty band.

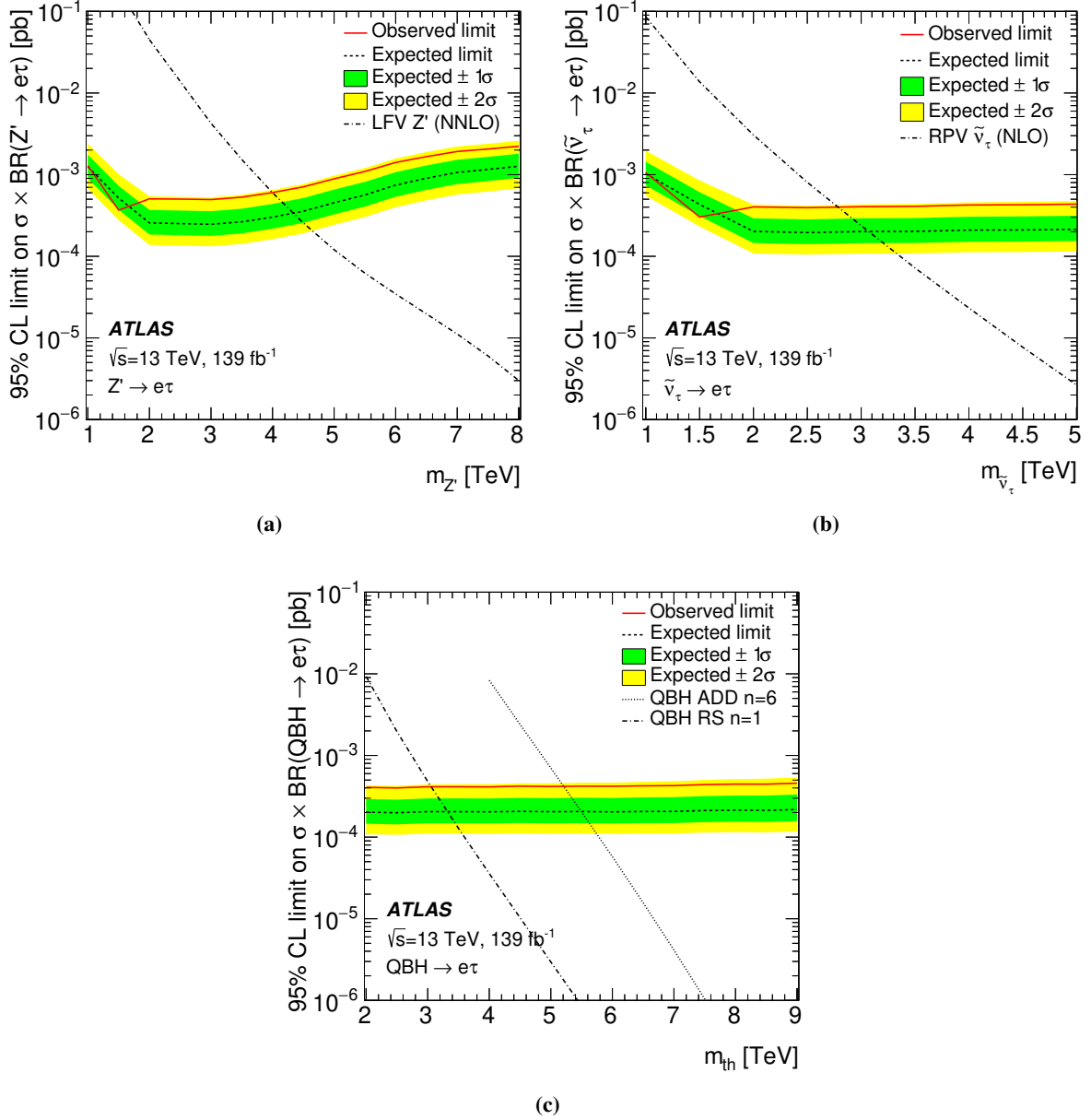


Figure 5: The observed and expected 95% CL upper limits on the (a) Z' boson, (b) RPV τ -sneutrino ($\tilde{\nu}_\tau$) and (c) QBH ADD and RS production cross-section times branching ratio for decays into an $e\tau$ final state. The signal theoretical cross-section times branching ratio lines for the Z' model, the QBH ADD model assuming six extra dimensions, and the RS model with one extra dimension are obtained from the simulation of each process, while the Z' is corrected to NNLO and the RPV $\tilde{\nu}_\tau$ is corrected to NLO. The theoretical uncertainties are not considered in the mass limit calculation. The acceptance times efficiency of the ADD and RS QBH models agree to within 1% and the same curve is used for limit extraction. The expected limits are shown with the ± 1 and ± 2 standard deviation uncertainty bands.

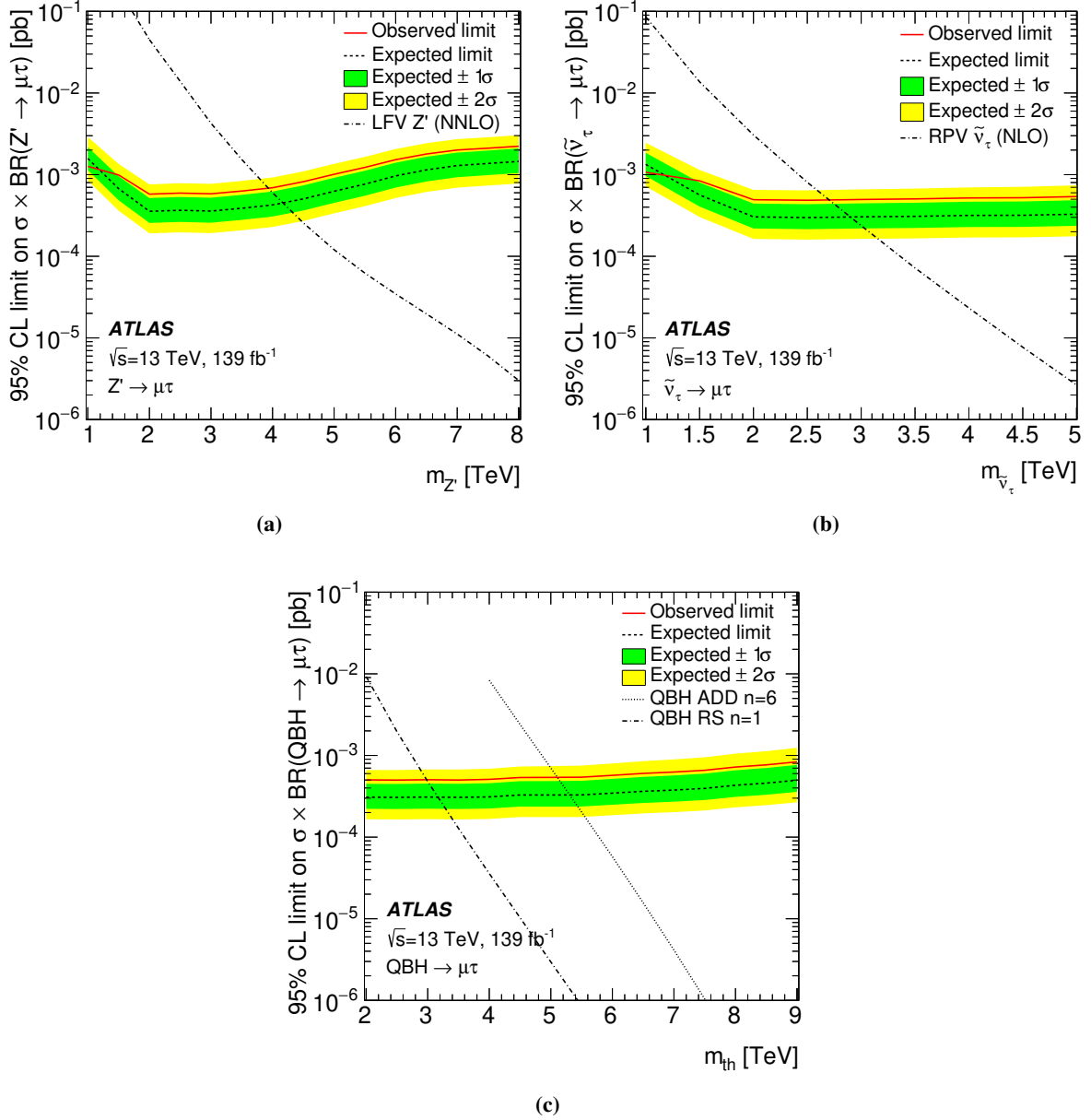


Figure 6: The observed and expected 95% CL upper limits on the (a) Z' boson, (b) RPV τ -sneutrino ($\tilde{\nu}_\tau$) and (c) QBH ADD and RS production cross-section times branching ratio for decays into a $\mu\tau$ final state. The signal theoretical cross-section times branching ratio lines for the Z' model, the QBH ADD model assuming six extra dimensions, and the RS model with one extra dimension are obtained from the simulation of each process, while the Z' is corrected to NNLO and the RPV $\tilde{\nu}_\tau$ is corrected to NLO. The theoretical uncertainties are not considered in the mass limit calculation. The acceptance times efficiency of the ADD and RS QBH models agree to within 1% and the same curve is used for limit extraction. The expected limits are shown with the ± 1 and ± 2 standard deviation uncertainty bands.

9 Conclusions

A search for a heavy particle decaying into $e\mu$, $e\tau$ or $\mu\tau$ final states is conducted using 139 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the Large Hadron Collider. The data are found to be consistent with the Standard Model expectation in the SR ($m_{\ell\ell'} > 600 \text{ GeV}$). With no evidence for new physics, profile likelihood fits are used to set 95% CL lower limits on the mass of a Z' vector boson with lepton-flavour-violating couplings at 5.0, 4.0 and 3.9 TeV for the $e\mu$, $e\tau$ or $\mu\tau$ final states, respectively; on the mass of a supersymmetric τ -sneutrino with R-parity-violating couplings at 3.9, 2.8 and 2.7 TeV; and on the threshold mass for quantum black-hole production in the context of the ADD $n=6$ (RS $n=1$) model at 5.9 (3.8), 5.2 (3.0) and 5.1 (3.0) TeV respectively.

