



A search for an unexpected asymmetry in the production of $e^+\mu^-$ and $e^-\mu^+$ pairs in proton–proton collisions recorded by the ATLAS detector at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration*

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ABSTRACT

This search, a type not previously performed at ATLAS, uses a comparison of the production cross sections for $e^+\mu^-$ and $e^-\mu^+$ pairs to constrain physics processes beyond the Standard Model. It uses 139fb^{-1} of proton–proton collision data recorded at $\sqrt{s} = 13$ TeV at the LHC. Targeting sources of new physics which prefer final states containing $e^+\mu^-$ to $e^-\mu^+$, the search contains two broad signal regions which are used to provide model-independent constraints on the ratio of cross sections at the 2% level. The search also has two special selections targeting supersymmetric models and leptoquark signatures. Observations using one of these selections are able to exclude, at 95% confidence level, singly produced smuons with masses up to 640 GeV in a model in which the only other light sparticle is a neutralino when the R -parity-violating coupling λ'_{231} is close to unity. Observations using the other selection exclude scalar leptoquarks with masses below 1880 GeV when $g_{1R}^{eu} = g_{1R}^{\mu c} = 1$, at 95% confidence level. The limit on the coupling reduces to $g_{1R}^{eu} = g_{1R}^{\mu c} = 0.46$ for a mass of 1420 GeV.

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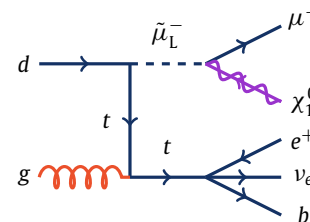
1. Introduction

Under the Standard Model of particle physics, the ratio of the production cross section of a positron and muon together in a proton–proton interaction is expected to be very similar to the production cross section for an electron and anti-muon. This similarity is a consequence of the lepton flavour universality of the electroweak boson interactions that produce these leptons, in combination with charge conservation and the relatively low mass of these leptons with respect to the mass of the electroweak bosons. As was explored in Ref. [1], measuring the ratio of these cross sections can serve as an experimental test of this aspect of the Standard Model (SM) and could have sensitivity to physics Beyond the Standard Model (BSM). Specifically, the ratio:

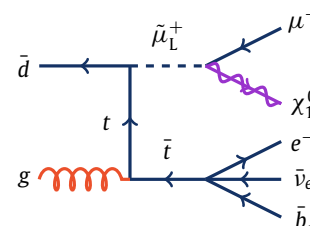
$$\rho \equiv \frac{\sigma(pp \rightarrow e^+\mu^- + X)}{\sigma(pp \rightarrow e^-\mu^+ + X)} \quad (1)$$

is defined, where the leptons are all taken to be promptly produced in the primary interaction.¹ Scenarios are considered where the presence of a BSM process would bias ρ to be significantly greater than one (more $e^+\mu^-$ than $e^-\mu^+$). Two concrete examples

of such BSM models are considered in this Letter. The first is an R -parity-violating supersymmetry model. As was noted in Ref. [1], a non-zero R -parity-violating λ'_{231} coupling (defined in Refs. [2–4]) linking smuons to top and down quarks could easily drive $\rho > 1$ as the proton's down quarks would result in



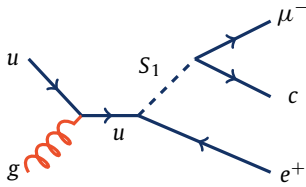
(and related s -channel processes) occurring more frequently than the charge conjugate process:



* E-mail address: atlas.publications@cern.ch.

¹ The X in Eq. (1) contains no further prompt leptons.

The second model considered to drive $\rho > 1$ is a scalar leptoquark with couplings permitting $S_1 \rightarrow ue^-$ and $S_1 \rightarrow c\mu^-$. In that case, processes such as



would be favoured over charge conjugates.

This Letter describes a measurement of ρ using the ATLAS detector at the LHC, which is used as a test for the existence of BSM physics that would bias ρ above one. While related BSM processes could also bias ρ to be significantly less than one, sensitivity to such processes are not considered in this Letter because of the existence of experimental effects that predominantly bias the measured ratio downwards. Examples of these effects are explored further in Ref. [1], but one such example is the presence of hadronic jets being incorrectly reconstructed as an electron more frequently than as a muon. This bias for fake electrons over fake muons, in combination with the predominance of W^+ over W^- bosons from the $(pp)^{2+}$ initial state [5,6], would manifest as a bias for $e^-\mu^+$ (with a fake e^-) over $e^+\mu^-$ (with a fake μ^-), and hence bias the measured ρ downwards. The analysis strategy presented in this Letter includes estimating corrections to account for some of these biasing experimental effects, the primary motivation for which is the enhancement of sensitivity to BSM physics that increases ρ rather than to improve the accuracy of the ρ measurement, and estimating systematic uncertainties to account for any remaining biases. In particular, for the model-independent statistical analysis of the measured ρ in this Letter it is assumed that the SM hypothesis covers values of ρ less than or equal to one, an assumption that is checked in data in the analysis event selections.² Thus evidence for new physics would only be claimed if the BSM contribution is strong enough to overcome any residual biases that have not been accounted for. For calculating limits on signal model parameters the strength of the residual biases are estimated from an SM-enriched control region.

The structure of this Letter is as follows: in Section 2 the ATLAS detector is described and Section 3 details the datasets used in the analysis. Section 4 describes the object reconstruction and Section 5 defines the regions of phase space that ρ is measured in and how experimental effects that could impact its measurement are corrected for, including the verification of these corrections with the measurement of ρ in SM-enriched control regions. Section 6 presents the measurement of ρ in generic signal regions designed to have broad sensitivity to BSM physics that would bias ρ upwards, then in optimised signal regions designed to have sensitivity to the two BSM models described above, alongside a statistical interpretation of the result in the parameter space of these models.

2. ATLAS detector

The ATLAS experiment [7] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.³ It consists of an inner

² See definitions of CR-RATIO and CR-JET in Section 5, and the estimates of fake-lepton contributions to Standard Model expectations.

³ 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

tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T·m across most of the detector. The muon spectrometer includes a system of precision chambers for tracking and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions.

An extensive software suite [8] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Data and Monte Carlo samples

The proton-proton collisions analysed in this Letter are those collected at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and a 25 ns interbunch spacing between 2015 and 2018. They correspond to an integrated luminosity of 139 fb^{-1} . The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [9], obtained using the LUCID-2 detector [10] for the primary luminosity measurements. In any given data-taking period the unrescaled two-lepton triggers (specifically ee , $e\mu$ or $\mu\mu$) with the lowest per-lepton p_T thresholds were used [11–13]. These thresholds ranged from 10 GeV to 24 GeV.

R-parity-violating (RPV) [14] models of supersymmetry [15–20] were tested using simulated events with $\mu^-\tilde{\chi}_1^0t$ or $\mu^+\tilde{\chi}_1^0\bar{t}$ in the final state, where $\tilde{\chi}_1^0$ is the lightest neutralino. This neutralino is considered stable enough on detector scales that it can only be detected through missing transverse momentum, unless it approaches or exceeds the top-quark mass, when it can decay through the RPV coupling. These events were generated at leading order using the Monte Carlo (MC) program MADGRAPH5_AMC@NLO [21] version 2.61 together with the RPV MSSM UFO model [22]. Shower evolution and hadronisation was performed by PYTHIA 8 [23] version 8.23. The NNPDF2.3LO [24] PDF was used with a set of tuned parameters called the A14 tune [25]. All RPV couplings except λ'_{231} were set to zero, so only the smuon RPV interaction is considered. Supersymmetric particles other than the neutralino and smuon were decoupled by setting their masses to a large value. The MADGRAPH hard processes permitted at most one additional light parton in the final state, and they were matched to the PYTHIA parton shower using the CKKW-L [26] merging scheme. Use of the matching scale $Q_{MS} = \frac{1}{4}(m(t) + m(\tilde{\chi}_1^0))$ gives a smooth transition between the matrix-element and parton-shower regimes, and distributions with little dependence on the exact scale value. Event samples were generated for a two-dimensional grid of points, distributed in a plane of smuon and neutralino masses, all with a coupling of

of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

$\lambda'_{231} = 1.0$. Samples for other values of the coupling were obtained by weighting the cross sections of the first set in proportion to the square of the desired value of λ'_{231} and changing the branching ratio for the smuon decay. The branching ratio for the desired smuon to muon decay is 2% (70%) at $\lambda'_{231} = 1$ (0.1), whilst the remaining smuons decay via the RPV vertex.

Leptoquark events were generated at leading order using MADGRAPH5_AMC@NLO 2.61 together with the ‘S₁’ model of Ref. [27], which is implemented as a Feynrules [28] package named ‘LO_LQ_S1’ available online [29] and described in Ref. [30]. Shower evolution and hadronisation were performed by PYTHIA 8.23. The NNPDF2.3LO PDF was used with the A14 tune. All leptoquark couplings were set to zero, apart from two flavours of the g_{1R} coupling of Ref. [27] which couples leptoquarks to leptons and quarks in weak singlet states. Specifically, $g_{1R}^{e\mu}$ and $g_{1R}^{\mu c}$ were assigned a common non-zero value simply denoted ‘ λ ’. The leptoquark signal events were generated for a set of leptoquark masses, all with a coupling of $\lambda = 1.0$. Charm-quark-initiated processes are neglected since they provide no charge–flavour asymmetry, and their cross section is only $\mathcal{O}(5\%)$ of that for up-quark-initiated processes. The hard processes specified no additional light jets in the final state and they were matched to the PYTHIA parton shower using the CKKW-L [31] merging scheme. The merging scale Q_{MS} was chosen to be $\frac{1}{4}(m(t) + m(S_1))$, where $m(S_1)$ is the mass of the leptoquark.

Next-to-leading order (NLO) cross sections are used for the samples and were calculated using MADGRAPH5_AMC@NLO 2.94 with a narrow-width (nw) approximation and the NNPDF2.3NLO PDF set. To include the effect of the finite-width (fw) approximation in the samples, the cross sections are corrected thus:

$$\sigma_{\text{Total}}^{\text{NLO,fw}} = \frac{\sigma_{e^+\mu^-}^{\text{NLO,nw}}}{\sigma_{e^+\mu^-}^{\text{LO,nw}}} \sigma_{e^+\mu^-}^{\text{LO,fw}} + \frac{\sigma_{e^-\mu^+}^{\text{NLO,nw}}}{\sigma_{e^-\mu^+}^{\text{LO,nw}}} \sigma_{e^-\mu^+}^{\text{LO,fw}}, \quad (2)$$

following an approach similar to that used in Ref. [32]. The narrow-width leading order (LO) cross sections are calculated using MADGRAPH5_AMC@NLO 2.94 and the NNPDF2.3LO PDF set. The finite-width LO cross sections are calculated using the same setup as the generated samples described above. Theoretical uncertainties in the NLO cross sections are calculated by MADGRAPH5_AMC@NLO using an envelope of nine variations of the renormalisation and factorisation scales, each taking values of either 0.5, 1.0 or 2.0 times their nominal value.

Samples for other values of the coupling λ were obtained by weighting the cross sections of the first set in proportion to the square of the desired value of λ and accounting for the change in leptoquark width. A two-dimensional grid of samples for a variety of leptoquark masses and couplings was thereby obtained. All signal sample events were then simulated using ATLFASSTII [33], a fast simulation of the ATLAS detector.

MC simulations of SM processes are not used in the final result of this analysis, but were used to guide the signal-region choices, to study the validity of the analysis strategy, to assist in deriving efficiencies and uncertainties for the fake-lepton background estimate, and to perform cross-checks (see Appendix A for MC sample details). Instead, measurements of ρ are based entirely on comparisons between $e^+\mu^-$ and $e^-\mu^+$ data, and contributions from jets misidentified as leptons, muon corrections and even expected SM yields (see Section 6) are also estimated primarily from data.

4. Reconstructed objects

Reconstructed objects (electrons, muons, jets, missing transverse momentum) are the building blocks of any analysis. In this analysis, leptons and jets exist in two forms: ‘BASELINE’ and

‘SIGNAL’. The former are used to define missing transverse momentum and the procedure to resolve ambiguities between objects with overlapping constituents, otherwise the analysis regions are built exclusively on the latter.

BASELINE electrons are required to have $|\eta| < 2.47$ and $p_T > 10$ GeV, and to pass the LOOSE likelihood-based identification working point defined in Ref. [34]. The same p_T and $|\eta|$ demands are placed on BASELINE muons, which are also required to pass the MEDIUM identification working point as defined in Ref. [35]. The anti- k_t algorithm [36,37] with a radius parameter of $R = 0.4$ is used to reconstruct jets with a four-momentum recombination scheme, using ‘particle-flow’ objects [38] as inputs. BASELINE jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$. The missing transverse momentum, \vec{p}_T^{miss} , is calculated from the BASELINE leptons and jets as described in Ref. [39] using the TIGHT working point and ‘particle-flow track-based soft term’ defined therein.

An overlap removal procedure is applied to BASELINE jets and BASELINE leptons to avoid double-counting. Firstly, any electron which shares a track with a muon is rejected. Any jet whose angular distance ΔR from an electron is less than 0.2 is removed, as is any which has fewer than three tracks lying within $\Delta R = 0.4$ of a muon. Finally, electrons and muons within $\Delta R = 0.4$ of the remaining jets are then discarded.

The ‘jet vertex tagger’ (JVT) [40] is applied to jets with $|\eta| < 2.4$ and $p_T < 120$ GeV, and helps to veto jets that are likely to have originated from pile-up (additional pp collisions from the same or nearby bunch crossings). A similar ‘forward jet vertex tagger’ (fJVT) is used to help identify and remove pile-up jets with $|\eta| > 2.5$ [41]. Jets surviving the overlap removal procedure are deemed SIGNAL if they pass the JVT or fJVT, and have $|\eta| < 2.8$.

Those leptons which remain are then given a status of SIGNAL if they meet the following five criteria: (i) they must have $p_T > 25$ GeV and $|\eta| < 2.47$, and (ii) be consistent with the hard-scatter vertex, through $|d_0/\sigma(d_0)| < 3$ and $|z_0 \sin(\theta)| < 0.3$ mm, where d_0 and z_0 are their transverse and longitudinal impact parameters; (iii) electrons must pass the TIGHT likelihood-based identification working point defined in Ref. [34], and have charge misidentification suppressed through the use of the boosted-decision-tree-based discriminant described in Ref. [34]; (iv) electrons with $p_T < 200$ GeV ($p_T > 200$ GeV) are required to pass the TIGHT (HighPtCaloOnly) isolation working point of Ref. [34] to reduce contamination by electrons from heavy-flavour decays or misidentified light hadrons; and (v) muons with $p_T < 200$ GeV ($p_T > 200$ GeV) are required to pass the TIGHT (FixedCutHighPtTrackOnly) isolation working point of Ref. [35] to reduce contamination by muons from semileptonic heavy-flavour and hadron decays.

In the rest of this Letter, leptons and jets are assumed to be only those with SIGNAL status, unless stated otherwise.

5. Analysis

The tests of whether ρ is significantly greater than one are made in four signal regions. Two of them, (SR-MET and SR-JET) aim to provide sensitivity to general sources of charge–flavour violation, while the other two (SR-RPV and SR-LQ) are less inclusive versions of their partners⁴ and target specific RPV supersymmetry and leptoquark theories mentioned in the introduction. These regions are summarised in Fig. 1.

The PRELIMINARY selection common to all signal regions requires the presence of exactly one electron and exactly one muon, of opposite charge. As there are few other constraints on the forms

⁴ Every event in SR-RPV is also in SR-MET, and every event in SR-LQ is also in SR-JET.

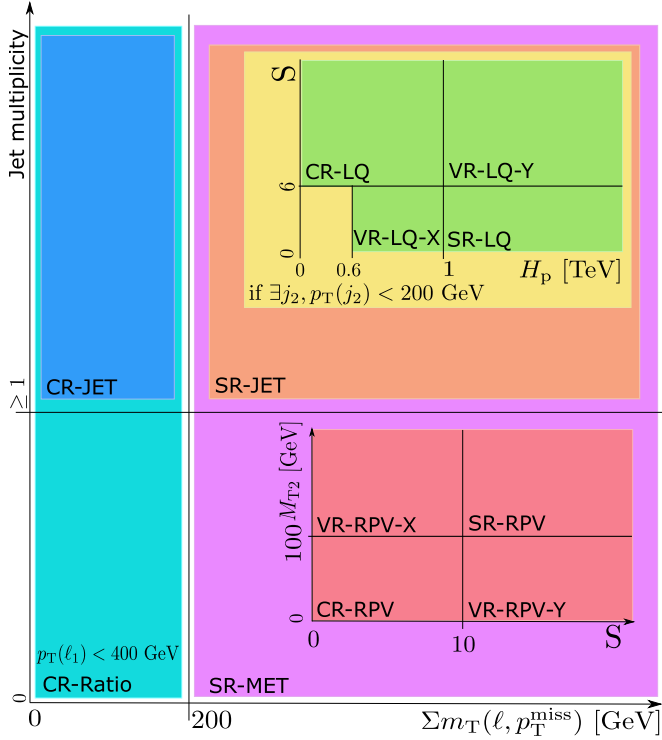


Fig. 1. Summary of the regions used in the analysis. ℓ_1 refers to the lepton with the largest p_T in each event. j_2 refers to the jet with the second-largest p_T in each event. SR-MET and SR-JET are used for the ρ measurement. CR-RATIO and CR-JET are used to check the SM expectation of $\rho \leq 1$, and CR-RATIO is used to derive the residual-bias uncertainty included in the ratio measurement. CR-RPV is used to derive the SM background expectation used to set limits on RPV supersymmetry models in SR-RPV, after being validated in VR-RPV-X and VR-RPV-Y. CR-LQ is used to derive the SM background expectation used to set limits on scalar leptoquark models in SR-LQ, after being validated in VR-LQ-X and VR-LQ-Y. Note that the horizontal positions of the boxes do not denote $\Sigma(m_T)$ thresholds beyond the 200 GeV cut.

that the signal regions should take, and as the ATLAS experiment has not previously published a charge-flavour asymmetry search, the approach taken in this first search is to prioritise simple selections over complex ones. With this principle in mind:

- when defining SR-MET, the only requirement which is added to the PRELIMINARY selection is that $\Sigma(m_T) > 200$ GeV, where $\Sigma(m_T) \equiv m_T(e, \vec{p}_T^{\text{miss}}) + m_T(\mu, \vec{p}_T^{\text{miss}})$ and m_T is the usual transverse mass:

$$m_T(\ell, \vec{p}_T^{\text{miss}}) \equiv \sqrt{2|\vec{p}_T^\ell| |\vec{p}_T^{\text{miss}}| - 2\vec{p}_T^\ell \cdot \vec{p}_T^{\text{miss}}},$$

- and when defining SR-JET (a subset of SR-MET) the only additional requirement is that events must contain at least one jet with transverse momentum greater than 20 GeV.

The primary purpose of the $\Sigma(m_T)$ requirement is to allow for the low $\Sigma(m_T)$ region to be available for studying the SM behaviour before unblinding the data in the signal regions. The benchmark BSM models have a low yield in $\Sigma(m_T) < 200$ GeV, and it can be assumed that they are representative of other general sources of charge-flavour violation, so BSM sensitivity is not reduced substantially by excluding this region from SR-MET or SR-JET. As shown in Fig. 1, the region $\Sigma(m_T) < 200$ GeV is designated as CR-RATIO. If the further requirement of at least one jet with $p_T > 20$ GeV is placed, the region is designated CR-JET, used to study the SM behaviour in a region more kinematically similar to SR-JET.

The signal-optimised regions make use of three more flavour-symmetric event variables: S , M_{T2} and H_p .

- S is the so-called ‘object-based \vec{p}_T^{miss} significance’ defined in Eq. (15) of Ref. [42]. It is a dimensionless measure of the degree to which the apparent missing transverse momentum in the event is ‘real’ (i.e. attributable to momentum carried away by invisible particles) rather than due to object mismeasurement or pile-up.
- $M_{T2} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_T^{\text{miss}}} \max[m_T(e, \vec{a}), m_T(\mu, \vec{b})]$ was proposed in Ref. [43], where \vec{a} and \vec{b} represent the contributions to p_T^{miss} from each semi-leptonic decay of a pair-produced particle, and all possible values that sum to the observed p_T^{miss} are minimised over. It is evaluated using the algorithm of Ref. [44].
- $H_p \equiv |\vec{p}_T^e| + |\vec{p}_T^\mu| + |\vec{p}_T^j|$ is a simple sum of the magnitudes of the transverse momenta of the two leptons and the most energetic jet in the event.