For the mass limit of the Z' signal model, as an illustration, the observed results based on the full data samples recorded by the ATLAS experiment at $\sqrt{s} = 13 \text{ TeV}$ are more stringent by 0.6, 0.3 and 0.4 TeV than the corresponding limits based on the 36.1 fb^{-1} data samples at $\sqrt{s} = 13 \text{ TeV}$ [9]. The expected sensitivity is improved by 0.5, 0.6 and 0.7 TeV for the $e\mu$, $e\tau$ and $\mu\tau$ channels respectively. The increases on the observed limits in $e\tau$ and $\mu\tau$ channels are not as strong as the expected ones due to the slight excess observed in data. The major improvement comes from the four times larger data sample. The increase of sensitivity is also due to more accurate data-driven background estimates, as well as better particle reconstruction and identification.

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The ATLAS Collaboration

G. Aad ¹⁰², B. Abbott ¹²⁰, K. Abeling ⁵⁵, N.J. Abicht ⁴⁹, S.H. Abidi ²⁹, A. Aboulhorma ^{35e}, H. Abramowicz ¹⁵¹, H. Abreu ¹⁵⁰, Y. Abulaiti ¹¹⁷, A.C. Abusleme Hoffman ^{137a}, B.S. Acharya ^{69a,69b,r}, C. Adam Bourdarios ⁴, L. Adameczyk ^{86a}, L. Adamek ¹⁵⁵, S.V. Addepalli ²⁶, M.J. Addison ¹⁰¹, J. Adelman ¹¹⁵, A. Adiguzel ^{21c}, T. Abye ¹³⁴, A.A. Affolder ¹³⁶, Y. Afik ³⁶, M.N. Agaras ¹³, J. Agarwala ^{73a,73b}, A. Aggarwal ¹⁰⁰, C. Agheorghiesei ^{27c}, A. Ahmad ³⁶, F. Ahmadov ^{38,ai}, W.S. Ahmed ¹⁰⁴, S. Ahuja ⁹⁵, X. Ai ^{62a}, G. Aielli ^{76a,76b}, A. Aikot ¹⁶³, M. Ait Tamlihat ^{35e}, B. Aitbenchikh ^{35a}, I. Aizenberg ¹⁶⁹, M. Akbiyik ¹⁰⁰, T.P.A. Åkesson ⁹⁸, A.V. Akimov ³⁷, D. Akiyama ¹⁶⁸, N.N. Akolkar ²⁴, K. Al Khoury ⁴¹, G.L. Alberghi ^{23b}, J. Albert ¹⁶⁵, P. Albicocco ⁵³, G.L. Albouy ⁶⁰, S. Alderweireldt ⁵², M. Aleksa ³⁶, I.N. Aleksandrov ³⁸, C. Alexa ^{27b}, T. Alexopoulos ¹⁰, F. Alfonsi ^{23b}, M. Algren ⁵⁶, M. Alhroob ¹²⁰, B. Ali ¹³², H.M.J. Ali ⁹¹, S. Ali ¹⁴⁸, S.W. Alibocus ⁹², M. Aliev ¹⁴⁵, G. Alimonti ^{71a}, W. Alkakh ⁵⁵, C. Allaire ⁶⁶, B.M.M. Allbrooke ¹⁴⁶, J.F. Allen ⁵², C.A. Allendes Flores ^{137f}, P.P. Allport ²⁰, A. Aloisio ^{72a,72b}, F. Alonso ⁹⁰, C. Alpigiani ¹³⁸, M. Alvarez Estevez ⁹⁹, A. Alvarez Fernandez ¹⁰⁰, M. Alves Cardoso ⁵⁶, M.G. Alviggi ^{72a,72b}, M. Aly ¹⁰¹, Y. Amaral Coutinho ^{83b}, A. Ambler ¹⁰⁴, C. Amelung ³⁶, M. Amerl ¹⁰¹, C.G. Ames ¹⁰⁹, D. Amidei ¹⁰⁶, S.P. Amor Dos Santos ^{130a}, K.R. Amos ¹⁶³, V. Ananiev ¹²⁵, C. Anastopoulos ¹³⁹, T. Andeen ¹¹, J.K. Anders ³⁶, S.Y. Andreev ^{47a,47b}, A. Andreatta ^{71a,71b}, S. Angelidakis ⁹, A. Angerami ^{41,am}, A.V. Anisenkov ³⁷, A. Annovi ^{74a}, C. Antel ⁵⁶, M.T. Anthony ¹³⁹, E. Antipov ¹⁴⁵, M. Antonelli ⁵³, F. Anulli ^{75a}, M. Aoki ⁸⁴, T. Aoki ¹⁵³, J.A. Aparisi Pozo ¹⁶³, M.A. Aparo ¹⁴⁶, L. Aperio Bella ⁴⁸, C. Appelt ¹⁸, A. Apyan ²⁶, N. Aranzabal ³⁶, C. Arcangeletti ⁵³, A.T.H. Arce ⁵¹, E. Arena ⁹², J-F. Arguin ¹⁰⁸, S. Argyropoulos ⁵⁴, J.-H. Arling ⁴⁸, O. Arnaez ⁴, H. Arnold ¹¹⁴, G. Artoni ^{75a,75b}, H. Asada ¹¹¹, K. Asai ¹¹⁸, S. Asai ¹⁵³, N.A. Asbah ⁶¹, J. Assahsah ^{35d}, K. Assamagan ²⁹, R. Astalos ^{28a}, S. Atashi ¹⁶⁰, R.J. Atkin ^{33a}, M. Atkinson ¹⁶², H. Atmani ^{35f}, P.A. Atlasiddha ¹⁰⁶, K. Augsten ¹³², S. Auricchio ^{72a,72b}, A.D. Auriol ²⁰, V.A. Austrup ¹⁰¹, G. Avolio ³⁶, K. Axiotis ⁵⁶, G. Azuelos ^{108,au}, D. Babal ^{28b}, H. Bachacou ¹³⁵, K. Bachas ^{152,x}, A. Bachiu ³⁴, F. Backman ^{47a,47b}, A. Badea ⁶¹, P. Bagnaia ^{75a,75b}, M. Bahmani ¹⁸, A.J. Bailey ¹⁶³, V.R. Bailey ¹⁶², J.T. Baines ¹³⁴, L. Baines ⁹⁴, C. Bakalis ¹⁰, O.K. Baker ¹⁷², E. Bakos ¹⁵, D. Bakshi Gupta ⁸, V. Balakrishnan ¹²⁰, R. Balasubramanian ¹¹⁴, E.M. Baldin ³⁷, P. Balek ^{86a}, E. Ballabene ^{23b,23a}, F. Balli ¹³⁵, L.M. Baltes ^{63a}, W.K. Balunas ³², J. Balz ¹⁰⁰, E. Banas ⁸⁷, M. Bandieramonte ¹²⁹, A. Bandyopadhyay ²⁴, S. Bansal ²⁴, L. Barak ¹⁵¹, M. Barakat ⁴⁸, E.L. Barberio ¹⁰⁵, D. Barberis ^{57b,57a}, M. Barbero ¹⁰², K.N. Barends ^{33a}, T. Barillari ¹¹⁰, M-S. Barisits ³⁶, T. Barklow ¹⁴³, P. Baron ¹²², D.A. Baron Moreno ¹⁰¹, A. Baroncelli ^{62a}, G. Barone ²⁹, A.J. Barr ¹²⁶, J.D. Barr ⁹⁶, L. Barranco Navarro ^{47a,47b}, F. Barreiro ⁹⁹, J. Barreiro Guimarães da Costa ^{14a}, U. Barron ¹⁵¹, M.G. Barros Teixeira ^{130a}, S. Barsov ³⁷, F. Bartels ^{63a}, R. Bartoldus ¹⁴³, A.E. Barton ⁹¹, P. Bartos ^{28a}, A. Basan ¹⁰⁰, M. Baselga ⁴⁹, A. Bassalat ^{66,b}, M.J. Basso ^{156a}, C.R. Basson ¹⁰¹, R.L. Bates ⁵⁹, S. Batlamous ^{35e}, J.R. Batley ³², B. Batool ¹⁴¹, M. Battaglia ¹³⁶, D. Battulga ¹⁸, M. Bauge ^{75a,75b}, M. Bauer ³⁶, P. Bauer ²⁴, L.T. Bazzano Hurrell ³⁰, J.B. Beacham ⁵¹, T. Beau ¹²⁷, P.H. Beauchemin ¹⁵⁸, F. Becherer ⁵⁴, P. Bechtel ²⁴, H.P. Beck ^{19,v}, K. Becker ¹⁶⁷, A.J. Beddall ⁸², V.A. Bednyakov ³⁸, C.P. Bee ¹⁴⁵, L.J. Beemster ¹⁵, T.A. Beermann ³⁶, M. Begalli ^{83d}, M. Begel ²⁹, A. Behera ¹⁴⁵, J.K. Behr ⁴⁸, J.F. Beirer ⁵⁵, F. Beisiegel ²⁴, M. Belfkir ¹⁵⁹, G. Bella ¹⁵¹, L. Bellagamba ^{23b}, A. Bellerive ³⁴, P. Bellos ²⁰, K. Beloborodov ³⁷, N.L. Belyaev ³⁷, D. Benckekroun ^{35a}, F. Bendebba ^{35a}, Y. Benhammou ¹⁵¹,