SR-RPV is defined to require $S > 10$ and $M_{T2} > 100$ GeV. The first requirement anticipates that neutralinos ($\tilde{\chi}_1^0$) of the supersymmetric signals should carry away missing transverse momentum, while the second suppresses SM W^+W^- backgrounds. In all other respects, SR-RPV is identical to SR-MET.

In contrast, the targeted leptoquark model processes have no invisible particles in the final state, so SR-LQ requires $S < 6$. Furthermore, SM backgrounds in this region are suppressed by requiring events to have $H_p > 1$ TeV. In all other respects, SR-LQ is the same as SR-JET.

Once the analysis regions are defined, potential biases to the measurement must be considered. The largest source of strictly one-sided charge-flavour bias in the ratio measurement is the misreconstruction of jets as light leptons in W +jet events. In particular: (i) more W^+ than W^- are produced in LHC proton collisions, and (ii) jets misreconstructed as ‘fake’ leptons are more likely to appear to be electrons than muons. If uncorrected, these two factors would cause $e_{\text{fake}}^- \mu_{\text{real}}^+$ to be more prevalent than $e_{\text{fake}}^+ \mu_{\text{real}}^-$ and therefore the so-called ‘fake’ background would favour $\rho < 1$. To remove the bias, a data-driven estimate of the number of fake-lepton events passing any particular selection is determined, separately for each charge combination, and is subtracted from the raw data counts before the ratio ρ of $e^+\mu^-$ to $e^-\mu^+$ counts is calculated.

The fake-lepton estimate itself is determined using a Likelihood Matrix Method approach of the form described in Ref. [45] or ‘Method B’ of Ref. [46]. This method predicts the fake lepton background where either one or both leptons is fake, and relies on two lepton definitions with different stringencies. The tighter selection corresponds to the SIGNAL definition used in the rest of the analysis, and the looser ‘LOOSE’ definition relaxes this by removing the isolation requirements, vertex requirements, and loosening the electron identification requirement to the LOOSE likelihood-based working point defined in Ref. [34]. Real-lepton efficiencies are derived in $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ regions, dominated by $Z \rightarrow \ell\ell$ events, as the number of events with two SIGNAL leptons divided by the number of events with a given lepton loosened to pass the LOOSE requirements. The fake-lepton efficiencies are derived using a muon tag-and-probe method, using $\mu^\pm \mu^\pm$ pairs for the muon efficiency and $e^\pm \mu^\pm$ pairs for the electron efficiency. The ‘tag’ lepton must pass the SIGNAL requirements as well as $p_T > 50$ GeV, and the efficiency is defined as the fraction of LOOSE probe leptons also passing the SIGNAL requirements, once the small SM real-lepton background (estimated from MC) has been subtracted. The requirement for same-charge-sign rather than opposite-charge-sign increases the contribution from events with fake leptons relative to real SM processes, dominantly W +jets events. The efficiencies are calculated separately for each lepton flavour and charge (such that the flavour and charge match the lepton that has its selection loosened), and are binned in lepton p_T . These efficiencies, together

with event counts in regions orthogonal to the signal regions and where one lepton is required to pass the Loose selection, are used to calculate a prediction for the yield of fake-lepton events in the signal regions. The fake-lepton estimate accounts for $\mathcal{O}(2\%)$ of the events in the signal regions used for the ratio measurement, and $\mathcal{O}(6\%)$ or $\mathcal{O}(17\%)$ of the events in the signal region used for the RPV supersymmetry or leptoquark interpretation, respectively. As can be seen in Fig. 2, the fake-lepton estimate in $e^-\mu^+$ events is indeed generally higher than in $e^+\mu^-$ events.

The uncertainty in the fake-lepton estimate includes two uncertainties: one propagated from uncertainty in the values of the efficiencies, and a ‘non-closure’ uncertainty. The non-closure uncertainty is derived in the region used to calculate electron fake efficiencies: an $e^\pm\mu^\pm$ region (with the electron failing the SIGNAL selection but passing the Loose selection, and the muon passing the ‘tag’ selection described above), which – like the signal regions – has fake leptons originating mostly from W +jet events. The region is split into two bins, with either $\Sigma(m_T) < 200$ GeV or $\Sigma(m_T) > 200$ GeV. The non-closure uncertainty is taken as the fractional difference in event counts in these bins between the total background estimate and the data. Here, the total background estimate includes the Likelihood Matrix Method fake-background estimate, as well as the real-lepton background estimated using SM MC. It was checked that the real-lepton background contamination in this region has no significant impact on the uncertainty value. The non-closure uncertainty has a magnitude of 21% (13%) for events with $\Sigma(m_T) > 200$ GeV ($\Sigma(m_T) < 200$ GeV), which is applied to the signal (control) region.

Only two other sources of potential charge-flavour bias motivate application of an explicit correction to data. Firstly, in certain regions of the detector there are small differences between the reconstruction (and trigger) efficiencies for positively and negatively charged muons. These are largely a result of the toroidal magnetic field that the muons move in while traversing the muon spectrometer, increasing the relative acceptance of muons of one charge in certain regions, usually anti-symmetrically in η . To remove these differences, weights (depending on muon charge, transverse momentum and pseudorapidity, and derived from $Z \rightarrow \mu\mu$ samples following the tag-and-probe approach described in Ref. [35]) are applied to events after data-taking but before any other use in the analysis. These weights correct for the bias by taking the efficiency values back to the charge-averaged values. Approximately two thirds of these weights have values within 1% of unity. In addition to introducing an overall acceptance change of $\sim 0.05\%$, these weights are responsible for event yields acquiring non-integer values. Uncertainties associated with this correction are obtained by propagating the statistical uncertainty of the charge-bias measurement. Secondly, a small correction is applied to data to account for the muon sagitta bias, which is derived in accord with Ref. [47], and comes with associated uncertainties which are also applied to data. This charge-dependent bias in muon momentum is caused by misalignment of the detector, and is found to be very minor: 68% of muons have a bias of less than 0.2% of the muon p_T .

Before unblinding the signal regions, the hypothesis that the proton–proton initial state and experimental effects lead to a bias favouring $\rho \leq 1$ in the SM was confirmed by measuring ρ , binned in ‘transverse mass’ M_{T2} [43], in CR-RATIO. Whilst the ratio is consistent with one within uncertainties, the maximal deviation from one is used to define a 2% ‘residual-bias’ uncertainty encompassing small remaining uncorrected detector biases. The extrapolation of the uncertainty to high $\Sigma(m_T)$ was validated by inspecting its impact on the ρ measurement in CR-RATIO and CR-JET when binned in $\Sigma(m_T)$.

6. Results

The observed data and fake-lepton background estimate in the $e^+\mu^-$ and $e^-\mu^+$ channels of SR-MET and SR-JET are shown in bins of M_{T2} and H_P respectively in Fig. 2. Benchmark RPV-supersymmetry or leptoquark signal yields are included to demonstrate that these BSM models favour $e^+\mu^-$ over $e^-\mu^+$. In the lower panels of Fig. 2, an estimate of the proportion of SM background processes in each bin is given, showing that $t\bar{t}$ is expected to dominate in most bins apart from the tails, where the fake-lepton, diboson, and single-top backgrounds become proportionally more important.

The ratio, ρ , is measured in bins, i , of M_{T2} (H_P) in the SR-MET (SR-JET) by maximising a parameterised likelihood model of the observed yields, $\bar{N}_{\text{obs},i}^{+/-/+}$. The likelihood model assumes an independent Poisson distribution for the yield in each bin of the charge-flavour channels ($e^+\mu^-$ or $e^-\mu^+$):

$$\begin{aligned} \mathcal{L}(\bar{N}_{\text{obs}}^{+/-/+} | \vec{\theta}, \vec{\alpha}, \vec{\rho}) &= \prod_{i \in \text{bins}} \left[\text{Pois}(N_{\text{obs},i}^{+/-/+} | w_i^{+/-/+}(\vec{\theta}) N_{\text{exp},i} + F_i^{+/-/+}(\vec{\alpha})) \right. \\ &\quad \times \left. \text{Pois}(N_{\text{obs},i}^{+/-/+} | \rho_i w_i^{+/-/+}(\vec{\theta}) N_{\text{exp},i} + F_i^{+/-/+}(\vec{\alpha})) \right] \\ &\quad \times \prod_{k \in \text{fake lepton uncertainties}} \text{Gaus}(0 | \alpha_k, 1) \\ &\quad \times \prod_{j \in \text{data uncertainties}} \text{Gaus}(0 | \theta_j, 1), \end{aligned} \quad (3)$$

where the expectation in each bin is the combination of a fake-lepton background estimate, $F_i^{+/-/+}$, and a total irreducible (real-lepton) SM expectation, $N_{\text{exp},i}$, which is a floating parameter in the likelihood. Uncertainties associated with the Likelihood Matrix Method estimate and the non-closure uncertainty in the fake-lepton background estimate are included by parameterising $F_i^{+/-/+}$ with Gaussian-constrained nuisance parameters, α . Muon charge and sagitta-bias corrections are already applied to the observed yields,⁵ $\bar{N}_{\text{obs},i}^{+/-/+}$, with the relative uncertainties on these corrections included in the $w_i^{+/-/+}(\vec{\theta})$ term and corresponding Gaussian-constrained nuisance parameters on the expected yields, θ_j . The ‘residual-bias’ uncertainty is included in the same manner. A global ratio measurement from combining all bins in a region gives $\rho = 0.987_{-0.021}^{+0.022}$ for SR-MET and SR-JET. The binned measured ratios (maximum-likelihood estimators of ρ_i) are shown in Fig. 3. In the lower bins of these variables the residual-bias uncertainty dominates; in the final two bins of M_{T2} and three bins of H_P the fake-lepton and statistical uncertainties dominate. Fig. 3 also shows *one-sided* p-values for a hypothesis test of $\rho = 1$ using a modified profile-likelihood-ratio test statistic that equals zero when $\rho_i \leq 1$, calculated using asymptotic approximations [48]. No significant upward deviation from one is seen in any bin, meaning that the SM hypothesis of $\rho \leq 1$ is not excluded anywhere. The largest upward deviation of ρ from one has a local significance of 1σ . The largest downward deviation from one is $\rho = 0.929_{-0.022}^{+0.023}$, in the 80 – 100 GeV bin of M_{T2} , with a local significance of 3.1σ . The goodness-of-fit significance to the model that $\rho = 1$ in all bins is 1.6σ , estimated using a likelihood ratio test statistic with the asymptotic approximation.

The CL_s method [49] is used to obtain 95% confidence level (CL) upper limits on the number of possible signal events S entering SR-MET and SR-JET, with a fraction z entering the $e^+\mu^-$ channel,

⁵ These corrections are sufficiently close to unity to support the Poisson modelling assumption for the corrected yields (further evidence can be seen in Table 1).

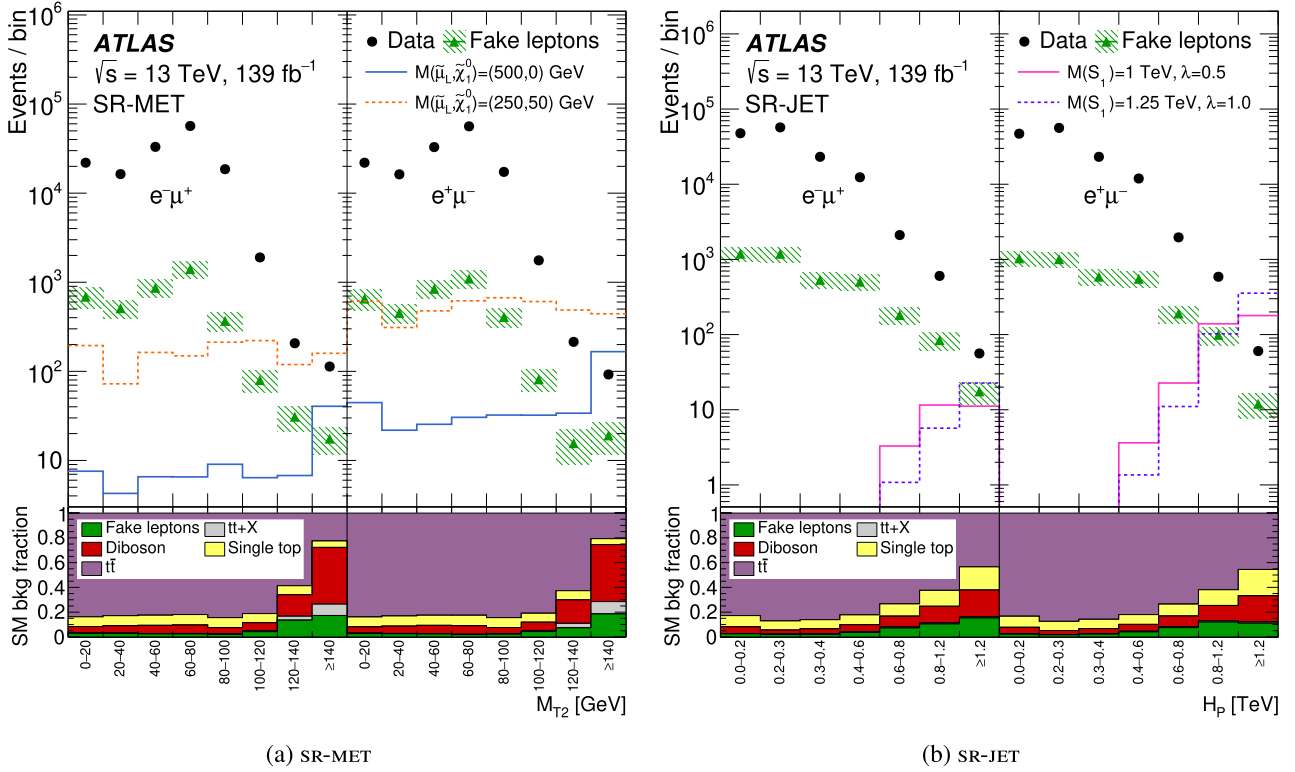


Fig. 2. Distributions of data in the $e^+\mu^-$ and $e^-\mu^+$ channels of the model-independent signal regions, binned in M_{T2} for SR-MET, and H_p for SR-JET, to correspond to the ratio measurement binning. The data has the muon charge and sagitta-bias corrections applied and corresponding uncertainties are added in quadrature in the error bar with the statistical uncertainty of the data. The fake-lepton background estimate is also shown, along with its uncertainty components added in quadrature, illustrating larger yields in the $e^-\mu^+$ channel as expected. The lower panel shows the fraction that each SM process contributes to the total SM background in each bin, estimated using standard MC simulations. The dominant background is $t\bar{t}$, whilst the importance of the fake-lepton background increases in higher bins of each variable. Benchmark RPV-supersymmetry signal models are shown for SR-MET, and benchmark scalar leptoquark models are shown for SR-JET, which all strongly favour the $e^+\mu^-$ final state over $e^-\mu^+$, as expected.

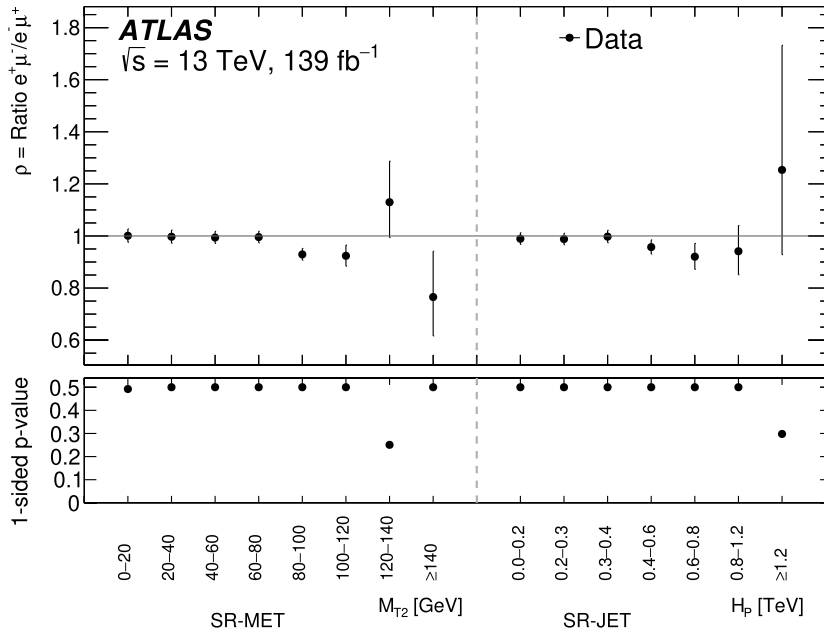


Fig. 3. A summary of the ratio ρ measurement in the full Run-2 data for SR-MET binned in M_{T2} , and SR-JET binned in H_p . Muon charge and sagitta-bias corrections are applied to data along with corresponding uncertainties, and the likelihood matrix method is used to estimate the charge-flavour-biased fake-lepton background such that it can be subtracted from the data. A 2% uncertainty in ρ , encompassing remaining observed detector biases, is also included. The lower panel shows the p -value for a one-sided discovery test to reject the SM hypothesis that $\rho \leq 1$.

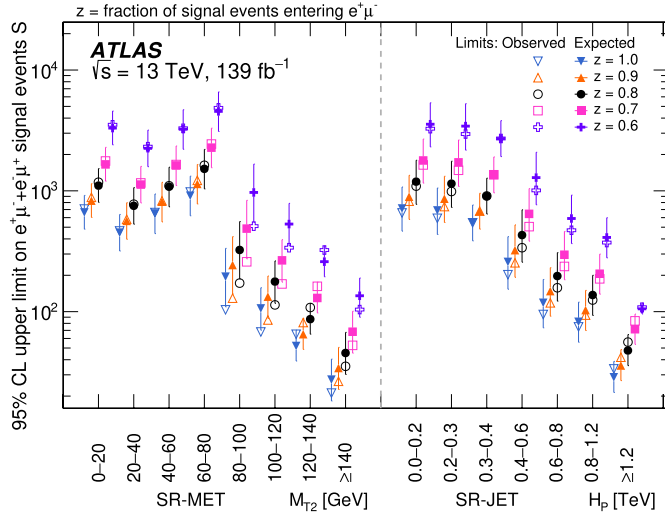


Fig. 4. Observed and expected 95% CL upper limits on the total number of signal events entering the $e^+\mu^-$ and $e^-\mu^+$ channels in each bin of SR-MET and SR-JET. The regions are binned in the same way as the ratio (ρ) measurement. The limits are shown for a selection of ‘ z ’ values, where ‘ z ’ is the fraction of the total number of signal events entering the $e^+\mu^-$ channel. The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CLs, under the hypothesis that $S = 0$ and $\rho_i = 1$.

and these are shown in Fig. 4 for a range of z values. These limits are calculated using a profile-likelihood-ratio test statistic with the likelihood function from Eq. (3) after fixing the ratio values to $\rho_i = 1$ and adding signal components to the Poisson expectations: Sz in the $e^+\mu^-$ channel, and $S(1-z)$ in the $e^-\mu^+$ channel, where S is the parameter of interest.

Having seen consistency with the SM hypothesis in the ratio measurement, limits are placed on parameters of the two benchmark BSM models. RPV-supersymmetry model exclusion limits are calculated with a one-sided profile-likelihood-ratio test statistic, where a likelihood function is defined for the observed yields in the $e^+\mu^-$ and $e^-\mu^+$ channels of both SR-RPV and a corresponding control region CR-RPV. This likelihood function is similar to Eq. (3) with signal yield terms added to the Poisson expectations (these signal terms are scaled by a signal strength parameter μ_{sig}) and i labelling the regions instead of the bins (each region in this model has a single bin). The ρ_i are also replaced by a single ρ that is common to both regions. In this respect, the control region drives the measurement of ρ and the signal region determines the value of μ_{sig} , which is used as the parameter of interest in the test statistic. The variance of ρ across the (S, M_{T2}) -plane (‘RPV-plane’) outside of the signal region is estimated with measurements of the ratio in bins of the plane axis observables: the binning was chosen to approximately match the statistical precision of the signal region. The estimated variance of 6% is added to the likelihood model as an uncertainty in ρ to cover the modelling assumption that ρ is invariant across the plane. This uncertainty covers both statistical and systematic sources of variance. The model is validated by finding good agreement between the observed and post-fit expected yields in the $e^+\mu^-$ channel of validation regions orthogonal to SR-RPV and CR-RPV (defined in Fig. 1), where the $e^-\mu^+$ channel of these regions is included in the fit along with both channels of CR-RPV. These validation regions are not included for the test statistic calculations when calculating the limits. Fig. 5(a) shows the observed and expected yields after the fit in the RPV-plane, demonstrating good agreement in the validation regions. This analysis is repeated in the (H_p, S) -plane (‘LQ-plane’) for leptoquark benchmark models (see Fig. 1), with an estimated 9% variance of ρ across the plane. Fig. 5(b) shows the fit result in the LQ-plane, demonstrating again good agreement in the validation regions. Un-

certainties are included in the signal terms for lepton reconstruction efficiency, energy scale and resolution, and trigger efficiency differences between MC simulation and data; uncertainties in the jet-energy scale and resolution [50], the modelling of the \vec{p}_T^{miss} soft term [39], and electron charge identification [51] are also included. The RPV signal model yields include theoretical uncertainties in the signal acceptance due to the choice of parton shower model and factorisation and renormalisation scales. The LQ signal models include effects of factorisation and renormalisation scale uncertainties on the NLO cross-section prediction, which form the $\pm 1\sigma_{\text{theory}}$ band on the observed limit.

As shown in Table 1, no statistically significant deviations of the data from the total SM background prediction are seen in the $e^+\mu^-$ channels of either signal region. By construction, since $N_{\text{exp},i}$ is a freely floating parameter, good agreement is seen between the data and SM prediction in the $e^-\mu^+$ channels after the fit excluding the $e^+\mu^-$ channels. These are included in the Table 1 for completeness and comparison with the benchmark signal yields.

The observed and expected RPV-supersymmetry limits are shown in Fig. 6 for the case where the λ'_{231} coupling is fixed at one, and in Fig. 7 where the coupling takes values between 0.1 and 1.5. The perturbative upper limit for the λ'_{231} coupling is 1.12 at the Z -boson mass [53], and increases with the energy scale. For coupling values above 1, the limit at high smuon mass becomes constant since the cross-section increase and the branching-ratio decrease cancel each other out. Neutralino masses near and above the top-quark mass are not excluded, as here the neutralino can decay through the RPV coupling and no real \vec{p}_T^{miss} remains in the final state. For the largest coupling value considered, smuon masses up to 650 GeV are excluded.

Fig. 8 shows the observed and expected limits on the leptoquark models considered. Since the energy required to produce a pair of leptoquarks is always double that required to make a single one, the suppression of high centre-of-mass energies by steeply falling parton distribution functions naturally leads to places where this analysis has better reach in leptoquark mass than analyses which have targeted pair production.⁶ Notably, leptoquark couplings of $g_{1R}^{eu} = g_{1R}^{\mu c} > 0.46$ are newly excluded for masses above 1420 GeV, up to a value of unity (the largest coupling considered) for a leptoquark mass of 1880 GeV.

7. Conclusion

To search for evidence of new physics, this analysis compares the production cross sections for $e^+\mu^-$ and $e^-\mu^+$ by investigating the ratio $\rho = \frac{\sigma(pp \rightarrow e^+\mu^- + X)}{\sigma(pp \rightarrow e^-\mu^+ + X)}$ in a variety of signal regions. New physics processes could potentially raise or lower ρ from one, but even though the largest Standard Model effect known to lower ρ was subtracted, the model-independent tests presented in the first half of this analysis look only for evidence of the ‘unexpected’ scenario of $\rho > 1$. No significant model-independent evidence for $\rho > 1$ was seen when analysing 139 fb⁻¹ of proton–proton collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC.

Further observations were conducted in more exclusive regions optimised for particular signals beyond the Standard Model. These regions targeted: (i) R -parity-violating supersymmetric models with non-zero λ'_{231} couplings, with smuons and stable neutralinos, and (ii) scalar leptoquark models with $g_{1R}^{eu} = g_{1R}^{\mu c}$. The secondary measurements were then used to create exclusions in planes in

⁶ This benefit comes, though, at the cost of requiring two non-zero leptoquark couplings $g_{1R}^{eu} \neq 0 \neq g_{1R}^{\mu c}$ rather than just the one assumed by existing pair-production searches.

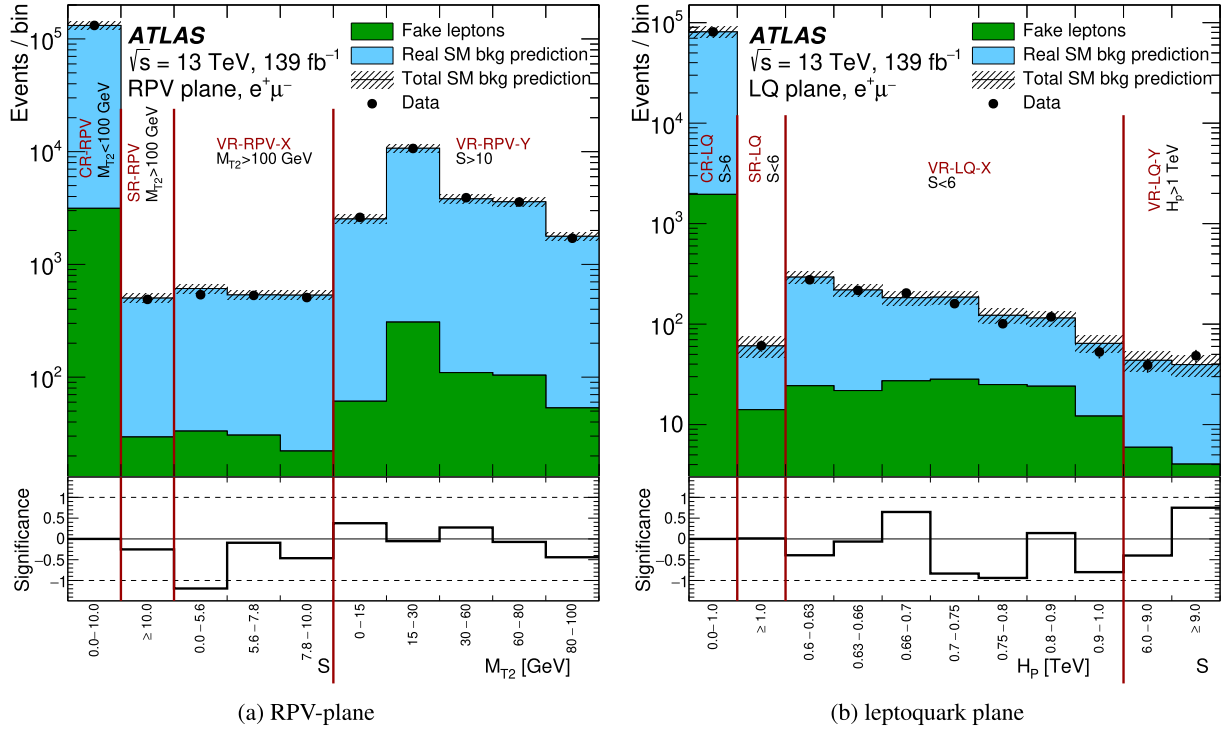


Fig. 5. Distributions of data in the $e^+\mu^-$ channel of the signal, control, and validation regions, used for the R -parity-violating supersymmetry model and leptoquark model limit fits. Note that ‘VR-LQ-x’ has a lower bound of $H_p > 600$ GeV, as it is not necessary to validate the ratio extrapolation any further away, kinematically, from the signal region. The data has the muon charge and sagitta-bias corrections applied. The fake-lepton background estimate and data-driven real SM background prediction derived from the fit are also shown. The sum of these is the total SM background estimate, and its error bar includes contributions from the fake-lepton background estimate, muon charge-bias and sagitta-bias uncertainties on the denominator data yields used to fit the SM background estimate. The lower panel shows the significance of any deviation between the observed data yields and total SM background prediction in each bin, defined in Ref. [52].

Table 1

Observed yields, and (post-fit) expected yields for the data-driven SM estimates in the case where $\mu_{\text{sig}} = 0$ and the fit excludes the $e^+\mu^-$ signal region; in such a fit the post-fit expected yields in the $e^-\mu^+$ channel are constrained to match the data exactly. Additionally, signal yields are shown for the benchmark RPV-supersymmetry signal points in SR-RPV and the leptoquark signal points in SR-LQ obtained from a fit excluding the $e^+\mu^-$ signal region and setting $\mu_{\text{sig}} = 1$. Small weights correcting for muon charge biases affect all rows except that containing the fake-lepton estimate. These weights, w_i , cause non-integer yields. The uncertainties, $\sqrt{\sum_i w_i^2}$, are given for data to support the choice made to model the yields with a Poisson distribution.

	SR-RPV		SR-LQ	
	$e^+\mu^-$	$e^-\mu^+$	$e^+\mu^-$	$e^-\mu^+$
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (0, 500)$ GeV, $\lambda'_{231} = 1$	191 ± 23	46.8 ± 7.7		
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (50, 250)$ GeV, $\lambda'_{231} = 1$	1160 ± 130	361 ± 97		
$M(S_1) = 1$ TeV, $\lambda = 0.5$			214 ± 15	14.5 ± 1.8
$M(S_1) = 1.25$ TeV, $\lambda = 1.0$			356 ± 53	22.9 ± 3.7
Data	489 ± 22	510 ± 23	60.9 ± 7.8	69.1 ± 8.3
Total SM expectation	503 ± 48	510 ± 26	61 ± 15	69 ± 12
• part due to real leptons	473 ± 47	479 ± 24	47 ± 13	47 ± 11
• part due to fake leptons	29.4 ± 8.2	30.3 ± 8.3	14.1 ± 6.5	22.1 ± 6.6

sparticle or leptoquark model spaces. The search was able to exclude singly produced smuons in certain models in which the only other light sparticle is a neutralino, albeit with those exclusions dependent on the existence of λ'_{231} R -parity-violating couplings. Scalar leptoquarks with $g_{1R}^{e\mu} = g_{1R}^{\mu c} \leq 1$ were excluded for masses below 1880 GeV. This value reduces to $g_{1R}^{e\mu} = g_{1R}^{\mu c} = 0.46$ for 1420 GeV (close to the limits obtained in analyses based on leptoquark pair production).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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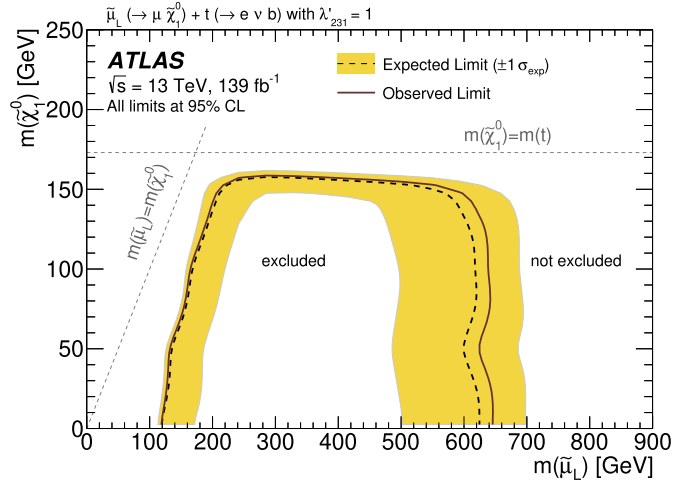


Fig. 6. Expected and observed exclusion limits are shown for RPV-supersymmetry models which allow for production of a single smuon (decaying into a muon and neutralino) in association with a top quark (decaying leptonically). The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL_s, under the SM-only hypothesis. The smuon is produced through the λ'_{231} coupling, which is fixed at unity. All limits are computed at 95% CL and all uncertainties are included. Also shown are dotted lines to indicate the two kinematic limits for the RPV process considered.

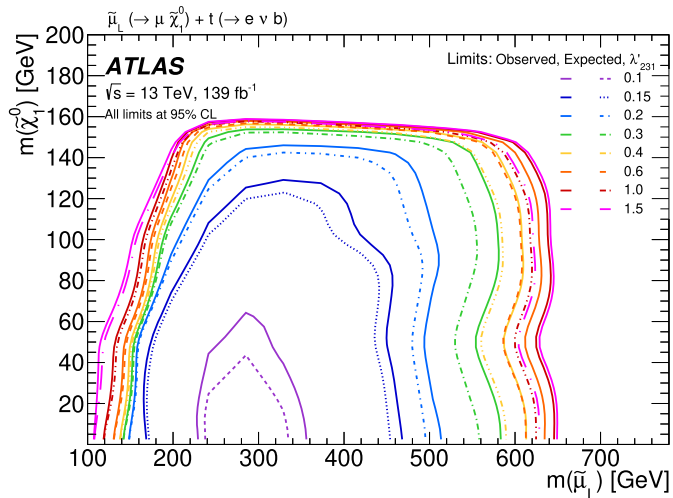


Fig. 7. Expected and observed exclusion limits are shown for RPV-supersymmetry models which allow for production of a single smuon (decaying into a muon and neutralino) in association with a top quark (decaying leptonically). The expected limits is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL_s, under the SM-only hypothesis. The smuon is produced through the λ'_{231} coupling, which takes values up to 1.5. All limits are computed at 95% CL and all uncertainties are included.

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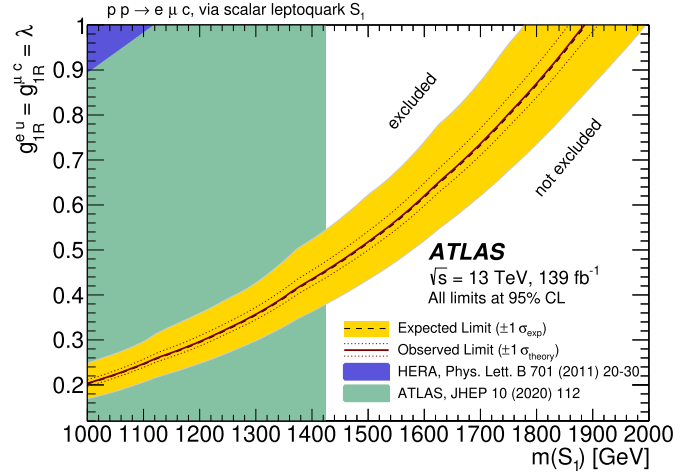


Fig. 8. Expected and observed exclusion limits are shown for models featuring production of a single scalar leptoquark which decays into a muon and charm quark. All limits are computed at 95% CL and all uncertainties are included. The $\pm 1\sigma_{theory}$ band considers the theoretical uncertainty of the NLO cross section used for the leptoquark signals. The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL_s, under the SM-only hypothesis. The underlaid exclusion is derived from a previous ATLAS leptoquark pair-production search [54], considering the result from μc final states. Since the model in this analysis requires leptoquarks to have two decay modes while that of Ref. [54] assumes only one, a branching ratio of 50% into μc was used when determining the position of the exclusion boundary. The interpretation of Ref. [54] also assumes that the narrow-width approximation is valid for leptoquarks over the range of coupling values shown.

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Appendix A

The top pair and single-top backgrounds were modelled using POWHEG BOX [56] v2 interfaced to PYTHIA 8 [23] and EVTGEN [57] and the NNPDF2.3LO [24] PDF. A dilepton filter was applied to the $t\bar{t}$ and tW processes.

The diboson backgrounds were modelled using SHERPA [58]. Hard processes with no or one additional jet in the final state were simulated at NLO, while up to three additional jets were included at LO. SHERPA 2.2.2 was used for the fully leptonic final states ($llll$, $lllv$, $llvv$ and $lvvv$) together with the CT10 PDF [59]. For the semileptonic final states ($llqq$ and $lvqq$), SHERPA 2.2.1 was used with the NNPDF [24] PDF. The loop-induced processes ($ggllll$, $ggllvv$, $lllljj$, $lllvjj$ and same-sign $llvvjj$) were generated using SHERPA 2.1.1 and the CT10 PDF.

The Z + jets background was modelled using SHERPA 2.2.1 with the NNPDF PDF. Up to two jets were generated at NLO and up to four at LO.

The $t\bar{t} + X$ processes were simulated using MADGRAPH5_AMC@NLO + PYTHIA 8. The EVTGEN program was used for properties of the bottom and charm hadron decays. The events are normalised to their respective NLO cross sections.