M. Benoit ²⁹, J.R. Bensinger ²⁶, S. Bentvelsen ¹¹⁴, L. Beresford ⁴⁸, M. Beretta ⁵³,
E. Bergeaas Kuutmann ¹⁶¹, N. Berger ⁴, B. Bergmann ¹³², J. Beringer ^{17a}, G. Bernardi ⁵,
C. Bernius ¹⁴³, F.U. Bernlochner ²⁴, F. Bernon ^{36,102}, T. Berry ⁹⁵, P. Berta ¹³³, A. Berthold ⁵⁰,
I.A. Bertram ⁹¹, S. Bethke ¹¹⁰, A. Betti ^{75a,75b}, A.J. Bevan ⁹⁴, M. Bhamjee ^{33c}, S. Bhatta ¹⁴⁵,
D.S. Bhattacharya ¹⁶⁶, P. Bhattarai ¹⁴³, V.S. Bhopatkar ¹²¹, R. Bi ^{29,aw}, R.M. Bianchi ¹²⁹,
G. Bianco ^{23b,23a}, O. Biebel ¹⁰⁹, R. Bielski ¹²³, M. Biglietti ^{77a}, T.R.V. Billoud ¹³², M. Bindi ⁵⁵,
A. Bingul ^{21b}, C. Bini ^{75a,75b}, A. Biondini ⁹², C.J. Birch-sykes ¹⁰¹, G.A. Bird ^{20,134},
M. Birman ¹⁶⁹, M. Biros ¹³³, T. Bisanz ⁴⁹, E. Bisceglie ^{43b,43a}, D. Biswas ¹⁴¹, A. Bitadze ¹⁰¹,
K. Bjørke ¹²⁵, I. Bloch ⁴⁸, C. Blocker ²⁶, A. Blue ⁵⁹, U. Blumenschein ⁹⁴, J. Blumenthal ¹⁰⁰,
G.J. Bobbink ¹¹⁴, V.S. Bobrovnikov ³⁷, M. Boehler ⁵⁴, B. Boehm ¹⁶⁶, D. Bogavac ³⁶,
A.G. Bogdanchikov ³⁷, C. Bohm ^{47a}, V. Boisvert ⁹⁵, P. Bokan ⁴⁸, T. Bold ^{86a}, M. Bomben ⁵,
M. Bona ⁹⁴, M. Boonekamp ¹³⁵, C.D. Booth ⁹⁵, A.G. Borbély ^{59,ar}, I.S. Bordulev ³⁷,
H.M. Borecka-Bielska ¹⁰⁸, L.S. Borgna ⁹⁶, G. Borissov ⁹¹, D. Bortoletto ¹²⁶, D. Boscherini ^{23b},
M. Bosman ¹³, J.D. Bossio Sola ³⁶, K. Bouaouda ^{35a}, N. Bouchhar ¹⁶³, J. Boudreau ¹²⁹,
E.V. Bouhova-Thacker ⁹¹, D. Boumediene ⁴⁰, R. Bouquet ⁵, A. Boveia ¹¹⁹, J. Boyd ³⁶,
D. Boye ²⁹, I.R. Boyko ³⁸, J. Bracik ²⁰, N. Brahimi ^{62d}, G. Brandt ¹⁷¹, O. Brandt ³²,
F. Braren ⁴⁸, B. Brau ¹⁰³, J.E. Brau ¹²³, R. Brenner ¹⁶⁹, L. Brenner ¹¹⁴, R. Brenner ¹⁶¹,
S. Bressler ¹⁶⁹, D. Britton ⁵⁹, D. Britzger ¹¹⁰, I. Brock ²⁴, G. Brooijmans ⁴¹, W.K. Brooks ^{137f},
E. Brost ²⁹, L.M. Brown ^{165,o}, L.E. Bruce ⁶¹, T.L. Bruckler ¹²⁶, P.A. Bruckman de Renstrom ⁸⁷,
B. Brüers ⁴⁸, A. Bruni ^{23b}, G. Bruni ^{23b}, M. Bruschi ^{23b}, N. Bruscinò ^{75a,75b}, T. Buanes ¹⁶,
Q. Buat ¹³⁸, D. Buchin ¹¹⁰, A.G. Buckley ⁵⁹, M.K. Bugge ¹²⁵, O. Bulekov ³⁷, B.A. Bullard ¹⁴³,
S. Burdin ⁹², C.D. Burgard ⁴⁹, A.M. Burger ⁴⁰, B. Burghgrave ⁸, O. Burlayenko ⁵⁴,
J.T.P. Burr ³², C.D. Burton ¹¹, J.C. Burzynski ¹⁴², E.L. Busch ⁴¹, V. Büscher ¹⁰⁰, P.J. Bussey ⁵⁹,
J.M. Butler ²⁵, C.M. Buttar ⁵⁹, J.M. Butterworth ⁹⁶, W. Buttinger ¹³⁴, C.J. Buxo Vazquez ¹⁰⁷,
A.R. Buzykaev ³⁷, S. Cabrera Urbán ¹⁶³, L. Cadamuro ⁶⁶, D. Caforio ⁵⁸, H. Cai ¹²⁹,
Y. Cai ^{14a,14e}, V.M.M. Cairo ³⁶, O. Cakir ^{3a}, N. Calace ³⁶, P. Calafiura ^{17a}, G. Calderini ¹²⁷,
P. Calfayan ⁶⁸, G. Callea ⁵⁹, L.P. Caloba ^{83b}, D. Calvet ⁴⁰, S. Calvet ⁴⁰, T.P. Calvet ¹⁰²,
M. Calvetti ^{74a,74b}, R. Camacho Toro ¹²⁷, S. Camarda ³⁶, D. Camarero Munoz ²⁶,
P. Camarri ^{76a,76b}, M.T. Camerlingo ^{72a,72b}, D. Cameron ^{36,h}, C. Camincher ¹⁶⁵,
M. Campanelli ⁹⁶, A. Camplani ⁴², V. Canale ^{72a,72b}, A. Canesse ¹⁰⁴, J. Cantero ¹⁶³, Y. Cao ¹⁶²,
F. Capocasa ²⁶, M. Capua ^{43b,43a}, A. Carbone ^{71a,71b}, R. Cardarelli ^{76a}, J.C.J. Cardenas ⁸,
F. Cardillo ¹⁶³, T. Carli ³⁶, G. Carlino ^{72a}, J.I. Carlotta ¹³, B.T. Carlson ^{129,y},
E.M. Carlson ^{165,156a}, L. Carminati ^{71a,71b}, A. Carnelli ¹³⁵, M. Carnesale ^{75a,75b}, S. Caron ¹¹³,
E. Carquin ^{137f}, S. Carrá ^{71a,71b}, G. Carratta ^{23b,23a}, F. Carri Argos ^{33g}, J.W.S. Carter ¹⁵⁵,
T.M. Carter ⁵², M.P. Casado ^{13,k}, M. Caspar ⁴⁸, E.G. Castiglia ¹⁷², F.L. Castillo ⁴,
L. Castillo Garcia ¹³, V. Castillo Gimenez ¹⁶³, N.F. Castro ^{130a,130e}, A. Catinaccio ³⁶,
J.R. Catmore ¹²⁵, V. Cavaliere ²⁹, N. Cavalli ^{23b,23a}, V. Cavasinni ^{74a,74b}, Y.C. Cekmecelioglu ⁴⁸,
E. Celebi ^{21a}, F. Celli ¹²⁶, M.S. Centonze ^{70a,70b}, V. Cepaitis ⁵⁶, K. Cerny ¹²²,
A.S. Cerqueira ^{83a}, A. Cerri ¹⁴⁶, L. Cerrito ^{76a,76b}, F. Cerutti ^{17a}, B. Cervato ¹⁴¹, A. Cervelli ^{23b},
G. Cesarini ⁵³, S.A. Cetin ⁸², Z. Chadi ^{35a}, D. Chakraborty ¹¹⁵, J. Chan ¹⁷⁰, W.Y. Chan ¹⁵³,
J.D. Chapman ³², E. Chapon ¹³⁵, B. Chargeishvili ^{149b}, D.G. Charlton ²⁰, T.P. Charman ⁹⁴,
M. Chatterjee ¹⁹, C. Chauhan ¹³³, S. Chekanov ⁶, S.V. Chekulaev ^{156a}, G.A. Chelkov ^{38,a},
A. Chen ¹⁰⁶, B. Chen ¹⁵¹, B. Chen ¹⁶⁵, H. Chen ^{14c}, H. Chen ²⁹, J. Chen ^{62c}, J. Chen ¹⁴²,
M. Chen ¹²⁶, S. Chen ¹⁵³, S.J. Chen ^{14c}, X. Chen ^{62c,135}, X. Chen ^{14b,at}, Y. Chen ^{62a},
C.L. Cheng ¹⁷⁰, H.C. Cheng ^{64a}, S. Cheong ¹⁴³, A. Cheplakov ³⁸, E. Cheremushkina ⁴⁸,
E. Cherepanova ¹¹⁴, R. Cherkaoui El Moursli ^{35e}, E. Cheu ⁷, K. Cheung ⁶⁵, L. Chevalier ¹³⁵,
V. Chiarella ⁵³, G. Chiarelli ^{74a}, N. Chiedde ¹⁰², G. Chiodini ^{70a}, A.S. Chisholm ²⁰,