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G. Aad⁹⁸, B. Abbott¹²⁴, D.C. Abbott⁹⁹, A. Abed Abud³⁴, K. Abeling⁵¹, D.K. Abhayasinghe⁹¹, S.H. Abidi²⁷, A. Aboulhorma^{33e}, H. Abramowicz¹⁵⁷, H. Abreu¹⁵⁶, Y. Abulaiti⁵, A.C. Abusleme Hoffman^{142a}, B.S. Acharya^{64a,64b,o}, B. Achkar⁵¹, L. Adam⁹⁶, C. Adam Bourdarios⁴, L. Adamczyk^{81a}, L. Adamek¹⁶², S.V. Addepalli²⁴, J. Adelman¹¹⁶, A. Adiguzel^{11c,ac}, S. Adorni⁵², T. Adye¹³⁹, A.A. Affolder¹⁴¹, Y. Afik³⁴, C. Agapopoulou⁶², M.N. Agarar¹², J. Agarwala^{68a,68b}, A. Aggarwal¹¹⁴, C. Agheorghiesei^{25c}, J.A. Aguilar-Saavedra^{135f,135a,ab}, A. Ahmad³⁴, F. Ahmadov⁷⁷, W.S. Ahmed¹⁰⁰, X. Ai⁴⁴, G. Aielli^{71a,71b}, I. Aizenberg¹⁷⁵, S. Akatsuka⁸³, M. Akbiyik⁹⁶, T.P.A. Åkesson⁹⁴, A.V. Akimov¹⁰⁷, K. Al Khoury³⁷, G.L. Alberghi^{21b}, J. Albert¹⁷¹, P. Albicocco⁴⁹, M.J. Alconada Verzini⁸⁶, S. Alderweireldt⁴⁸, M. Aleksa³⁴, I.N. Aleksandrov⁷⁷, C. Alexa^{25b}, T. Alexopoulos⁹, A. Alfonsi¹¹⁵, F. Alfonsi^{21b}, M. Alhroob¹²⁴, B. Ali¹³⁷, S. Ali¹⁵⁴, M. Aliev¹⁶¹, G. Alimonti^{66a}, C. Allaire³⁴, B.M.M. Allbrooke¹⁵², P.P. Allport¹⁹, A. Aloisio^{67a,67b}, F. Alonso⁸⁶, C. Alpigiani¹⁴⁴, E. Alunno Camelia^{71a,71b}, M. Alvarez Estevez⁹⁵, M.G. Alviggi^{67a,67b}, Y. Amaral Coutinho^{78b}, A. Ambler¹⁰⁰, L. Ambroz¹³⁰, C. Amelung³⁴, D. Amidei¹⁰², S.P. Amor Dos Santos^{135a}, S. Amoroso⁴⁴, K.R. Amos¹⁶⁹, C.S. Amrouche⁵², V. Ananiev¹²⁹, C. Anastopoulos¹⁴⁵, N. Andari¹⁴⁰, T. Andeen¹⁰, J.K. Anders¹⁸, S.Y. Andread^{43a,43b}, A. Andreatza^{66a,66b}, S. Angelidakis⁸, A. Angerami³⁷, A.V. Anisenkov^{117b,117a}, A. Annovi^{69a}, C. Antel⁵², M.T. Anthony¹⁴⁵, E. Antipov¹²⁵, M. Antonelli⁴⁹, D.J.A. Antrim¹⁶, F. Anulli^{70a}, M. Aoki⁷⁹, J.A. Aparisi Pozo¹⁶⁹, M.A. Aparo¹⁵², L. Aperio Bella⁴⁴, N. Aranzabal³⁴, V. Araujo Ferraz^{78a}, C. Arcangeletti⁴⁹, A.T.H. Arce⁴⁷, E. Arena⁸⁸, J.-F. Arguin¹⁰⁶, S. Argyropoulos⁵⁰, J.-H. Arling⁴⁴, A.J. Armbruster³⁴, A. Armstrong¹⁶⁶, O. Arnaez¹⁶², H. Arnold³⁴, Z.P. Arrubarrena Tame¹¹⁰, G. Artoni¹³⁰, H. Asada¹¹², K. Asai¹²², S. Asai¹⁵⁹, N.A. Asbah⁵⁷, E.M. Asimakopoulou¹⁶⁷, L. Asquith¹⁵², J. Assahsah^{33d}, K. Assamagan²⁷, R. Astalos^{26a}, R.J. Atkin^{31a}, M. Atkinson¹⁶⁸, N.B. Atlay¹⁷, H. Atmani^{58b}, P.A. Atmasiddha¹⁰², K. Augsten¹³⁷, S. Auricchio^{67a,67b}, V.A. Austrup¹⁷⁷, G. Avner¹⁵⁶, G. Avolio³⁴, M.K. Ayoub^{13c}, G. Azuelos^{106,aj}, D. Babal^{26a}, H. Bachacou¹⁴⁰, K. Bachas¹⁵⁸, A. Bachiou³², F. Backman^{43a,43b}, A. Badea⁵⁷, P. Bagnaia^{70a,70b}, H. Bahrasemani¹⁴⁸, A.J. Bailey¹⁶⁹, V.R. Bailey¹⁶⁸, J.T. Baines¹³⁹, C. Bakalis⁹, O.K. Baker¹⁷⁸, P.J. Bakker¹¹⁵, E. Bakos¹⁴, D. Bakshi Gupta⁷, S. Balaji¹⁵³, R. Balasubramanian¹¹⁵, E.M. Baldin^{117b,117a}, P. Balek¹³⁸, E. Ballabene^{66a,66b}, F. Balli¹⁴⁰, L.M. Balthes^{59a}, W.K. Balunas¹³⁰, J. Balz⁹⁶, E. Banas⁸², M. Bandieramonte¹³⁴, A. Bandyopadhyay²², S. Bansal²², L. Barak¹⁵⁷, E.L. Barberio¹⁰¹, D. Barberis^{53b,53a}, M. Barbero⁹⁸, G. Barbour⁹², K.N. Barends^{31a}, T. Barillari¹¹¹, M.-S. Barisits³⁴, J. Barkeloo¹²⁷, T. Barklow¹⁴⁹, B.M. Barnett¹³⁹, R.M. Barnett¹⁶, A. Baroncelli^{58a}, G. Barone²⁷, A.J. Barr¹³⁰, L. Barranco Navarro^{43a,43b}, F. Barreiro⁹⁵, J. Barreiro Guimarães da Costa^{13a}, U. Barron¹⁵⁷, S. Barsov¹³³, F. Bartels^{59a}, R. Bartoldus¹⁴⁹, G. Bartolini⁹⁸, A.E. Barton⁸⁷, P. Bartos^{26a}, A. Basalae⁴⁴, A. Basan⁹⁶, M. Baselga⁴⁴, I. Bashta^{72a,72b}, A. Bassalat^{62,ag}, M.J. Basso¹⁶², C.R. Basson⁹⁷, R.L. Bates⁵⁵, S. Batlamous^{33e}, J.R. Batley³⁰, B. Batool¹⁴⁷, M. Battaglia¹⁴¹, M. Bauce^{70a,70b}, F. Bauer^{140,*}, P. Bauer²², H.S. Bawa²⁹, A. Bayirli^{11c}, J.B. Beacham⁴⁷, T. Beau¹³¹, P.H. Beauchemin¹⁶⁵, F. Becherer⁵⁰, P. Bechtel²², H.P. Beck^{18,q}, K. Becker¹⁷³, C. Becot⁴⁴, A.J. Beddall^{11a}, V.A. Bednyakov⁷⁷, C.P. Bee¹⁵¹, T.A. Beermann³⁴, M. Begalli^{78b}, M. Begel²⁷, A. Behera¹⁵¹, J.K. Behr⁴⁴, C. Beirao Da Cruz E Silva³⁴, J.F. Beirer^{51,34}, F. Beisiegel²², M. Belfkir⁴, G. Bella¹⁵⁷, L. Bellagamba^{21b}, A. Bellerive³², P. Bellos¹⁹, K. Beloborodov^{117b,117a}, K. Belotskiy¹⁰⁸, N.L. Belyaev¹⁰⁸, D. Benckekroun^{33a}, Y. Benhammou¹⁵⁷, D.P. Benjamin²⁷, M. Benoit²⁷, J.R. Bensinger²⁴, S. Bentvelsen¹¹⁵, L. Beresford³⁴, M. Beretta⁴⁹, D. Berge¹⁷, E. Bergeaas Kuutmann¹⁶⁷, N. Berger⁴, B. Bergmann¹³⁷, L.J. Bergsten²⁴, J. Beringer¹⁶, S. Berlendis⁶, G. Bernardi¹³¹, C. Bernius¹⁴⁹, F.U. Bernlochner²², T. Berry⁹¹, P. Berta¹³⁸, A. Berthold⁴⁶, I.A. Bertram⁸⁷, O. Bessidskaia Bylund¹⁷⁷, S. Bethke¹¹¹, A. Betti⁴⁰, A.J. Bevan⁹⁰, S. Bhatta¹⁵¹, D.S. Bhattacharya¹⁷², P. Bhattarai²⁴, V.S. Bhopatkar⁵, R. Bi¹³⁴, R.M. Bianchi¹³⁴, O. Biebel¹¹⁰, R. Bielski¹²⁷, N.V. Biesuz^{69a,69b}, M. Biglietti^{72a}, T.R.V. Billoud¹³⁷, M. Bindi⁵¹, A. Bingul^{11d}, C. Bini^{70a,70b}, S. Biondi^{21b,21a}, A. Biondini⁸⁸, C.J. Birch-sykes⁹⁷, G.A. Bird^{19,139}, M. Birman¹⁷⁵, T. Bisanz³⁴, J.P. Biswal², D. Biswas^{176,j}, A. Bitadze⁹⁷, C. Bittrich⁴⁶, K. Björke¹²⁹, I. Bloch⁴⁴, C. Blocker²⁴, A. Blue⁵⁵, U. Blumenschein⁹⁰, J. Blumenthal⁹⁶, G.J. Bobbink¹¹⁵, V.S. Bobrovnikov^{117b,117a}, M. Boehler⁵⁰, D. Bogavac¹², A.G. Bogdanchikov^{117b,117a}, C. Böhm^{43a}, V. Boisvert⁹¹, P. Bokan⁴⁴, T. 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O. Brandt³⁰, F. Braren⁴⁴, B. Brau⁹⁹, J.E. Brau¹²⁷, W.D. Breaden Madden⁵⁵, K. Brendlinger⁴⁴, R. Brenner¹⁷⁵, L. Brenner³⁴, R. Brenner¹⁶⁷, S. Bressler¹⁷⁵, B. Brickwedde⁹⁶, D.L. Briglin¹⁹, D. Britton⁵⁵, D. Britzger¹¹¹, I. Brock²², R. Brock¹⁰³, G. Brooijmans³⁷, W.K. Brooks^{142e}, E. Brost²⁷, P.A. Bruckman de Renstrom⁸², B. Brüers⁴⁴, D. Bruncko^{26b}, A. Bruni^{21b}, G. Bruni^{21b}, B.H. Brunt³⁰, M. Bruschi^{21b}, N. Brusino^{70a,70b}, L. Bryngemark¹⁴⁹, T. Buanes¹⁵, Q. Buat¹⁵¹, P. Buchholz¹⁴⁷, A.G. Buckley⁵⁵, I.A. Budagov⁷⁷, M.K. Bugge¹²⁹, O. Bulekov¹⁰⁸, B.A. Bullard⁵⁷, S. Burdin⁸⁸, C.D. Burgard⁴⁴, A.M. Burger¹²⁵, B. Burghgrave⁷, J.T.P. Burr⁴⁴, C.D. Burton¹⁰, J.C. Burzynski¹⁴⁸, E.L. Busch³⁷, V. Büscher⁹⁶, P.J. Bussey⁵⁵, J.M. Butler²³, C.M. Buttar⁵⁵, J.M. Butterworth⁹², W. Buttinger¹³⁹, C.J. Buxo Vazquez¹⁰³, A.R. Buzykaev^{117b,117a}, G. Cabras^{21b}, S. Cabrera Urbán¹⁶⁹, D. Caforio⁵⁴, H. Cai¹³⁴, V.M.M. Cairo¹⁴⁹, O. Cakir^{3a}, N. Calace³⁴, P. Calafiura¹⁶, G. Calderini¹³¹, P. Calfayan⁶³, G. Callea⁵⁵, L.P. Caloba^{78b}, D. Calvet³⁶, S. Calvet³⁶, T.P. Calvet⁹⁸, M. Calvetti^{69a,69b}, R. Camacho Toro¹³¹, S. Camarda³⁴, D. Camarero Munoz⁹⁵, P. Camarri^{71a,71b}, M.T. Camerlingo^{72a,72b}, D. Cameron¹²⁹, C. Camincher¹⁷¹, M. Campanelli⁹², A. Camplani³⁸, V. Canale^{67a,67b}, A. Canesse¹⁰⁰, M. Cano Bret⁷⁵, J. Cantero¹²⁵, Y. Cao¹⁶⁸, F. Capocasa²⁴, M. Capua^{39b,39a}, A. Carbone^{66a,66b}, R. Cardarelli^{71a}, J.C.J. Cardenas⁷, F. Cardillo¹⁶⁹, G. Carducci^{39b,39a}, T. Carli³⁴, G. Carlino^{67a}, B.T. Carlson¹³⁴, E.M. Carlson^{171,163a}, L. Carminati^{66a,66b}, M. Carnesale^{70a,70b}, R.M.D. Carney¹⁴⁹, S. Caron¹¹⁴, E. Carquin^{142e}, S. Carrá⁴⁴, G. Carratta^{21b,21a}, J.W.S. Carter¹⁶², T.M. Carter⁴⁸, D. Casadei^{31c}, M.P. Casado^{12,g}, A.F. Casha¹⁶², E.G. Castiglia¹⁷⁸, F.L. Castillo^{59a}, L. Castillo Garcia¹², V. Castillo Gimenez¹⁶⁹, N.F. Castro^{135a,135e}, A. Catinaccio³⁴, J.R. Catmore¹²⁹, A. Cattai³⁴, V. Cavaliere²⁷, N. Cavalli^{21b,21a}, V. Cavasinni^{69a,69b}, E. 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Christopher^{31f}, M.C. Chu^{60a}, X. Chu^{13a,13d}, J. Chudoba¹³⁶, J.J. Chwastowski⁸², D. Cieri¹¹¹, K.M. Ciesla⁸², V. Cindro⁸⁹, I.A. Cioară^{25b}, A. Ciocio¹⁶, F. Ciotto^{67a,67b}, Z.H. Citron^{175,k}, M. Citterio^{66a}, D.A. Ciubotaru^{25b}, B.M. Ciungu¹⁶², A. Clark⁵², P.J. Clark⁴⁸, J.M. Clavijo Columbie⁴⁴, S.E. Clawson⁹⁷, C. Clement^{43a,43b}, L. Clissa^{21b,21a}, Y. Coadou⁹⁸, M. Cobal^{64a,64c}, A. Coccaro^{53b}, J. Cochran⁷⁶, R.F. Coelho Barrue^{135a}, R. Coelho Lopes De Sa⁹⁹, S. Coelli^{66a}, H. Cohen¹⁵⁷, A.E.C. Coimbra³⁴, B. Cole³⁷, J. Collot⁵⁶, P. Conde Muiño^{135a,135g}, S.H. Connell^{31c}, I.A. Connelly⁵⁵, E.I. Conroy¹³⁰, F. Conventi^{67a,ak}, H.G. Cooke¹⁹, A.M. Cooper-Sarkar¹³⁰, F. Cormier¹⁷⁰, L.D. Corpe³⁴, M. Corradi^{70a,70b}, E.E. Corrigan⁹⁴, F. Corriveau^{100,y}, M.J. Costa¹⁶⁹, F. Costanza⁴, D. Costanzo¹⁴⁵, B.M. Cote¹²³, G. Cowan⁹¹, J.W. Cowley³⁰, K. Cranmer¹²¹, S. Crépe-Renaudin⁵⁶, F. Crescioli¹³¹, M. Cristinziani¹⁴⁷, M. Cristoforetti^{73a,73b,b}, V. Croft¹⁶⁵, G. Crosetti^{39b,39a}, A. Cueto³⁴, T. Cuhadar Donszelmann¹⁶⁶, H. Cui^{13a,13d}, A.R. Cukierman¹⁴⁹, W.R. Cunningham⁵⁵, F. Curcio^{39b,39a}, P. Czodrowski³⁴, M.M. Czurylo^{59b}, M.J. Da Cunha Sargedas De Sousa^{58a}, J.V. Da Fonseca Pinto^{78b}, C. Da Via⁹⁷, W. Dabrowski^{81a}, T. Dado⁴⁵, S. Dahbi^{31f}, T. Dai¹⁰², C. Dallapiccola⁹⁹, M. Dam³⁸, G. D'amen²⁷, V. D'Amico^{72a,72b}, J. Damp⁹⁶, J.R. Dandoy¹³², M.F. Daneri²⁸, M. Danninger¹⁴⁸, V. Dao³⁴, G. Darbo^{53b}, S. Darmora⁵, A. Dattagupta¹²⁷, S. D'Auria^{66a,66b}, C. David^{163b}, T. Davidek¹³⁸, D.R. Davis⁴⁷, B. Davis-Purcell³², I. Dawson⁹⁰, K. De⁷, R. De Asmundis^{67a}, M. De Beurs¹¹⁵, S. De Castro^{21b,21a}, N. De Groot¹¹⁴, P. de Jong¹¹⁵, H. De la Torre¹⁰³, A. De Maria^{13c}, D. De Pedis^{70a}, A. De Salvo^{70a}, U. De Sanctis^{71a,71b}, M. De Santis^{71a,71b}, A. De Santo¹⁵², J.B. De Vivie De Regie⁵⁶, D.V. Dedovich⁷⁷, J. Degens¹¹⁵, A.M. Deiana⁴⁰, J. Del Peso⁹⁵, Y. Delabat Diaz⁴⁴, F. Deliot¹⁴⁰, C.M. Delitzsch⁶, M. Della Pietra^{67a,67b}, D. Della Volpe⁵², A. Dell'Acqua³⁴, L. Dell'Asta^{66a,66b}, M. Delmastro⁴, P.A. Delsart⁵⁶, S. Demers¹⁷⁸, M. Demichev⁷⁷, S.P. Denisov¹¹⁸, L. D'Eramo¹¹⁶, D. Derendarz⁸², J.E. Derkaoui^{33d}, F. Derue¹³¹, P. Dervan⁸⁸, K. Desch²², K. Dette¹⁶², C. Deutsch²², P.O. Deviveiros³⁴, F.A. Di Bello^{70a,70b}, A. Di Ciaccio^{71a,71b}, L. Di Ciaccio⁴, A. Di Domenico^{70a,70b}, C. Di Donato^{67a,67b}, A. Di Girolamo³⁴, G. Di Gregorio^{69a,69b}, A. Di Luca^{73a,73b}, B. Di Micco^{72a,72b}, R. Di Nardo^{72a,72b}, C. Diaconu⁹⁸, F.A. Dias¹¹⁵, T. Dias Do Vale^{135a}, M.A. Diaz^{142a}, F.G. Diaz Capriles²²,

J. Dickinson ¹⁶, M. Didenko ¹⁶⁹, E.B. Diehl ¹⁰², J. Dietrich ¹⁷, S. Díez Cornell ⁴⁴, C. Diez Pardos ¹⁴⁷, A. Dimitrievska ¹⁶, W. Ding ^{13b}, J. Dingfelder ²², I.-M. Dinu ^{25b}, S.J. Dittmeier ^{59b}, F. Dittus ³⁴, F. Djama ⁹⁸, T. Djobava ^{155b}, J.I. Djuvsland ¹⁵, M.A.B. Do Vale ¹⁴³, D. Dodsworth ²⁴, C. Doglioni ⁹⁴, J. Dolejsi ¹³⁸, Z. Dolezal ¹³⁸, M. Donadelli ^{78c}, B. Dong ^{58c}, J. Donini ³⁶, A. D'Onofrio ^{13c}, M. D'Onofrio ⁸⁸, J. Dopke ¹³⁹, A. Doria ^{67a}, M.T. Dova ⁸⁶, A.T. Doyle ⁵⁵, E. Drechsler ¹⁴⁸, E. Dreyer ¹⁴⁸, T. Dreyer ⁵¹, A.S. Drobac ¹⁶⁵, D. Du ^{58a}, T.A. du Pree ¹¹⁵, F. Dubinin ¹⁰⁷, M. Dubovsky ^{26a}, A. Dubreuil ⁵², E. Duchovni ¹⁷⁵, G. Duckeck ¹¹⁰, O.A. Ducu ^{34,25b}, D. Duda ¹¹¹, A. Dudarev ³⁴, M. D'uffizi ⁹⁷, L. Duflot ⁶², M. Dührssen ³⁴, C. Dülzen ¹⁷⁷, A.E. Dumitriu ^{25b}, M. Dunford ^{59a}, S. Dungs ⁴⁵, K. Dunne ^{43a,43b}, A. Duperrin ⁹⁸, H. Duran Yildiz ^{3a}, M. Düren ⁵⁴, A. Durglishvili ^{155b}, B. Dutta ⁴⁴, B.L. Dwyer ¹¹⁶, G.I. Dyckes ¹⁶, M. Dyndal ^{81a}, S. Dych ⁹⁷, B.S. Dziedzic ⁸², B. Eckerova ^{26a}, M.G. Eggleston ⁴⁷, E. Egidio Purcino De Souza ^{78b}, L.F. Ehrke ⁵², T. Eifert ⁷, G. Eigen ¹⁵, K. Einsweiler ¹⁶, T. Ekelof ¹⁶⁷, Y. El Ghazali ^{33b}, H. El Jarrari ^{33e}, A. El Moussaouy ^{33a}, V. Ellajosyula ¹⁶⁷, M. Ellert ¹⁶⁷, F. Ellinghaus ¹⁷⁷, A.A. Elliot ⁹⁰, N. Ellis ³⁴, J. Elmsheuser ²⁷, M. Elsing ³⁴, D. Emelianov ¹³⁹, A. Emerman ³⁷, Y. Enari ¹⁵⁹, J. Erdmann ⁴⁵, A. Ereditato ¹⁸, P.A. Erland ⁸², M. Errenst ¹⁷⁷, M. Escalier ⁶², C. Escobar ¹⁶⁹, O. Estrada Pastor ¹⁶⁹, E. Etzion ¹⁵⁷, G. Evans ^{135a}, H. Evans ⁶³, M.O. Evans ¹⁵², A. Ezhilov ¹³³, F. Fabbri ⁵⁵, L. Fabbri ^{21b,21a}, G. Facini ¹⁷³, V. Fadeyev ¹⁴¹, R.M. Fakhruddinov ¹¹⁸, S. Falciano ^{70a}, P.J. Falke ²², S. Falke ³⁴, J. Faltova ¹³⁸, Y. Fan ^{13a}, Y. Fang ^{13a}, G. Fanourakis ⁴², M. Fanti ^{66a,66b}, M. Faraj ^{58c}, A. Farbin ⁷, A. Farilla ^{72a}, E.M. Farina ^{68a,68b}, T. Farooque ¹⁰³, S.M. Farrington ⁴⁸, P. Farthouat ³⁴, F. Fassi ^{33e}, D. Fassouliotis ⁸, M. Fauci Giannelli ^{71a,71b}, W.J. Fawcett ³⁰, L. Fayard ⁶², O.L. Fedin ^{133,p}, M. Feickert ¹⁶⁸, L. Feligioni ⁹⁸, A. Fell ¹⁴⁵, C. Feng ^{58b}, M. Feng ^{13b}, M.J. Fenton ¹⁶⁶, A.B. Fenyuk ¹¹⁸, S.W. Ferguson ⁴¹, J. Ferrando ⁴⁴, A. Ferrari ¹⁶⁷, P. Ferrari ¹¹⁵, R. Ferrari ^{68a}, D. Ferrere ⁵², C. Ferretti ¹⁰², F. Fiedler ⁹⁶, A. Filipčič ⁸⁹, F. Filthaut ¹¹⁴, M.C.N. Fiolhais ^{135a,135c,a}, L. Fiorini ¹⁶⁹, F. Fischer ¹⁴⁷, W.C. Fisher ¹⁰³, T. Fitschen ¹⁹, I. Fleck ¹⁴⁷, P. Fleischmann ¹⁰², T. Flick ¹⁷⁷, B.M. Flierl ¹¹⁰, L. Flores ¹³², M. Flores ^{31d}, L.R. Flores Castillo ^{60a}, F.M. Follega ^{73a,73b}, N. Fomin ¹⁵, J.H. Foo ¹⁶², B.C. Forland ⁶³, A. Formica ¹⁴⁰, F.A. Förster ¹², A.C. Forti ⁹⁷, E. Fortin ⁹⁸, M.G. Foti ¹³⁰, L. Fountas ⁸, D. Fournier ⁶², H. Fox ⁸⁷, P. Francavilla ^{69a,69b}, S. Francescato ⁵⁷, M. Franchini ^{21b,21a}, S. Franchino ^{59a}, D. Francis ³⁴, L. Franco ⁴, L. Franconi ¹⁸, M. Franklin ⁵⁷, G. Frattari ^{70a,70b}, A.C. Freegard ⁹⁰, P.M. Freeman ¹⁹, W.S. Freund ^{78b}, E.M. Freundlich ⁴⁵, D. Froidevaux ³⁴, J.A. Frost ¹³⁰, Y. Fu ^{58a}, M. Fujimoto ¹²², E. Fullana Torregrosa ¹⁶⁹, J. Fuster ¹⁶⁹, A. Gabrielli ^{21b,21a}, A. Gabrielli ³⁴, P. Gadow ⁴⁴, G. Gagliardi ^{53b,53a}, L.G. Gagnon ¹⁶, G.E. Gallardo ¹³⁰, E.J. Gallas ¹³⁰, B.J. Gallop ¹³⁹, R. Gamboa Goni ⁹⁰, K.K. Gan ¹²³, S. Ganguly ¹⁵⁹, J. Gao ^{58a}, Y. Gao ⁴⁸, Y.S. Gao ^{29,m}, F.M. Garay Walls ^{142a}, C. García ¹⁶⁹, J.E. García Navarro ¹⁶⁹, J.A. García Pascual ^{13a}, M. Garcia-Sciveres ¹⁶, R.W. Gardner ³⁵, D. Garg ⁷⁵, R.B. Garg ¹⁴⁹, S. Gargiulo ⁵⁰, C.A. Garner ¹⁶², V. Garonne ¹²⁹, S.J. Gasiorowski ¹⁴⁴, P. Gaspar ^{78b}, G. Gaudio ^{68a}, P. Gauzzi ^{70a,70b}, I.L. Gavrilenko ¹⁰⁷, A. Gavrilyuk ¹¹⁹, C. Gay ¹⁷⁰, G. Gaycken ⁴⁴, E.N. Gazis ⁹, A.A. Geanta ^{25b}, C.M. Gee ¹⁴¹, C.N.P. Gee ¹³⁹, J. Geisen ⁹⁴, M. Geisen ⁹⁶, C. Gemme ^{53b}, M.H. Genest ⁵⁶, S. Gentile ^{70a,70b}, S. George ⁹¹, W.F. George ¹⁹, T. Geralis ⁴², L.O. Gerlach ⁵¹, P. Gessinger-Befurt ³⁴, M. Ghasemi Bostanabad ¹⁷¹, A. Ghosh ¹⁶⁶, A. Ghosh ⁷⁵, B. Giacobbe ^{21b}, S. Giagu ^{70a,70b}, N. Giangiacomi ¹⁶², P. Giannetti ^{69a}, A. Giannini ^{67a,67b}, S.M. Gibson ⁹¹, M. Gignac ¹⁴¹, D.T. Gil ^{81b}, B.J. Gilbert ³⁷, D. Gillberg ³², G. Gilles ¹¹⁵, N.E.K. Gillwald ⁴⁴, D.M. Gingrich ^{2,aj}, M.P. Giordani ^{64a,64c}, P.F. Giraud ¹⁴⁰, G. Giugliarelli ^{64a,64c}, D. Giugni ^{66a}, F. Giuli ^{71a,71b}, I. Gkialas ^{8,h}, P. Gkoutoumis ⁹, L.K. Gladilin ¹⁰⁹, C. Glasman ⁹⁵, G.R. Gledhill ¹²⁷, M. Glisic ¹²⁷, I. Gnesi ^{39b,d}, M. Goblirsch-Kolb ²⁴, D. Godin ¹⁰⁶, S. Goldfarb ¹⁰¹, T. Golling ⁵², D. Golubkov ¹¹⁸, J.P. Gombas ¹⁰³, A. Gomes ^{135a,135b}, R. Goncalves Gama ⁵¹, R. Gonçalves ^{135a,135c}, G. Gonella ¹²⁷, L. Gonella ¹⁹, A. Gongadze ⁷⁷, F. Gonnella ¹⁹, J.L. Gonski ³⁷, S. González de la Hoz ¹⁶⁹, S. Gonzalez Fernandez ¹², R. Gonzalez Lopez ⁸⁸, C. Gonzalez Renteria ¹⁶, R. Gonzalez Suarez ¹⁶⁷, S. Gonzalez-Sevilla ⁵², G.R. Gonzalvo Rodriguez ¹⁶⁹, R.Y. González Andana ^{142a}, L. Goossens ³⁴, N.A. Gorasia ¹⁹, P.A. Gorbounov ¹¹⁹, H.A. Gordon ²⁷, B. Gorini ³⁴, E. Gorini ^{65a,65b}, A. Gorišek ⁸⁹, A.T. Goshaw ⁴⁷, M.I. Gostkin ⁷⁷, C.A. Gottardo ¹¹⁴, M. Gouighri ^{33b}, V. Goumarre ⁴⁴, A.G. Goussiou ¹⁴⁴, N. Govender ^{31c}, C. Goy ⁴, I. Grabowska-Bold ^{81a}, K. Graham ³², E. Gramstad ¹²⁹, S. Grancagnolo ¹⁷, M. Grandi ¹⁵², V. Gratchev ¹³³, P.M. Gravila ^{25f}, F.G. Gravili ^{65a,65b}, H.M. Gray ¹⁶, C. Grefe ²², I.M. Gregor ⁴⁴, P. Grenier ¹⁴⁹, K. Grevtsov ⁴⁴, C. Grieco ¹², N.A. Grieser ¹²⁴, A.A. Grillo ¹⁴¹, K. Grimm ^{29,l}, S. Grinstein ^{12,v}, J.-F. Grivaz ⁶², S. Groh ⁹⁶, E. Gross ¹⁷⁵, J. Grosse-Knetter ⁵¹, C. Grud ¹⁰², A. Grummer ¹¹³, J.C. Grundy ¹³⁰, L. Guan ¹⁰², W. Guan ¹⁷⁶, C. Gubbels ¹⁷⁰, J. Guenther ³⁴, J.G.R. Guerrero Rojas ¹⁶⁹, F. Guescini ¹¹¹, D. Guest ¹⁷, R. Gugel ⁹⁶, A. Guida ⁴⁴, T. Guillemin ⁴, S. Guindon ³⁴, J. Guo ^{58c}, L. Guo ⁶², Y. Guo ¹⁰², R. Gupta ⁴⁴, S. Gurbuz ²², G. Gustavino ¹²⁴, M. Guth ⁵², P. Gutierrez ¹²⁴,