A. Chitan ^{27b}, M. Chitishvili ¹⁶³, M.V. Chizhov ³⁸, K. Choi ¹¹, A.R. Chomont ^{75a,75b},
 Y. Chou ¹⁰³, E.Y.S. Chow ¹¹⁴, T. Chowdhury ^{33g}, K.L. Chu ¹⁶⁹, M.C. Chu ^{64a}, X. Chu ^{14a,14e},
 J. Chudoba ¹³¹, J.J. Chwastowski ⁸⁷, D. Cieri ¹¹⁰, K.M. Ciesla ^{86a}, V. Cindro ⁹³, A. Ciocio ^{17a},
 F. Cirotto ^{72a,72b}, Z.H. Citron ^{169,p}, M. Citterio ^{71a}, D.A. Ciubotaru ^{27b}, B.M. Ciungu ¹⁵⁵,
 A. Clark ⁵⁶, P.J. Clark ⁵², J.M. Clavijo Columbie ⁴⁸, S.E. Clawson ⁴⁸, C. Clement ^{47a,47b},
 J. Clercx ⁴⁸, L. Clissa ^{23b,23a}, Y. Coadou ¹⁰², M. Cobal ^{69a,69c}, A. Coccaro ^{57b},
 R.F. Coelho Barrue ^{130a}, R. Coelho Lopes De Sa ¹⁰³, S. Coelli ^{71a}, H. Cohen ¹⁵¹,
 A.E.C. Coimbra ^{71a,71b}, B. Cole ⁴¹, J. Collot ⁶⁰, P. Conde Muiño ^{130a,130g}, M.P. Connell ^{33c},
 S.H. Connell ^{33c}, I.A. Connelly ⁵⁹, E.I. Conroy ¹²⁶, F. Conventi ^{72a,av}, H.G. Cooke ²⁰,
 A.M. Cooper-Sarkar ¹²⁶, A. Cordeiro Oudot Choi ¹²⁷, F. Cormier ¹⁶⁴, L.D. Corpe ⁴⁰,
 M. Corradi ^{75a,75b}, F. Corriveau ^{104,ag}, A. Cortes-Gonzalez ¹⁸, M.J. Costa ¹⁶³, F. Costanza ⁴,
 D. Costanzo ¹³⁹, B.M. Cote ¹¹⁹, G. Cowan ⁹⁵, K. Cranmer ¹⁷⁰, D. Cremonini ^{23b,23a},
 S. Crépe-Renaudin ⁶⁰, F. Crescioli ¹²⁷, M. Cristinziani ¹⁴¹, M. Cristoforetti ^{78a,78b}, V. Croft ¹¹⁴,
 J.E. Crosby ¹²¹, G. Crosetti ^{43b,43a}, A. Cueto ⁹⁹, T. Cuhadar Donszelmann ¹⁶⁰, H. Cui ^{14a,14e},
 Z. Cui ⁷, W.R. Cunningham ⁵⁹, F. Curcio ^{43b,43a}, P. Czodrowski ³⁶, M.M. Czurylo ^{63b},
 M.J. Da Cunha Sargedas De Sousa ^{57b,57a}, J.V. Da Fonseca Pinto ^{83b}, C. Da Via ¹⁰¹,
 W. Dabrowski ^{86a}, T. Dado ⁴⁹, S. Dahbi ^{33g}, T. Dai ¹⁰⁶, D. Dal Santo ¹⁹, C. Dallapiccola ¹⁰³,
 M. Dam ⁴², G. D'amen ²⁹, V. D'Amico ¹⁰⁹, J. Damp ¹⁰⁰, J.R. Dandoy ¹²⁸, M.F. Daneri ³⁰,
 M. Danninger ¹⁴², V. Dao ³⁶, G. Darbo ^{57b}, S. Darmora ⁶, S.J. Das ^{29,aw}, S. D'Auria ^{71a,71b},
 C. David ^{156b}, T. Davidek ¹³³, B. Davis-Purcell ³⁴, I. Dawson ⁹⁴, H.A. Day-hall ¹³², K. De ⁸,
 R. De Asmundis ^{72a}, N. De Biase ⁴⁸, S. De Castro ^{23b,23a}, N. De Groot ¹¹³, P. de Jong ¹¹⁴,
 H. De la Torre ¹¹⁵, A. De Maria ^{14c}, A. De Salvo ^{75a}, U. De Sanctis ^{76a,76b}, A. De Santo ¹⁴⁶,
 J.B. De Vivie De Regie ⁶⁰, D.V. Dedovich ³⁸, J. Degens ¹¹⁴, A.M. Deiana ⁴⁴, F. Del Corso ^{23b,23a},
 J. Del Peso ⁹⁹, F. Del Rio ^{63a}, F. Deliot ¹³⁵, C.M. Delitzsch ⁴⁹, M. Della Pietra ^{72a,72b},
 D. Della Volpe ⁵⁶, A. Dell'Acqua ³⁶, L. Dell'Asta ^{71a,71b}, M. Delmastro ⁴, P.A. Delsart ⁶⁰,
 S. Demers ¹⁷², M. Demichev ³⁸, S.P. Denisov ³⁷, L. D'Eramo ⁴⁰, D. Derendarz ⁸⁷, F. Derue ¹²⁷,
 P. Dervan ⁹², K. Desch ²⁴, C. Deutsch ²⁴, F.A. Di Bello ^{57b,57a}, A. Di Ciaccio ^{76a,76b},
 L. Di Ciaccio ⁴, A. Di Domenico ^{75a,75b}, C. Di Donato ^{72a,72b}, A. Di Girolamo ³⁶,
 G. Di Gregorio ⁵, A. Di Luca ^{78a,78b}, B. Di Micco ^{77a,77b}, R. Di Nardo ^{77a,77b}, C. Diaconu ¹⁰²,
 M. Diamantopoulou ³⁴, F.A. Dias ¹¹⁴, T. Dias Do Vale ¹⁴², M.A. Diaz ^{137a,137b},
 F.G. Diaz Capriles ²⁴, M. Didenko ¹⁶³, E.B. Diehl ¹⁰⁶, L. Diehl ⁵⁴, S. Díez Cornell ⁴⁸,
 C. Diez Pardos ¹⁴¹, C. Dimitriadi ^{161,24,161}, A. Dimitrievska ^{17a}, J. Dingfelder ²⁴, I-M. Dinu ^{27b},
 S.J. Dittmeier ^{63b}, F. Dittus ³⁶, F. Djama ¹⁰², T. Djobava ^{149b}, J.I. Djuvsland ¹⁶,
 C. Doglioni ^{101,98}, A. Dohnalova ^{28a}, J. Dolejsi ¹³³, Z. Dolezal ¹³³, M. Donadelli ^{83c},
 B. Dong ¹⁰⁷, J. Donini ⁴⁰, A. D'Onofrio ^{77a,77b}, M. D'Onofrio ⁹², J. Dopke ¹³⁴, A. Doria ^{72a},
 N. Dos Santos Fernandes ^{130a}, P. Dougan ¹⁰¹, M.T. Dova ⁹⁰, A.T. Doyle ⁵⁹, M.A. Draguet ¹²⁶,
 E. Dreyer ¹⁶⁹, I. Drivas-koulouris ¹⁰, A.S. Drobac ¹⁵⁸, M. Drozdova ⁵⁶, D. Du ^{62a},
 T.A. du Pree ¹¹⁴, F. Dubinin ³⁷, M. Dubovsky ^{28a}, E. Duchovni ¹⁶⁹, G. Duckeck ¹⁰⁹,
 O.A. Ducu ^{27b}, D. Duda ⁵², A. Dudarev ³⁶, E.R. Duden ²⁶, M. D'uffizi ¹⁰¹, L. Duflot ⁶⁶,
 M. Dührssen ³⁶, C. Dülsen ¹⁷¹, A.E. Dumitriu ^{27b}, M. Dunford ^{63a}, S. Dungs ⁴⁹,
 K. Dunne ^{47a,47b}, A. Duperrin ¹⁰², H. Duran Yildiz ^{3a}, M. Düren ⁵⁸, A. Durglishvili ^{149b},
 B.L. Dwyer ¹¹⁵, G.I. Dyckes ^{17a}, M. Dyndal ^{86a}, S. Dysch ¹⁰¹, B.S. Dziedzic ⁸⁷,
 Z.O. Earnshaw ¹⁴⁶, G.H. Eberwein ¹²⁶, B. Eckerova ^{28a}, S. Eggebrecht ⁵⁵,
 E. Egidio Purcino De Souza ¹²⁷, L.F. Ehrke ⁵⁶, G. Eigen ¹⁶, K. Einsweiler ^{17a}, T. Ekelof ¹⁶¹,
 P.A. Ekman ⁹⁸, S. El Farkh ^{35b}, Y. El Ghazali ^{35b}, H. El Jarrari ^{35e,148}, A. El Moussaouy ^{35a},
 V. Ellajosyula ¹⁶¹, M. Ellert ¹⁶¹, F. Ellinghaus ¹⁷¹, A.A. Elliot ⁹⁴, N. Ellis ³⁶, J. Elmsheuser ²⁹,
 M. Elsing ³⁶, D. Emeliyanov ¹³⁴, Y. Enari ¹⁵³, I. Ene ^{17a}, S. Epari ¹³, J. Erdmann ⁴⁹,

P.A. Erland [ID87](#), M. Errenst [ID171](#), M. Escalier [ID66](#), C. Escobar [ID163](#), E. Etzion [ID151](#), G. Evans [ID130a](#),
 H. Evans [ID68](#), L.S. Evans [ID95](#), M.O. Evans [ID146](#), A. Ezhilov [ID37](#), S. Ezzarqtouni [ID35a](#), F. Fabbri [ID59](#),
 L. Fabbri [ID23b,23a](#), G. Facini [ID96](#), V. Fadeyev [ID136](#), R.M. Fakhruddinov [ID37](#), S. Falciano [ID75a](#),
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J. Grosse-Knetter ⁵⁵, C. Grud ¹⁰⁶, J.C. Grundy ¹²⁶, L. Guan ¹⁰⁶, W. Guan ¹⁷⁰, C. Gubbels ¹⁶⁴, J.G.R. Guerrero Rojas ¹⁶³, G. Guerrieri ^{69a,69c}, F. Guescini ¹¹⁰, R. Gugel ¹⁰⁰, J.A.M. Guhit ¹⁰⁶, A. Guida ¹⁸, T. Guillemain ⁴, E. Guilloton ^{167,134}, S. Guindon ³⁶, F. Guo ^{14a,14e}, J. Guo ^{62c}, L. Guo ⁴⁸, Y. Guo ¹⁰⁶, R. Gupta ⁴⁸, S. Gurbuz ²⁴, S.S. Gurdasani ⁵⁴, G. Gustavino ³⁶, M. Guth ⁵⁶, P. Gutierrez ¹²⁰, L.F. Gutierrez Zagazeta ¹²⁸, C. Gutschow ⁹⁶, C. Gwenlan ¹²⁶, C.B. Gwilliam ⁹², E.S. Haaland ¹²⁵, A. Haas ¹¹⁷, M. Habedank ⁴⁸, C. Haber ^{17a}, H.K. Hadavand ⁸, A. Hadeef ¹⁰⁰, S. Hadzic ¹¹⁰, J.J. Hahn ¹⁴¹, E.H. Haines ⁹⁶, M. Haleem ¹⁶⁶, J. Haley ¹²¹, J.J. Hall ¹³⁹, G.D. Hallewell ¹⁰², L. Halser ¹⁹, K. Hamano ¹⁶⁵, M. Hamer ²⁴, G.N. Hamity ⁵², E.J. Hampshire ⁹⁵, J. Han ^{62b}, K. Han ^{62a}, L. Han ^{14c}, L. Han ^{62a}, S. Han ^{17a}, Y.F. Han ¹⁵⁵, K. Hanagaki ⁸⁴, M. Hance ¹³⁶, D.A. Hangal ^{41,am}, H. Hanif ¹⁴², M.D. Hank ¹²⁸, R. Hankache ¹⁰¹, J.B. Hansen ⁴², J.D. Hansen ⁴², P.H. Hansen ⁴², K. Hara ¹⁵⁷, D. Harada ⁵⁶, T. Harenberg ¹⁷¹, S. Harkusha ³⁷, M.L. Harris ¹⁰³, Y.T. Harris ¹²⁶, J. Harrison ¹³, N.M. Harrison ¹¹⁹, P.F. Harrison ¹⁶⁷, N.M. Hartman ¹⁴³, N.M. Hartmann ¹⁰⁹, Y. Hasegawa ¹⁴⁰, A. Hasib ⁵², S. Haug ¹⁹, R. Hauser ¹⁰⁷, C.M. Hawkes ²⁰, R.J. Hawkins ³⁶, Y. Hayashi ¹⁵³, S. Hayashida ¹¹¹, D. Hayden ¹⁰⁷, C. Hayes ¹⁰⁶, R.L. Hayes ¹¹⁴, C.P. Hays ¹²⁶, J.M. Hays ⁹⁴, H.S. Hayward ⁹², F. He ^{62a}, M. He ^{14a,14e}, Y. He ¹⁵⁴, Y. He ¹²⁷, N.B. Heatley ⁹⁴, V. Hedberg ⁹⁸, A.L. Heggelund ¹²⁵, N.D. Hehir ⁹⁴, C. Heidegger ⁵⁴, K.K. Heidegger ⁵⁴, W.D. Heidorn ⁸¹, J. Heilman ³⁴, S. Heim ⁴⁸, T. Heim ^{17a}, J.G. Heinlein ¹²⁸, J.J. Heinrich ¹²³, L. Heinrich ^{110,as}, J. Hejbal ¹³¹, L. Helary ⁴⁸, A. Held ¹⁷⁰, S. Hellesund ¹⁶, C.M. Helling ¹⁶⁴, S. Hellman ^{47a,47b}, R.C.W. Henderson ⁹¹, L. Henkelmann ³², A.M. Henriques Correia ³⁶, H. Herde ⁹⁸, Y. Hernández Jiménez ¹⁴⁵, L.M. Herrmann ²⁴, T. Herrmann ⁵⁰, G. Herten ⁵⁴, R. Hertenberger ¹⁰⁹, L. Hervas ³⁶, M.E. Hespings ¹⁰⁰, N.P. Hessey ^{156a}, H. Hibi ⁸⁵, S.J. Hillier ²⁰, J.R. Hinds ¹⁰⁷, F. Hinterkeuser ²⁴, M. Hirose ¹²⁴, S. Hirose ¹⁵⁷, D. Hirschbuehl ¹⁷¹, T.G. Hitchings ¹⁰¹, B. Hiti ⁹³, J. Hobbs ¹⁴⁵, R. Hobincu ^{27e}, N. Hod ¹⁶⁹, M.C. Hodgkinson ¹³⁹, B.H. Hodgkinson ³², A. Hoecker ³⁶, J. Hofer ⁴⁸, T. Holm ²⁴, M. Holzbock ¹¹⁰, L.B.A.H. Hommels ³², B.P. Honan ¹⁰¹, J. Hong ^{62c}, T.M. Hong ¹²⁹, B.H. Hooberman ¹⁶², W.H. Hopkins ⁶, Y. Horii ¹¹¹, S. Hou ¹⁴⁸, A.S. Howard ⁹³, J. Howarth ⁵⁹, J. Hoya ⁶, M. Hrabovsky ¹²², A. Hrynevich ⁴⁸, T. Hryn'ova ⁴, P.J. Hsu ⁶⁵, S.-C. Hsu ¹³⁸, Q. Hu ⁴¹, Y.F. Hu ^{14a,14e}, S. Huang ^{64b}, X. Huang ^{14c}, Y. Huang ^{139,n}, Y. Huang ^{14a}, Z. Huang ¹⁰¹, Z. Hubacek ¹³², M. Huebner ²⁴, F. Huegging ²⁴, T.B. Huffman ¹²⁶, C.A. Hugli ⁴⁸, M. Huhtinen ³⁶, S.K. Huiberts ¹⁶, R. Hulsken ¹⁰⁴, N. Huseynov ^{12,a}, J. Huston ¹⁰⁷, J. Huth ⁶¹, R. Hyneman ¹⁴³, G. Iacobucci ⁵⁶, G. Iakovidis ²⁹, I. Ibragimov ¹⁴¹, L. Iconomidou-Fayard ⁶⁶, P. Iengo ^{72a,72b}, R. Iguchi ¹⁵³, T. Iizawa ^{126,s}, Y. Ikegami ⁸⁴, N. Ilic ¹⁵⁵, H. Imam ^{35a}, M. Ince Lezki ⁵⁶, T. Ingebretsen Carlson ^{47a,47b}, G. Introzzi ^{73a,73b}, M. Iodice ^{77a}, V. Ippolito ^{75a,75b}, R.K. Irwin ⁹², M. Ishino ¹⁵³, W. Islam ¹⁷⁰, C. Issever ^{18,48}, S. Istin ^{21a,ay}, H. Ito ¹⁶⁸, J.M. Iturbe Ponce ^{64a}, R. Iuppa ^{78a,78b}, A. Ivina ¹⁶⁹, J.M. Izen ⁴⁵, V. Izzo ^{72a}, P. Jacka ^{131,132}, P. Jackson ¹, R.M. Jacobs ⁴⁸, B.P. Jaeger ¹⁴², C.S. Jagfeld ¹⁰⁹, P. Jain ⁵⁴, G. Jäkel ¹⁷¹, K. Jakobs ⁵⁴, T. Jakoubek ¹⁶⁹, J. Jamieson ⁵⁹, K.W. Janas ^{86a}, M. Javurkova ¹⁰³, F. Jeanneau ¹³⁵, L. Jeanty ¹²³, J. Jejelava ^{149a,aj}, P. Jenni ^{54,i}, C.E. Jessiman ³⁴, S. Jézéquel ⁴, C. Jia ^{62b}, J. Jia ¹⁴⁵, X. Jia ⁶¹, X. Jia ^{14a,14e}, Z. Jia ^{14c}, Y. Jiang ^{62a}, S. Jiggins ⁴⁸, J. Jimenez Pena ¹³, S. Jin ^{14c}, A. Jinaru ^{27b}, O. Jinnouchi ¹⁵⁴, P. Johansson ¹³⁹, K.A. Johns ⁷, J.W. Johnson ¹³⁶, D.M. Jones ³², E. Jones ⁴⁸, P. Jones ³², R.W.L. Jones ⁹¹, T.J. Jones ⁹², R. Joshi ¹¹⁹, J. Jovicevic ¹⁵, X. Ju ^{17a}, J.J. Junggeburth ^{103,w}, T. Junkermann ^{63a}, A. Juste Rozas ^{13,ac}, M.K. Juzek ⁸⁷, S. Kabana ^{137e}, A. Kaczmarzka ⁸⁷, M. Kado ¹¹⁰, H. Kagan ¹¹⁹, M. Kagan ¹⁴³, A. Kahn ⁴¹, A. Kahn ¹²⁸, C. Kahra ¹⁰⁰, T. Kaji ¹⁵³, E. Kajomovitz ¹⁵⁰, N. Kakati ¹⁶⁹, I. Kalaitzidou ⁵⁴, C.W. Calderon ²⁹, A. Kamenshchikov ¹⁵⁵, N.J. Kang ¹³⁶, D. Kar ^{33g}, K. Karava ¹²⁶, M.J. Kareem ^{156b}, E. Karentzos ⁵⁴, I. Karkanias ¹⁵², O. Karkout ¹¹⁴, S.N. Karpov ³⁸, Z.M. Karpova ³⁸,