L.F. Gutierrez Zagazeta ¹³², C. Gutsche ⁹², C. Guyot ¹⁴⁰, C. Gwenlan ¹³⁰, C.B. Gwilliam ⁸⁸, E.S. Haaland ¹²⁹, A. Haas ¹²¹, M. Habedank ⁴⁴, C. Haber ¹⁶, H.K. Hadavand ⁷, A. Hadeef ⁹⁶, S. Hadzic ¹¹¹, M. Haleem ¹⁷², J. Haley ¹²⁵, J.J. Hall ¹⁴⁵, G. Halladjian ¹⁰³, G.D. Hallowell ⁹⁸, L. Halser ¹⁸, K. Hamano ¹⁷¹, H. Hamdaoui ^{33e}, M. Hamer ²², G.N. Hamity ⁴⁸, K. Han ^{58a}, L. Han ^{13c}, L. Han ^{58a}, S. Han ¹⁶, Y.F. Han ¹⁶², K. Hanagaki ^{79,t}, M. Hance ¹⁴¹, M.D. Hank ³⁵, R. Hankache ⁹⁷, E. Hansen ⁹⁴, J.B. Hansen ³⁸, J.D. Hansen ³⁸, M.C. Hansen ²², P.H. Hansen ³⁸, K. Hara ¹⁶⁴, T. Harenberg ¹⁷⁷, S. Harkusha ¹⁰⁴, Y.T. Harris ¹³⁰, P.F. Harrison ¹⁷³, N.M. Hartman ¹⁴⁹, N.M. Hartmann ¹¹⁰, Y. Hasegawa ¹⁴⁶, A. Hasib ⁴⁸, S. Hassani ¹⁴⁰, S. Haug ¹⁸, R. Hauser ¹⁰³, M. Havranek ¹³⁷, C.M. Hawkes ¹⁹, R.J. Hawkins ³⁴, S. Hayashida ¹¹², D. Hayden ¹⁰³, C. Hayes ¹⁰², R.L. Hayes ¹⁷⁰, C.P. Hays ¹³⁰, J.M. Hays ⁹⁰, H.S. Hayward ⁸⁸, S.J. Haywood ¹³⁹, F. He ^{58a}, Y. He ¹⁶⁰, Y. He ¹³¹, M.P. Heath ⁴⁸, V. Hedberg ⁹⁴, A.L. Heggelund ¹²⁹, N.D. Hehir ⁹⁰, C. Heidegger ⁵⁰, K.K. Heidegger ⁵⁰, W.D. Heidorn ⁷⁶, J. Heilman ³², S. Heim ⁴⁴, T. Heim ¹⁶, B. Heinemann ^{44,ah}, J.G. Heinlein ¹³², J.J. Heinrich ¹²⁷, L. Heinrich ³⁴, J. Hejbal ¹³⁶, L. Helary ⁴⁴, A. Held ¹²¹, C.M. Helling ¹⁴¹, S. Hellman ^{43a,43b}, C. Helsens ³⁴, R.C.W. Henderson ⁸⁷, L. Henkelmann ³⁰, A.M. Henriques Correia ³⁴, H. Herde ¹⁴⁹, Y. Hernández Jiménez ¹⁵¹, H. Herr ⁹⁶, M.G. Herrmann ¹¹⁰, T. Herrmann ⁴⁶, G. Herten ⁵⁰, R. Hertenberger ¹¹⁰, L. Hervas ³⁴, N.P. Hessey ^{163a}, H. Hibi ⁸⁰, S. Higashino ⁷⁹, E. Higón-Rodríguez ¹⁶⁹, K.H. Hiller ⁴⁴, S.J. Hillier ¹⁹, M. Hils ⁴⁶, I. Hinchliffe ¹⁶, F. Hinterkeuser ²², M. Hirose ¹²⁸, S. Hirose ¹⁶⁴, D. Hirschbuehl ¹⁷⁷, B. Hiti ⁸⁹, O. Hladik ¹³⁶, J. Hobbs ¹⁵¹, R. Hobincu ^{25e}, N. Hod ¹⁷⁵, M.C. Hodgkinson ¹⁴⁵, B.H. Hodgkinson ³⁰, A. Hoecker ³⁴, J. Hofer ⁴⁴, D. Hohn ⁵⁰, T. Holm ²², T.R. Holmes ³⁵, M. Holzbock ¹¹¹, L.B.A.H. Hommels ³⁰, B.P. Honan ⁹⁷, J. Hong ^{58c}, T.M. Hong ¹³⁴, Y. Hong ⁵¹, J.C. Honig ⁵⁰, A. Hönle ¹¹¹, B.H. Hooberman ¹⁶⁸, W.H. Hopkins ⁵, Y. Horii ¹¹², L.A. Horyn ³⁵, S. Hou ¹⁵⁴, J. Howarth ⁵⁵, J. Hoya ⁸⁶, M. Hrabovsky ¹²⁶, A. Hrynevich ¹⁰⁵, T. Hryn'ova ⁴, P.J. Hsu ⁶¹, S.-C. Hsu ¹⁴⁴, Q. Hu ³⁷, S. Hu ^{58c}, Y.F. Hu ^{13a,13d,al}, D.P. Huang ⁹², X. Huang ^{13c}, Y. Huang ^{58a}, Y. Huang ^{13a}, Z. Hubacek ¹³⁷, F. Hubaut ⁹⁸, M. Huebner ²², F. Huegging ²², T.B. Huffman ¹³⁰, M. Huhtinen ³⁴, S.K. Huiberts ¹⁵, R. Hulsken ⁵⁶, N. Huseynov ^{77,z}, J. Huston ¹⁰³, J. Huth ⁵⁷, R. Hyneman ¹⁴⁹, S. Hyrych ^{26a}, G. Iacobucci ⁵², G. Iakovidis ²⁷, I. Ibragimov ¹⁴⁷, L. Iconomidou-Fayard ⁶², P. Iengo ³⁴, R. Iguchi ¹⁵⁹, T. Iizawa ⁵², Y. Ikegami ⁷⁹, A. Ilg ¹⁸, N. Ilic ¹⁶², H. Imam ^{33a}, T. Ingebretsen Carlson ^{43a,43b}, G. Introzzi ^{68a,68b}, M. Iodice ^{72a}, V. Ippolito ^{70a,70b}, M. Ishino ¹⁵⁹, W. Islam ¹⁷⁶, C. Issever ^{17,44}, S. Istin ^{11c,am}, J.M. Iturbe Ponce ^{60a}, R. Iuppa ^{73a,73b}, A. Ivina ¹⁷⁵, J.M. Izen ⁴¹, V. Izzo ^{67a}, P. Jacka ¹³⁶, P. Jackson ¹, R.M. Jacobs ⁴⁴, B.P. Jaeger ¹⁴⁸, C.S. Jagfeld ¹¹⁰, G. Jäkel ¹⁷⁷, K. Jakobs ⁵⁰, T. Jakoubek ¹⁷⁵, J. Jamieson ⁵⁵, K.W. Janas ^{81a}, G. Jarlskog ⁹⁴, A.E. Jaspan ⁸⁸, N. Javadov ^{77,z}, T. Javůrek ³⁴, M. Javurkova ⁹⁹, F. Jeanneau ¹⁴⁰, L. Jeanty ¹²⁷, J. Jejelava ^{155a,aa}, P. Jenni ^{50,e}, S. Jézéquel ⁴, J. Jia ¹⁵¹, Z. Jia ^{13c}, Y. Jiang ^{58a}, S. Jiggins ⁴⁸, J. Jimenez Pena ¹¹¹, S. Jin ^{13c}, A. Jinaru ^{25b}, O. Jinnouchi ¹⁶⁰, H. Jivan ^{31f}, P. Johansson ¹⁴⁵, K.A. Johns ⁶, C.A. Johnson ⁶³, D.M. Jones ³⁰, E. Jones ¹⁷³, R.W.L. Jones ⁸⁷, T.J. Jones ⁸⁸, J. Jovicevic ¹⁴, X. Ju ¹⁶, J.J. Junggeburth ³⁴, A. Juste Rozas ^{12,v}, S. Kabana ^{142d}, A. Kaczmarska ⁸², M. Kado ^{70a,70b}, H. Kagan ¹²³, M. Kagan ¹⁴⁹, A. Kahn ³⁷, A. Kahn ¹³², C. Kahra ⁹⁶, T. Kaji ¹⁷⁴, E. Kajomovitz ¹⁵⁶, C.W. Kalderon ²⁷, A. Kamenshchikov ¹¹⁸, M. Kaneda ¹⁵⁹, N.J. Kang ¹⁴¹, S. Kang ⁷⁶, Y. Kano ¹¹², D. Kar ^{31f}, K. Karava ¹³⁰, M.J. Kareem ^{163b}, I. Karkanas ¹⁵⁸, S.N. Karpov ⁷⁷, Z.M. Karpova ⁷⁷, V. Kartvelishvili ⁸⁷, A.N. Karyukhin ¹¹⁸, E. Kasimi ¹⁵⁸, C. Kato ^{58d}, J. Katzy ⁴⁴, K. Kawade ¹⁴⁶, K. Kawagoe ⁸⁵, T. Kawaguchi ¹¹², T. Kawamoto ¹⁴⁰, G. Kawamura ⁵¹, E.F. Kay ¹⁷¹, F.I. Kaya ¹⁶⁵, S. Kazakos ¹², V.F. Kazanin ^{117b,117a}, Y. Ke ¹⁵¹, J.M. Keaveney ^{31a}, R. Keeler ¹⁷¹, J.S. Keller ³², A.S. Kelly ⁹², D. Kelsey ¹⁵², J.J. Kempster ¹⁹, J. Kendrick ¹⁹, K.E. Kennedy ³⁷, O. Kepka ¹³⁶, S. Kersten ¹⁷⁷, B.P. Kerševan ⁸⁹, S. Ketabchi Haghighat ¹⁶², M. Khandoga ¹³¹, A. Khanov ¹²⁵, A.G. Kharlamov ^{117b,117a}, T. Kharlamova ^{117b,117a}, E.E. Khoda ¹⁴⁴, T.J. Khoo ¹⁷, G. Khorauli ¹⁷², E. Khramov ⁷⁷, J. Khubua ^{155b}, S. Kido ⁸⁰, M. Kiehn ³⁴, A. Kilgallon ¹²⁷, E. Kim ¹⁶⁰, Y.K. Kim ³⁵, N. Kimura ⁹², A. Kirchhoff ⁵¹, D. Kirchmeier ⁴⁶, C. Kirfel ²², J. Kirk ¹³⁹, A.E. Kiryunin ¹¹¹, T. Kishimoto ¹⁵⁹, D.P. Kisliuk ¹⁶², C. Kitsaki ⁹, O. Kivernyk ²², T. Klapdor-Kleingrothaus ⁵⁰, M. Klassen ^{59a}, C. Klein ³², L. Klein ¹⁷², M.H. Klein ¹⁰², M. Klein ⁸⁸, U. Klein ⁸⁸, P. Klimek ³⁴, A. Klimentov ²⁷, F. Klimpel ¹¹¹, T. Klingl ²², T. Klioutchnikova ³⁴, F.F. Klitzner ¹¹⁰, P. Kluit ¹¹⁵, S. Kluth ¹¹¹, E. Kneringer ⁷⁴, T.M. Knight ¹⁶², A. Knue ⁵⁰, D. Kobayashi ⁸⁵, R. Kobayashi ⁸³, M. Kobel ⁴⁶, M. Kocian ¹⁴⁹, T. Kodama ¹⁵⁹, P. Kodys ¹³⁸, D.M. Koeck ¹⁵², P.T. Koenig ²², T. Koffas ³², N.M. Köhler ³⁴, M. Kolb ¹⁴⁰, I. Koletsou ⁴, T. Komarek ¹²⁶, K. Köneke ⁵⁰, A.X.Y. Kong ¹, T. Kono ¹²², V. Konstantinides ⁹², N. Konstantinidis ⁹², B. Konya ⁹⁴, R. Kopeliansky ⁶³, S. Koperny ^{81a}, K. Korcyl ⁸², K. Kordas ¹⁵⁸, G. Koren ¹⁵⁷, A. Korn ⁹², S. Korn ⁵¹, I. Korolkov ¹², E.V. Korolkova ¹⁴⁵, N. Korotkova ¹⁰⁹, B. Kortman ¹¹⁵, O. Kortner ¹¹¹, S. Kortner ¹¹¹, W.H. Kostecka ¹¹⁶, V.V. Kostyukhin ^{147,161}, A. Kotskechagia ⁶², A. Kotwal ⁴⁷, A. Koulouris ³⁴, A. Kourkoumeli-Charalampidi ^{68a,68b}, C. Kourkoumelis ⁸,