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 M. Mikestikova ¹³¹, M. Mikuž ⁹³, H. Mildner ¹⁰⁰, A. Milic ³⁶, C.D. Milke ⁴⁴, D.W. Miller ³⁹,
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 L.M. Mir ¹³, M. Miralles Lopez ¹⁶³, M. Mironova ^{17a}, A. Mishima ¹⁵³, M.C. Missio ¹¹³,
 A. Mitra ¹⁶⁷, V.A. Mitsou ¹⁶³, Y. Mitsumori ¹¹¹, O. Miu ¹⁵⁵, P.S. Miyagawa ⁹⁴,
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G.N. Taylor [id105](#), W. Taylor [id156b](#), H. Teagle⁹², A.S. Tee [id170](#), R. Teixeira De Lima [id143](#), P. Teixeira-Dias [id95](#), J.J. Teoh [id155](#), K. Terashi [id153](#), J. Terron [id99](#), S. Terzo [id13](#), M. Testa [id53](#), R.J. Teuscher [id155,ag](#), A. Thaler [id79](#), O. Theiner [id56](#), N. Themistokleous [id52](#), T. Thevenaux-Pelzer [id102](#), O. Thielmann [id171](#), D.W. Thomas⁹⁵, J.P. Thomas [id20](#), E.A. Thompson [id17a](#), P.D. Thompson [id20](#), E. Thomson [id128](#), Y. Tian [id55](#), V. Tikhomirov [id37,a](#), Yu.A. Tikhonov [id37](#), S. Timoshenko³⁷, D. Timoshyn [id133](#), E.X.L. Ting [id1](#), P. Tipton [id172](#), S.H. Tlou [id33g](#), A. Tnourji [id40](#), K. Todome [id154](#), S. Todorova-Nova [id133](#), S. Todt⁵⁰, M. Togawa [id84](#), J. Tojo [id89](#), S. Tokár [id28a](#), K. Tokushuku [id84](#), O. Toldaiev [id68](#), R. Tombs [id32](#), M. Tomoto [id84,111](#), L. Tompkins [id143,u](#), K.W. Topolnicki [id86b](#), E. Torrence [id123](#), H. Torres [id102,al](#), E. Torró Pastor [id163](#), M. Toscani [id30](#), C. Toscirri [id39](#), M. Tost [id11](#), D.R. Tovey [id139](#), A. Traeet¹⁶, I.S. Trandafir [id27b](#), T. Trefzger [id166](#), A. Tricoli [id29](#), I.M. Trigger [id156a](#), S. Trincaz-Duvoid [id127](#), D.A. Trischuk [id26](#), B. Trocmé [id60](#), C. Troncon [id71a](#), L. Truong [id33c](#), M. Trzebinski [id87](#), A. Trzupsek [id87](#), F. Tsai [id145](#), M. Tsai [id106](#), A. Tsiamis [id152,f](#), P.V. Tsiareshka³⁷, S. Tsigaridas [id156a](#), A. Tsirigotis [id152,ab](#), V. Tsiskaridze [id155](#), E.G. Tskhadadze^{149a}, M. Tsopoulou [id152,f](#), Y. Tsujikawa [id88](#), I.I. Tsukerman [id37](#), V. Tsulaia [id17a](#), S. Tsuno [id84](#), O. Tsur¹⁵⁰, K. Tsurii¹¹⁸, D. Tsybychev [id145](#), Y. Tu [id64b](#), A. Tudorache [id27b](#), V. Tudorache [id27b](#), A.N. Tuna [id36](#), S. Turchikhin [id38](#), I. Turk Cakir [id3a](#), R. Turra [id71a](#), T. Turtuvshin [id38,ah](#), P.M. Tuts [id41](#), S. Tzamarias [id152,f](#), P. Tzanis [id10](#), E. Tzovara [id100](#), F. Ukegawa [id157](#), P.A. Ulloa Poblete [id137c,137b](#), E.N. Umaka [id29](#), G. Unal [id36](#), M. Unal [id11](#), A. Undrus [id29](#), G. Unel [id160](#), J. Urban [id28b](#), P. Urquijo [id105](#), G. Usai [id8](#), R. Ushioda [id154](#), M. Usman [id108](#), Z. Uysal [id21b](#), L. Vacavant [id102](#), V. Vacek [id132](#), B. Vachon [id104](#), K.O.H. Vadla [id125](#), T. Vafeiadis [id36](#), A. Vaitkus [id96](#), C. Valderanis [id109](#), E. Valdes Santurio [id47a,47b](#), M. Valente [id156a](#), S. Valentinetti [id23b,23a](#), A. Valero [id163](#), E. Valiente Moreno [id163](#), A. Vallier [id102,al](#), J.A. Valls Ferrer [id163](#), D.R. Van Arneeman [id114](#), T.R. Van Daalen [id138](#), A. Van Der Graaf [id49](#), P. Van Gemmeren [id6](#), M. Van Rijnbach [id125,36](#), S. Van Stroud [id96](#), I. Van Vulpen [id114](#), M. Vanadia [id76a,76b](#), W. Vandelli [id36](#), M. Vandenbroucke [id135](#), E.R. Vandewall [id121](#), D. Vannicola [id151](#), L. Vannoli [id57b,57a](#), R. Vari [id75a](#), E.W. Varnes [id7](#), C. Varni [id17b](#), T. Varol [id148](#), D. Varouchas [id66](#), L. Varriale [id163](#), K.E. Varvell [id147](#), M.E. Vasile [id27b](#), L. Vaslin⁴⁰, G.A. Vasquez [id165](#), A. Vasyukov [id38](#), F. Vazeille [id40](#), T. Vazquez Schroeder [id36](#), J. Veatch [id31](#), V. Vecchio [id101](#), M.J. Veen [id103](#), I. Veliscek [id126](#), L.M. Veloce [id155](#), F. Veloso [id130a,130c](#), S. Veneziano [id75a](#), A. Ventura [id70a,70b](#), S. Ventura Gonzalez [id135](#), A. Verbytskyi [id110](#), M. Verducci [id74a,74b](#), C. Vergis [id24](#), M. Verissimo De Araujo [id83b](#), W. Verkerke [id114](#), J.C. Vermeulen [id114](#), C. Vernieri [id143](#), M. Vessella [id103](#), M.C. Vetterli [id142,au](#), A. Vgenopoulos [id152,f](#), N. Viaux Maira [id137f](#), T. Vickey [id139](#), O.E. Vickey Boeriu [id139](#), G.H.A. Viehhauser [id126](#), L. Vigani [id63b](#), M. Villa [id23b,23a](#), M. Villaplana Perez [id163](#), E.M. Villhauer⁵², E. Vilucchi [id53](#), M.G. Vincter [id34](#), G.S. Virdee [id20](#), A. Vishwakarma [id52](#), A. Visibile¹¹⁴, C. Vittori [id36](#), I. Vivarelli [id146](#), V. Vladimirov¹⁶⁷, E. Voevodina [id110](#), F. Vogel [id109](#), P. Vokac [id132](#), Yu. Volkotrub [id86a](#), J. Von Ahnen [id48](#), E. Von Toerne [id24](#), B. Vormwald [id36](#), V. Vorobel [id133](#), K. Vorobev [id37](#), M. Vos [id163](#), K. Voss [id141](#), J.H. Vosseveld [id92](#), M. Vozak [id114](#), L. Vozdecky [id94](#), N. Vranjes [id15](#), M. Vranjes Milosavljevic [id15](#), M. Vreeswijk [id114](#), N.K. Vu [id62d,62c](#), R. Vuillermet [id36](#), O. Vujinovic [id100](#), I. Vukotic [id39](#), S. Wada [id157](#), C. Wagner¹⁰³, J.M. Wagner [id17a](#), W. Wagner [id171](#), S. Wahdan [id171](#), H. Wahlberg [id90](#), M. Wakida [id111](#), J. Walder [id134](#), R. Walker [id109](#), W. Walkowiak [id141](#), A. Wall [id128](#), T. Wamorkar [id6](#), A.Z. Wang [id170](#), C. Wang [id100](#), C. Wang [id62c](#), H. Wang [id17a](#), J. Wang [id64a](#), R.-J. Wang [id100](#), R. Wang [id61](#), R. Wang [id6](#), S.M. Wang [id148](#), S. Wang [id62b](#), T. Wang [id62a](#), W.T. Wang [id80](#), W. Wang [id14a](#), X. Wang [id14c](#), X. Wang [id162](#), X. Wang [id62c](#), Y. Wang [id62d](#), Y. Wang [id14c](#), Z. Wang [id106](#), Z. Wang [id62d,51,62c](#), Z. Wang [id106](#), A. Warburton [id104](#), R.J. Ward [id20](#), N. Warrack [id59](#), A.T. Watson [id20](#), H. Watson [id59](#), M.F. Watson [id20](#), E. Watton [id59,134](#), G. Watts [id138](#), B.M. Waugh [id96](#), C. Weber [id29](#), H.A. Weber [id18](#), M.S. Weber [id19](#), S.M. Weber [id63a](#), C. Wei^{62a}, Y. Wei [id126](#), A.R. Weidberg [id126](#), E.J. Weik [id117](#), J. Weingarten [id49](#), M. Weirich [id100](#), C. Weiser [id54](#), C.J. Wells [id48](#), T. Wenaus [id29](#), B. Wendland [id49](#), T. Wengler [id36](#), N.S. Wenke¹¹⁰,

N. Wermes ¹[ID](#)²⁴, M. Wessels ¹[ID](#)^{63a}, A.M. Wharton ¹[ID](#)⁹¹, A.S. White ¹[ID](#)⁶¹, A. White ¹[ID](#)⁸, M.J. White ¹[ID](#)¹, D. Whiteson ¹[ID](#)¹⁶⁰, L. Wickremasinghe ¹[ID](#)¹²⁴, W. Wiedenmann ¹[ID](#)¹⁷⁰, C. Wiel ¹[ID](#)⁵⁰, M. Wieler ¹[ID](#)¹³⁴, C. Wiglesworth ¹[ID](#)⁴², D.J. Wilbern ¹[ID](#)¹²⁰, H.G. Wilkens ¹[ID](#)³⁶, D.M. Williams ¹[ID](#)⁴¹, H.H. Williams ¹[ID](#)¹²⁸, S. Williams ¹[ID](#)³², S. Willocq ¹[ID](#)¹⁰³, B.J. Wilson ¹[ID](#)¹⁰¹, P.J. Windischhofer ¹[ID](#)³⁹, F.I. Winkel ¹[ID](#)³⁰, F. Winklmeier ¹[ID](#)¹²³, B.T. Winter ¹[ID](#)⁵⁴, J.K. Winter ¹[ID](#)¹⁰¹, M. Wittgen ¹[ID](#)¹⁴³, M. Wobisch ¹[ID](#)⁹⁷, Z. Wolffs ¹[ID](#)¹¹⁴, R. Wölker ¹[ID](#)¹²⁶, J. Wollrath ¹[ID](#)¹⁶⁰, M.W. Wolter ¹[ID](#)⁸⁷, H. Wolters ¹[ID](#)^{130a,130c}, A.F. Wongel ¹[ID](#)⁴⁸, S.D. Worm ¹[ID](#)⁴⁸, B.K. Wosiek ¹[ID](#)⁸⁷, K.W. Woźniak ¹[ID](#)⁸⁷, S. Wozniewski ¹[ID](#)⁵⁵, K. Wraight ¹[ID](#)⁵⁹, C. Wu ¹[ID](#)²⁰, J. Wu ¹[ID](#)^{14a,14e}, M. Wu ¹[ID](#)^{64a}, M. Wu ¹[ID](#)¹¹³, S.L. Wu ¹[ID](#)¹⁷⁰, X. Wu ¹[ID](#)⁵⁶, Y. Wu ¹[ID](#)^{62a}, Z. Wu ¹[ID](#)¹³⁵, J. Wuerzinger ¹[ID](#)^{110,as}, T.R. Wyatt ¹[ID](#)¹⁰¹, B.M. Wynne ¹[ID](#)⁵², S. Xella ¹[ID](#)⁴², L. Xia ¹[ID](#)^{14c}, M. Xia ¹[ID](#)^{14b}, J. Xiang ¹[ID](#)^{64c}, M. Xie ¹[ID](#)^{62a}, X. Xie ¹[ID](#)^{62a}, S. Xin ¹[ID](#)^{14a,14e}, J. Xiong ¹[ID](#)^{17a}, D. Xu ¹[ID](#)^{14a}, H. Xu ¹[ID](#)^{62a}, L. Xu ¹[ID](#)^{62a}, R. Xu ¹[ID](#)¹²⁸, T. Xu ¹[ID](#)¹⁰⁶, Y. Xu ¹[ID](#)^{14b}, Z. Xu ¹[ID](#)⁵², Z. Xu ¹[ID](#)^{14a}, B. Yabsley ¹[ID](#)¹⁴⁷, S. Yacoob ¹[ID](#)^{33a}, Y. Yamaguchi ¹[ID](#)¹⁵⁴, E. Yamashita ¹[ID](#)¹⁵³, H. Yamauchi ¹[ID](#)¹⁵⁷, T. Yamazaki ¹[ID](#)^{17a}, Y. Yamazaki ¹[ID](#)⁸⁵, J. Yan ¹[ID](#)^{62c}, S. Yan ¹[ID](#)¹²⁶, Z. Yan ¹[ID](#)²⁵, H.J. Yang ¹[ID](#)^{62c,62d}, H.T. Yang ¹[ID](#)^{62a}, S. Yang ¹[ID](#)^{62a}, T. Yang ¹[ID](#)^{64c}, X. Yang ¹[ID](#)^{62a}, X. Yang ¹[ID](#)^{14a}, Y. Yang ¹[ID](#)⁴⁴, Y. Yang ¹[ID](#)^{62a}, Z. Yang ¹[ID](#)^{62a}, W-M. Yao ¹[ID](#)^{17a}, Y.C. Yap ¹[ID](#)⁴⁸, H. Ye ¹[ID](#)^{14c}, H. Ye ¹[ID](#)⁵⁵, J. Ye ¹[ID](#)⁴⁴, S. Ye ¹[ID](#)²⁹, X. Ye ¹[ID](#)^{62a}, Y. Yeh ¹[ID](#)⁹⁶, I. Yeletsikh ¹[ID](#)³⁸, B.K. Yeo ¹[ID](#)^{17b}, M.R. Yexley ¹[ID](#)⁹⁶, P. Yin ¹[ID](#)⁴¹, K. Yorita ¹[ID](#)¹⁶⁸, S. Younas ¹[ID](#)^{27b}, C.J.S. Young ¹[ID](#)³⁶, C. Young ¹[ID](#)¹⁴³, Y. Yu ¹[ID](#)^{62a}, M. Yuan ¹[ID](#)¹⁰⁶, R. Yuan ¹[ID](#)^{62b,m}, L. Yue ¹[ID](#)⁹⁶, M. Zaazoua ¹[ID](#)^{62a}, B. Zabinski ¹[ID](#)⁸⁷, E. Zaid ¹[ID](#)⁵², T. Zakareishvili ¹[ID](#)^{149b}, N. Zakharchuk ¹[ID](#)³⁴, S. Zambito ¹[ID](#)⁵⁶, J.A. Zamora Saa ¹[ID](#)^{137d,137b}, J. Zang ¹[ID](#)¹⁵³, D. Zanzi ¹[ID](#)⁵⁴, O. Zaplatilek ¹[ID](#)¹³², C. Zeitnitz ¹[ID](#)¹⁷¹, H. Zeng ¹[ID](#)^{14a}, J.C. Zeng ¹[ID](#)¹⁶², D.T. Zenger Jr ¹[ID](#)²⁶, O. Zenin ¹[ID](#)³⁷, T. Ženiš ¹[ID](#)^{28a}, S. Zenz ¹[ID](#)⁹⁴, S. Zerradi ¹[ID](#)^{35a}, D. Zerwas ¹[ID](#)⁶⁶, M. Zhai ¹[ID](#)^{14a,14e}, B. Zhang ¹[ID](#)^{14c}, D.F. Zhang ¹[ID](#)¹³⁹, J. Zhang ¹[ID](#)^{62b}, J. Zhang ¹[ID](#)⁶, K. Zhang ¹[ID](#)^{14a,14e}, L. Zhang ¹[ID](#)^{62a}, L. Zhang ¹[ID](#)^{14c}, P. Zhang ¹[ID](#)^{14a,14e}, R. Zhang ¹[ID](#)¹⁷⁰, S. Zhang ¹[ID](#)¹⁰⁶, T. Zhang ¹[ID](#)¹⁵³, X. Zhang ¹[ID](#)^{62c}, X. Zhang ¹[ID](#)^{62b}, Y. Zhang ¹[ID](#)^{62c,5}, Y. Zhang ¹[ID](#)⁹⁶, Z. Zhang ¹[ID](#)^{17a}, Z. Zhang ¹[ID](#)⁶⁶, H. Zhao ¹[ID](#)¹³⁸, P. Zhao ¹[ID](#)⁵¹, T. Zhao ¹[ID](#)^{62b}, Y. Zhao ¹[ID](#)¹³⁶, Z. Zhao ¹[ID](#)^{62a}, A. Zhemchugov ¹[ID](#)³⁸, J. Zheng ¹[ID](#)^{14c}, K. Zheng ¹[ID](#)¹⁶², X. Zheng ¹[ID](#)^{62a}, Z. Zheng ¹[ID](#)¹⁴³, D. Zhong ¹[ID](#)¹⁶², B. Zhou ¹[ID](#)¹⁰⁶, H. Zhou ¹[ID](#)⁷, N. Zhou ¹[ID](#)^{62c}, Y. Zhou ¹[ID](#)⁷, C.G. Zhu ¹[ID](#)^{62b}, J. Zhu ¹[ID](#)¹⁰⁶, Y. Zhu ¹[ID](#)^{62c}, Y. Zhu ¹[ID](#)^{62a}, X. Zhuang ¹[ID](#)^{14a}, K. Zhukov ¹[ID](#)³⁷, V. Zhulanov ¹[ID](#)³⁷, N.I. Zimine ¹[ID](#)³⁸, J. Zinsser ¹[ID](#)^{63b}, M. Ziolkowski ¹[ID](#)¹⁴¹, L. Živković ¹[ID](#)¹⁵, A. Zoccoli ¹[ID](#)^{23b,23a}, K. Zoch ¹[ID](#)⁵⁶, T.G. Zorbas ¹[ID](#)¹³⁹, O. Zormpa ¹[ID](#)⁴⁶, W. Zou ¹[ID](#)⁴¹, L. Zwalinski ¹[ID](#)³⁶.

¹Department of Physics, University of Adelaide, Adelaide; Australia.

²Department of Physics, University of Alberta, Edmonton AB; Canada.

³(^a)Department of Physics, Ankara University, Ankara; (^b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department of Physics, University of Texas at Austin, Austin TX; United States of America.

¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹³Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

¹⁴(^a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (^b)Physics Department, Tsinghua University, Beijing; (^c)Department of Physics, Nanjing University, Nanjing; (^d)School of Science, Shenzhen Campus of Sun Yat-sen University; (^e)University of Chinese Academy of Science (UCAS),

Beijing; China.

¹⁵Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁶Department for Physics and Technology, University of Bergen, Bergen; Norway.

¹⁷(^a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (^b) University of California, Berkeley CA; United States of America.

¹⁸Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

¹⁹Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

²⁰School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

²¹(^a) Department of Physics, Bogazici University, Istanbul; (^b) Department of Physics Engineering, Gaziantep University, Gaziantep; (^c) Department of Physics, Istanbul University, Istanbul; Türkiye.

²²(^a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (^b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; (^c) Pontificia Universidad Javeriana, Bogota; Colombia.