E. Kourlitis⁵, O. Kovanda¹⁵², R. Kowalewski¹⁷¹, W. Kozanecki¹⁴⁰, A.S. Kozhin¹¹⁸, V.A. Kramarenko¹⁰⁹, G. Kramberger⁸⁹, P. Kramer⁹⁶, D. Krasnopevtsev^{58a}, M.W. Krasny¹³¹, A. Krasznahorkay³⁴, J.A. Kremer⁹⁶, J. Kretzschmar⁸⁸, K. Kreul¹⁷, P. Krieger¹⁶², F. Krieter¹¹⁰, S. Krishnamurthy⁹⁹, A. Krishnan^{59b}, M. Krivos¹³⁸, K. Krizka¹⁶, K. Kroeninger⁴⁵, H. Kroha¹¹¹, J. Kroll¹³⁶, J. Kroll¹³², K.S. Krowpman¹⁰³, U. Kruchonak⁷⁷, H. Krüger²², N. Krumnack⁷⁶, M.C. Kruse⁴⁷, J.A. Krzysiak⁸², A. Kubota¹⁶⁰, O. Kuchinskaia¹⁶¹, S. Kudah^{3a}, D. Kuechler⁴⁴, J.T. Kuechler⁴⁴, S. Kuehn³⁴, T. Kuhl⁴⁴, V. Kukhtin⁷⁷, Y. Kulchitsky^{104,ad}, S. Kuleshov^{142c}, M. Kumar^{31f}, N. Kumari⁹⁸, M. Kuna⁵⁶, A. Kupco¹³⁶, T. Kupfer⁴⁵, O. Kuprash⁵⁰, H. Kurashige⁸⁰, L.L. Kurchaninov^{163a}, Y.A. Kurochkin¹⁰⁴, A. Kurova¹⁰⁸, M.G. Kurth^{13a,13d}, E.S. Kuwertz³⁴, M. Kuze¹⁶⁰, A.K. Kvam¹⁴⁴, J. Kvita¹²⁶, T. Kwan¹⁰⁰, K.W. Kwok^{60a}, C. Lacasta¹⁶⁹, F. Lacava^{70a,70b}, H. Lacker¹⁷, D. Lacour¹³¹, N.N. Lad⁹², E. Ladygin⁷⁷, R. Lafaye⁴, B. Laforge¹³¹, T. Lagouri^{142d}, S. Lai⁵¹, I.K. Lakomic^{81a}, N. Lalloue⁵⁶, J.E. Lambert¹²⁴, S. Lammers⁶³, W. Lampl⁶, C. Lampoudis¹⁵⁸, E. Lançon²⁷, U. Landgraf⁵⁰, M.P.J. Landon⁹⁰, V.S. Lang⁵⁰, J.C. Lange⁵¹, R.J. Langenberg⁹⁹, A.J. Lankford¹⁶⁶, F. Lanni²⁷, K. Lantzsch²², A. Lanza^{68a}, A. Lapertosa^{53b,53a}, J.F. Laporte¹⁴⁰, T. Lari^{66a}, F. Lasagni Manghi^{21b}, M. Lassnig³⁴, V. Latonova¹³⁶, T.S. Lau^{60a}, A. Laudrain⁹⁶, A. Laurier³², M. Lavorgna^{67a,67b}, S.D. Lawlor⁹¹, Z. Lawrence⁹⁷, M. Lazzaroni^{66a,66b}, B. Le⁹⁷, B. Leban⁸⁹, A. Lebedev⁷⁶, M. LeBlanc³⁴, T. LeCompte⁵, F. Ledroit-Guillon⁵⁶, A.C.A. Lee⁹², G.R. Lee¹⁵, L. Lee⁵⁷, S.C. Lee¹⁵⁴, S. Lee⁷⁶, L.L. Leeuw^{31c}, B. Lefebvre^{163a}, H.P. Lefebvre⁹¹, M. Lefebvre¹⁷¹, C. Leggett¹⁶, K. Lehmann¹⁴⁸, N. Lehmann¹⁸, G. Lehmann Miotto³⁴, W.A. Leight⁴⁴, A. Leisos^{158,u}, M.A.L. Leite^{78c}, C.E. Leitgeb⁴⁴, R. Leitner¹³⁸, K.J.C. Leney⁴⁰, T. Lenz²², S. Leone^{69a}, C. Leonidopoulos⁴⁸, A. Leopold¹⁵⁰, C. Leroy¹⁰⁶, R. Les¹⁰³, C.G. Lester³⁰, M. Levchenko¹³³, J. Levêque⁴, D. Levin¹⁰², L.J. Levinson¹⁷⁵, D.J. Lewis¹⁹, B. Li^{13b}, B. Li^{58b}, C. Li^{58a}, C-Q. Li^{58c,58d}, H. Li^{58a}, H. Li^{58b}, H. Li^{58b}, J. Li^{58c}, K. Li¹⁴⁴, L. Li^{58c}, M. Li^{13a,13d}, Q.Y. Li^{58a}, S. Li^{58d,58c,c}, T. Li^{58b}, X. Li⁴⁴, Y. Li⁴⁴, Z. Li^{58b}, Z. Li¹³⁰, Z. Li¹⁰⁰, Z. Li⁸⁸, Z. Liang^{13a}, M. Liberatore⁴⁴, B. Liberti^{71a}, K. Lie^{60c}, J. Lieber Marin^{78b}, K. Lin¹⁰³, R.A. Linck⁶³, R.E. Lindley⁶, J.H. Lindon², A. Linss⁴⁴, E. Lipeles¹³², A. Lipniacka¹⁵, T.M. Liss^{168,ai}, A. Lister¹⁷⁰, J.D. Little⁷, B. Liu^{13a}, B.X. Liu¹⁴⁸, J.B. Liu^{58a}, J.K.K. Liu³⁵, K. Liu^{58d,58c}, M. Liu^{58a}, M.Y. Liu^{58a}, P. Liu^{13a}, X. Liu^{58a}, Y. Liu⁴⁴, Y. Liu^{13c,13d}, Y.L. Liu¹⁰², Y.W. Liu^{58a}, M. Livan^{68a,68b}, J. Llorente Merino¹⁴⁸, S.L. Lloyd⁹⁰, E.M. Lobodzinska⁴⁴, P. Loch⁶, S. Loffredo^{71a,71b}, T. Lohse¹⁷, K. Lohwasser¹⁴⁵, M. Lokajicek¹³⁶, J.D. Long¹⁶⁸, I. Longarini^{70a,70b}, L. Longo³⁴, R. Longo¹⁶⁸, I. Lopez Paz¹², A. Lopez Solis⁴⁴, J. Lorenz¹¹⁰, N. Lorenzo Martinez⁴, A.M. Lory¹¹⁰, A. Lösle⁵⁰, X. Lou^{43a,43b}, X. Lou^{13a}, A. Lounis⁶², J. Love⁵, P.A. Love⁸⁷, J.J. Lozano Bahilo¹⁶⁹, G. Lu^{13a}, M. Lu^{58a}, S. Lu¹³², Y.J. Lu⁶¹, H.J. Lubatti¹⁴⁴, C. Luci^{70a,70b}, F.L. Lucio Alves^{13c}, A. Lucotte⁵⁶, F. Luehring⁶³, I. Luise¹⁵¹, L. Luminari^{70a}, O. Lundberg¹⁵⁰, B. Lund-Jensen¹⁵⁰, N.A. Luongo¹²⁷, M.S. Lutz¹⁵⁷, D. Lynn²⁷, H. Lyons⁸⁸, R. Lysak¹³⁶, E. Lytken⁹⁴, F. Lyu^{13a}, V. Lyubushkin⁷⁷, T. Lyubushkina⁷⁷, H. Ma²⁷, L.L. Ma^{58b}, Y. Ma⁹², D.M. Mac Donell¹⁷¹, G. Maccarrone⁴⁹, C.M. Macdonald¹⁴⁵, J.C. MacDonald¹⁴⁵, R. Madar³⁶, W.F. Mader⁴⁶, M. Madugoda Ralalage Don¹²⁵, N. Madysa⁴⁶, J. Maeda⁸⁰, T. Maeno²⁷, M. Maerker⁴⁶, V. Magerl⁵⁰, J. Magro^{64a,64c}, D.J. Mahon³⁷, C. Maidantchik^{78b}, A. Maio^{135a,135b,135d}, K. Maj^{81a}, O. Majersky^{26a}, S. Majewski¹²⁷, N. Makovec⁶², V. Maksimovic¹⁴, B. Malaescu¹³¹, Pa. Malecki⁸², V.P. Maleev¹³³, F. Malek⁵⁶, D. Malito^{39b,39a}, U. Mallik⁷⁵, C. Malone³⁰, S. Maltezos⁹, S. Malyukov⁷⁷, J. Mamuzic¹⁶⁹, G. Mancini⁴⁹, J.P. Mandalia⁹⁰, I. Mandić⁸⁹, L. Manhaes de Andrade Filho^{78a}, I.M. Maniatis¹⁵⁸, M. Manisha¹⁴⁰, J. Manjarres Ramos⁴⁶, K.H. Mankinen⁹⁴, A. Mann¹¹⁰, A. Manousos⁷⁴, B. Mansoulie¹⁴⁰, I. Mantos¹⁵⁸, S. Manzoni¹¹⁵, A. Marantis^{158,u}, G. Marchiori¹³¹, M. Marcisovsky¹³⁶, L. Marcoccia^{71a,71b}, C. Marcon⁹⁴, M. Marjanovic¹²⁴, Z. Marshall¹⁶, S. Marti-Garcia¹⁶⁹, T.A. Martin¹⁷³, V.J. Martin⁴⁸, B. Martin dit Latour¹⁵, L. Martinelli^{70a,70b}, M. Martinez^{12,v}, P. Martinez Agullo¹⁶⁹, V.I. Martinez Outschoorn⁹⁹, S. Martin-Haugh¹³⁹, V.S. Martoiu^{25b}, A.C. Martyniuk⁹², A. Marzin³⁴, S.R. Maschek¹¹¹, L. Masetti⁹⁶, T. Mashimo¹⁵⁹, J. Masik⁹⁷, A.L. Maslennikov^{117b,117a}, L. Massa^{21b}, P. Massarotti^{67a,67b}, P. Mastrandrea^{69a,69b}, A. Mastroberardino^{39b,39a}, T. Masubuchi¹⁵⁹, D. Matakias²⁷, T. Mathisen¹⁶⁷, A. Matic¹¹⁰, N. Matsuzawa¹⁵⁹, J. Maurer^{25b}, B. Maček⁸⁹, D.A. Maximov^{117b,117a}, R. Mazini¹⁵⁴, I. Maznas¹⁵⁸, S.M. Mazza¹⁴¹, C. Mc Ginn²⁷, J.P. Mc Gowan¹⁰⁰, S.P. Mc Kee¹⁰², T.G. McCarthy¹¹¹, W.P. McCormack¹⁶, E.F. McDonald¹⁰¹, A.E. McDougall¹¹⁵, J.A. MCFayden¹⁵², G. Mchedlidze^{155b}, M.A. McKay⁴⁰, K.D. McLean¹⁷¹, S.J. McMahon¹³⁹, P.C. McNamara¹⁰¹, R.A. McPherson^{171,y}, J.E. Mdhluli^{31f}, Z.A. Meadows⁹⁹, S. Meehan³⁴, T. Megy³⁶, S. Mehlhase¹¹⁰, A. Mehta⁸⁸, B. Meirose⁴¹, D. Melini¹⁵⁶, B.R. Mellado Garcia^{31f}, A.H. Melo⁵¹, F. Meloni⁴⁴, A. Melzer²², E.D. Mendes Gouveia^{135a}, A.M. Mendes Jacques Da Costa¹⁹, H.Y. Meng¹⁶², L. Meng³⁴, S. Menke¹¹¹,

M. Mentink³⁴, E. Meoni^{39b,39a}, C. Merlassino¹³⁰, P. Mermod^{52,*}, L. Merola^{67a,67b}, C. Meroni^{66a}, G. Merz¹⁰², O. Meshkov^{107,109}, J.K.R. Meshreki¹⁴⁷, J. Metcalfe⁵, A.S. Mete⁵, C. Meyer⁶³, J.-P. Meyer¹⁴⁰, M. Michetti¹⁷, R.P. Middleton¹³⁹, L. Mijović⁴⁸, G. Mikenberg¹⁷⁵, M. Mikestikova¹³⁶, M. Mikuž⁸⁹, H. Mildner¹⁴⁵, A. Milic¹⁶², C.D. Milke⁴⁰, D.W. Miller³⁵, L.S. Miller³², A. Milov¹⁷⁵, D.A. Milstead^{43a,43b}, T. Min^{13c}, A.A. Minaenko¹¹⁸, I.A. Minashvili^{155b}, L. Mince⁵⁵, A.I. Mincer¹²¹, B. Mindur^{81a}, M. Mineev⁷⁷, Y. Minegishi¹⁵⁹, Y. Mino⁸³, L.M. Mir¹², M. Miralles Lopez¹⁶⁹, M. Mironova¹³⁰, T. Mitani¹⁷⁴, V.A. Mitsou¹⁶⁹, M. Mittal^{58c}, O. Miu¹⁶², P.S. Miyagawa⁹⁰, Y. Miyazaki⁸⁵, A. Mizukami⁷⁹, J.U. Mjörnmark⁹⁴, T. Mkrtchyan^{59a}, M. Mlynarikova¹¹⁶, T. Moa^{43a,43b}, S. Mobius⁵¹, K. Mochizuki¹⁰⁶, P. Moder⁴⁴, P. Mogg¹¹⁰, A.F. Mohammed^{13a}, S. Mohapatra³⁷, G. Mokgatitswane^{31f}, B. Mondal¹⁴⁷, S. Mondal¹³⁷, K. Mönig⁴⁴, E. Monnier⁹⁸, L. Monsonis Romero¹⁶⁹, A. Montalbano¹⁴⁸, J. Montejo Berlingen³⁴, M. Montella¹²³, F. Monticelli⁸⁶, N. Morange⁶², A.L. Moreira De Carvalho^{135a}, M. Moreno Llacer¹⁶⁹, C. Moreno Martinez¹², P. Morettini^{53b}, S. Morgenstern¹⁷³, D. Mori¹⁴⁸, M. Morii⁵⁷, M. Morinaga¹⁵⁹, V. Morisbak¹²⁹, A.K. Morley³⁴, A.P. Morris⁹², L. Morvaj³⁴, P. Moschovakos³⁴, B. Moser¹¹⁵, M. Mosidze^{155b}, T. Moskalets⁵⁰, P. Moskvitina¹¹⁴, J. Moss^{29,n}, E.J.W. Moyse⁹⁹, S. Muanza⁹⁸, J. Mueller¹³⁴, R. Mueller¹⁸, D. Muenstermann⁸⁷, G.A. Mullier⁹⁴, J.J. Mullin¹³², D.P. Mungo^{66a,66b}, J.L. Munoz Martinez¹², F.J. Munoz Sanchez⁹⁷, M. Murin⁹⁷, P. Murin^{26b}, W.J. Murray^{173,139}, A. Murrone^{66a,66b}, J.M. Muse¹²⁴, M. Muškinja¹⁶, C. Mwewa²⁷, A.G. Myagkov^{118,ae}, A.J. Myers⁷, A.A. Myers¹³⁴, G. Myers⁶³, M. Myska¹³⁷, B.P. Nachman¹⁶, O. Nackenhorst⁴⁵, A. Nag Nag⁴⁶, K. Nagai¹³⁰, K. Nagano⁷⁹, J.L. Nagle²⁷, E. Nagy⁹⁸, A.M. Nairz³⁴, Y. Nakahama¹¹², K. Nakamura⁷⁹, H. Nanjo¹²⁸, F. Napolitano^{59a}, R. Narayan⁴⁰, E.A. Narayanan¹¹³, I. Naryshkin¹³³, M. Naseri³², C. Nass²², T. Naumann⁴⁴, G. Navarro^{20a}, J. Navarro-Gonzalez¹⁶⁹, R. Nayak¹⁵⁷, P.Y. Nechaeva¹⁰⁷, F. Nechansky⁴⁴, T.J. Neep¹⁹, A. Negri^{68a,68b}, M. Negrini^{21b}, C. Nellist¹¹⁴, C. Nelson¹⁰⁰, K. Nelson¹⁰², S. Nemecek¹³⁶, M. Nessi^{34,f}, M.S. Neubauer¹⁶⁸, F. Neuhaus⁹⁶, J. Neundorff⁴⁴, R. Newhouse¹⁷⁰, P.R. Newman¹⁹, C.W. Ng¹³⁴, Y.S. Ng¹⁷, Y.W.Y. Ng¹⁶⁶, B. Ngair^{33e}, H.D.N. Nguyen¹⁰⁶, R.B. Nickerson¹³⁰, R. Nicolaidou¹⁴⁰, D.S. Nielsen³⁸, J. Nielsen¹⁴¹, M. Niemeyer⁵¹, N. Nikiforou¹⁰, V. Nikolaenko^{118,ae}, I. Nikolic-Audit¹³¹, K. Nikolopoulos¹⁹, P. Nilsson²⁷, H.R. Nindhito⁵², A. Nisati^{70a}, N. Nishu², R. Nisius¹¹¹, T. Nitta¹⁷⁴, T. Nobe¹⁵⁹, D.L. Noel³⁰, Y. Noguchi⁸³, I. Nomidis¹³¹, M.A. Nomura²⁷, M.B. Norfolk¹⁴⁵, R.R.B. Norisam⁹², J. Novak⁸⁹, T. Novak⁴⁴, O. Novgorodova⁴⁶, L. Novotny¹³⁷, R. Novotny¹¹³, L. Nozka¹²⁶, K. Ntekas¹⁶⁶, E. Nurse⁹², F.G. Oakham^{32,aj}, J. Ocariz¹³¹, A. Ochi⁸⁰, I. Ochoa^{135a}, J.P. Ochoa-Ricoux^{142a}, S. Oda⁸⁵, S. Odaka⁷⁹, S. Oerdek¹⁶⁷, A. Ogrodnik^{81a}, A. Oh⁹⁷, C.C. Ohm¹⁵⁰, H. Oide¹⁶⁰, R. Oishi¹⁵⁹, M.L. Ojeda⁴⁴, Y. Okazaki⁸³, M.W. O'Keefe⁸⁸, Y. Okumura¹⁵⁹, A. Olariu^{25b}, L.F. Oleiro Seabra^{135a}, S.A. Olivares Pino^{142d}, D. Oliveira Damazio²⁷, D. Oliveira Goncalves^{78a}, J.L. Oliver¹⁶⁶, M.J.R. Olsson¹⁶⁶, A. Olszewski⁸², J. Olszowska⁸², Ö.O. Öncel²², D.C. O'Neil¹⁴⁸, A.P. O'Neill¹³⁰, A. Onofre^{135a,135e}, P.U.E. Onyisi¹⁰, R.G. Oreamuno Madriz¹¹⁶, M.J. Oreglia³⁵, G.E. Orellana⁸⁶, D. Orestano^{72a,72b}, N. Orlando¹², R.S. Orr¹⁶², V. O'Shea⁵⁵, R. Ospanov^{58a}, G. Otero y Garzon²⁸, H. Otono⁸⁵, P.S. Ott^{59a}, G.J. Ottino¹⁶, M. Ouchrif^{33d}, J. Ouellette²⁷, F. Ould-Saada¹²⁹, A. Ouraou^{140,*}, Q. Ouyang^{13a}, M. Owen⁵⁵, R.E. Owen¹³⁹, K.Y. Oyulmaz^{11c}, V.E. Ozcan^{11c}, N. Ozturk⁷, S. Ozturk^{11c}, J. Pacalt¹²⁶, H.A. Pacey³⁰, K. Pachal⁴⁷, A. Pacheco Pages¹², C. Padilla Aranda¹², S. Pagan Griso¹⁶, G. Palacino⁶³, S. Palazzo⁴⁸, S. Palestini³⁴, M. Palka^{81b}, P. Palni^{81a}, D.K. Panchal¹⁰, C.E. Pandini⁵², J.G. Panduro Vazquez⁹¹, P. Pani⁴⁴, G. Panizzo^{64a,64c}, L. Paolozzi⁵², C. Papadatos¹⁰⁶, S. Parajuli⁴⁰, A. Paramonov⁵, C. Paraskevopoulos⁹, D. Paredes Hernandez^{60b}, S.R. Paredes Saenz¹³⁰, B. Parida¹⁷⁵, T.H. Park¹⁶², A.J. Parker²⁹, M.A. Parker³⁰, F. Parodi^{53b,53a}, E.W. Parrish¹¹⁶, J.A. Parsons³⁷, U. Parzefall⁵⁰, L. Pascual Dominguez¹⁵⁷, V.R. Pascuzzi¹⁶, F. Pasquali¹¹⁵, E. Pasqualucci^{70a}, S. Passaggio^{53b}, F. Pastore⁹¹, P. Pasuwan^{43a,43b}, J.R. Pater⁹⁷, A. Pathak¹⁷⁶, J. Patton⁸⁸, T. Pauly³⁴, J. Pearkes¹⁴⁹, M. Pedersen¹²⁹, L. Pedraza Diaz¹¹⁴, R. Pedro^{135a}, T. Peiffer⁵¹, S.V. Peleganchuk^{117b,117a}, O. Penc¹³⁶, C. Peng^{60b}, H. Peng^{58a}, M. Penzin¹⁶¹, B.S. Peralva^{78a}, A.P. Pereira Peixoto^{135a}, L. Pereira Sanchez^{43a,43b}, D.V. Perepelitsa²⁷, E. Perez Codina^{163a}, M. Perganti⁹, L. Perini^{66a,66b}, H. Pernegger³⁴, S. Perrella³⁴, A. Perrevoort¹¹⁵, K. Peters⁴⁴, R.F.Y. Peters⁹⁷, B.A. Petersen³⁴, T.C. Petersen³⁸, E. Petit⁹⁸, V. Petousis¹³⁷, C. Petridou¹⁵⁸, P. Petroff⁶², F. Petrucci^{72a,72b}, A. Petrukhin¹⁴⁷, M. Pettee¹⁷⁸, N.E. Pettersson³⁴, K. Petukhova¹³⁸, A. Peyaud¹⁴⁰, R. Pezoa^{142e}, L. Pezzotti³⁴, G. Pezzullo¹⁷⁸, T. Pham¹⁰¹, P.W. Phillips¹³⁹, M.W. Phipps¹⁶⁸, G. Piacquadio¹⁵¹, E. Pianori¹⁶, F. Piazza^{66a,66b}, A. Picazio⁹⁹, R. Piegai²⁸, D. Pietreanu^{25b}, J.E. Pilcher³⁵, A.D. Pilkington⁹⁷, M. Pinamonti^{64a,64c}, J.L. Pinfold², C. Pitman Donaldson⁹², D.A. Pizzi³², L. Pizzimento^{71a,71b}, A. Pizzini¹¹⁵, M.-A. Pleier²⁷, V. Plesanovs⁵⁰, V. Pleskot¹³⁸, E. Plotnikova⁷⁷, P. Podberezko^{117b,117a},

R. Poettgen⁹⁴, R. Poggi⁵², L. Poggioli¹³¹, I. Pogrebnyak¹⁰³, D. Pohl²², I. Pokharel⁵¹, G. Polesello^{68a}, A. Poley^{148,163a}, A. Policicchio^{70a,70b}, R. Polifka¹³⁸, A. Polini^{21b}, C.S. Pollard¹³⁰, Z.B. Pollock¹²³, V. Polychronakos²⁷, D. Ponomarenko¹⁰⁸, L. Pontecorvo³⁴, S. Popa^{25a}, G.A. Popeneciu^{25d}, L. Portales⁴, D.M. Portillo Quintero^{163a}, S. Pospisil¹³⁷, P. Postolache^{25c}, K. Potamianos¹³⁰, I.N. Potrap⁷⁷, C.J. Potter³⁰, H. Potti¹, T. Poulsen⁴⁴, J. Poveda¹⁶⁹, T.D. Powell¹⁴⁵, G. Pownall⁴⁴, M.E. Pozo Astigarraga³⁴, A. Prades Ibanez¹⁶⁹, P. Pralavorio⁹⁸, M.M. Prapa⁴², S. Prell⁷⁶, D. Price⁹⁷, M. Primavera^{65a}, M.A. Principe Martin⁹⁵, M.L. Proffitt¹⁴⁴, N. Proklova¹⁰⁸, K. Prokofiev^{60c}, F. Prokoshin⁷⁷, S. Protopopescu²⁷, J. Proudfoot⁵, M. Przybycien^{81a}, D. Pudzha¹³³, P. Puzo⁶², D. Pyatiizbyantseva¹⁰⁸, J. Qian¹⁰², Y. Qin⁹⁷, T. Qiu⁹⁰, A. Quadt⁵¹, M. Queitsch-Maitland³⁴, G. Rabanal Bolanos⁵⁷, F. Ragusa^{66a,66b}, J.A. Raine⁵², S. Rajagopalan²⁷, K. Ran^{13a,13d}, D.F. Rassloff^{59a}, D.M. Rauch⁴⁴, S. Rave⁹⁶, B. Ravina⁵⁵, I. Ravinovich¹⁷⁵, M. Raymond³⁴, A.L. Read¹²⁹, N.P. Readioff¹⁴⁵, D.M. Rebuffi^{68a,68b}, G. Redlinger²⁷, K. Reeves⁴¹, D. Reikher¹⁵⁷, A. Reiss⁹⁶, A. Rej¹⁴⁷, C. Rembser³⁴, A. Renardi⁴⁴, M. Renda^{25b}, M.B. Rendel¹¹¹, A.G. Rennie⁵⁵, S. Resconi^{66a}, M. Ressegotti^{53b,53a}, E.D. Resseguie¹⁶, S. Rettie⁹², B. Reynolds¹²³, E. Reynolds¹⁹, M. Rezaei Estabragh¹⁷⁷, O.L. Rezanova^{117b,117a}, P. Reznicek¹³⁸, E. Ricci^{73a,73b}, R. Richter¹¹¹, S. Richter⁴⁴, E. Richter-Was^{81b}, M. Ridel¹³¹, P. Rieck¹¹¹, P. Riedler³⁴, O. Rifki⁴⁴, M. Rijssenbeek¹⁵¹, A. Rimoldi^{68a,68b}, M. Rimoldi⁴⁴, L. Rinaldi^{21b,21a}, T.T. Rinn¹⁶⁸, M.P. Rinnagel¹¹⁰, G. Ripellino¹⁵⁰, I. Riu¹², P. Rivadeneira⁴⁴, J.C. Rivera Vergara¹⁷¹, F. Rizatdinova¹²⁵, E. Rizvi⁹⁰, C. Rizzi⁵², B.A. Roberts¹⁷³, B.R. Roberts¹⁶, S.H. Robertson^{100,y}, M. Robin⁴⁴, D. Robinson³⁰, C.M. Robles Gajardo^{142e}, M. Robles Manzano⁹⁶, A. Robson⁵⁵, A. Rocchi^{71a,71b}, C. Roda^{69a,69b}, S. Rodriguez Bosca^{59a}, A. Rodriguez Rodriguez⁵⁰, A.M. Rodríguez Vera^{163b}, S. Roe³⁴, A.R. Roepe¹²⁴, J. Roggel¹⁷⁷, O. Røhne¹²⁹, R.A. Rojas¹⁷¹, B. Roland⁵⁰, C.P.A. Roland⁶³, J. Roloff²⁷, A. Romaniouk¹⁰⁸, M. Romano^{21b}, A.C. Romero Hernandez¹⁶⁸, N. Rompotis⁸⁸, M. Ronzani¹²¹, L. Roos¹³¹, S. Rosati^{70a}, B.J. Rosser¹³², E. Rossi¹⁶², E. Rossi⁴, E. Rossi^{67a,67b}, L.P. Rossi^{53b}, L. Rossini⁴⁴, R. Rosten¹²³, M. Rotaru^{25b}, B. Rottler⁵⁰, D. Rousseau⁶², D. Rousso³⁰, G. Rovelli^{68a,68b}, A. Roy¹⁰, A. Rozanov⁹⁸, Y. Rozen¹⁵⁶, X. Ruan^{31f}, A.J. Ruby⁸⁸, T.A. Ruggeri¹, F. Rühr⁵⁰, A. Ruiz-Martinez¹⁶⁹, A. Rummler³⁴, Z. Rurikova⁵⁰, N.A. Rusakovich⁷⁷, H.L. Russell³⁴, L. Rustige³⁶, J.P. Rutherford⁶, E.M. Rüttinger¹⁴⁵, M. Rybar¹³⁸, E.B. Rye¹²⁹, A. Ryzhov¹¹⁸, J.A. Sabater Iglesias⁴⁴, P. Sabatini¹⁶⁹, L. Sabetta^{70a,70b}, H.F.W. Sadrozinski¹⁴¹, R. Sadykov⁷⁷, F. Safai Tehrani^{70a}, B. Safarzadeh Samani¹⁵², M. Safdari¹⁴⁹, S. Saha¹⁰⁰, M. Sahinsoy¹¹¹, A. Sahu¹⁷⁷, M. Saimpert¹⁴⁰, M. Saito¹⁵⁹, T. Saito¹⁵⁹, D. Salamani³⁴, G. Salamanna^{72a,72b}, A. Salnikov¹⁴⁹, J. Salt¹⁶⁹, A. Salvador Salas¹², D. Salvatore^{39b,39a}, F. Salvatore¹⁵², A. Salzburger³⁴, D. Sammel⁵⁰, D. Sampsonidis¹⁵⁸, D. Sampsonidou^{58d,58c}, J. Sánchez¹⁶⁹, A. Sanchez Pineda⁴, V. Sanchez Sebastian¹⁶⁹, H. Sandaker¹²⁹, C.O. Sander⁴⁴, I.G. Sanderswood⁸⁷, J.A. Sandesara⁹⁹, M. Sandhoff¹⁷⁷, C. Sandoval^{20b}, D.P.C. Sankey¹³⁹, M. Sannino^{53b,53a}, A. Sansoni⁴⁹, C. Santoni³⁶, H. Santos^{135a,135b}, S.N. Santpur¹⁶, A. Santra¹⁷⁵, K.A. Saoucha¹⁴⁵, A. Saponov⁷⁷, J.G. Saraiva^{135a,135d}, J. Sardain⁹⁸, O. Sasaki⁷⁹, K. Sato¹⁶⁴, C. Sauer^{59b}, F. Sauerburger⁵⁰, E. Sauvan⁴, P. Savard^{162,aj}, R. Sawada¹⁵⁹, C. Sawyer¹³⁹, L. Sawyer⁹³, I. Sayago Galvan¹⁶⁹, C. Sbarra^{21b}, A. Sbrizzi^{21b,21a}, T. Scanlon⁹², J. Schaarschmidt¹⁴⁴, P. Schacht¹¹¹, D. Schaefer³⁵, U. Schäfer⁹⁶, A.C. Schaffer⁶², D. Schaile¹¹⁰, R.D. Schamberger¹⁵¹, E. Schanet¹¹⁰, C. Scharf¹⁷, N. Scharmberg⁹⁷, V.A. Schegelsky¹³³, D. Scheirich¹³⁸, F. Schenck¹⁷, M. Schernau¹⁶⁶, C. Schiavi^{53b,53a}, L.K. Schildgen²², Z.M. Schillaci²⁴, E.J. Schioppa^{65a,65b}, M. Schioppa^{39b,39a}, B. Schlag⁹⁶, K.E. Schleicher⁵⁰, S. Schlenker³⁴, K. Schmieden⁹⁶, C. Schmitt⁹⁶, S. Schmitt⁴⁴, L. Schoeffel¹⁴⁰, A. Schoening^{59b}, P.G. Scholer⁵⁰, E. Schopf¹³⁰, M. Schott⁹⁶, J. Schovancova³⁴, S. Schramm⁵², F. Schroeder¹⁷⁷, H-C. Schultz-Coulon^{59a}, M. Schumacher⁵⁰, B.A. Schumm¹⁴¹, Ph. Schune¹⁴⁰, A. Schwartzman¹⁴⁹, T.A. Schwarz¹⁰², Ph. Schwemling¹⁴⁰, R. Schwienhorst¹⁰³, A. Sciandra¹⁴¹, G. Sciolla²⁴, F. Scuri^{69a}, F. Scutti¹⁰¹, C.D. Sebastiani⁸⁸, K. Sedlaczek⁴⁵, P. Seema¹⁷, S.C. Seidel¹¹³, A. Seiden¹⁴¹, B.D. Seidlitz²⁷, T. Seiss³⁵, C. Seitz⁴⁴, J.M. Seixas^{78b}, G. Sekhniaidze^{67a}, S.J. Sekula⁴⁰, L. Selam⁴, N. Semprini-Cesari^{21b,21a}, S. Sen⁴⁷, C. Serfon²⁷, L. Serin⁶², L. Serkin^{64a,64b}, M. Sessa^{72a,72b}, H. Severini¹²⁴, S. Sevova¹⁴⁹, F. Sforza^{53b,53a}, A. Sfyrila⁵², E. Shabalina⁵¹, R. Shaheen¹⁵⁰, J.D. Shahinian¹³², N.W. Shaikh^{43a,43b}, D. Shaked Renous¹⁷⁵, L.Y. Shan^{13a}, M. Shapiro¹⁶, A. Sharma³⁴, A.S. Sharma¹, S. Sharma⁴⁴, P.B. Shatalov¹¹⁹, K. Shaw¹⁵², S.M. Shaw⁹⁷, P. Sherwood⁹², L. Shi⁹², C.O. Shimmin¹⁷⁸, Y. Shimogama¹⁷⁴, J.D. Shinner⁹¹, I.P.J. Shipsey¹³⁰, S. Shirabe⁵², M. Shiyakova⁷⁷, J. Shlomi¹⁷⁵, M.J. Shochet³⁵, J. Shojaii¹⁰¹, D.R. Shope¹⁵⁰, S. Shrestha¹²³, E.M. Shrif^{31f}, M.J. Shroff¹⁷¹, E. Shulga¹⁷⁵, P. Sicho¹³⁶, A.M. Sickles¹⁶⁸, E. Sideras Haddad^{31f}, O. Sidiropoulou³⁴, A. Sidoti^{21b}, F. Siegert⁴⁶, Dj. Sijacki¹⁴, J.M. Silva¹⁹,

M.V. Silva Oliveira³⁴, S.B. Silverstein^{43a}, S. Simion⁶², R. Simoniello³⁴, N.D. Simpson⁹⁴, S. Simsek^{11b}, P. Sinervo¹⁶², V. Sinetckii¹⁰⁹, S. Singh¹⁴⁸, S. Singh¹⁶², S. Sinha⁴⁴, S. Sinha^{31f}, M. Sioli^{21b,21a}, I. Siral¹²⁷, S.Yu. Sivoklokov¹⁰⁹, J. Sjölin^{43a,43b}, A. Skaf⁵¹, E. Skorda⁹⁴, P. Skubic¹²⁴, M. Slawinska⁸², K. Sliwa¹⁶⁵, V. Smakhtin¹⁷⁵, B.H. Smart¹³⁹, J. Smiesko¹³⁸, S.Yu. Smirnov¹⁰⁸, Y. Smirnov¹⁰⁸, L.N. Smirnova^{109,r}, O. Smirnova⁹⁴, E.A. Smith³⁵, H.A. Smith¹³⁰, M. Smizanska⁸⁷, K. Smolek¹³⁷, A. Smykiewicz⁸², A.A. Snesev¹⁰⁷, H.L. Snoek¹¹⁵, S. Snyder²⁷, R. Sobie^{171,y}, A. Soffer¹⁵⁷, F. Sohns⁵¹, C.A. Solans Sanchez³⁴, E.Yu. Soldatov¹⁰⁸, U. Soldevila¹⁶⁹, A.A. Solodkov¹¹⁸, S. Solomon⁵⁰, A. Soloshenko⁷⁷, O.V. Solovyanov¹¹⁸, V. Solovyev¹³³, P. Sommer¹⁴⁵, H. Son¹⁶⁵, A. Sonay¹², W.Y. Song^{163b}, A. Sopczak¹³⁷, A.L. Sapiro⁹², F. Sopkova^{26b}, S. Sottocornola^{68a,68b}, R. Soualah^{64a,64c}, A.M. Soukharev^{117b,117a}, Z. Soumami^{33e}, D. South⁴⁴, S. Spagnolo^{65a,65b}, M. Spalla¹¹¹, M. Spangenberg¹⁷³, F. Spanò⁹¹, D. Sperlich⁵⁰, T.M. Spieker^{59a}, G. Spigo³⁴, M. Spina¹⁵², D.P. Spiteri⁵⁵, M. Spousta¹³⁸, A. Stabile^{66a,66b}, R. Stamen^{59a}, M. Stamenkovic¹¹⁵, A. Stampekis¹⁹, M. Standke²², E. Stanecka⁸², B. Stanislaus³⁴, M.M. Stanitzki⁴⁴, M. Stankaityte¹³⁰, B. Stapf⁴⁴, E.A. Starchenko¹¹⁸, G.H. Stark¹⁴¹, J. Stark⁹⁸, D.M. Starke^{163b}, P. Staroba¹³⁶, P. Starovoitov^{59a}, S. Stärz¹⁰⁰, R. Staszewski⁸², G. Stavropoulos⁴², P. Steinberg²⁷, A.L. Steinhebel¹²⁷, B. Stelzer^{148,163a}, H.J. Stelzer¹³⁴, O. Stelzer-Chilton^{163a}, H. Stenzel⁵⁴, T.J. Stevenson¹⁵², G.A. Stewart³⁴, M.C. Stockton³⁴, G. Stoicea^{25b}, M. Stolarski^{135a}, S. Stonjek¹¹¹, A. Straessner⁴⁶, J. Strandberg¹⁵⁰, S. Strandberg^{43a,43b}, M. Strauss¹²⁴, T. Strebler⁹⁸, P. Strizenec^{26b}, R. Ströhmer¹⁷², D.M. Strom¹²⁷, L.R. Strom⁴⁴, R. Stroynowski⁴⁰, A. Strubig^{43a,43b}, S.A. Stucci²⁷, B. Stugu¹⁵, J. Stupak¹²⁴, N.A. Styles⁴⁴, D. Su¹⁴⁹, S. Su^{58a}, W. Su^{58d,144,58c}, X. Su^{58a}, K. Sugizaki¹⁵⁹, V.V. Sulim¹⁰⁷, M.J. Sullivan⁸⁸, D.M.S. Sultan⁵², L. Sultanaliyeva¹⁰⁷, S. Sultansoy^{3c}, T. Sumida⁸³, S. Sun¹⁰², S. Sun¹⁷⁶, X. Sun⁹⁷, O. Sunneborn Gudnadottir¹⁶⁷, C.J.E. Suster¹⁵³, M.R. Sutton¹⁵², M. Svatos¹³⁶, M. Swiatlowski^{163a}, T. Swirski¹⁷², I. Sykora^{26a}, M. Sykora¹³⁸, T. Sykora¹³⁸, D. Ta⁹⁶, K. Tackmann^{44,w}, A. Taffard¹⁶⁶, R. Tafirout^{163a}, R.H.M. Taibah¹³¹, R. Takashima⁸⁴, K. Takeda⁸⁰, T. Takeshita¹⁴⁶, E.P. Takeva⁴⁸, Y. Takubo⁷⁹, M. Talby⁹⁸, A.A. Talyshev^{117b,117a}, K.C. Tam^{60b}, N.M. Tamir¹⁵⁷, A. Tanaka¹⁵⁹, J. Tanaka¹⁵⁹, R. Tanaka⁶², J. Tang^{58c}, Z. Tao¹⁷⁰, S. Tapia Araya⁷⁶, S. Tapprogge⁹⁶, A. Tarek Abouelfadl Mohamed¹⁰³, S. Tarem¹⁵⁶, K. Tariq^{58b}, G. Tarna^{25b}, G.F. Tartarelli^{66a}, P. Tas¹³⁸, M. Tasevsky¹³⁶, E. Tassi^{39b,39a}, G. Tateno¹⁵⁹, Y. Tayalati^{33e}, G.N. Taylor¹⁰¹, W. Taylor^{163b}, H. Teagle⁸⁸, A.S. Tee¹⁷⁶, R. Teixeira De Lima¹⁴⁹, P. Teixeira-Dias⁹¹, H. Ten Kate³⁴, J.J. Teoh¹¹⁵, K. Terashi¹⁵⁹, J. Terron⁹⁵, S. Terzo¹², M. Testa⁴⁹, R.J. Teuscher^{162,y}, N. Themistokleous⁴⁸, T. Theveneaux-Pelzer¹⁷, O. Thielmann¹⁷⁷, D.W. Thomas⁹¹, J.P. Thomas¹⁹, E.A. Thompson⁴⁴, P.D. Thompson¹⁹, E. Thomson¹³², E.J. Thorpe⁹⁰, Y. Tian⁵¹, V.O. Tikhomirov^{107,af}, Yu.A. Tikhonov^{117b,117a}, S. Timoshenko¹⁰⁸, P. Tipton¹⁷⁸, S. Tisserant⁹⁸, S.H. Tlou^{31f}, A. Tmourji³⁶, K. Todome^{21b,21a}, S. Todorova-Nova¹³⁸, S. Todt⁴⁶, M. Togawa⁷⁹, J. Tojo⁸⁵, S. Tokár^{26a}, K. Tokushuku⁷⁹, E. Tolley¹²³, R. Tombs³⁰, M. Tomoto^{79,112}, L. Tompkins¹⁴⁹, P. Tornambe⁹⁹, E. Torrence¹²⁷, H. Torres⁴⁶, E. Torró Pastor¹⁶⁹, M. Toscani²⁸, C. Toscari³⁵, J. Toth^{98,x}, D.R. Tovey¹⁴⁵, A. Traet¹⁵, C.J. Treado¹²¹, T. Trefzger¹⁷², A. Tricoli²⁷, I.M. Trigger^{163a}, S. Trincaz-Duvold¹³¹, D.A. Trischuk¹⁷⁰, W. Trischuk¹⁶², B. Trocmé⁵⁶, A. Trofymov⁶², C. Troncon^{66a}, F. Trovato¹⁵², L. Truong^{31c}, M. Trzebinski⁸², A. Trzupek⁸², F. Tsai¹⁵¹, A. Tsiamis¹⁵⁸, P.V. Tsiarehka^{104,ad}, A. Tsigotis^{158,u}, V. Tsiskaridze¹⁵¹, E.G. Tskhadadze^{155a}, M. Tsopoulou¹⁵⁸, Y. Tsujikawa⁸³, I.I. Tsukerman¹¹⁹, V. Tsulaia¹⁶, S. Tsuno⁷⁹, O. Tsur¹⁵⁶, D. Tsybychev¹⁵¹, Y. Tu^{60b}, A. Tudorache^{25b}, V. Tudorache^{25b}, A.N. Tuna³⁴, S. Turchikhin⁷⁷, I. Turk Cakir^{3a}, R.J. Turner¹⁹, R. Turra^{66a}, P.M. Tuts³⁷, S. Tzamarias¹⁵⁸, P. Tzanis⁹, E. Tzovara⁹⁶, K. Uchida¹⁵⁹, F. Ukegawa¹⁶⁴, P.A. Ulloa Poblete^{142c}, G. Unal³⁴, M. Unal¹⁰, A. Undrus²⁷, G. Unel¹⁶⁶, F.C. Ungaro¹⁰¹, K. Uno¹⁵⁹, J. Urban^{26b}, P. Urquijo¹⁰¹, G. Usai⁷, R. Ushioda¹⁶⁰, M. Usman¹⁰⁶, Z. Uysal^{11d}, V. Vacek¹³⁷, B. Vachon¹⁰⁰, K.O.H. Vadla¹²⁹, T. Vafeiadis³⁴, C. Valderanis¹¹⁰, E. Valdes Santurio^{43a,43b}, M. Valente^{163a}, S. Valentinetti^{21b,21a}, A. Valero¹⁶⁹, R.A. Vallance¹⁹, A. Vallier⁹⁸, J.A. Valls Ferrer¹⁶⁹, T.R. Van Daalen¹⁴⁴, P. Van Gemmeren⁵, S. Van Stroud⁹², I. Van Vulpen¹¹⁵, M. Vanadia^{71a,71b}, W. Vandelli³⁴, M. Vandenbroucke¹⁴⁰, E.R. Vandewall¹²⁵, D. Vannicola¹⁵⁷, L. Vannoli^{53b,53a}, R. Vari^{70a}, E.W. Varnes⁶, C. Varni¹⁶, T. Varol¹⁵⁴, D. Varouchas⁶², K.E. Varvell¹⁵³, M.E. Vasile^{25b}, L. Vaslin³⁶, G.A. Vasquez¹⁷¹, F. Vazeille³⁶, D. Vazquez Furelos¹², T. Vazquez Schroeder³⁴, J. Veatch⁵¹, V. Vecchio⁹⁷, M.J. Veen¹¹⁵, I. Veliscek¹³⁰, L.M. Veloce¹⁶², F. Veloso^{135a,135c}, S. Veneziano^{70a}, A. Ventura^{65a,65b}, A. Verbytskyi¹¹¹, M. Verducci^{69a,69b}, C. Vergis²², M. Verissimo De Araujo^{78b}, W. Verkerke¹¹⁵, A.T. Vermeulen¹¹⁵, J.C. Vermeulen¹¹⁵, C. Vernieri¹⁴⁹, P.J. Verschuur⁹¹, M. Vessella⁹⁹, M.L. Vesterbacka¹²¹,

M.C. Vetterli^{148,aj}, A. Vgenopoulos¹⁵⁸, N. Viaux Maira^{142e}, T. Vickey¹⁴⁵, O.E. Vickey Boeriu¹⁴⁵, G.H.A. Viehhauser¹³⁰, L. Vigani^{59b}, M. Villa^{21b,21a}, M. Villaplana Perez¹⁶⁹, E.M. Villhauer⁴⁸, E. Vilucchi⁴⁹, M.G. Vincter³², G.S. Virdee¹⁹, A. Vishwakarma⁴⁸, C. Vittori^{21b,21a}, I. Vivarelli¹⁵², V. Vladimirov¹⁷³, E. Voevodina¹¹¹, M. Vogel¹⁷⁷, P. Vokac¹³⁷, J. Von Ahnen⁴⁴, E. Von Toerne²², V. Vorobel¹³⁸, K. Vorobev¹⁰⁸, M. Vos¹⁶⁹, J.H. Vosseveld⁸⁸, M. Vozak⁹⁷, L. Vozdecky⁹⁰, N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba^{137,*}, M. Vreeswijk¹¹⁵, N.K. Vu⁹⁸, R. Vuillermet³⁴, O.V. Vujanovic⁹⁶, I. Vukotic³⁵, S. Wada¹⁶⁴, C. Wagner⁹⁹, W. Wagner¹⁷⁷, S. Wahdan¹⁷⁷, H. Wahlberg⁸⁶, R. Wakasa¹⁶⁴, M. Wakida¹¹², V.M. Walbrecht¹¹¹, J. Walder¹³⁹, R. Walker¹¹⁰, S.D. Walker⁹¹, W. Walkowiak¹⁴⁷, A.M. Wang⁵⁷, A.Z. Wang¹⁷⁶, C. Wang^{58a}, C. Wang^{58c}, H. Wang¹⁶, J. Wang^{60a}, P. Wang⁴⁰, R.-J. Wang⁹⁶, R. Wang⁵⁷, R. Wang¹¹⁶, S.M. Wang¹⁵⁴, S. Wang^{58b}, T. Wang^{58a}, W.T. Wang⁷⁵, W.X. Wang^{58a}, X. Wang^{13c}, X. Wang¹⁶⁸, X. Wang^{58c}, Y. Wang^{58a}, Z. Wang¹⁰², C. Wanotayaroj³⁴, A. Warburton¹⁰⁰, C.P. Ward³⁰, R.J. Ward¹⁹, N. Warrack⁵⁵, A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹⁴⁴, B.M. Waugh⁹², A.F. Webb¹⁰, C. Weber²⁷, M.S. Weber¹⁸, S.A. Weber³², S.M. Weber^{59a}, C. Wei^{58a}, Y. Wei¹³⁰, A.R. Weidberg¹³⁰, J. Weingarten⁴⁵, M. Weirich⁹⁶, C. Weiser⁵⁰, T. Wenaus²⁷, B. Wendland⁴⁵, T. Wengler³⁴, S. Wenig³⁴, N. Wermes²², M. Wessels^{59a}, K. Whalen¹²⁷, A.M. Wharton⁸⁷, A.S. White⁵⁷, A. White⁷, M.J. White¹, D. Whiteson¹⁶⁶, L. Wickremasinghe¹²⁸, W. Wiedenmann¹⁷⁶, C. Wiel⁴⁶, M. Wielers¹³⁹, N. Wieseotte⁹⁶, C. Wiglesworth³⁸, L.A.M. Wiik-Fuchs⁵⁰, D.J. Wilbern¹²⁴, H.G. Wilkens³⁴, L.J. Wilkins⁹¹, D.M. Williams³⁷, H.H. Williams¹³², S. Williams³⁰, S. Willocq⁹⁹, P.J. Windischhofer¹³⁰, I. Wingerter-Seez⁴, F. Winklmeier¹²⁷, B.T. Winter⁵⁰, M. Wittgen¹⁴⁹, M. Wobisch⁹³, A. Wolf⁹⁶, R. Wölker¹³⁰, J. Wollrath¹⁶⁶, M.W. Wolter⁸², H. Wolters^{135a,135c}, V.W.S. Wong¹⁷⁰, A.F. Wongel⁴⁴, S.D. Worm⁴⁴, B.K. Wosiek⁸², K.W. Woźniak⁸², K. Wraight⁵⁵, J. Wu^{13a,13d}, S.L. Wu¹⁷⁶, X. Wu⁵², Y. Wu^{58a}, Z. Wu^{140,58a}, J. Wuerzinger¹³⁰, T.R. Wyatt⁹⁷, B.M. Wynne⁴⁸, S. Xella³⁸, L. Xia^{13c}, M. Xia^{13b}, J. Xiang^{60c}, X. Xiao¹⁰², M. Xie^{58a}, X. Xie^{58a}, I. Xioidis¹⁵², D. Xu^{13a}, H. Xu^{58a}, H. Xu^{58a}, L. Xu^{58a}, R. Xu¹³², T. Xu^{58a}, W. Xu¹⁰², Y. Xu^{13b}, Z. Xu^{58b}, Z. Xu¹⁴⁹, B. Yabsley¹⁵³, S. Yacoob^{31a}, N. Yamaguchi⁸⁵, Y. Yamaguchi¹⁶⁰, M. Yamatani¹⁵⁹, H. Yamauchi¹⁶⁴, T. Yamazaki¹⁶, Y. Yamazaki⁸⁰, J. Yan^{58c}, S. Yan¹³⁰, Z. Yan²³, H.J. Yang^{58c,58d}, H.T. Yang¹⁶, S. Yang^{58a}, T. Yang^{60c}, X. Yang^{58a}, X. Yang^{13a}, Y. Yang¹⁵⁹, Z. Yang^{102,58a}, W.-M. Yao¹⁶, Y.C. Yap⁴⁴, H. Ye^{13c}, J. Ye⁴⁰, S. Ye²⁷, I. Yeletsikh⁷⁷, M.R. Yexley⁸⁷, P. Yin³⁷, K. Yorita¹⁷⁴, K. Yoshihara⁷⁶, C.J.S. Young⁵⁰, C. Young¹⁴⁹, M. Yuan¹⁰², R. Yuan^{58b,i}, X. Yue^{59a}, M. Zaazoua^{33e}, B. Zabinski⁸², G. Zacharis⁹, E. Zaid⁴⁸, A.M. Zaitsev^{118,ae}, T. Zakareishvili^{155b}, N. Zakharchuk³², S. Zambito³⁴, D. Zanzi⁵⁰, S.V. Zeißner⁴⁵, C. Zeitnitz¹⁷⁷, J.C. Zeng¹⁶⁸, D.T. Zenger Jr²⁴, O. Zenin¹¹⁸, T. Ženiš^{26a}, S. Zenz⁹⁰, S. Zerradi^{33a}, D. Zerwas⁶², B. Zhang^{13c}, D.F. Zhang¹⁴⁵, G. Zhang^{13b}, J. Zhang⁵, K. Zhang^{13a}, L. Zhang^{13c}, M. Zhang¹⁶⁸, R. Zhang¹⁷⁶, S. Zhang¹⁰², X. Zhang^{58c}, X. Zhang^{58b}, Z. Zhang⁶², P. Zhao⁴⁷, T. Zhao^{58b}, Y. Zhao¹⁴¹, Z. Zhao^{58a}, A. Zhemchugov⁷⁷, Z. Zheng¹⁴⁹, D. Zhong¹⁶⁸, B. Zhou¹⁰², C. Zhou¹⁷⁶, H. Zhou⁶, N. Zhou^{58c}, Y. Zhou⁶, C.G. Zhu^{58b}, C. Zhu^{13a,13d}, H.L. Zhu^{58a}, H. Zhu^{13a}, J. Zhu¹⁰², Y. Zhu^{58a}, X. Zhuang^{13a}, K. Zhukov¹⁰⁷, V. Zhulanov^{117b,117a}, D. Zieminska⁶³, N.I. Zimine⁷⁷, S. Zimmermann^{50,*}, J. Zinsser^{59b}, M. Ziolkowski¹⁴⁷, L. Živković¹⁴, A. Zoccoli^{21b,21a}, K. Zoch⁵², T.G. Zorbas¹⁴⁵, O. Zormpa⁴², W. Zou³⁷, L. Zwalinski³⁴

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

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

³ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul; (c) Division of Physics, TOBB

University of Economics and Technology, Ankara; Turkey

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

⁵ High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America

⁶ Department of Physics, University of Arizona, Tucson AZ; United States of America

⁷ Department of Physics, University of Texas at Arlington, Arlington TX; United States of America

⁸ Physics Department, National and Kapodistrian University of Athens, Athens; Greece

⁹ Physics Department, National Technical University of Athens, Zografou; Greece

¹⁰ Department of Physics, University of Texas at Austin, Austin TX; United States of America

¹¹ (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of

Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey

¹² Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain

¹³ (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) University of Chinese Academy of Science (UCAS), Beijing; China

¹⁴ Institute of Physics, University of Belgrade, Belgrade; Serbia

¹⁵ Department for Physics and Technology, University of Bergen, Bergen; Norway

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America

¹⁷ Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany

¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland

¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom

²⁰ (a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia

²¹ (a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (b) INFN Sezione di Bologna; Italy

- ²² Physikalisches Institut, Universität Bonn, Bonn; Germany
- ²³ Department of Physics, Boston University, Boston MA; United States of America
- ²⁴ Department of Physics, Brandeis University, Waltham MA; United States of America
- ²⁵ (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; Romania
- ²⁶ (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
- ²⁷ Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
- ²⁸ Departamento de Física (FCEN) and IFIBA, Universidad de Buenos Aires and CONICET, Buenos Aires; Argentina
- ²⁹ California State University, CA; United States of America
- ³⁰ Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- ³¹ (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) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- ³² Department of Physics, Carleton University, Ottawa ON; Canada
- ³³ (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) Mohammed VI Polytechnic University, Ben Guerir; Morocco
- ³⁴ CERN, Geneva; Switzerland
- ³⁵ Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- ³⁶ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- ³⁷ Nevis Laboratory, Columbia University, Irvington NY; United States of America
- ³⁸ Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- ³⁹ (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX; United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- ⁴² National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
- ⁴³ (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm; Sweden
- ⁴⁴ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- ⁴⁵ Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- ⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- ⁴⁷ Department of Physics, Duke University, Durham NC; United States of America
- ⁴⁸ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
- ⁴⁹ INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- ⁵⁰ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- ⁵¹ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- ⁵² Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- ⁵³ (a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova; Italy
- ⁵⁴ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- ⁵⁵ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- ⁵⁶ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- ⁵⁸ (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
- ⁵⁹ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- ⁶⁰ (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
- ⁶¹ Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- ⁶² IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- ⁶³ Department of Physics, Indiana University, Bloomington IN; United States of America
- ⁶⁴ (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
- ⁶⁵ (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- ⁶⁶ (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano; Italy
- ⁶⁷ (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- ⁶⁸ (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- ⁶⁹ (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- ⁷⁰ (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
- ⁷¹ (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- ⁷² (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- ⁷³ (a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento; Italy
- ⁷⁴ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria
- ⁷⁵ University of Iowa, Iowa City IA; United States of America
- ⁷⁶ Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- ⁷⁷ Joint Institute for Nuclear Research, Dubna; Russia
- ⁷⁸ (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; Brazil
- ⁷⁹ KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- ⁸⁰ Graduate School of Science, Kobe University, Kobe; Japan
- ⁸¹ (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
- ⁸² Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- ⁸³ Faculty of Science, Kyoto University, Kyoto; Japan
- ⁸⁴ Kyoto University of Education, Kyoto; Japan
- ⁸⁵ Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
- ⁸⁶ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
- ⁸⁷ Physics Department, Lancaster University, Lancaster; United Kingdom
- ⁸⁸ Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
- ⁸⁹ Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia

- ⁹⁰ School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
- ⁹¹ Department of Physics, Royal Holloway University of London, Egham; United Kingdom
- ⁹² Department of Physics and Astronomy, University College London, London; United Kingdom
- ⁹³ Louisiana Tech University, Ruston LA; United States of America
- ⁹⁴ Fysiska institutionen, Lunds universitet, Lund; Sweden
- ⁹⁵ Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
- ⁹⁶ Institut für Physik, Universität Mainz, Mainz; Germany
- ⁹⁷ School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
- ⁹⁸ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
- ⁹⁹ Department of Physics, University of Massachusetts, Amherst MA; United States of America
- ¹⁰⁰ Department of Physics, McGill University, Montreal QC; Canada
- ¹⁰¹ School of Physics, University of Melbourne, Victoria; Australia
- ¹⁰² Department of Physics, University of Michigan, Ann Arbor MI; United States of America
- ¹⁰³ Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
- ¹⁰⁴ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus
- ¹⁰⁵ Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus
- ¹⁰⁶ Group of Particle Physics, University of Montreal, Montreal QC; Canada
- ¹⁰⁷ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia
- ¹⁰⁸ National Research Nuclear University MEPhI, Moscow; Russia
- ¹⁰⁹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia
- ¹¹⁰ Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
- ¹¹¹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
- ¹¹² Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
- ¹¹³ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
- ¹¹⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
- ¹¹⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
- ¹¹⁶ Department of Physics, Northern Illinois University, DeKalb IL; United States of America
- ¹¹⁷ ^(a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; ^(b) Novosibirsk State University Novosibirsk; Russia
- ¹¹⁸ Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia
- ¹¹⁹ Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow; Russia
- ¹²⁰ ^(a) New York University Abu Dhabi, Abu Dhabi; ^(b) United Arab Emirates University, Al Ain; ^(c) University of Sharjah, Sharjah; United Arab Emirates
- ¹²¹ Department of Physics, New York University, New York NY; United States of America
- ¹²² Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
- ¹²³ Ohio State University, Columbus OH; United States of America
- ¹²⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
- ¹²⁵ Department of Physics, Oklahoma State University, Stillwater OK; United States of America
- ¹²⁶ Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
- ¹²⁷ Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
- ¹²⁸ Graduate School of Science, Osaka University, Osaka; Japan
- ¹²⁹ Department of Physics, University of Oslo, Oslo; Norway
- ¹³⁰ Department of Physics, Oxford University, Oxford; United Kingdom
- ¹³¹ LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris; France
- ¹³² Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
- ¹³³ Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia
- ¹³⁴ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
- ¹³⁵ ^(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) Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- ¹³⁶ Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- ¹³⁷ Czech Technical University in Prague, Prague; Czech Republic
- ¹³⁸ Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- ¹³⁹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- ¹⁴⁰ IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- ¹⁴¹ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- ¹⁴² ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; ^(c) Universidad Andres Bello, Department of Physics, Santiago; ^(d) Instituto de Alta Investigación, Universidad de Tarapacá, Arica; ^(e) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- ¹⁴³ Universidade Federal de São João del Rei (UFSJ), São João del Rei; Brazil
- ¹⁴⁴ Department of Physics, University of Washington, Seattle WA; United States of America
- ¹⁴⁵ Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- ¹⁴⁶ Department of Physics, Shinshu University, Nagano; Japan
- ¹⁴⁷ Department Physik, Universität Siegen, Siegen; Germany
- ¹⁴⁸ Department of Physics, Simon Fraser University, Burnaby BC; Canada
- ¹⁴⁹ SLAC National Accelerator Laboratory, Stanford CA; United States of America
- ¹⁵⁰ Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- ¹⁵¹ Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- ¹⁵² Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- ¹⁵³ School of Physics, University of Sydney, Sydney; Australia
- ¹⁵⁴ Institute of Physics, Academia Sinica, Taipei; Taiwan
- ¹⁵⁵ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia
- ¹⁵⁶ Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
- ¹⁵⁷ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
- ¹⁵⁸ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
- ¹⁵⁹ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
- ¹⁶⁰ Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
- ¹⁶¹ Tomsk State University, Tomsk; Russia
- ¹⁶² Department of Physics, University of Toronto, Toronto ON; Canada
- ¹⁶³ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON; Canada
- ¹⁶⁴ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
- ¹⁶⁵ Department of Physics and Astronomy, Tufts University, Medford MA; United States of America

- ¹⁶⁶ Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
¹⁶⁷ Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
¹⁶⁸ Department of Physics, University of Illinois, Urbana IL; United States of America
¹⁶⁹ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain
¹⁷⁰ Department of Physics, University of British Columbia, Vancouver BC; Canada
¹⁷¹ Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
¹⁷² Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
¹⁷³ Department of Physics, University of Warwick, Coventry; United Kingdom
¹⁷⁴ Waseda University, Tokyo; Japan
¹⁷⁵ Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
¹⁷⁶ Department of Physics, University of Wisconsin, Madison WI; United States of America
¹⁷⁷ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
¹⁷⁸ Department of Physics, Yale University, New Haven CT; United States of America

- ^a Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
^b Also at Bruno Kessler Foundation, Trento; Italy.
^c Also at Center for High Energy Physics, Peking University; China.
^d Also at Centro Studi e Ricerche Enrico Fermi; Italy.
^e Also at CERN, Geneva; Switzerland.
^f Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
^g Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
^h Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
ⁱ Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
^j Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
^k Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
^l Also at Department of Physics, California State University, East Bay; United States of America.
^m Also at Department of Physics, California State University, Fresno; United States of America.
ⁿ Also at Department of Physics, California State University, Sacramento; United States of America.
^o Also at Department of Physics, King's College London, London; United Kingdom.
^p Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
^q Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
^r Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
^s Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
^t Also at Graduate School of Science, Osaka University, Osaka; Japan.
^u Also at Hellenic Open University, Patras; Greece.
^v Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
^w Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
^x Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
^y Also at Institute of Particle Physics (IPP); Canada.
^z Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
^{aa} Also at Institute of Theoretical Physics, Iliia State University, Tbilisi; Georgia.
^{ab} Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid; Spain.
^{ac} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
^{ad} Also at Joint Institute for Nuclear Research, Dubna; Russia.
^{ae} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
^{af} Also at National Research Nuclear University MEPhI, Moscow; Russia.
^{ag} Also at Physics Department, An-Najah National University, Nablus; Palestine.
^{ah} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
^{ai} Also at The City College of New York, New York NY; United States of America.
^{aj} Also at TRIUMF, Vancouver BC; Canada.
^{ak} Also at Università di Napoli Parthenope, Napoli; Italy.
^{al} Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
^{am} Also at Yeditepe University, Physics Department, Istanbul; Turkey.
^{*} Deceased.