²³(^a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (^b) INFN Sezione di Bologna; Italy.

²⁴Physikalisches Institut, Universität Bonn, Bonn; Germany.

²⁵Department of Physics, Boston University, Boston MA; United States of America.

²⁶Department of Physics, Brandeis University, Waltham MA; United States of America.

²⁷(^a) Transilvania University of Brasov, Brasov; (^b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (^c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (^d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (^e) University Politehnica Bucharest, Bucharest; (^f) West University in Timisoara, Timisoara; (^g) Faculty of Physics, University of Bucharest, Bucharest; Romania.

²⁸(^a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (^b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.

²⁹Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.

³⁰Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.

³¹California State University, CA; United States of America.

³²Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.

³³(^a) Department of Physics, University of Cape Town, Cape Town; (^b) iThemba Labs, Western

Cape; (^c) Department of Mechanical Engineering Science, University of Johannesburg,

Johannesburg; (^d) National Institute of Physics, University of the Philippines Diliman

(Philippines); (^e) University of South Africa, Department of Physics, Pretoria; (^f) University of Zululand, KwaDlangezwa; (^g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa.

³⁴Department of Physics, Carleton University, Ottawa ON; Canada.

³⁵(^a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (^b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; (^c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (^d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (^e) Faculté des sciences, Université Mohammed V, Rabat; (^f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

³⁶CERN, Geneva; Switzerland.

³⁷Affiliated with an institute covered by a cooperation agreement with CERN.

³⁸Affiliated with an international laboratory covered by a cooperation agreement with CERN.

³⁹Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

- ⁴⁰LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴¹Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴²Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ⁴³(^a)Dipartimento di Fisica, Università della Calabria, Rende; (^b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁴Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴⁵Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ⁴⁶National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ⁴⁷(^a)Department of Physics, Stockholm University; (^b)Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁸Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁹Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- ⁵⁰Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵¹Department of Physics, Duke University, Durham NC; United States of America.
- ⁵²SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵³INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁴Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁵II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁶Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁷(^a)Dipartimento di Fisica, Università di Genova, Genova; (^b)INFN Sezione di Genova; Italy.
- ⁵⁸II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁹SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁶⁰LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶¹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶²(^a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (^b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (^c)School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; (^d)Tsung-Dao Lee Institute, Shanghai; China.
- ⁶³(^a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (^b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶⁴(^a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (^b)Department of Physics, University of Hong Kong, Hong Kong; (^c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
- ⁶⁵Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶⁶IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁷Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁶⁸Department of Physics, Indiana University, Bloomington IN; United States of America.
- ⁶⁹(^a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (^b)ICTP, Trieste; (^c)Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- ⁷⁰(^a)INFN Sezione di Lecce; (^b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ⁷¹(^a)INFN Sezione di Milano; (^b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ⁷²(^a)INFN Sezione di Napoli; (^b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ⁷³(^a)INFN Sezione di Pavia; (^b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ⁷⁴(^a)INFN Sezione di Pisa; (^b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ⁷⁵(^a)INFN Sezione di Roma; (^b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ⁷⁶(^a)INFN Sezione di Roma Tor Vergata; (^b)Dipartimento di Fisica, Università di Roma Tor Vergata,

Roma; Italy.

^{77(a)}INFN Sezione di Roma Tre; ^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

^{78(a)}INFN-TIFPA; ^(b)Università degli Studi di Trento, Trento; Italy.

⁷⁹Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.

⁸⁰University of Iowa, Iowa City IA; United States of America.

⁸¹Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

⁸²Istinye University, Sariyer, Istanbul; Türkiye.

^{83(a)}Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c)Instituto de Física, Universidade de São Paulo, São Paulo; ^(d)Rio de Janeiro State University, Rio de Janeiro; Brazil.

⁸⁴KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.

⁸⁵Graduate School of Science, Kobe University, Kobe; Japan.

^{86(a)}AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.

⁸⁷Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

⁸⁸Faculty of Science, Kyoto University, Kyoto; Japan.

⁸⁹Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.

⁹⁰Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

⁹¹Physics Department, Lancaster University, Lancaster; United Kingdom.

⁹²Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

⁹³Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

⁹⁴School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

⁹⁵Department of Physics, Royal Holloway University of London, Egham; United Kingdom.

⁹⁶Department of Physics and Astronomy, University College London, London; United Kingdom.

⁹⁷Louisiana Tech University, Ruston LA; United States of America.

⁹⁸Fysiska institutionen, Lunds universitet, Lund; Sweden.

⁹⁹Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.

¹⁰⁰Institut für Physik, Universität Mainz, Mainz; Germany.

¹⁰¹School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

¹⁰²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.

¹⁰³Department of Physics, University of Massachusetts, Amherst MA; United States of America.

¹⁰⁴Department of Physics, McGill University, Montreal QC; Canada.

¹⁰⁵School of Physics, University of Melbourne, Victoria; Australia.

¹⁰⁶Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

¹⁰⁷Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.

¹⁰⁸Group of Particle Physics, University of Montreal, Montreal QC; Canada.

¹⁰⁹Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.

¹¹⁰Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.

¹¹¹Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.

¹¹²Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.

¹¹³Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.

- ¹¹⁴Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹¹⁵Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ¹¹⁶(^a)New York University Abu Dhabi, Abu Dhabi; (^b)University of Sharjah, Sharjah; United Arab Emirates.
- ¹¹⁷Department of Physics, New York University, New York NY; United States of America.
- ¹¹⁸Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ¹¹⁹Ohio State University, Columbus OH; United States of America.
- ¹²⁰Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- ¹²¹Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- ¹²²Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
- ¹²³Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
- ¹²⁴Graduate School of Science, Osaka University, Osaka; Japan.
- ¹²⁵Department of Physics, University of Oslo, Oslo; Norway.
- ¹²⁶Department of Physics, Oxford University, Oxford; United Kingdom.
- ¹²⁷LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
- ¹²⁸Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
- ¹²⁹Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- ¹³⁰(^a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (^b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; (^c)Departamento de Física, Universidade de Coimbra, Coimbra; (^d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (^e)Departamento de Física, Universidade do Minho, Braga; (^f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); (^g)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
- ¹³¹Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
- ¹³²Czech Technical University in Prague, Prague; Czech Republic.
- ¹³³Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
- ¹³⁴Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
- ¹³⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- ¹³⁶Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
- ¹³⁷(^a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (^b)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; (^c)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; (^d)Universidad Andres Bello, Department of Physics, Santiago; (^e)Instituto de Alta Investigación, Universidad de Tarapacá, Arica; (^f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
- ¹³⁸Department of Physics, University of Washington, Seattle WA; United States of America.
- ¹³⁹Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ¹⁴⁰Department of Physics, Shinshu University, Nagano; Japan.
- ¹⁴¹Department Physik, Universität Siegen, Siegen; Germany.
- ¹⁴²Department of Physics, Simon Fraser University, Burnaby BC; Canada.
- ¹⁴³SLAC National Accelerator Laboratory, Stanford CA; United States of America.
- ¹⁴⁴Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
- ¹⁴⁵Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of

America.

¹⁴⁶Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

¹⁴⁷School of Physics, University of Sydney, Sydney; Australia.

¹⁴⁸Institute of Physics, Academia Sinica, Taipei; Taiwan.

¹⁴⁹^(a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; ^(c)University of Georgia, Tbilisi; Georgia.

¹⁵⁰Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

¹⁵¹Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

¹⁵²Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

¹⁵³International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

¹⁵⁴Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

¹⁵⁵Department of Physics, University of Toronto, Toronto ON; Canada.

¹⁵⁶^(a)TRIUMF, Vancouver BC; ^(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.

¹⁵⁷Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

¹⁵⁸Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

¹⁵⁹United Arab Emirates University, Al Ain; United Arab Emirates.

¹⁶⁰Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

¹⁶¹Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

¹⁶²Department of Physics, University of Illinois, Urbana IL; United States of America.

¹⁶³Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

¹⁶⁴Department of Physics, University of British Columbia, Vancouver BC; Canada.

¹⁶⁵Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

¹⁶⁶Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

¹⁶⁷Department of Physics, University of Warwick, Coventry; United Kingdom.

¹⁶⁸Waseda University, Tokyo; Japan.

¹⁶⁹Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.

¹⁷⁰Department of Physics, University of Wisconsin, Madison WI; United States of America.

¹⁷¹Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

¹⁷²Department of Physics, Yale University, New Haven CT; United States of America.

^a Also Affiliated with an institute covered by a cooperation agreement with CERN.

^b Also at An-Najah National University, Nablus; Palestine.

^c Also at APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

^d Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

^e Also at Center for High Energy Physics, Peking University; China.

^f Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki ; Greece.

^g Also at Centro Studi e Ricerche Enrico Fermi; Italy.

^h Also at CERN Tier-0; Switzerland.

ⁱ Also at CERN, Geneva; Switzerland.

^j Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

^k Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

- ^l Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^m Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ⁿ Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ^o Also at Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- ^p Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
- ^q Also at Department of Physics, California State University, Sacramento; United States of America.
- ^r Also at Department of Physics, King's College London, London; United Kingdom.
- ^s Also at Department of Physics, Oxford University, Oxford; United Kingdom.
- ^t Also at Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ^u Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ^v Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^w Also at Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ^x Also at Department of Physics, University of Thessaly; Greece.
- ^y Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^z Also at Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ^{aa} Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- ^{ab} Also at Hellenic Open University, Patras; Greece.
- ^{ac} Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^{ad} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^{ae} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^{af} Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^{ag} Also at Institute of Particle Physics (IPP); Canada.
- ^{ah} Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
- ^{ai} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{aj} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ak} Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- ^{al} Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ^{am} Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
- ^{an} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{ao} Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ^{ap} Also at School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
- ^{aq} Also at School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ^{ar} Also at SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ^{as} Also at Technical University of Munich, Munich; Germany.
- ^{at} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{au} Also at TRIUMF, Vancouver BC; Canada.
- ^{av} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{aw} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{ax} Also at Washington College, Chestertown, MD; United States of America.
- ^{ay} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased