



Letter

# Measurement of the Z boson invisible width at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration <sup>\*</sup>

## ARTICLE INFO

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## ABSTRACT

A measurement of the invisible width of the Z boson using events with jets and missing transverse momentum is presented using  $37 \text{ fb}^{-1}$  of 13 TeV proton–proton data collected by the ATLAS detector in 2015 and 2016. The ratio of  $Z \rightarrow \text{inv}$  to  $Z \rightarrow \ell\ell$  events, where inv refers to non-detected particles and  $\ell$  is either an electron or a muon, is measured and corrected for detector effects. Events with at least one energetic central jet with  $p_T \geq 110$  GeV are selected for both the  $Z \rightarrow \text{inv}$  and  $Z \rightarrow \ell\ell$  final states to obtain a similar phase space in the ratio. The invisible width is measured to be  $506 \pm 2$  (stat.)  $\pm 12$  (syst.) MeV and is the single most precise recoil-based measurement. The result is in agreement with the most precise determination from LEP and the Standard Model prediction based on three neutrino generations.

## 1. Introduction

Precision measurements of fundamental parameters of the Standard Model, such as properties of the Z boson, are crucial probes of the Standard Model and may provide hints of new physics. A measurement of the invisible width of the Z boson,  $\Gamma(Z \rightarrow \text{inv})$ , reveals the number of light neutrinos that couple to the Z boson and any potential non-Standard Model contributions. Measurements of  $\Gamma(Z \rightarrow \text{inv})$  via different final states and analysis strategies test the consistency of the Standard Model as differences amongst measurements would indicate possible sources of new physics.

The most precise measurement of the invisible width of the Z boson is that obtained by the LEP experiments via measurements of the total Z boson width [1–4] and subtracting the partial width to visible final states: pairs of leptons (electrons, muons, taus) and hadrons. The invisible width is measured to a precision of 0.3% assuming charged lepton universality, and 0.5% without this assumption [5]. Measurements of  $\Gamma(Z \rightarrow \text{inv})$  using photon-tagged events were also performed by the LEP experiments with a combined precision of 3.2% [6–9]. The CMS Collaboration measured  $\Gamma(Z \rightarrow \text{inv})$  using a jet+ $E_T^{\text{miss}}$  final state, where  $E_T^{\text{miss}}$  is the missing transverse momentum, with a precision of 3.2% dominated by systematic uncertainties in the electron and muon identification and jet energy scale [10]. Jet+ $E_T^{\text{miss}}$  final states are also sensitive to anomalous production of missing transverse momentum with dedicated analyses generally targeting regions with large  $E_T^{\text{miss}}$  [11,12].

This paper presents a measurement of  $\Gamma(Z \rightarrow \text{inv})$  using the ratio of  $Z(\rightarrow \text{inv}) + \text{jets}$  to  $Z(\rightarrow \ell\ell) + \text{jets}$  cross sections, defined as

$$R^{\text{miss}}(p_{T,Z}) \equiv \left( \frac{d\sigma(Z(\rightarrow \text{inv}) + \text{jets})}{dp_{T,Z}} \right) / \left( \frac{d\sigma(Z(\rightarrow \ell\ell) + \text{jets})}{dp_{T,Z}} \right) \\ = \left( \frac{d\sigma(Z + \text{jets}) \times BR(Z \rightarrow \text{inv})}{dp_{T,Z}} \right) / \left( \frac{d\sigma(Z + \text{jets}) \times BR(Z \rightarrow \ell\ell)}{dp_{T,Z}} \right), \quad (1)$$

where  $\ell$  refers to electrons and muons,  $p_{T,Z}$  is the Z boson  $p_T$ , as defined in Section 4 and  $BR(Z \rightarrow \ell\ell)$  are the leptonic branching ratios measured by the LEP experiments. In this ratio, the numerator and the denominator are corrected to a common phase space so that many of the dominant systematic uncertainties cancel. After all corrections, the value of the ratio is constant as a function of  $p_{T,Z}$ .  $\Gamma(Z \rightarrow \text{inv})$  is determined by utilising the measured value of the leptonic width [5,9] and fitting a constant value of  $R^{\text{miss}}(p_{T,Z})$ :

$$\Gamma(Z \rightarrow \text{inv}) = \hat{R}^{\text{miss}} \cdot \Gamma(Z \rightarrow \ell\ell), \quad (2)$$

where  $\Gamma(Z \rightarrow \ell\ell)$  is the leptonic width and  $\hat{R}^{\text{miss}}$  is the result of the fit.

The  $Z \rightarrow \text{inv}$ ,  $Z \rightarrow ee$ , and  $Z \rightarrow \mu\mu$  regions are defined to require at least one energetic jet. This criterion is applied to all regions to ensure that the dominant systematic uncertainties in the individual processes cancel in the ratio. Residual differences in the phase space between the numerator and the denominator of Equation (1) are accounted for using simulations.

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

## 2. ATLAS detector

The ATLAS experiment [13] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an inner 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 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers 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 [14] 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 set and simulated samples

The data used were recorded with the ATLAS detector from 2015 to 2016 in  $pp$  collisions at  $\sqrt{s} = 13$  TeV and correspond to a total integrated luminosity of  $36.65 \pm 0.32$  fb<sup>-1</sup> [15]. The mean number of  $pp$  interactions per bunch crossing, including the hard scattering and other interactions in the same bunch crossings (pile-up), was  $\langle \mu \rangle = 23$ .

Monte Carlo (MC) simulation samples are used to correct the data for detector effects and to estimate contributions from some background events. The generated samples were processed using the GEANT4-based ATLAS detector simulation [16,17] and the same event-reconstruction algorithms are used for both the MC samples and the data.

The production of  $Z$  bosons in association with jets for all leptonic decay modes was simulated with the ATLAS configuration of SHERPA 2.2.11 [18], which includes matrix elements for up to five partons at leading order (LO) and up to two partons at next-to-leading order (NLO). They are calculated with the COMIX [19] and OPEN-LOOPS [20–22] libraries and matched with the SHERPA parton shower (PS) [23] using the MEPS@NLO prescription [24–27] with a set of tuned parameters (“tune”) developed by the SHERPA authors. It includes a modified Catani–Seymour (CS) subtraction scheme [28], the Hessian NNPDF3.0NNLO Parton Density Function (PDF) set [29], and an analytic enhancement technique [18]. The prediction from SHERPA 2.2.11 also includes NLO virtual Electroweak corrections [18] that were found to have a negligible effect on the measured width and are therefore not considered.

An alternative  $Z$  + jets MC signal sample, referred to as MG5\_AMC+PY8 FxFx [18], was produced with the MADGRAPH5\_AMC@NLO 2.6.5 [30] program to generate matrix elements at NLO accuracy in Quantum-Chromodynamics (QCD) for up to three additional partons in the final

state. The NNPDF3.1NNLO set [29] was used in the generation. The parton showering and subsequent hadronisation were performed using PYTHIA 8.240 [31] with the A14 tune [32] and the NNPDF2.3LO PDF set [33]. The jet multiplicities were merged using the FxFx prescription [34].

For background processes,  $W$  + jets production is modelled with the same SHERPA configuration as the nominal  $Z$  + jets production. Samples of diboson and triboson final states ( $VV$ ,  $VVV$ , where  $V$  is either a  $W$  or  $Z$  boson and indicates all possible multi- $W$  or  $Z$  boson combinations) were produced with the SHERPA 2.2.1 or SHERPA 2.2.2 generator depending on the process, including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were simulated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. The matrix element calculations were matched and merged with the SHERPA parton shower using the MEPS@NLO prescription with a set of tuned parameters developed by the SHERPA authors, and the NNPDF3.0NNLO set of PDFs was used.

Electroweak production of  $\ell\ell jj$ ,  $\ell\nu jj$  and  $\nu\nu jj$  final states was simulated with SHERPA 2.2.11 [35] using LO matrix elements with up to one additional parton emission. The matrix elements were merged with the SHERPA parton shower [23] following the MEPS@LO prescription [26] and using the set of tuned parameters developed by the SHERPA authors. The NNPDF3.0NNLO set of PDFs [29] was employed. The samples were produced using the vector-boson-fusion approximation, which avoids overlap with semileptonic diboson topologies by requiring a  $t$ -channel colour-singlet exchange. The starting conditions of the CS shower are set according to the large- $N_c$  amplitudes supplied by Comix [36] to achieve the correct vector-boson-fusion-appropriate radiation pattern.

Production of  $t\bar{t}$  is simulated at NLO accuracy in perturbative QCD using the POWHEG BOX v2 [37–40] generator with the NNPDF3.0NNLO PDF set and the  $h_{\text{damp}}$  parameter<sup>2</sup> set to  $1.5 m_{\text{top}}$  [41]. The events were interfaced to PYTHIA 8.230 [31] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune and using the NNPDF2.3LO set of PDFs. The  $t\bar{t}$  sample is normalised to the cross-section prediction at next-to-next-to-leading order (NNLO) accuracy, including the resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms calculated with TOP++ 2.0 [42–48].

Single top quark production in the  $s$ -channel, in the  $t$ -channel, and in association with a  $W$  boson ( $tW$ ) was modelled using the POWHEG BOX v2 generator at NLO in QCD with the four-flavour scheme for the  $t$ -channel and five-flavour scheme for the  $s$ - and  $tW$ -channels and, the NNPDF3.0NNLO set of PDFs. The diagram-removal scheme [49] was used to remove interference and overlap with  $t\bar{t}$  production. The  $tW$  cross section is corrected to the theory prediction at approximate NNLO accuracy [50,51], while the  $s$ - and  $t$ -channel cross sections are corrected to the prediction at NLO accuracy [52,53].

For bottom and charm hadron decays, the EVTGEN 1.7.0 program [54] was used for MG5\_AMC+PY8 FxFx samples, and EVTGEN 1.2.0 was used for the POWHEG samples. Pile-up was modelled by overlaying the simulated hard-scattering event with inelastic  $pp$  events generated with PYTHIA 8.186 [55] using the NNPDF2.3LO PDF set and the A3 tune [56]. The small differences in lepton reconstruction, isolation, and trigger efficiencies between simulation and data are corrected in the simulation on an event-by-event basis by applying efficiency scale factors for each lepton [57–59].

<sup>1</sup> 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 upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

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

#### 4. Event selection

This analysis uses only data taken during 2015–2016 to profit from lower  $E_T^{\text{miss}}$  trigger thresholds. Events are used if they were recorded during stable beam conditions and if they satisfy detector and data-quality requirements [60]. They are required to have a primary vertex, defined as the vertex with the highest sum of track  $p_T^2$ , with at least two associated tracks with  $p_T > 500$  MeV [61]. The triggers used to collect  $Z \rightarrow \text{inv}$  and  $Z \rightarrow \mu\mu$  events require an  $E_T^{\text{miss}}$  threshold between 70–110 GeV depending on the data-taking period [62–64]. In these trigger algorithms, input from the muon spectrometer is not included and therefore muons are treated like non-interacting particles. The trigger efficiencies plateau in the region of  $E_T^{\text{miss}} \geq 170$  GeV. For the  $Z \rightarrow ee$  events, the data were collected using single-electron triggers, with  $p_T$  thresholds ranging from 20 to 26 GeV and varying identification and isolation criteria.

Electron candidates are reconstructed from inner-detector tracks that come from the primary vertex and are matched to clusters of energy deposits in the EM calorimeter. They must satisfy likelihood-based identification requirements [57] based on EM shower shapes, track quality, and track–cluster matching. Baseline electron candidates are used if they pass the ‘Loose’ identification requirements, and have  $p_T \geq 7$  GeV and  $|\eta| < 1.37$  or  $1.52 < |\eta| < 2.47$ . For the signal region, electron candidates must in addition satisfy the ‘Tight’ identification requirements and the ‘FCHighPtCaloOnly’ [57] isolation requirement, which is based on calorimeter information only and has good background rejection in the high  $p_T$  region. To fulfil the primary-vertex condition, the signal-region electron track’s transverse impact parameter significance must also satisfy  $|d_0|/\sigma(d_0) < 5.0$ , where  $d_0$  is the transverse impact parameter and  $\sigma(d_0)$  its uncertainty, and the longitudinal impact parameter  $z_0$  must satisfy  $|z_0 \sin(\theta)| < 0.5$  mm, where  $\theta$  is the angle of the track to the beamline.

Muon candidates are identified by matching inner-detector tracks from the primary vertex to either full tracks or track segments reconstructed in the muon spectrometer. They are required to satisfy identification requirements [58,59] based on quality criteria applied to the inner-detector and muon-spectrometer tracks. Baseline muon candidates are used in the analysis if they pass the ‘Loose’ identification requirements and have  $p_T \geq 7$  GeV and  $|\eta| < 2.5$ . Signal-region muon candidates in addition are required to satisfy ‘Medium’ identification requirements [58,59] and must satisfy the ‘FCLoose’ isolation requirement, built from tracking and calorimeter information, with a muon- $p_T$ -dependent variable cone size  $\Delta R$  [59] for isolation to other tracks. The signal region candidates must satisfy the following primary-vertex requirements: the transverse impact parameter significance must satisfy  $|d_0|/\sigma(d_0) < 3.0$  and the longitudinal impact parameter must satisfy  $|z_0 \sin(\theta)| < 0.5$  mm, where  $d_0$ ,  $\sigma(d_0)$ ,  $z_0$  and  $\theta$  are as defined above for the electrons.

Hadronically decaying taus are required to satisfy the ‘JETIDRNNOOSE’ selection [65], based on a recurrent neural network using single-track variables, and reconstructed kinematic and topological variables. They must have either one or three tracks associated with the tau candidate with an absolute charge of 1. Tau candidates are used if they have  $p_T > 20$  GeV and  $|\eta| < 1.37$  or  $1.52 < |\eta| < 2.47$ . Tau identification is used to reject background events.

Jets of hadrons are reconstructed using a particle-flow algorithm [66] based on noise-suppressed positive-energy topological clusters in the calorimeter. Energy deposited in the calorimeter by charged particles is subtracted and replaced by the momenta of tracks that are matched to those topological clusters. The jets are clustered using the anti- $k_r$  [67] algorithm implemented in the FASTJET package [68] with a radius parameter  $R = 0.4$ . They are initially calibrated using simulations and corrected using in situ measurements [69]. Jets are required to have a calibrated  $p_T \geq 30$  GeV and  $|\eta| < 4.4$ . Jets with  $p_T < 60$  GeV and  $|\eta| < 2.5$  need to satisfy the ‘Tight’ jet vertex tagger (JVT) working point [70], which uses tracking information to suppress pile-up

jets. The forward-jet-vertex tagger (fJVT) [71] identifies pile-up jets in the forward region with  $|\eta| > 2.5$  using the ‘Tight’ working point that sets constraints on the timing and the momentum of the jet. Events in which a jet is removed by the JVT algorithms are vetoed to reduce contributions of topologies where a falsely removed jet leads to  $E_T^{\text{miss}}$ . To reduce calorimeter noise ‘Loose’ jet quality criteria [72] are applied rejecting events with any jet potentially originating from anomalous energy depositions due to coherent noise and electronic noise bursts in the calorimeter [73]. For a further suppression of non-collision backgrounds either due to beam-induced or cosmic muons, the leading jet must satisfy the ‘Tight’ cleaning criteria. This requires the ratio of the charge fraction, which is the scalar sum of the  $p_T$  of tracks over the scalar sum of the calorimeter energy in the jet, to the maximum sampling fraction of the jet energy collected by a single calorimeter layer to be larger than 0.1.

Electrons, muons, taus, and jets are reconstructed and identified independently. An overlap-removal procedure is then applied to uniquely identify these objects in an event. Jets are removed if the  $\Delta R$  between the jet and a lepton is smaller than 0.2. Then, electrons and muons closer than  $\Delta R = 0.4$  to any remaining jet are removed.

The  $E_T^{\text{miss}}$  is computed as the negative of the vectorial sum of the transverse momenta of tracks associated with electrons, muons, hadronically decaying taus and any other object classified as a jet. Tracks in the inner detector that are associated to the primary vertex but not with any other component are also included [74]. A  $p_{T,Z}$  variable is defined to have a common observable between all regions. For the  $Z \rightarrow \text{inv}$  region,  $p_{T,Z}$  is the  $E_T^{\text{miss}}$ . For the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions,  $p_{T,Z}$  is the vectorial sum of the  $E_T^{\text{miss}}$  and the  $p_T$  of the two electrons or muons. For the  $W$  boson control regions, defined below, the  $p_{T,Z}$  is the vectorial sum of the  $E_T^{\text{miss}}$  and the  $p_T$  of the electron or muon.

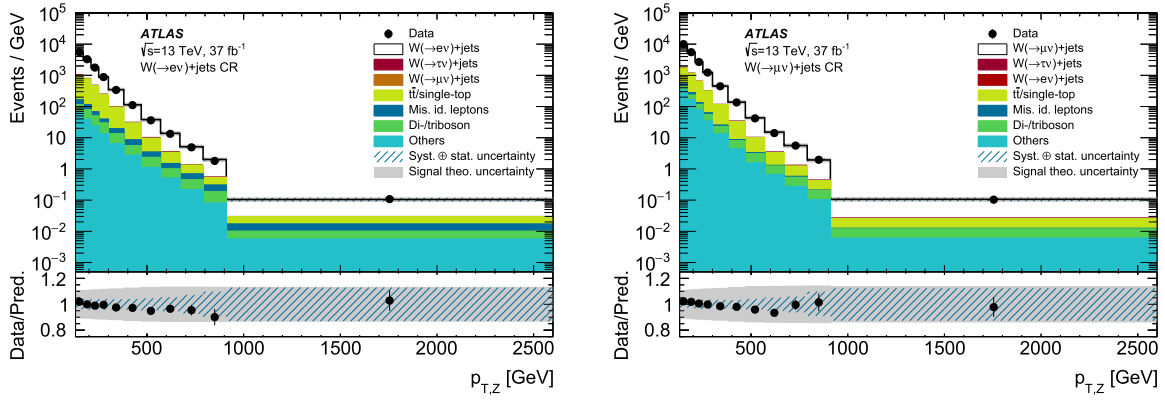
All regions are required to have  $p_{T,Z} \geq 130$  GeV and at least one jet with  $p_T \geq 110$  GeV and  $|\eta| < 2.4$ . To suppress the multijet background, events are vetoed if the separation in azimuthal angle between any jet and the  $p_{T,Z}$  vector,  $\Delta\phi(\text{jet}, p_{T,Z})$ , is less than 0.4. For the  $Z \rightarrow \text{inv}$  region, events are vetoed if any baseline lepton, including any tau lepton, is present.

For the  $Z \rightarrow ee$  region, events are required to have exactly two electrons passing the ‘Tight’ likelihood-based identification requirements, the ‘FCHighPtCaloOnly’ [57] isolation requirement and the track-to-vertex association requirements. The leading (sub-leading) electron is selected with a  $p_T$  larger than 50 (25) GeV. This selection reduces background processes without removing many  $Z \rightarrow ee$  events as the  $p_{T,Z}$  criterion selects  $Z$  events where the leading lepton has a high  $p_T$ . The two electrons must have opposite charges and the invariant mass of the di-electron system needs to satisfy  $66 < m_{ee} < 116$  GeV. Events are vetoed if any additional baseline lepton, including any tau lepton, is present.

For the  $Z \rightarrow \mu\mu$  region, events are required to have exactly two ‘Medium’, isolated muons from the primary vertex with  $p_T \geq 50$  (25) GeV for the leading (sub-leading) muon. The muons must have opposite charges and the invariant mass of the di-muon system must satisfy  $66 < m_{\mu\mu} < 116$  GeV. Events are vetoed if any additional baseline lepton, including any tau lepton, is present.

#### 5. Background estimates

The dominant background processes in the  $Z \rightarrow \text{inv}$  region are those from  $W + \text{jets}$  production (38% of the total number of events), multijet processes (5%), top-quark production (6%), diboson production,  $Z \rightarrow \ell\ell$  production (less than 2%) and non-collision events (1%). Contributions from the  $W + \text{jets}$  production are estimated using simulations but constrained by dedicated  $W + \text{jets}$  control regions. The multijet and non-collision processes are estimated with data-driven methods. All other background processes are estimated using simulations. For the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions, the dominant background processes are top-quark production (2% of the total number of events), diboson



**Fig. 1.** Data-to-predictions comparisons in (left)  $W(\rightarrow e\nu) + \text{jets}$  and (right)  $W(\rightarrow \mu\nu) + \text{jets}$  events as a function of  $p_{T,Z}$  in the respective control regions. Statistical uncertainties in the data are shown as error bars and the total combined statistical and systematic uncertainties are shown as hashed bands. The theory uncertainties in the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  processes are shown by the light grey shaded bands. The experimental and theory uncertainties are shown separately and not added in quadrature.

production (less than 2%) and contributions from non-prompt and mis-reconstructed leptons (1%). The latter is estimated via a data-driven method, whereas all others are determined via simulations.

The  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  control regions are defined using the same  $p_{T,Z}$ , jet and  $\Delta\phi(\text{jet}, p_{T,Z})$  criteria as in the  $Z \rightarrow \text{inv}$  region. The  $W \rightarrow e\nu$  control region definition requires in addition one electron with the same characteristics as the leading electron in the  $Z \rightarrow ee$  region,  $E_T^{\text{miss}} > 50$  GeV and a transverse mass  $50 \leq m_T \leq 110$  GeV, where  $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\phi^\ell - \phi_T^{\text{miss}}))}$ ,  $\phi^\ell$  and  $\phi_T^{\text{miss}}$  are the azimuthal angles of the lepton and the  $E_T^{\text{miss}}$  respectively. The  $W \rightarrow \mu\nu$  region requires exactly one muon as defined in the  $Z \rightarrow \mu\mu$  region with  $p_T > 50$  GeV and  $50 \leq m_T \leq 110$  GeV. In both the control regions, backgrounds from non-prompt and mis-reconstructed leptons are estimated via the matrix method, as described below. All other backgrounds, which amount to less than 25% of the total number of events, are estimated using simulations. Fig. 1 shows the number of events as a function of  $p_{T,Z}$  for the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  control regions.

The  $W \rightarrow e\nu$  ( $W \rightarrow \mu\nu$ ) simulations in the  $Z \rightarrow \text{inv}$  region are scaled by the ratio of data to simulations obtained in the  $W \rightarrow e\nu$  ( $W \rightarrow \mu\nu$ )-enhanced control region in each bin of the  $p_{T,Z}$  distributions. The  $p_{T,Z}$ -integrated scale factors for both channels are within 1% of unity and agree with each other within their systematic uncertainties. For contributions from  $W \rightarrow \tau\nu$ , where obtaining a sufficiently pure control region is difficult, the  $W \rightarrow \tau\nu$  simulation is scaled by the average value of those obtained in the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  control regions. This average value was checked in a tau-enhanced region, defined by selecting hadronically decaying taus with a  $p_T > 30$  GeV. The average value was found to be appropriate in this region.

The multijet background in the  $Z \rightarrow \text{inv}$  region originates largely from the mis-reconstruction of the energy of a jet in the calorimeter and, to a lesser extent, the presence of neutrinos in the final state from heavy-flavour hadron decays. The multijet background is determined from data, using the jet smearing method as described in Ref. [11,75]. It relies on the assumption that the  $E_T^{\text{miss}}$  value of multijet events is dominated by fluctuations in the jet response in the detector, which can be measured in the data. The method was validated using a region where events were selected as in the  $Z \rightarrow \text{inv}$  region, except for a modified requirement that the minimum azimuthal distance between a jet and  $E_T^{\text{miss}}$  is between 0.3 and 0.4, which indicates events with mis-measured jets. After the event selection, the multijet background is estimated to be about 8% in the lowest  $p_{T,Z}$  bin and falls below 1% for  $p_{T,Z}$  above 250 GeV.

Non-collision backgrounds in the  $Z \rightarrow \text{inv}$  region, which arise when beam-halo protons intercept the LHC collimators resulting in muon-producing particle cascades are estimated via the method outlined in

Ref. [73]. In particular, the jet timing,  $t_j$ , calculated from the energy-weighted average of the time of the jet energy deposits, defined relative to the event time in nominal collisions, is used. A dedicated region enhanced in beam-induced background, defined by inverting the tight jet-quality selection imposed on the leading jet, is used to estimate the amount of non-collision background from the fraction of events with a leading-jet timing  $|t_j| > 5$  ns. The results indicate a contribution of 1.2% from non-collision backgrounds in the signal region again steeply falling with  $p_{T,Z}$ .

In the  $Z \rightarrow ee$ ,  $Z \rightarrow \mu\mu$  regions and the  $W + \text{jets}$  control regions, contributions from non-prompt and mis-reconstructed electrons and muons are determined using the matrix method [76]. In this approach, the number of events with a mis-identified electron or muon is determined via a set of linear equations, based on the number of events in the signal region, the number of events in a sample where the lepton selection criteria are loosened to ensure a high fraction of mis-identified leptons and the efficiencies of real and mis-identified leptons to satisfy the signal region lepton criteria. The sample with loosened lepton criteria is defined as events that satisfy the baseline lepton selection but fail to meet the additional signal region lepton criteria. The efficiency of real leptons to satisfy the signal region lepton criteria relative to the loosened lepton criteria is determined from MC samples. The efficiency for mis-identified leptons is determined in an independent control region. For the mis-identified electrons, this control region uses the same criteria as with the  $W \rightarrow e\nu$  region but without applying the  $p_{T,Z}$  and  $m_T$  selection criteria and inverting the  $E_T^{\text{miss}}$  criterion. For the mis-identified muons, the control region uses the same criteria as with the  $W \rightarrow \mu\nu$  region but without applying the  $m_T$  selection criterion. With this method, the non-prompt and mis-reconstructed backgrounds are estimated to be about 1.0% and 0.7% in the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions, respectively. The background is roughly 1% in the  $W + \text{jets}$  control regions.

The matrix method is cross-checked for  $W \rightarrow e\nu$  events using a data-driven template fit approach. Here, the  $E_T^{\text{miss}}$  distribution for the mis-identified electron background is derived from data in a background-enriched control region. This region is defined by inverting the identification criteria and dropping the track-to-vertex association criteria. The contributions to the background template that do not originate from mis-identified electrons are evaluated and subtracted using simulation. A fit to the  $E_T^{\text{miss}}$  distribution is performed to determine the number of events with non-prompt and mis-reconstructed electrons. The resulting fraction of mis-identified electron events in the signal region agrees within the respective uncertainties to that obtained from the matrix method.

Distributions of the  $p_{T,Z}$  for the  $Z \rightarrow \text{inv}$ ,  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions are shown in Fig. 2. The predictions agree well with the data

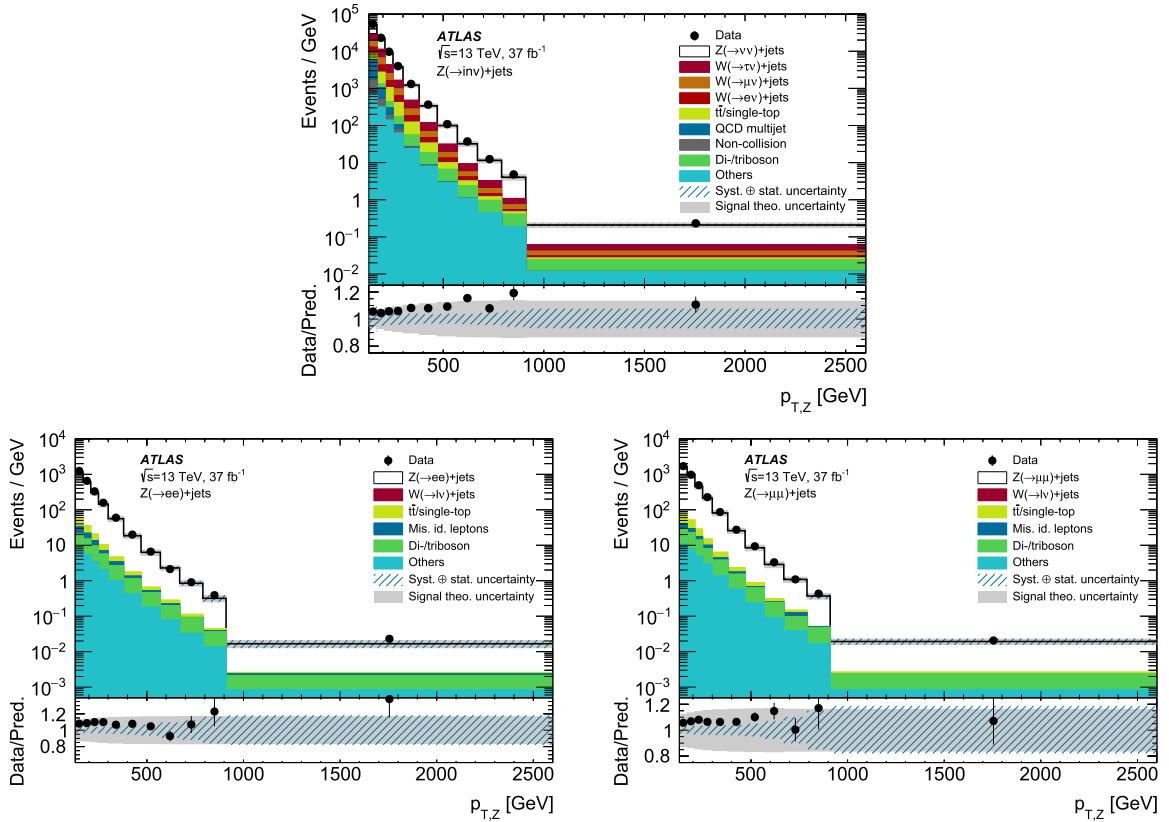


Fig. 2. Data-to-predictions comparisons in the  $Z \rightarrow \text{inv}$  (top),  $Z \rightarrow ee$  (bottom left) and  $Z \rightarrow \mu\mu$  (bottom right) signal regions as a function of  $p_{T,Z}$ . In the  $Z \rightarrow \text{inv}$ , the  $W$  boson scale factors are applied as described in the text. Statistical uncertainties in the data are shown as error bars and the total combined statistical and systematic uncertainties are shown as hashed bands. The theory uncertainties in the  $Z \rightarrow \text{inv}$ ,  $Z \rightarrow ee$ , and  $Z \rightarrow \mu\mu$  processes are shown by the light grey shaded bands. The experimental and theory uncertainties are shown separately and not added in quadrature.

within the experimental and theoretical uncertainties. The binning is optimised such that the bin width is at least two times the detector resolution. The highest  $p_{T,Z}$  bin in each region has at least 20 events and the bin ends at 2600 GeV above which the expected number of events is small.

## 6. Systematic uncertainties

Systematic uncertainties in the measured distributions and ratio stem from experimental and simulation modelling uncertainties. The uncertainties are estimated by applying them to simulation, and then re-estimating the background contributions and the detector-correction factors. The impact of the systematic uncertainties in the measured width is summarised in Table 1 and the relative uncertainties are shown in Fig. 6 in the appendix.

Systematic uncertainties associated with jet reconstruction are addressed via jet-energy-scale (JES) variations in a 29 nuisance-parameter scheme and jet-energy-resolution (JER) variations in a 13 nuisance-parameter scheme [69]. The uncertainty in the efficiency to satisfy the (f)JVT requirement for pile-up suppression was derived in  $Z(\rightarrow \mu\mu) + \text{jets}$  events and is also considered [77]. The uncertainty in  $E_T^{\text{miss}}$  due to a possible miscalibration of its soft-track component was derived from data–simulation comparisons of the  $p_T$  balance between the hard and soft  $E_T^{\text{miss}}$  components [74]. Imperfect modelling of the effects of pile-up leads to acceptance changes for different jet multiplicities. To assess this uncertainty, the average number of pile-up interactions is varied in simulation. The uncertainty in the combined 2015–2016 integrated luminosity is 0.87% [15], obtained using the LUCID-2 detector [78] for the primary luminosity measurements; this uncertainty cancels in the ratio, apart from small residual dependencies on the luminosity in the background estimates.

Systematic uncertainties in the lepton selection are related to the reconstruction, identification, isolation, and trigger [57–59] efficiencies and scale factors. Uncertainties in the electron energy scale and resolution are also taken into account [79]. The largest impact on this result is that from the uncertainties on the electron identification and then to a lesser extent that from the uncertainties on the isolation. For the muons, the uncertainties are related to the muon momentum scale, inner-detector and muon-spectrometer resolution, and sagitta-bias correction [80]. The largest impact due to the muon uncertainties are those from the isolation and reconstruction. For the  $\tau$ -leptons, energy scale uncertainties are included [81].

Modelling uncertainties in MC samples used in the signal and control regions are taken into account by varying the QCD scales and the PDF parameterisation. The effect of QCD scale uncertainties is defined by the envelope of variations resulting from changing the renormalisation ( $\mu_r$ ) and factorisation ( $\mu_f$ ) scales by factors of two with an additional constraint of  $0.5 \leq \mu_r/\mu_f \leq 2$ . Uncertainties due to the PDF parameterisation are evaluated using sets of PDF variations [82] and consistent variations of  $\alpha_s$  in the PDF and in the hard scatter based on NNPDF3.0<sub>NNLO</sub> [29]. The diagram-removal scheme [49] is used to remove interference and overlap between  $tW$  and  $t\bar{t}$  production. A related uncertainty was estimated by comparing to an alternative sample simulated using the diagram-subtraction scheme [41,49]. The uncertainty in  $\Gamma(Z \rightarrow \ell\ell)$  is taken from the Particle Data Group combination [9].

For the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$ -enhanced control regions, these uncertainties are applied to all simulation-based contributions. For the non-prompt and mis-reconstructed electrons and muons control regions, only scale uncertainties in the simulation-based contributions are significant and therefore considered. For these control regions, an additional uncertainty is estimated by varying the selection criteria. For the multi-

**Table 1**

Impact on  $\Gamma(Z \rightarrow \text{inv})$  of different sources of systematic uncertainties, their total, the statistical uncertainty in the data and the overall total uncertainty in MeV and percentage. The individual systematic uncertainties do not sum in quadrature to the total systematic uncertainty due to correlations between uncertainty sources.

Systematic Uncertainty	Impact on $\Gamma(Z \rightarrow \text{inv})$	in [MeV]	in [%]
Muon efficiency		7.4	1.5
Renormalisation & factorisation scales		5.9	1.2
Electron efficiency		4.9	1.0
Detector correction		4.4	0.9
QCD multijet		3.2	0.6
$E_T^{\text{miss}}$		2.4	0.5
$Z(\rightarrow \mu\mu)$ +jets misid. lepton estimate		1.9	0.4
Jet energy resolution		1.6	0.3
$W(\rightarrow \ell\nu)$ +jets normalisation		1.5	0.3
Pile-up reweighting		1.5	0.3
Non-collision background estimate		1.3	0.3
Jet energy scale		1.3	0.3
$\gamma^*$ -correction		1.0	0.2
$Z(\rightarrow ee)$ +jets misid. lepton estimate		1.0	0.2
Luminosity		1.0	0.2
Parton distribution functions + $\alpha_s$		0.7	0.1
$\Gamma(Z \rightarrow \ell\ell)$ [5,9]		0.5	0.1
Tau energy scale		0.4	0.1
Muon momentum scale		0.3	0.1
$W(\rightarrow \ell\nu)$ +jets misid. lepton estimate		0.3	0.1
(Forward) jet vertex tagging		0.2	< 0.1
Top subtraction scheme		0.2	< 0.1
Electron energy scale		0.1	< 0.1
Systematic		12	2.4
Statistical		2	0.4
Total		13	2.5

jet background and non-collision background estimates, a conservative 100% uncertainty is assigned.

To account for uncertainties on the detector correction, an uncertainty in the correction method itself is estimated by taking the difference between the corrected ratio using these bin-wise correction factors, as detailed below in Equation (3), and when using two iterations of Bayesian unfolding [83].

## 7. Invisible width measurement

The value of  $\Gamma(Z \rightarrow \text{inv})$  is determined via the ratio defined in Equations (1) and (2). In the  $R^{\text{miss}}$  ratio, both the numerator and denominator are extrapolated to a common phase space and are corrected to account for detector-related effects. The particle-level phase space is defined as:

- at least one jet, where the leading jet must have  $p_T \geq 110$  GeV and  $|\eta| < 2.4$ ,
- $p_{T,Z} \geq 130$  GeV.

Electrons and muons are defined as before any final-state radiation, the so-called ‘Born’ level, to ensure consistency between the electron, muon, and neutrino regions. Particle-level jets are found by applying the anti- $k_r$  algorithm with radius parameter  $R = 0.4$  to final-state particles with decay length  $c\tau > 10$  mm, excluding the decay products from the  $Z$  boson decay. The  $p_{T,Z}$  is defined as the  $Z$  boson  $p_T$ , calculated from either the two neutrinos or the two charged leptons from the  $Z$  boson decay.

For each bin,  $i$ , as a function of  $p_{T,Z}$ , the ratios of  $Z(\rightarrow \text{inv}) + \text{jets}/Z(\rightarrow ee) + \text{jets}$  and  $Z(\rightarrow \text{inv}) + \text{jets}/Z(\rightarrow \mu\mu) + \text{jets}$  are corrected for detector effects using a bin-wise correction factor, defined as

$$U_{i,\ell} = \frac{\left( \frac{N_i(Z(\rightarrow \text{inv}) + \text{jets})}{N_i(Z(\rightarrow \ell\ell) + \text{jets})} \right)^{\text{detector-level}}}{\left( \frac{N_i(Z(\rightarrow \text{inv}) + \text{jets})}{N_i(Z(\rightarrow \ell\ell) + \text{jets})} \right)^{\text{particle-level}}}, \quad (3)$$

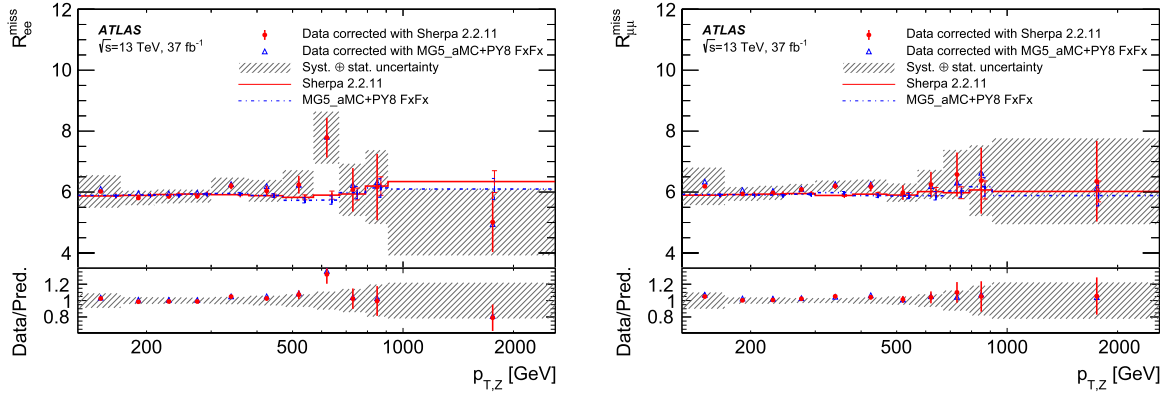
where  $\ell$  is either an electron or muon and  $N_i$  is the number of simulated events in that bin for a given process at either detector-level or particle-level. For the  $Z \rightarrow ee$  region, the value of  $U$  ranges from 0.3 at low  $p_{T,Z}$  to 0.6 at high  $p_{T,Z}$ . For the  $Z \rightarrow \mu\mu$  region, it ranges from 0.4 to 0.7. These factors are shown as a function of the  $p_{T,Z}$  in Fig. 7 of the appendix. They are dominated by the corrections to the full phase space, which range from 0.5 at low  $p_{T,Z}$  to 0.9 at high  $p_{T,Z}$ . A bin-wise correction of the ratio is justified as the migrations across bins, which are around 30%, are similar between the  $Z(\rightarrow \text{inv}) + \text{jets}$  and  $Z(\rightarrow \ell\ell) + \text{jets}$  processes and therefore largely cancel. This assumption was checked using a Bayesian unfolding method to correct the  $Z(\rightarrow \text{inv}) + \text{jets}$ ,  $Z(\rightarrow ee) + \text{jets}$  and  $Z(\rightarrow \mu\mu) + \text{jets}$  distributions individually and then form the ratio. In addition, the correction factors derived from SHERPA 2.2.11 are validated against those determined using MG5\_AMC+PY8 FxFx simulations and found to be consistent.

An additional correction is applied to the  $Z \rightarrow \ell\ell$  regions to extrapolate to a phase space with no  $Z$  boson  $m_{\ell\ell}$  criterion and to remove contributions from  $\gamma^*$  production, which is only present in charged lepton final states. The correction is derived by comparing PYTHIA simulations where the  $\gamma^*$  interference and a  $Z$  boson  $m_{\ell\ell}$  selection is included to  $Z$  boson production without interference and no mass selection. This correction factor is roughly 2% and is applied to the measured ratio and the predictions. Statistical uncertainties from the MC sample and the theoretical scale uncertainties, as described above, are included as uncertainties in the correction factor. The QCD scale uncertainties are on the sub-percent level.

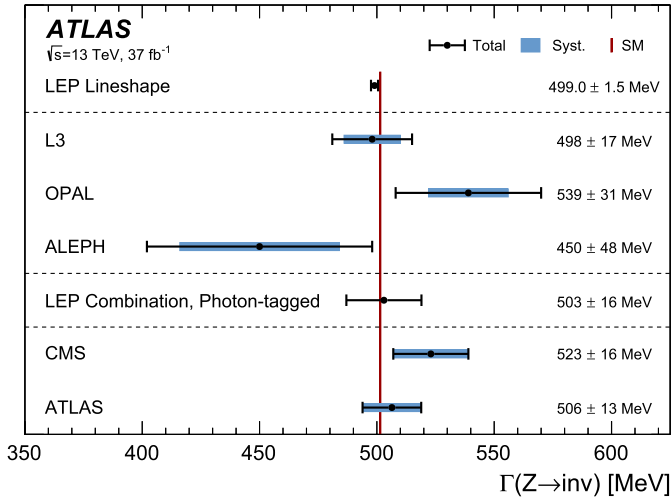
The measured values of  $R^{\text{miss}}$  with electrons and muons final states are shown in Fig. 3. In the electron channel, the increase in the bin at around 600 GeV is attributed to a statistical fluctuation and is found to diminish with the additional Run 2 data. The data is fully corrected for detector-effects and compared with predictions from SHERPA 2.2.11 and MG5\_AMC+PY8 FxFx. Both the predictions agree well with the data.

The value of  $\hat{R}^{\text{miss}}$  is determined via a  $\chi^2$  minimisation. Determining the value of  $\hat{R}^{\text{miss}}$  via a constant fit helps to reduce the systematic uncertainties as the Standard Model predicts that  $R^{\text{miss}}$  should be flat as a function of  $p_{T,Z}$ . The value of  $\Gamma(Z \rightarrow \text{inv})$  is then determined using Equation (2), utilising the  $\Gamma(Z \rightarrow \ell\ell)$  value, assuming lepton universality, obtained by the LEP experiments [5,9]. The function is defined as  $\chi^2 = (y_{\text{data},I} - \bar{y})^T \mathbf{V}^{-1} (y_{\text{data},I} - \bar{y})$ , where the index  $I$  runs over all  $p_{T,Z}$  bins and both the  $Z \rightarrow \text{inv}/Z \rightarrow ee$  and  $Z \rightarrow \text{inv}/Z \rightarrow \mu\mu$  ratios,  $y_{\text{data},I}$  is the measured  $Z \rightarrow \text{inv}/Z \rightarrow ee$  or  $Z \rightarrow \text{inv}/Z \rightarrow \mu\mu$  ratio,  $\bar{y}$  is the predicted ratio, which is independent of  $I$ , and  $\mathbf{V}^{-1}$  is the inverse covariance matrix. Statistical and systematic correlations between the  $Z \rightarrow \text{inv}$ ,  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions are accounted for via the covariance matrix. The lowest  $p_{T,Z}$  bin from 130 to 170 GeV is not considered in the minimisation due to large uncertainties in the multijet background.

The value of  $\Gamma(Z \rightarrow \text{inv})$  obtained is  $506 \pm 2$  (stat.)  $\pm 12$  (syst.) MeV with a  $\chi^2$  value from the fit of 17.3 for 19 degrees of freedom. The values of  $\Gamma(Z \rightarrow \text{inv})$  obtained using  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  individually are  $490 \pm 3$  (stat.)  $\pm 16$  (syst.) MeV and  $511 \pm 2$  (stat.)  $\pm 13$  (syst.) MeV respectively. They are in agreement with each other and with the combined result and also have good  $\chi^2$  values. The result is dominated by systematic uncertainties, mainly driven by lepton uncertainties in the denominator of the ratio. The muon channel is more precise and therefore has greater impact in the combination. This is the most precise recoil-based determination of  $\Gamma(Z \rightarrow \text{inv})$ . Fig. 4 summarises this result and other recoil-based results. Also shown are the combined value determined from fits of the lineshape of the  $Z$  resonance from LEP,  $499.0 \pm 1.5$  MeV [5] (assuming lepton universality), and the Standard Model prediction of  $501.445 \pm 0.047$  MeV [9], which is based on inputs such as the Higgs boson and top quark masses. The LEP combination of the photon-tagged results and the result from the lineshape measurements only quote their total uncertainty. The result is compatible with LEP and CMS results and with the Standard Model prediction.



**Fig. 3.** Measured  $R^{\text{miss}}$  of (left) electrons and (right) muons as a function of  $p_{T,Z}$  in the corrected phase space as defined in Section 7. The error bars on the measured red points show the statistical uncertainty and the grey hashed bands show the combined statistical and systematic uncertainties. The results are compared with the prediction for the SHERPA 2.2.11 (red) and for the MG5\_AMC+PY8 FxFx (blue) samples. For both the predictions, statistical uncertainties and uncertainties due to the  $\gamma^*$  correction are shown by the vertical bars.



**Fig. 4.**  $\Gamma(Z \rightarrow \text{inv})$  measured in this paper and by the LEP experiments L3, OPAL, ALEPH and the photon-tagged combination and by the CMS experiment. The total uncertainties are represented by the black error bars and the systematic uncertainty as the blue bands. The LEP combination of the photon-tagged results and the result from the lineshape measurements only quote their total uncertainty. The Standard Model prediction is shown by the solid red line.

## 8. Conclusion

A measurement of the invisible width of the  $Z$  boson using  $37 \text{ fb}^{-1}$  of 13 TeV proton–proton data collected by the ATLAS detector is presented. Measurements of  $\Gamma(Z \rightarrow \text{inv})$  in multiple final states are an important consistency test of the Standard Model and thereby a probe of new physics. The ratio of the number of  $Z(\rightarrow \text{inv}) + \text{jets}$  to  $Z(\rightarrow \ell\ell) + \text{jets}$  events corrected for detector effects is used. Events with at least one energetic central jet with  $p_T \geq 110 \text{ GeV}$  are selected for both the  $Z \rightarrow \text{inv}$  and  $Z \rightarrow \ell\ell$  processes to obtain a similar phase space between the numerator and the denominator of the ratio.

The obtained value of  $506 \pm 2$  (stat.)  $\pm 12$  (syst.) MeV is the most precise experimental result for recoil-based final states to date. The result is in agreement with other recoil-based measurements, with the most precise determination of  $\Gamma(Z \rightarrow \text{inv})$  from LEP and with the Standard Model prediction based on three neutrino generations. The dominant uncertainties of this result are due to lepton uncertainties in the denominator of the ratio. A future combination of the recoil-based measurements could further improve the precision of this fundamental parameter of the Standard Model.

## 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.

## Data availability

Data will be made available on request.

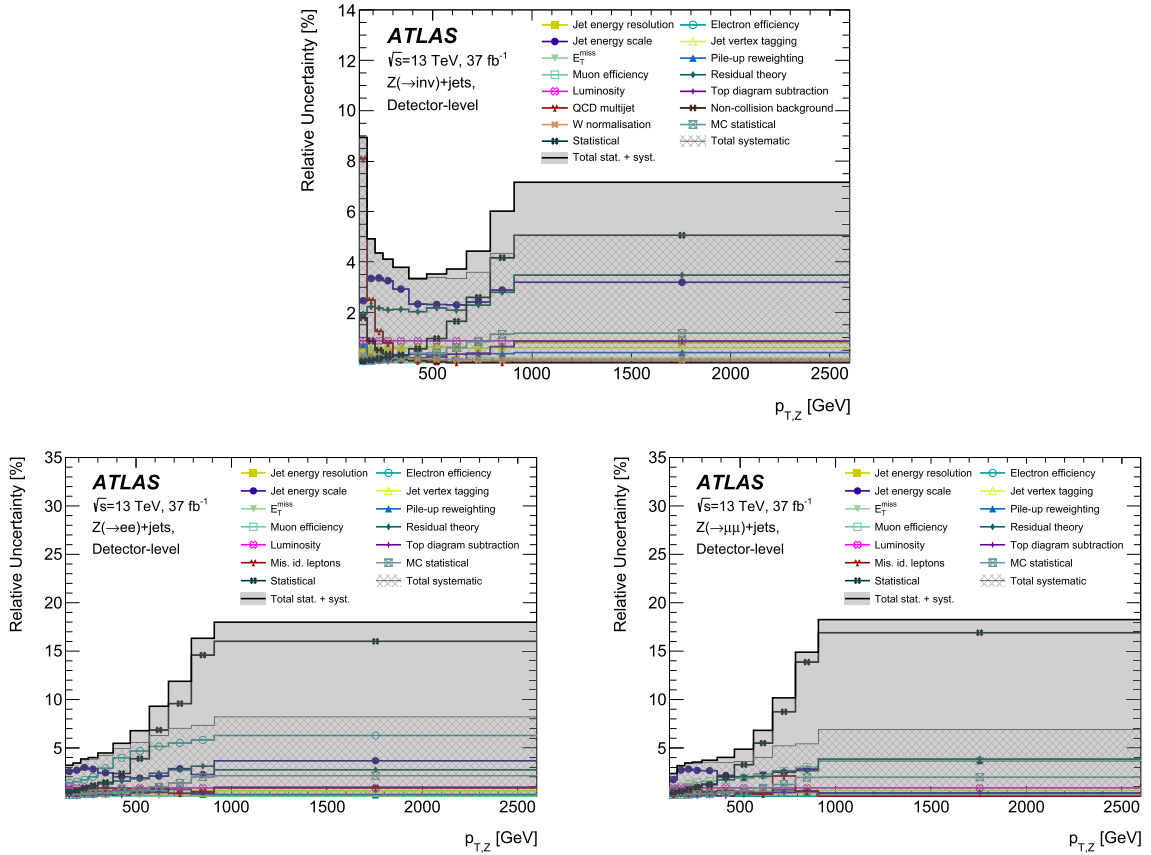
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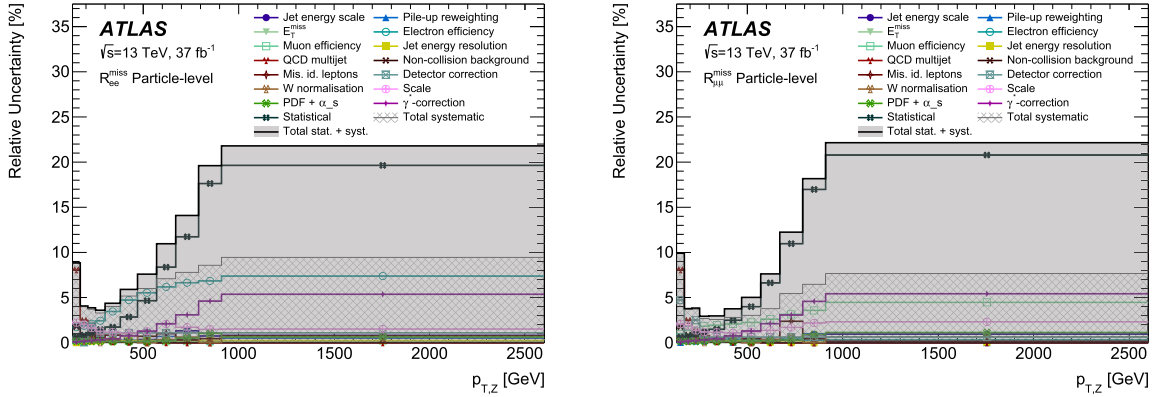
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**Fig. 5.** Relative uncertainties in percentage in the number of predicted events, as a function of  $p_{T,Z}$  for  $Z \rightarrow \text{inv}$  (top),  $Z \rightarrow ee$  (bottom left) and  $Z \rightarrow \mu\mu$  (bottom right) regions before detector corrections. Only uncertainties that are larger than 0.5% in any bin are shown.



**Fig. 6.** Relative uncertainties in percentage in  $R^{\text{miss}}$ , as a function of  $p_{T,Z}$  for the (left) electron and (right) muon channels after detector corrections. Only uncertainties that are larger than 0.5% in any bin are shown.

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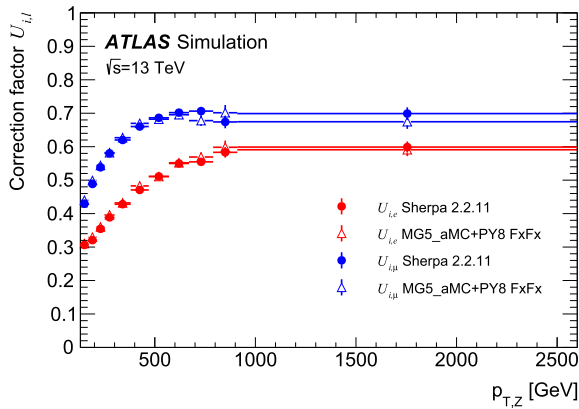


Fig. 7. The value of the correction factor,  $U_{i,l}$ , as a function of  $p_{T,Z}$  for both the  $Z \rightarrow ee$  (in red) and  $Z \rightarrow \mu\mu$  (in blue) regions. Shown in solid dots is the correction as determined with SHERPA 2.2.11 simulations and in open triangles that determined with MG5\_AMC+PY8 FxFx simulations. Only the Monte Carlo statistical uncertainties are shown.

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## Appendix A

A breakdown of the systematic uncertainties in the  $Z \rightarrow \text{inv}$ ,  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions is shown in Fig. 5. The systematic uncertainties in  $R^{\text{miss}}$ , after all corrections are applied, are indicated in Fig. 6. The values of the correction factor,  $U_{i,l}$  are shown in Fig. 7 as a function of  $p_{T,Z}$  for both the  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  regions.



























































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## The ATLAS Collaboration

G. Aad<sup>102, </sup>, B. Abbott<sup>120, </sup>, K. Abeling<sup>55, </sup>, N.J. Abicht<sup>49, </sup>, S.H. Abidi<sup>29, </sup>, A. Abouhorma<sup>35e, </sup>,  
H. Abramowicz<sup>151, </sup>, H. Abreu<sup>150, </sup>, Y. Abulaiti<sup>117, </sup>, B.S. Acharya<sup>69a,69b, </sup>,<sup>m</sup>, C. Adam Bourdarios<sup>4, </sup>,  
L. Adamczyk<sup>86a, </sup>, S.V. Addepalli<sup>26, </sup>, M.J. Addison<sup>101, </sup>, J. Adelman<sup>115, </sup>, A. Adiguzel<sup>21c, </sup>, T. Adye<sup>134, </sup>,  
A.A. Affolder<sup>136, </sup>, Y. Afik<sup>36, </sup>, M.N. Agaras<sup>13, </sup>, J. Agarwala<sup>73a,73b, </sup>, A. Aggarwal<sup>100, </sup>,  
C. Agheorghiesei<sup>27c, </sup>, A. Ahmad<sup>36, </sup>, F. Ahmadov<sup>38, </sup>,<sup>y</sup>, W.S. Ahmed<sup>104, </sup>, S. Ahuja<sup>95, </sup>, X. Ai<sup>62a, </sup>,  
G. Aielli<sup>76a,76b, </sup>, A. Aikot<sup>163, </sup>, M. Ait Tamliah<sup>35e, </sup>, B. Aitbenkhik<sup>35a, </sup>, I. Aizenberg<sup>169, </sup>,  
M. Akbiyik<sup>100, </sup>, T.P.A. Åkesson<sup>98, </sup>, A.V. Akimov<sup>37, </sup>, D. Akiyama<sup>168, </sup>, N.N. Akolkar<sup>24, </sup>, S. Aktas<sup>21a, </sup>,  
K. Al Khoury<sup>41, </sup>, G.L. Alberghi<sup>23b, </sup>, J. Albert<sup>165, </sup>, P. Albicocco<sup>53, </sup>, G.L. Albouy<sup>60, </sup>, S. Alderweireldt<sup>52, </sup>,  
Z.L. Alegria<sup>121, </sup>, M. Aleksa<sup>36, </sup>, I.N. Aleksandrov<sup>38, </sup>, C. Alexa<sup>27b, </sup>, T. Alexopoulos<sup>10, </sup>, F. Alfonsi<sup>23b, </sup>,  
M. Algren<sup>56, </sup>, M. Alhroob<sup>120, </sup>, B. Ali<sup>132, </sup>, H.M.J. Ali<sup>91, </sup>, S. Ali<sup>148, </sup>, S.W. Alibocus<sup>92, </sup>, M. Aliev<sup>145, </sup>,

G. Alimonti <sup>71a, [id](#)</sup>, W. Alkakhri <sup>55, [id](#)</sup>, C. Allaire <sup>66, [id](#)</sup>, B.M.M. Allbrooke <sup>146, [id](#)</sup>, J.F. Allen <sup>52, [id](#)</sup>,  
C.A. Allendes Flores <sup>137f, [id](#)</sup>, P.P. Allport <sup>20, [id](#)</sup>, A. Aloisio <sup>72a,72b, [id](#)</sup>, F. Alonso <sup>90, [id](#)</sup>, C. Alpigiani <sup>138, [id](#)</sup>,  
M. Alvarez Estevez <sup>99, [id](#)</sup>, A. Alvarez Fernandez <sup>100, [id](#)</sup>, M. Alves Cardoso <sup>56, [id](#)</sup>, M.G. Alviggi <sup>72a,72b, [id](#)</sup>, M. Aly <sup>101, [id](#)</sup>,  
Y. Amaral Coutinho <sup>83b, [id](#)</sup>, A. Ambler <sup>104, [id](#)</sup>, C. Amelung <sup>36, [id](#)</sup>, M. Amerl <sup>101, [id](#)</sup>, C.G. Ames <sup>109, [id](#)</sup>, D. Amidei <sup>106, [id](#)</sup>,  
S.P. Amor Dos Santos <sup>130a, [id](#)</sup>, K.R. Amos <sup>163, [id](#)</sup>, V. Ananiev <sup>125, [id](#)</sup>, C. Anastopoulos <sup>139, [id](#)</sup>, T. Andeen <sup>11, [id](#)</sup>,  
J.K. Anders <sup>36, [id](#)</sup>, S.Y. Andread <sup>47a,47b, [id](#)</sup>, A. Andreatza <sup>71a,71b, [id](#)</sup>, S. Angelidakis <sup>9, [id](#)</sup>, A. Angerami <sup>41, [id](#), [ab](#)</sup>,  
A.V. Anisenkov <sup>37, [id](#)</sup>, A. Annovi <sup>74a, [id](#)</sup>, C. Antel <sup>56, [id](#)</sup>, M.T. Anthony <sup>139, [id](#)</sup>, E. Antipov <sup>145, [id](#)</sup>, M. Antonelli <sup>53, [id](#)</sup>,  
F. Anulli <sup>75a, [id](#)</sup>, M. Aoki <sup>84, [id](#)</sup>, T. Aoki <sup>153, [id](#)</sup>, J.A. Aparisi Pozo <sup>163, [id](#)</sup>, M.A. Aparo <sup>146, [id](#)</sup>, L. Aperio Bella <sup>48, [id](#)</sup>,  
C. Appelt <sup>18, [id](#)</sup>, A. Apyan <sup>26, [id](#)</sup>, N. Aranzabal <sup>36, [id](#)</sup>, S.J. Arbiol Val <sup>87, [id](#)</sup>, C. Arcangeletti <sup>53, [id](#)</sup>, A.T.H. Arce <sup>51, [id](#)</sup>,  
E. Arena <sup>92, [id](#)</sup>, J-F. Arguin <sup>108, [id](#)</sup>, S. Argyropoulos <sup>54, [id](#)</sup>, J.-H. Arling <sup>48, [id](#)</sup>, O. Arnaez <sup>4, [id](#)</sup>, H. Arnold <sup>114, [id](#)</sup>,  
G. Artoni <sup>75a,75b, [id](#)</sup>, H. Asada <sup>111, [id](#)</sup>, K. Asai <sup>118, [id](#)</sup>, S. Asai <sup>153, [id](#)</sup>, N.A. Asbah <sup>61, [id](#)</sup>, K. Assamagan <sup>29, [id](#)</sup>,  
R. Astalos <sup>28a, [id](#)</sup>, S. Atashi <sup>160, [id](#)</sup>, R.J. Atkin <sup>33a, [id](#)</sup>, M. Atkinson <sup>162, [id](#)</sup>, H. Atmani <sup>35f, [id](#)</sup>, P.A. Atmasiddha <sup>128, [id](#)</sup>,  
K. Augsten <sup>132, [id](#)</sup>, S. Auricchio <sup>72a,72b, [id](#)</sup>, A.D. Auriol <sup>20, [id](#)</sup>, V.A. Austrup <sup>101, [id](#)</sup>, G. Avolio <sup>36, [id](#)</sup>, K. Axiotis <sup>56, [id](#)</sup>,  
G. Azuelos <sup>108, [id](#), [af](#)</sup>, D. Babal <sup>28b, [id](#)</sup>, H. Bachacou <sup>135, [id](#)</sup>, K. Bachas <sup>152, [id](#), [p](#)</sup>, A. Bachiu <sup>34, [id](#)</sup>, F. Backman <sup>47a,47b, [id](#)</sup>,  
A. Badea <sup>61, [id](#)</sup>, T.M. Baer <sup>106, [id](#)</sup>, P. Bagnaia <sup>75a,75b, [id](#)</sup>, M. Bahmani <sup>18, [id](#)</sup>, D. Bahner <sup>54, [id](#)</sup>, A.J. Bailey <sup>163, [id](#)</sup>,  
V.R. Bailey <sup>162, [id](#)</sup>, J.T. Baines <sup>134, [id](#)</sup>, L. Baines <sup>94, [id](#)</sup>, O.K. Baker <sup>172, [id](#)</sup>, E. Bakos <sup>15, [id](#)</sup>, D. Bakshi Gupta <sup>8, [id](#)</sup>,  
V. Balakrishnan <sup>120, [id](#)</sup>, R. Balasubramanian <sup>114, [id](#)</sup>, E.M. Baldin <sup>37, [id](#)</sup>, P. Balek <sup>86a, [id](#)</sup>, E. Ballabene <sup>23b,23a, [id](#)</sup>,  
F. Balli <sup>135, [id](#)</sup>, L.M. Balmes <sup>63a, [id](#)</sup>, W.K. Balunas <sup>32, [id](#)</sup>, J. Balz <sup>100, [id](#)</sup>, E. Banas <sup>87, [id](#)</sup>, M. Bandieramonte <sup>129, [id](#)</sup>,  
A. Bandyopadhyay <sup>24, [id](#)</sup>, S. Bansal <sup>24, [id](#)</sup>, L. Barak <sup>151, [id](#)</sup>, M. Barakat <sup>48, [id](#)</sup>, E.L. Barberio <sup>105, [id](#)</sup>, D. Barberis <sup>57b,57a, [id](#)</sup>,  
M. Barbero <sup>102, [id](#)</sup>, M.Z. Barel <sup>114, [id](#)</sup>, K.N. Barends <sup>33a, [id](#)</sup>, T. Barillari <sup>110, [id](#)</sup>, M-S. Barisits <sup>36, [id](#)</sup>, T. Barklow <sup>143, [id](#)</sup>,  
P. Baron <sup>122, [id](#)</sup>, D.A. Baron Moreno <sup>101, [id](#)</sup>, A. Baroncelli <sup>62a, [id](#)</sup>, G. Barone <sup>29, [id](#)</sup>, A.J. Barr <sup>126, [id](#)</sup>, J.D. Barr <sup>96, [id](#)</sup>,  
L. Barranco Navarro <sup>47a,47b, [id](#)</sup>, F. Barreiro <sup>99, [id](#)</sup>, J. Barreiro Guimarães da Costa <sup>14a, [id](#)</sup>, U. Barron <sup>151, [id](#)</sup>,  
M.G. Barros Teixeira <sup>130a, [id](#)</sup>, S. Barsov <sup>37, [id](#)</sup>, F. Bartels <sup>63a, [id](#)</sup>, R. Bartoldus <sup>143, [id](#)</sup>, A.E. Barton <sup>91, [id](#)</sup>, P. Bartos <sup>28a, [id](#)</sup>,  
A. Basan <sup>100, [id](#)</sup>, M. Baselga <sup>49, [id](#)</sup>, A. Bassalat <sup>66, [id](#), [b](#)</sup>, M.J. Basso <sup>156a, [id](#)</sup>, C.R. Basson <sup>101, [id](#)</sup>, R.L. Bates <sup>59, [id](#)</sup>,  
S. Batlamous <sup>35e, [id](#)</sup>, J.R. Batley <sup>32, [id](#)</sup>, B. Batool <sup>141, [id](#)</sup>, M. Battaglia <sup>136, [id](#)</sup>, D. Battulga <sup>18, [id](#)</sup>, M. Bauce <sup>75a,75b, [id](#)</sup>,  
M. Bauer <sup>36, [id](#)</sup>, P. Bauer <sup>24, [id](#)</sup>, L.T. Bazzano Hurrell <sup>30, [id](#)</sup>, J.B. Beacham <sup>51, [id](#)</sup>, T. Beau <sup>127, [id](#)</sup>, J.Y. Beaucamp <sup>90, [id](#)</sup>,  
P.H. Beauchemin <sup>158, [id](#)</sup>, F. Becherer <sup>54, [id](#)</sup>, P. Bechtel <sup>24, [id](#)</sup>, H.P. Beck <sup>19, [id](#), [o](#)</sup>, K. Becker <sup>167, [id](#)</sup>, A.J. Beddall <sup>82, [id](#)</sup>,  
V.A. Bednyakov <sup>38, [id](#)</sup>, C.P. Bee <sup>145, [id](#)</sup>, L.J. Beemster <sup>15, [id](#)</sup>, T.A. Beermann <sup>36, [id](#)</sup>, M. Begalli <sup>83d, [id](#)</sup>, M. Begel <sup>29, [id](#)</sup>,  
A. Behera <sup>145, [id](#)</sup>, J.K. Behr <sup>48, [id](#)</sup>, J.F. Beirer <sup>36, [id](#)</sup>, F. Beisiegel <sup>24, [id](#)</sup>, M. Belfkir <sup>159, [id](#)</sup>, G. Bella <sup>151, [id](#)</sup>,  
L. Bellagamba <sup>23b, [id](#)</sup>, A. Bellerive <sup>34, [id](#)</sup>, P. Bellos <sup>20, [id](#)</sup>, K. Beloborodov <sup>37, [id](#)</sup>, D. Benckekroun <sup>35a, [id](#)</sup>,  
F. Bendebba <sup>35a, [id](#)</sup>, Y. Benhammou <sup>151, [id](#)</sup>, M. Benoit <sup>29, [id](#)</sup>, J.R. Bensingher <sup>26, [id](#)</sup>, S. Bentvelsen <sup>114, [id](#)</sup>,  
L. Beresford <sup>48, [id](#)</sup>, M. Beretta <sup>53, [id](#)</sup>, E. Bergeas Kuutmann <sup>161, [id](#)</sup>, N. Berger <sup>4, [id](#)</sup>, B. Bergmann <sup>132, [id](#)</sup>,  
J. Beringer <sup>17a, [id](#)</sup>, G. Bernardi <sup>5, [id](#)</sup>, C. Bernius <sup>143, [id](#)</sup>, F.U. Bernlochner <sup>24, [id](#)</sup>, F. Bernon <sup>36,102, [id](#)</sup>,  
A. Berrocal Guardia <sup>13, [id](#)</sup>, T. Berry <sup>95, [id](#)</sup>, P. Berta <sup>133, [id](#)</sup>, A. Berthold <sup>50, [id](#)</sup>, I.A. Bertram <sup>91, [id](#)</sup>, S. Bethke <sup>110, [id](#)</sup>,  
A. Betti <sup>75a,75b, [id](#)</sup>, A.J. Bevan <sup>94, [id](#)</sup>, N.K. Bhalla <sup>54, [id](#)</sup>, M. Bhamjee <sup>33c, [id](#)</sup>, S. Bhatta <sup>145, [id](#)</sup>, D.S. Bhattacharya <sup>166, [id](#)</sup>,  
P. Bhattarai <sup>143, [id](#)</sup>, V.S. Bhopatkar <sup>121, [id](#)</sup>, R. Bi <sup>29, [ai](#)</sup>, R.M. Bianchi <sup>129, [id](#)</sup>, G. Bianco <sup>23b,23a, [id](#)</sup>, O. Biebel <sup>109, [id](#)</sup>,  
R. Bielski <sup>123, [id](#)</sup>, M. Biglietti <sup>77a, [id](#)</sup>, M. Bindi <sup>55, [id](#)</sup>, A. Bingul <sup>21b, [id](#)</sup>, C. Bini <sup>75a,75b, [id](#)</sup>, A. Biondini <sup>92, [id](#)</sup>,  
C.J. Birch-sykes <sup>101, [id](#)</sup>, G.A. Bird <sup>20,134, [id](#)</sup>, M. Birman <sup>169, [id](#)</sup>, M. Biros <sup>133, [id](#)</sup>, S. Biryukov <sup>146, [id](#)</sup>, T. Bisanz <sup>49, [id](#)</sup>,  
E. Bisceglie <sup>43b,43a, [id](#)</sup>, J.P. Biswal <sup>134, [id](#)</sup>, D. Biswas <sup>141, [id](#)</sup>, A. Bitadze <sup>101, [id](#)</sup>, K. Bjørke <sup>125, [id](#)</sup>, I. Bloch <sup>48, [id](#)</sup>,  
A. Blue <sup>59, [id](#)</sup>, U. Blumenschein <sup>94, [id](#)</sup>, J. Blumenthal <sup>100, [id](#)</sup>, G.J. Bobbink <sup>114, [id](#)</sup>, V.S. Bobrovnikov <sup>37, [id](#)</sup>,  
M. Boehler <sup>54, [id](#)</sup>, B. Boehm <sup>166, [id](#)</sup>, D. Bogavac <sup>36, [id](#)</sup>, A.G. Bogdanchikov <sup>37, [id](#)</sup>, C. Boehm <sup>47a, [id](#)</sup>, V. Boisvert <sup>95, [id](#)</sup>,  
P. Bokan <sup>48, [id](#)</sup>, T. Bold <sup>86a, [id](#)</sup>, M. Bomben <sup>5, [id](#)</sup>, M. Bona <sup>94, [id](#)</sup>, M. Boonekamp <sup>135, [id](#)</sup>, C.D. Booth <sup>95, [id](#)</sup>,

A.G. Borbély<sup>59, [id](#)</sup>, I.S. Bordulev<sup>37, [id](#)</sup>, H.M. Borecka-Bielska<sup>108, [id](#)</sup>, G. Borissov<sup>91, [id](#)</sup>, D. Bortoletto<sup>126, [id](#)</sup>,  
 D. Boscherini<sup>23b, [id](#)</sup>, M. Bosman<sup>13, [id](#)</sup>, J.D. Bossio Sola<sup>36, [id](#)</sup>, K. Bouaouda<sup>35a, [id](#)</sup>, N. Bouchhar<sup>163, [id](#)</sup>,  
 J. Boudreau<sup>129, [id](#)</sup>, E.V. Bouhova-Thacker<sup>91, [id](#)</sup>, D. Boumediene<sup>40, [id](#)</sup>, R. Bouquet<sup>165, [id](#)</sup>, A. Boveia<sup>119, [id](#)</sup>,  
 J. Boyd<sup>36, [id](#)</sup>, D. Boye<sup>29, [id](#)</sup>, I.R. Boyko<sup>38, [id](#)</sup>, J. Bracinik<sup>20, [id](#)</sup>, N. Brahimi<sup>62d, [id](#)</sup>, G. Brandt<sup>171, [id](#)</sup>, O. Brandt<sup>32, [id](#)</sup>,  
 F. Braren<sup>48, [id](#)</sup>, B. Brau<sup>103, [id](#)</sup>, J.E. Brau<sup>123, [id](#)</sup>, R. Brenner<sup>169, [id](#)</sup>, L. Brenner<sup>114, [id](#)</sup>, R. Brenner<sup>161, [id](#)</sup>, S. Bressler<sup>169, [id](#)</sup>,  
 D. Britton<sup>59, [id](#)</sup>, D. Britzger<sup>110, [id](#)</sup>, I. Brock<sup>24, [id](#)</sup>, G. Brooijmans<sup>41, [id](#)</sup>, W.K. Brooks<sup>137f, [id](#)</sup>, E. Brost<sup>29, [id](#)</sup>,  
 L.M. Brown<sup>165, [id](#)</sup>, L.E. Bruce<sup>61, [id](#)</sup>, T.L. Bruckler<sup>126, [id](#)</sup>, P.A. Bruckman de Renstrom<sup>87, [id](#)</sup>, B. Brüers<sup>48, [id](#)</sup>,  
 A. Bruni<sup>23b, [id](#)</sup>, G. Bruni<sup>23b, [id](#)</sup>, M. Bruschi<sup>23b, [id](#)</sup>, N. Brusino<sup>75a,75b, [id](#)</sup>, T. Buanes<sup>16, [id](#)</sup>, Q. Buat<sup>138, [id](#)</sup>,  
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 A.M. Burger<sup>40, [id](#)</sup>, B. Burghgrave<sup>8, [id](#)</sup>, O. Burlayenko<sup>54, [id](#)</sup>, J.T.P. Burr<sup>32, [id](#)</sup>, C.D. Burton<sup>11, [id](#)</sup>,  
 J.C. Burzynski<sup>142, [id](#)</sup>, E.L. Busch<sup>41, [id](#)</sup>, V. Büscher<sup>100, [id](#)</sup>, P.J. Bussey<sup>59, [id](#)</sup>, J.M. Butler<sup>25, [id](#)</sup>, C.M. Buttar<sup>59, [id](#)</sup>,  
 J.M. Butterworth<sup>96, [id](#)</sup>, W. Buttinger<sup>134, [id](#)</sup>, C.J. Buxo Vazquez<sup>107, [id](#)</sup>, A.R. Buzykaev<sup>37, [id](#)</sup>, S. Cabrera Urbán<sup>163, [id](#)</sup>,  
 L. Cadamuro<sup>66, [id](#)</sup>, D. Caforio<sup>58, [id](#)</sup>, H. Cai<sup>129, [id](#)</sup>, Y. Cai<sup>14a,14e, [id](#)</sup>, Y. Cai<sup>14c, [id](#)</sup>, V.M.M. Cairo<sup>36, [id](#)</sup>, O. Cakir<sup>3a, [id](#)</sup>,  
 N. Calace<sup>36, [id](#)</sup>, P. Calafiura<sup>17a, [id](#)</sup>, G. Calderini<sup>127, [id](#)</sup>, P. Calfayan<sup>68, [id](#)</sup>, G. Callea<sup>59, [id](#)</sup>, L.P. Caloba<sup>83b, [id](#)</sup>,  
 D. Calvet<sup>40, [id](#)</sup>, S. Calvet<sup>40, [id](#)</sup>, T.P. Calvet<sup>102, [id](#)</sup>, M. Calvetti<sup>74a,74b, [id](#)</sup>, R. Camacho Toro<sup>127, [id](#)</sup>, S. Camarda<sup>36, [id](#)</sup>,  
 D. Camarero Munoz<sup>26, [id](#)</sup>, P. Camarri<sup>76a,76b, [id](#)</sup>, M.T. Camerlingo<sup>72a,72b, [id](#)</sup>, D. Cameron<sup>36, [id](#)</sup>, C. Camincher<sup>165, [id](#)</sup>,  
 M. Campanelli<sup>96, [id](#)</sup>, A. Camplani<sup>42, [id](#)</sup>, V. Canale<sup>72a,72b, [id](#)</sup>, A. Canesse<sup>104, [id](#)</sup>, J. Cantero<sup>163, [id](#)</sup>, Y. Cao<sup>162, [id](#)</sup>,  
 F. Capocasa<sup>26, [id](#)</sup>, M. Capua<sup>43b,43a, [id](#)</sup>, A. Carbone<sup>71a,71b, [id](#)</sup>, R. Cardarelli<sup>76a, [id](#)</sup>, J.C.J. Cardenas<sup>8, [id](#)</sup>,  
 F. Cardillo<sup>163, [id](#)</sup>, G. Carducci<sup>43b,43a, [id](#)</sup>, T. Carli<sup>36, [id](#)</sup>, G. Carlino<sup>72a, [id](#)</sup>, J.I. Carlotto<sup>13, [id](#)</sup>, B.T. Carlson<sup>129, [id](#)</sup>,  
 E.M. Carlson<sup>165,156a, [id](#)</sup>, L. Carminati<sup>71a,71b, [id](#)</sup>, A. Carnelli<sup>135, [id](#)</sup>, M. Carnesale<sup>75a,75b, [id](#)</sup>, S. Caron<sup>113, [id](#)</sup>,  
 E. Carquin<sup>137f, [id](#)</sup>, S. Carrá<sup>71a, [id](#)</sup>, G. Carratta<sup>23b,23a, [id](#)</sup>, F. Carrio Argos<sup>33g, [id](#)</sup>, J.W.S. Carter<sup>155, [id](#)</sup>, T.M. Carter<sup>52, [id](#)</sup>,  
 M.P. Casado<sup>13, [id](#)</sup>, M. Caspar<sup>48, [id](#)</sup>, F.L. Castillo<sup>4, [id](#)</sup>, L. Castillo Garcia<sup>13, [id](#)</sup>, V. Castillo Gimenez<sup>163, [id](#)</sup>,  
 N.F. Castro<sup>130a,130e, [id](#)</sup>, A. Catinaccio<sup>36, [id](#)</sup>, J.R. Catmore<sup>125, [id](#)</sup>, V. Cavaliere<sup>29, [id](#)</sup>, N. Cavalli<sup>23b,23a, [id](#)</sup>,  
 V. Cavasinni<sup>74a,74b, [id](#)</sup>, Y.C. Cekmecelioglu<sup>48, [id](#)</sup>, E. Celebi<sup>21a, [id](#)</sup>, F. Celli<sup>126, [id](#)</sup>, M.S. Centonze<sup>70a,70b, [id](#)</sup>,  
 V. Cepaitis<sup>56, [id](#)</sup>, K. Cerny<sup>122, [id](#)</sup>, A.S. Cerqueira<sup>83a, [id](#)</sup>, A. Cerri<sup>146, [id](#)</sup>, L. Cerrito<sup>76a,76b, [id](#)</sup>, F. Cerutti<sup>17a, [id](#)</sup>,  
 B. Cervato<sup>141, [id](#)</sup>, A. Cervelli<sup>23b, [id](#)</sup>, G. Cesarini<sup>53, [id](#)</sup>, S.A. Cetin<sup>82, [id](#)</sup>, D. Chakraborty<sup>115, [id](#)</sup>, J. Chan<sup>170, [id](#)</sup>,  
 W.Y. Chan<sup>153, [id](#)</sup>, J.D. Chapman<sup>32, [id](#)</sup>, E. Chapon<sup>135, [id](#)</sup>, B. Chargeishvili<sup>149b, [id](#)</sup>, D.G. Charlton<sup>20, [id](#)</sup>,  
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 H.C. Cheng<sup>64a, [id](#)</sup>, S. Cheong<sup>143, [id](#)</sup>, A. Cheplakov<sup>38, [id](#)</sup>, E. Cheremushkina<sup>48, [id](#)</sup>, E. Cherepanova<sup>114, [id](#)</sup>,  
 R. Cherkaoui El Moursli<sup>35e, [id](#)</sup>, E. Cheu<sup>7, [id](#)</sup>, K. Cheung<sup>65, [id](#)</sup>, L. Chevalier<sup>135, [id](#)</sup>, V. Chiarella<sup>53, [id](#)</sup>,  
 G. Chiarelli<sup>74a, [id](#)</sup>, N. Chiedde<sup>102, [id](#)</sup>, G. Chiodini<sup>70a, [id](#)</sup>, A.S. Chisholm<sup>20, [id](#)</sup>, A. Chitan<sup>27b, [id](#)</sup>, M. Chitishvili<sup>163, [id](#)</sup>,  
 M.V. Chizhov<sup>38, [id](#)</sup>, K. Choi<sup>11, [id](#)</sup>, A.R. Chomont<sup>75a,75b, [id](#)</sup>, Y. Chou<sup>103, [id](#)</sup>, E.Y.S. Chow<sup>113, [id](#)</sup>, T. Chowdhury<sup>33g, [id](#)</sup>,  
 K.L. Chu<sup>169, [id](#)</sup>, M.C. Chu<sup>64a, [id](#)</sup>, X. Chu<sup>14a,14e, [id](#)</sup>, J. Chudoba<sup>131, [id](#)</sup>, J.J. Chwastowski<sup>87, [id](#)</sup>, D. Cieri<sup>110, [id](#)</sup>,  
 K.M. Ciesla<sup>86a, [id](#)</sup>, V. Cindro<sup>93, [id](#)</sup>, A. Ciocio<sup>17a, [id](#)</sup>, F. Ciroto<sup>72a,72b, [id](#)</sup>, Z.H. Citron<sup>169, [id](#)</sup>, M. Citterio<sup>71a, [id](#)</sup>,  
 D.A. Ciubotaru<sup>27b, [id](#)</sup>, A. Clark<sup>56, [id](#)</sup>, P.J. Clark<sup>52, [id](#)</sup>, C. Clarry<sup>155, [id](#)</sup>, J.M. Clavijo Columbie<sup>48, [id](#)</sup>, S.E. Clawson<sup>48, [id](#)</sup>,  
 C. Clement<sup>47a,47b, [id](#)</sup>, J. Clercx<sup>48, [id](#)</sup>, Y. Coadou<sup>102, [id](#)</sup>, M. Cobal<sup>69a,69c, [id](#)</sup>, A. Coccaro<sup>57b, [id](#)</sup>,  
 R.F. Coelho Barrue<sup>130a, [id](#)</sup>, R. Coelho Lopes De Sa<sup>103, [id](#)</sup>, S. Coelli<sup>71a, [id](#)</sup>, A.E.C. Coimbra<sup>71a,71b, [id](#)</sup>, B. Cole<sup>41, [id](#)</sup>,  
 J. Collot<sup>60, [id](#)</sup>, P. Conde Muiño<sup>130a,130g, [id](#)</sup>, M.P. Connell<sup>33c, [id](#)</sup>, S.H. Connell<sup>33c, [id](#)</sup>, I.A. Connelly<sup>59, [id](#)</sup>,  
 E.I. Conroy<sup>126, [id](#)</sup>, F. Conventi<sup>72a, [id](#)</sup>, H.G. Cooke<sup>20, [id](#)</sup>, A.M. Cooper-Sarkar<sup>126, [id](#)</sup>, A. Cordeiro Oudot Choi<sup>127, [id](#)</sup>,  
 L.D. Corpe<sup>40, [id](#)</sup>, M. Corradi<sup>75a,75b, [id](#)</sup>, F. Corriveau<sup>104, [id](#)</sup>, A. Cortes-Gonzalez<sup>18, [id](#)</sup>, M.J. Costa<sup>163, [id](#)</sup>,  
 F. Costanza<sup>4, [id](#)</sup>, D. Costanzo<sup>139, [id](#)</sup>, B.M. Cote<sup>119, [id](#)</sup>, G. Cowan<sup>95, [id](#)</sup>, K. Cranmer<sup>170, [id](#)</sup>, D. Cremonini<sup>23b,23a, [id](#)</sup>,

S. Crépé-Renaudin <sup>60, [id](#)</sup>, F. Crescioli <sup>127, [id](#)</sup>, M. Cristinziani <sup>141, [id](#)</sup>, M. Cristoforetti <sup>78a,78b, [id](#)</sup>, V. Croft <sup>114, [id](#)</sup>, J.E. Crosby <sup>121, [id](#)</sup>, G. Crosetti <sup>43b,43a, [id](#)</sup>, A. Cueto <sup>99, [id](#)</sup>, T. Cuhadar Donszelmann <sup>160, [id](#)</sup>, H. Cui <sup>14a,14c, [id](#)</sup>, Z. Cui <sup>7, [id](#)</sup>, W.R. Cunningham <sup>59, [id](#)</sup>, F. Curcio <sup>43b,43a, [id](#)</sup>, P. Czodrowski <sup>36, [id](#)</sup>, M.M. Czurylo <sup>63b, [id](#)</sup>, M.J. Da Cunha Sargedas De Sousa <sup>57b,57a, [id](#)</sup>, J.V. Da Fonseca Pinto <sup>83b, [id](#)</sup>, C. Da Via <sup>101, [id](#)</sup>, W. Dabrowski <sup>86a, [id](#)</sup>, T. Dado <sup>49, [id](#)</sup>, S. Dahbi <sup>33g, [id](#)</sup>, T. Dai <sup>106, [id](#)</sup>, D. Dal Santo <sup>19, [id](#)</sup>, C. Dallapiccola <sup>103, [id](#)</sup>, M. Dam <sup>42, [id](#)</sup>, G. D'amen <sup>29, [id](#)</sup>, V. D'Amico <sup>109, [id](#)</sup>, J. Damp <sup>100, [id](#)</sup>, J.R. Dandoy <sup>34, [id](#)</sup>, M.F. Daneri <sup>30, [id](#)</sup>, M. Danninger <sup>142, [id](#)</sup>, V. Dao <sup>36, [id](#)</sup>, G. Darbo <sup>57b, [id](#)</sup>, S. Darmora <sup>6, [id](#)</sup>, S.J. Das <sup>29, [id](#), [ai](#)</sup>, S. D'Auria <sup>71a,71b, [id](#)</sup>, C. David <sup>156b, [id](#)</sup>, T. Davidek <sup>133, [id](#)</sup>, B. Davis-Purcell <sup>34, [id](#)</sup>, I. Dawson <sup>94, [id](#)</sup>, H.A. Day-hall <sup>132, [id](#)</sup>, K. De <sup>8, [id](#)</sup>, R. De Asmundis <sup>72a, [id](#)</sup>, N. De Biase <sup>48, [id](#)</sup>, S. De Castro <sup>23b,23a, [id](#)</sup>, N. De Groot <sup>113, [id](#)</sup>, P. de Jong <sup>114, [id](#)</sup>, H. De la Torre <sup>115, [id](#)</sup>, A. De Maria <sup>14c, [id](#)</sup>, A. De Salvo <sup>75a, [id](#)</sup>, U. De Sanctis <sup>76a,76b, [id](#)</sup>, F. De Santis <sup>70a,70b, [id](#)</sup>, A. De Santo <sup>146, [id](#)</sup>, J.B. De Vivie De Regie <sup>60, [id](#)</sup>, D.V. Dedovich <sup>38, [id](#)</sup>, J. Degens <sup>114, [id](#)</sup>, A.M. Deiana <sup>44, [id](#)</sup>, F. Del Corso <sup>23b,23a, [id](#)</sup>, J. Del Peso <sup>99, [id](#)</sup>, F. Del Rio <sup>63a, [id](#)</sup>, L. Delagrangé <sup>127, [id](#)</sup>, F. Deliot <sup>135, [id](#)</sup>, C.M. Delitzsch <sup>49, [id](#)</sup>, M. Della Pietra <sup>72a,72b, [id](#)</sup>, D. Della Volpe <sup>56, [id](#)</sup>, A. Dell'Acqua <sup>36, [id](#)</sup>, L. Dell'Asta <sup>71a,71b, [id](#)</sup>, M. Delmastro <sup>4, [id](#)</sup>, P.A. Delsart <sup>60, [id](#)</sup>, S. Demers <sup>172, [id](#)</sup>, M. Demichev <sup>38, [id](#)</sup>, S.P. Denisov <sup>37, [id](#)</sup>, L. D'Eramo <sup>40, [id](#)</sup>, D. Derendarz <sup>87, [id](#)</sup>, F. Derue <sup>127, [id](#)</sup>, P. Dervan <sup>92, [id](#)</sup>, K. Desch <sup>24, [id](#)</sup>, C. Deutsch <sup>24, [id](#)</sup>, F.A. Di Bello <sup>57b,57a, [id](#)</sup>, A. Di Ciaccio <sup>76a,76b, [id](#)</sup>, L. Di Ciaccio <sup>4, [id](#)</sup>, A. Di Domenico <sup>75a,75b, [id](#)</sup>, C. Di Donato <sup>72a,72b, [id](#)</sup>, A. Di Girolamo <sup>36, [id](#)</sup>, G. Di Gregorio <sup>36, [id](#)</sup>, A. Di Luca <sup>78a,78b, [id](#)</sup>, B. Di Micco <sup>77a,77b, [id](#)</sup>, R. Di Nardo <sup>77a,77b, [id](#)</sup>, C. Diaconu <sup>102, [id](#)</sup>, M. Diamantopoulou <sup>34, [id](#)</sup>, F.A. Dias <sup>114, [id](#)</sup>, T. Dias Do Vale <sup>142, [id](#)</sup>, M.A. Diaz <sup>137a,137b, [id](#)</sup>, F.G. Diaz Capriles <sup>24, [id](#)</sup>, M. Didenko <sup>163, [id](#)</sup>, E.B. Diehl <sup>106, [id](#)</sup>, L. Diehl <sup>54, [id](#)</sup>, S. Díez Cornell <sup>48, [id](#)</sup>, C. Díez Pardos <sup>141, [id](#)</sup>, C. Dimitriadi <sup>161,24, [id](#)</sup>, A. Dimitrievska <sup>17a, [id](#)</sup>, J. Dingfelder <sup>24, [id](#)</sup>, I-M. Dinu <sup>27b, [id](#)</sup>, S.J. Dittmeier <sup>63b, [id](#)</sup>, F. Dittus <sup>36, [id](#)</sup>, F. Djama <sup>102, [id](#)</sup>, T. Djobava <sup>149b, [id](#)</sup>, J.I. Djuvsland <sup>16, [id](#)</sup>, C. Doglioni <sup>101,98, [id](#)</sup>, A. Dohnalova <sup>28a, [id](#)</sup>, J. Dolejsi <sup>133, [id](#)</sup>, Z. Dolezal <sup>133, [id](#)</sup>, K.M. Dona <sup>39, [id](#)</sup>, M. Donadelli <sup>83c, [id](#)</sup>, B. Dong <sup>107, [id](#)</sup>, J. Donini <sup>40, [id](#)</sup>, A. D'Onofrio <sup>72a,72b, [id](#)</sup>, M. D'Onofrio <sup>92, [id](#)</sup>, J. Dopke <sup>134, [id](#)</sup>, A. Doria <sup>72a, [id](#)</sup>, N. Dos Santos Fernandes <sup>130a, [id](#)</sup>, P. Dougan <sup>101, [id](#)</sup>, M.T. Dova <sup>90, [id](#)</sup>, A.T. Doyle <sup>59, [id](#)</sup>, M.A. Draguet <sup>126, [id](#)</sup>, E. Dreyer <sup>169, [id](#)</sup>, I. Drivas-koulouris <sup>10, [id](#)</sup>, M. Drnevich <sup>117, [id](#)</sup>, A.S. Drobac <sup>158, [id](#)</sup>, M. Drozdova <sup>56, [id](#)</sup>, D. Du <sup>62a, [id](#)</sup>, T.A. du Pree <sup>114, [id](#)</sup>, F. Dubinin <sup>37, [id](#)</sup>, M. Dubovsky <sup>28a, [id](#)</sup>, E. Duchovni <sup>169, [id](#)</sup>, G. Duckeck <sup>109, [id](#)</sup>, O.A. Ducu <sup>27b, [id](#)</sup>, D. Duda <sup>52, [id](#)</sup>, A. Dudarev <sup>36, [id](#)</sup>, E.R. Duden <sup>26, [id](#)</sup>, M. D'uffizi <sup>101, [id](#)</sup>, L. Duflost <sup>66, [id](#)</sup>, M. Dührssen <sup>36, [id](#)</sup>, C. Dülsen <sup>171, [id](#)</sup>, A.E. Dumitriu <sup>27b, [id](#)</sup>, M. Dunford <sup>63a, [id](#)</sup>, S. Dungs <sup>49, [id](#)</sup>, K. Dunne <sup>47a,47b, [id](#)</sup>, A. Duperrin <sup>102, [id](#)</sup>, H. Duran Yildiz <sup>3a, [id](#)</sup>, M. Düren <sup>58, [id](#)</sup>, A. Durglishvili <sup>149b, [id](#)</sup>, B.L. Dwyer <sup>115, [id](#)</sup>, G.I. Dyckes <sup>17a, [id](#)</sup>, M. Dyndal <sup>86a, [id](#)</sup>, B.S. Dziedzic <sup>87, [id](#)</sup>, Z.O. Earnshaw <sup>146, [id](#)</sup>, G.H. Eberwein <sup>126, [id](#)</sup>, B. Eckerova <sup>28a, [id](#)</sup>, S. Eggebrecht <sup>55, [id](#)</sup>, E. Egidio Purcino De Souza <sup>127, [id](#)</sup>, L.F. Ehrke <sup>56, [id](#)</sup>, G. Eigen <sup>16, [id](#)</sup>, K. Einsweiler <sup>17a, [id](#)</sup>, T. Ekelof <sup>161, [id](#)</sup>, P.A. Ekman <sup>98, [id](#)</sup>, S. El Farkh <sup>35b, [id](#)</sup>, Y. El Ghazali <sup>35b, [id](#)</sup>, H. El Jarrari <sup>36, [id](#)</sup>, A. El Moussaouy <sup>108, [id](#)</sup>, V. Ellajosyula <sup>161, [id](#)</sup>, M. Ellert <sup>161, [id](#)</sup>, F. Ellinghaus <sup>171, [id](#)</sup>, N. Ellis <sup>36, [id](#)</sup>, J. Elmsheuser <sup>29, [id](#)</sup>, M. Elsing <sup>36, [id](#)</sup>, D. Emelianov <sup>134, [id](#)</sup>, Y. Enari <sup>153, [id](#)</sup>, I. Ene <sup>17a, [id](#)</sup>, S. Epari <sup>13, [id](#)</sup>, J. Erdmann <sup>49, [id](#)</sup>, P.A. Erland <sup>87, [id](#)</sup>, M. Errenst <sup>171, [id](#)</sup>, M. Escalier <sup>66, [id](#)</sup>, C. Escobar <sup>163, [id](#)</sup>, E. Etzion <sup>151, [id](#)</sup>, G. Evans <sup>130a, [id](#)</sup>, H. Evans <sup>68, [id](#)</sup>, L.S. Evans <sup>95, [id](#)</sup>, M.O. Evans <sup>146, [id](#)</sup>, A. Ezhilov <sup>37, [id](#)</sup>, S. Ezzarqtouni <sup>35a, [id](#)</sup>, F. Fabbri <sup>59, [id](#)</sup>, L. Fabbri <sup>23b,23a, [id](#)</sup>, G. Facini <sup>96, [id](#)</sup>, V. Fadeyev <sup>136, [id](#)</sup>, R.M. Fakhрутdinov <sup>37, [id](#)</sup>, D. Fakoudis <sup>100, [id](#)</sup>, S. Falciano <sup>75a, [id](#)</sup>, L.F. Falda Ulhoa Coelho <sup>36, [id](#)</sup>, P.J. Falke <sup>24, [id](#)</sup>, J. Faltova <sup>133, [id](#)</sup>, C. Fan <sup>162, [id](#)</sup>, Y. Fan <sup>14a, [id](#)</sup>, Y. Fang <sup>14a,14c, [id](#)</sup>, M. Fanti <sup>71a,71b, [id](#)</sup>, M. Faraj <sup>69a,69b, [id](#)</sup>, Z. Farazpay <sup>97, [id](#)</sup>, A. Farbin <sup>8, [id](#)</sup>, A. Farilla <sup>77a, [id](#)</sup>, T. Farooque <sup>107, [id](#)</sup>, S.M. Farrington <sup>52, [id](#)</sup>, F. Fassi <sup>35e, [id](#)</sup>, D. Fassouliotis <sup>9, [id](#)</sup>, M. Fauci Giannelli <sup>76a,76b, [id](#)</sup>, W.J. Fawcett <sup>32, [id](#)</sup>, L. Fayard <sup>66, [id](#)</sup>, P. Federic <sup>133, [id](#)</sup>, P. Federicova <sup>131, [id](#)</sup>, O.L. Fedin <sup>37, [id](#), [a](#)</sup>, G. Fedotov <sup>37, [id](#)</sup>, M. Feickert <sup>170, [id](#)</sup>, L. Felgioni <sup>102, [id](#)</sup>, D.E. Fellers <sup>123, [id](#)</sup>, C. Feng <sup>62b, [id](#)</sup>, M. Feng <sup>14b, [id](#)</sup>, Z. Feng <sup>114, [id](#)</sup>, M.J. Fenton <sup>160, [id](#)</sup>, A.B. Fenyuk <sup>37, [id](#)</sup>, L. Ferencz <sup>48, [id](#)</sup>, R.A.M. Ferguson <sup>91, [id](#)</sup>, S.I. Fernandez Luengo <sup>137f, [id](#)</sup>, P. Fernandez Martinez <sup>13, [id](#)</sup>,

M.J.V. Fernoux <sup>102, [id](#)</sup>, J. Ferrando <sup>48, [id](#)</sup>, A. Ferrari <sup>161, [id](#)</sup>, P. Ferrari <sup>114,113, [id](#)</sup>, R. Ferrari <sup>73a, [id](#)</sup>, D. Ferrere <sup>56, [id](#)</sup>, C. Ferretti <sup>106, [id](#)</sup>, F. Fiedler <sup>100, [id](#)</sup>, P. Fiedler <sup>132, [id](#)</sup>, A. Filipčič <sup>93, [id](#)</sup>, E.K. Filmer <sup>1, [id](#)</sup>, F. Filthaut <sup>113, [id](#)</sup>, M.C.N. Fiolhais <sup>130a,130c, [id](#), [c](#)</sup>, L. Fiorini <sup>163, [id](#)</sup>, W.C. Fisher <sup>107, [id](#)</sup>, T. Fitschen <sup>101, [id](#)</sup>, P.M. Fitzhugh <sup>135, [id](#)</sup>, I. Fleck <sup>141, [id](#)</sup>, P. Fleischmann <sup>106, [id](#)</sup>, T. Flick <sup>171, [id](#)</sup>, M. Flores <sup>33d, [id](#), [ac](#)</sup>, L.R. Flores Castillo <sup>64a, [id](#)</sup>, L. Flores Sanz De Acedo <sup>36, [id](#)</sup>, F.M. Follega <sup>78a,78b, [id](#)</sup>, N. Fomin <sup>16, [id](#)</sup>, J.H. Foo <sup>155, [id](#)</sup>, B.C. Forland <sup>68, [id](#)</sup>, A. Formica <sup>135, [id](#)</sup>, A.C. Forti <sup>101, [id](#)</sup>, E. Fortin <sup>36, [id](#)</sup>, A.W. Fortman <sup>61, [id](#)</sup>, M.G. Foti <sup>17a, [id](#)</sup>, L. Fountas <sup>9, [id](#), [j](#)</sup>, D. Fournier <sup>66, [id](#)</sup>, H. Fox <sup>91, [id](#)</sup>, P. Francavilla <sup>74a,74b, [id](#)</sup>, S. Francescato <sup>61, [id](#)</sup>, S. Franchellucci <sup>56, [id](#)</sup>, M. Franchini <sup>23b,23a, [id](#)</sup>, S. Franchino <sup>63a, [id](#)</sup>, D. Francis <sup>36, [id](#)</sup>, L. Franco <sup>113, [id](#)</sup>, V. Franco Lima <sup>36, [id](#)</sup>, L. Franconi <sup>48, [id](#)</sup>, M. Franklin <sup>61, [id](#)</sup>, G. Frattari <sup>26, [id](#)</sup>, A.C. Freegard <sup>94, [id](#)</sup>, W.S. Freund <sup>83b, [id](#)</sup>, Y.Y. Frid <sup>151, [id](#)</sup>, J. Friend <sup>59, [id](#)</sup>, N. Fritzsche <sup>50, [id](#)</sup>, A. Froch <sup>54, [id](#)</sup>, D. Froidevaux <sup>36, [id](#)</sup>, J.A. Frost <sup>126, [id](#)</sup>, Y. Fu <sup>62a, [id](#)</sup>, S. Fuenzalida Garrido <sup>137f, [id](#)</sup>, M. Fujimoto <sup>102, [id](#)</sup>, K.Y. Fung <sup>64a, [id](#)</sup>, E. Furtado De Simas Filho <sup>83b, [id](#)</sup>, M. Furukawa <sup>153, [id](#)</sup>, J. Fuster <sup>163, [id](#)</sup>, A. Gabrielli <sup>23b,23a, [id](#)</sup>, A. Gabrielli <sup>155, [id](#)</sup>, P. Gadow <sup>36, [id](#)</sup>, G. Gagliardi <sup>57b,57a, [id](#)</sup>, L.G. Gagnon <sup>17a, [id](#)</sup>, E.J. Gallas <sup>126, [id](#)</sup>, B.J. Gallop <sup>134, [id](#)</sup>, K.K. Gan <sup>119, [id](#)</sup>, S. Ganguly <sup>153, [id](#)</sup>, Y. Gao <sup>52, [id](#)</sup>, F.M. Garay Walls <sup>137a,137b, [id](#)</sup>, B. Garcia <sup>29, [id](#)</sup>, C. García <sup>163, [id](#)</sup>, A. Garcia Alonso <sup>114, [id](#)</sup>, A.G. Garcia Caffaro <sup>172, [id](#)</sup>, J.E. García Navarro <sup>163, [id](#)</sup>, M. Garcia-Sciveres <sup>17a, [id](#)</sup>, G.L. Gardner <sup>128, [id](#)</sup>, R.W. Gardner <sup>39, [id](#)</sup>, N. Garelli <sup>158, [id](#)</sup>, D. Garg <sup>80, [id](#)</sup>, R.B. Garg <sup>143, [id](#), [n](#)</sup>, J.M. Gargan <sup>52, [id](#)</sup>, C.A. Garner <sup>155, [id](#)</sup>, C.M. Garvey <sup>33a, [id](#)</sup>, P. Gaspar <sup>83b, [id](#)</sup>, V.K. Gassmann <sup>158, [id](#)</sup>, G. Gaudio <sup>73a, [id](#)</sup>, V. Gautam <sup>13, [id](#)</sup>, P. Gauzzi <sup>75a,75b, [id](#)</sup>, I.L. Gavrilenko <sup>37, [id](#)</sup>, A. Gavrilyuk <sup>37, [id](#)</sup>, C. Gay <sup>164, [id](#)</sup>, G. Gaycken <sup>48, [id](#)</sup>, E.N. Gazis <sup>10, [id](#)</sup>, A.A. Geanta <sup>27b, [id](#)</sup>, C.M. Gee <sup>136, [id](#)</sup>, A. Gekow <sup>119, [id](#)</sup>, C. Gemme <sup>57b, [id](#)</sup>, M.H. Genest <sup>60, [id](#)</sup>, S. Gentile <sup>75a,75b, [id](#)</sup>, A.D. Gentry <sup>112, [id](#)</sup>, S. George <sup>95, [id](#)</sup>, W.F. George <sup>20, [id](#)</sup>, T. Gerialis <sup>46, [id](#)</sup>, P. Gessinger-Befurt <sup>36, [id](#)</sup>, M.E. Geyik <sup>171, [id](#)</sup>, M. Ghani <sup>167, [id](#)</sup>, M. Ghneimat <sup>141, [id](#)</sup>, K. Ghorbanian <sup>94, [id](#)</sup>, A. Ghosal <sup>141, [id](#)</sup>, A. Ghosh <sup>160, [id](#)</sup>, A. Ghosh <sup>7, [id](#)</sup>, B. Giacobbe <sup>23b, [id](#)</sup>, S. Giagu <sup>75a,75b, [id](#)</sup>, T. Giani <sup>114, [id](#)</sup>, P. Giannetti <sup>74a, [id](#)</sup>, A. Giannini <sup>62a, [id](#)</sup>, S.M. Gibson <sup>95, [id](#)</sup>, M. Gignac <sup>136, [id](#)</sup>, D.T. Gil <sup>86b, [id](#)</sup>, A.K. Gilbert <sup>86a, [id](#)</sup>, B.J. Gilbert <sup>41, [id](#)</sup>, D. Gillberg <sup>34, [id](#)</sup>, G. Gilles <sup>114, [id](#)</sup>, N.E.K. Gillwald <sup>48, [id](#)</sup>, L. Ginabat <sup>127, [id](#)</sup>, D.M. Gingrich <sup>2, [id](#), [af](#)</sup>, M.P. Giordani <sup>69a,69c, [id](#)</sup>, P.F. Giraud <sup>135, [id](#)</sup>, G. Giugliarelli <sup>69a,69c, [id](#)</sup>, D. Giugni <sup>71a, [id](#)</sup>, F. Giuli <sup>36, [id](#)</sup>, I. Gkialas <sup>9, [id](#), [j](#)</sup>, L.K. Gladilin <sup>37, [id](#)</sup>, C. Glasman <sup>99, [id](#)</sup>, G.R. Gledhill <sup>123, [id](#)</sup>, G. Glemža <sup>48, [id](#)</sup>, M. Glisic <sup>123, [id](#)</sup>, I. Gnesi <sup>43b, [id](#), [f](#)</sup>, Y. Go <sup>29, [id](#), [ai](#)</sup>, M. Goblirsch-Kolb <sup>36, [id](#)</sup>, B. Gocke <sup>49, [id](#)</sup>, D. Godin <sup>108, [id](#)</sup>, B. Gokturk <sup>21a, [id](#)</sup>, S. Goldfarb <sup>105, [id](#)</sup>, T. Golling <sup>56, [id](#)</sup>, M.G.D. Gololo <sup>33g, [id](#)</sup>, D. Golubkov <sup>37, [id](#)</sup>, J.P. Gombas <sup>107, [id](#)</sup>, A. Gomes <sup>130a,130b, [id](#)</sup>, G. Gomes Da Silva <sup>141, [id](#)</sup>, A.J. Gomez Delegido <sup>163, [id](#)</sup>, R. Gonçalo <sup>130a,130c, [id](#)</sup>, G. Gonella <sup>123, [id](#)</sup>, L. Gonella <sup>20, [id](#)</sup>, A. Gongadze <sup>149c, [id](#)</sup>, F. Gonnella <sup>20, [id](#)</sup>, J.L. Gonski <sup>41, [id](#)</sup>, R.Y. González Andana <sup>52, [id](#)</sup>, S. González de la Hoz <sup>163, [id](#)</sup>, S. Gonzalez Fernandez <sup>13, [id](#)</sup>, R. Gonzalez Lopez <sup>92, [id](#)</sup>, C. Gonzalez Renteria <sup>17a, [id](#)</sup>, M.V. Gonzalez Rodrigues <sup>48, [id](#)</sup>, R. Gonzalez Suarez <sup>161, [id](#)</sup>, S. Gonzalez-Sevilla <sup>56, [id](#)</sup>, G.R. Gonzalvo Rodriguez <sup>163, [id](#)</sup>, L. Goossens <sup>36, [id](#)</sup>, B. Gorini <sup>36, [id](#)</sup>, E. Gorini <sup>70a,70b, [id](#)</sup>, A. Gorišek <sup>93, [id](#)</sup>, T.C. Gosart <sup>128, [id](#)</sup>, A.T. Goshaw <sup>51, [id](#)</sup>, M.I. Gostkin <sup>38, [id](#)</sup>, S. Goswami <sup>121, [id](#)</sup>, C.A. Gottardo <sup>36, [id](#)</sup>, S.A. Gotz <sup>109, [id](#)</sup>, M. Gouighri <sup>35b, [id](#)</sup>, V. Goumarre <sup>48, [id](#)</sup>, A.G. Goussiou <sup>138, [id](#)</sup>, N. Govender <sup>33c, [id](#)</sup>, I. Grabowska-Bold <sup>86a, [id](#)</sup>, K. Graham <sup>34, [id](#)</sup>, E. Gramstad <sup>125, [id](#)</sup>, S. Grancagnolo <sup>70a,70b, [id](#)</sup>, M. Grandi <sup>146, [id](#)</sup>, C.M. Grant <sup>1,135, [id](#)</sup>, P.M. Gravila <sup>27f, [id](#)</sup>, F.G. Gravili <sup>70a,70b, [id](#)</sup>, H.M. Gray <sup>17a, [id](#)</sup>, M. Greco <sup>70a,70b, [id](#)</sup>, C. Grefe <sup>24, [id](#)</sup>, I.M. Gregor <sup>48, [id](#)</sup>, P. Grenier <sup>143, [id](#)</sup>, S.G. Grewe <sup>110, [id](#)</sup>, C. Grieco <sup>13, [id](#)</sup>, A.A. Grillo <sup>136, [id](#)</sup>, K. Grimm <sup>31, [id](#)</sup>, S. Grinstein <sup>13, [id](#), [s](#)</sup>, J.-F. Grivaz <sup>66, [id](#)</sup>, E. Gross <sup>169, [id](#)</sup>, J. Grosse-Knetter <sup>55, [id](#)</sup>, C. Grud <sup>106, [id](#)</sup>, J.C. Grundy <sup>126, [id](#)</sup>, L. Guan <sup>106, [id](#)</sup>, W. Guan <sup>29, [id](#)</sup>, C. Gubbels <sup>164, [id](#)</sup>, J.G.R. Guerrero Rojas <sup>163, [id](#)</sup>, G. Guerrieri <sup>69a,69c, [id](#)</sup>, F. Guescini <sup>110, [id](#)</sup>, R. Gugel <sup>100, [id](#)</sup>, J.A.M. Guhit <sup>106, [id](#)</sup>, A. Guida <sup>18, [id](#)</sup>, E. Guilloton <sup>167,134, [id](#)</sup>, S. Guindon <sup>36, [id](#)</sup>, F. Guo <sup>14a,14e, [id](#)</sup>, J. Guo <sup>62c, [id](#)</sup>, L. Guo <sup>48, [id](#)</sup>, Y. Guo <sup>106, [id](#)</sup>, R. Gupta <sup>48, [id](#)</sup>, R. Gupta <sup>129, [id](#)</sup>, S. Gurbuz <sup>24, [id](#)</sup>, S.S. Gurdasani <sup>54, [id](#)</sup>, G. Gustavino <sup>36, [id](#)</sup>, M. Guth <sup>56, [id](#)</sup>, P. Gutierrez <sup>120, [id](#)</sup>, L.F. Gutierrez Zagazeta <sup>128, [id](#)</sup>, M. Gutsche <sup>50, [id](#)</sup>, C. Gutschow <sup>96, [id](#)</sup>, C. Gwenlan <sup>126, [id](#)</sup>, C.B. Gwilliam <sup>92, [id](#)</sup>, E.S. Haaland <sup>125, [id](#)</sup>, A. Haas <sup>117, [id](#)</sup>, M. Habedank <sup>48, [id](#)</sup>,

C. Haber <sup>17a, [id](#)</sup>, H.K. Hadavand <sup>8, [id](#)</sup>, A. Hadeef <sup>50, [id](#)</sup>, S. Hadzic <sup>110, [id](#)</sup>, A.I. Hagan <sup>91, [id](#)</sup>, J.J. Hahn <sup>141, [id](#)</sup>,  
E.H. Haines <sup>96, [id](#)</sup>, M. Haleem <sup>166, [id](#)</sup>, J. Haley <sup>121, [id](#)</sup>, J.J. Hall <sup>139, [id](#)</sup>, G.D. Hallewell <sup>102, [id](#)</sup>, L. Halser <sup>19, [id](#)</sup>,  
K. Hamano <sup>165, [id](#)</sup>, M. Hamer <sup>24, [id](#)</sup>, G.N. Hamity <sup>52, [id](#)</sup>, E.J. Hampshire <sup>95, [id](#)</sup>, J. Han <sup>62b, [id](#)</sup>, K. Han <sup>62a, [id](#)</sup>,  
L. Han <sup>14c, [id](#)</sup>, L. Han <sup>62a, [id](#)</sup>, S. Han <sup>17a, [id](#)</sup>, Y.F. Han <sup>155, [id](#)</sup>, K. Hanagaki <sup>84, [id](#)</sup>, M. Hance <sup>136, [id](#)</sup>, D.A. Hangal <sup>41, [id](#), [ab](#)</sup>,  
H. Hanif <sup>142, [id](#)</sup>, M.D. Hank <sup>128, [id](#)</sup>, R. Hankache <sup>101, [id](#)</sup>, J.B. Hansen <sup>42, [id](#)</sup>, J.D. Hansen <sup>42, [id](#)</sup>, P.H. Hansen <sup>42, [id](#)</sup>,  
K. Hara <sup>157, [id](#)</sup>, D. Harada <sup>56, [id](#)</sup>, T. Harenberg <sup>171, [id](#)</sup>, S. Harkusha <sup>37, [id](#)</sup>, M.L. Harris <sup>103, [id](#)</sup>, Y.T. Harris <sup>126, [id](#)</sup>,  
J. Harrison <sup>13, [id](#)</sup>, N.M. Harrison <sup>119, [id](#)</sup>, P.F. Harrison <sup>167</sup>, N.M. Hartman <sup>110, [id](#)</sup>, N.M. Hartmann <sup>109, [id](#)</sup>,  
Y. Hasegawa <sup>140, [id](#)</sup>, R. Hauser <sup>107, [id](#)</sup>, C.M. Hawkes <sup>20, [id](#)</sup>, R.J. Hawkins <sup>36, [id](#)</sup>, Y. Hayashi <sup>153, [id](#)</sup>, S. Hayashida <sup>111, [id](#)</sup>,  
D. Hayden <sup>107, [id](#)</sup>, C. Hayes <sup>106, [id](#)</sup>, R.L. Hayes <sup>114, [id](#)</sup>, C.P. Hays <sup>126, [id](#)</sup>, J.M. Hays <sup>94, [id](#)</sup>, H.S. Hayward <sup>92, [id](#)</sup>,  
F. He <sup>62a, [id](#)</sup>, M. He <sup>14a, 14e, [id](#)</sup>, Y. He <sup>154, [id](#)</sup>, Y. He <sup>48, [id](#)</sup>, N.B. Heatley <sup>94, [id](#)</sup>, V. Hedberg <sup>98, [id](#)</sup>, A.L. Heggelund <sup>125, [id](#)</sup>,  
N.D. Hehir <sup>94, [id](#), \*</sup>, C. Heidegger <sup>54, [id](#)</sup>, K.K. Heidegger <sup>54, [id](#)</sup>, W.D. Heidorn <sup>81, [id](#)</sup>, J. Heilman <sup>34, [id](#)</sup>, S. Heim <sup>48, [id](#)</sup>,  
T. Heim <sup>17a, [id](#)</sup>, J.G. Heinlein <sup>128, [id](#)</sup>, J.J. Heinrich <sup>123, [id](#)</sup>, L. Heinrich <sup>110, [id](#), [ad](#)</sup>, J. Hejbal <sup>131, [id](#)</sup>, L. Helary <sup>48, [id](#)</sup>,  
A. Held <sup>170, [id](#)</sup>, S. Hellesund <sup>16, [id](#)</sup>, C.M. Helling <sup>164, [id](#)</sup>, S. Hellman <sup>47a, 47b, [id](#)</sup>, R.C.W. Henderson <sup>91</sup>,  
L. Henkelmann <sup>32, [id](#)</sup>, A.M. Henriques Correia <sup>36</sup>, H. Herde <sup>98, [id](#)</sup>, Y. Hernández Jiménez <sup>145, [id](#)</sup>,  
L.M. Herrmann <sup>24, [id](#)</sup>, T. Herrmann <sup>50, [id](#)</sup>, G. Herten <sup>54, [id](#)</sup>, R. Hertenberger <sup>109, [id](#)</sup>, L. Hervas <sup>36, [id](#)</sup>,  
M.E. Hesping <sup>100, [id](#)</sup>, N.P. Hessey <sup>156a, [id](#)</sup>, H. Hibi <sup>85, [id](#)</sup>, E. Hill <sup>155, [id](#)</sup>, S.J. Hillier <sup>20, [id](#)</sup>, J.R. Hinds <sup>107, [id](#)</sup>,  
F. Hinterkeuser <sup>24, [id](#)</sup>, M. Hirose <sup>124, [id](#)</sup>, S. Hirose <sup>157, [id](#)</sup>, D. Hirschbuehl <sup>171, [id](#)</sup>, T.G. Hitchings <sup>101, [id](#)</sup>, B. Hiti <sup>93, [id](#)</sup>,  
J. Hobbs <sup>145, [id](#)</sup>, R. Hobincu <sup>27e, [id](#)</sup>, N. Hod <sup>169, [id](#)</sup>, M.C. Hodgkinson <sup>139, [id](#)</sup>, B.H. Hodgkinson <sup>32, [id](#)</sup>, A. Hoecker <sup>36, [id](#)</sup>,  
D.D. Hofer <sup>106, [id](#)</sup>, J. Hofer <sup>48, [id](#)</sup>, T. Holm <sup>24, [id](#)</sup>, M. Holzbock <sup>110, [id](#)</sup>, L.B.A.H. Hommels <sup>32, [id](#)</sup>, B.P. Honan <sup>101, [id](#)</sup>,  
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A.S. Howard <sup>93, [id](#)</sup>, J. Howarth <sup>59, [id](#)</sup>, J. Hoya <sup>6, [id](#)</sup>, M. Hrabovsky <sup>122, [id](#)</sup>, A. Hrynevich <sup>48, [id](#)</sup>, T. Hryn'ova <sup>4, [id](#)</sup>,  
P.J. Hsu <sup>65, [id](#)</sup>, S.-C. Hsu <sup>138, [id](#)</sup>, Q. Hu <sup>62a, [id](#)</sup>, Y.F. Hu <sup>14a, 14e, [id](#)</sup>, S. Huang <sup>64b, [id](#)</sup>, X. Huang <sup>14c, [id](#)</sup>, X. Huang <sup>14a, 14e, [id](#)</sup>,  
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J. Huston <sup>107, [id](#)</sup>, J. Huth <sup>61, [id](#)</sup>, R. Hyneman <sup>143, [id](#)</sup>, G. Iacobucci <sup>56, [id](#)</sup>, G. Iakovidis <sup>29, [id](#)</sup>, I. Ibragimov <sup>141, [id](#)</sup>,  
L. Iconomidou-Fayard <sup>66, [id](#)</sup>, P. Iengo <sup>72a, 72b, [id](#)</sup>, R. Iguchi <sup>153, [id](#)</sup>, T. Iizawa <sup>126, [id](#)</sup>, Y. Ikegami <sup>84, [id](#)</sup>, N. Ilic <sup>155, [id](#)</sup>,  
H. Imam <sup>35a, [id](#)</sup>, M. Ince Lezki <sup>56, [id](#)</sup>, T. Ingebretsen Carlson <sup>47a, 47b, [id](#)</sup>, G. Introzzi <sup>73a, 73b, [id](#)</sup>, M. Iodice <sup>77a, [id](#)</sup>,  
V. Ippolito <sup>75a, 75b, [id](#)</sup>, R.K. Irwin <sup>92, [id](#)</sup>, M. Ishino <sup>153, [id](#)</sup>, W. Islam <sup>170, [id](#)</sup>, C. Issever <sup>18, 48, [id](#)</sup>, S. Istin <sup>21a, [id](#), [ak](#)</sup>,  
H. Ito <sup>168, [id](#)</sup>, J.M. Iturbe Ponce <sup>64a, [id](#)</sup>, R. Iuppa <sup>78a, 78b, [id](#)</sup>, A. Ivina <sup>169, [id](#)</sup>, J.M. Izen <sup>45, [id](#)</sup>, V. Izzo <sup>72a, [id](#)</sup>,  
P. Jacka <sup>131, 132, [id](#)</sup>, P. Jackson <sup>1, [id](#)</sup>, R.M. Jacobs <sup>48, [id](#)</sup>, B.P. Jaeger <sup>142, [id](#)</sup>, C.S. Jagfeld <sup>109, [id](#)</sup>, G. Jain <sup>156a, [id](#)</sup>,  
P. Jain <sup>54, [id](#)</sup>, K. Jakobs <sup>54, [id](#)</sup>, T. Jakoubek <sup>169, [id](#)</sup>, J. Jamieson <sup>59, [id](#)</sup>, K.W. Janas <sup>86a, [id](#)</sup>, M. Javurkova <sup>103, [id](#)</sup>,  
F. Jeanneau <sup>135, [id](#)</sup>, L. Jeanty <sup>123, [id](#)</sup>, J. Jejelava <sup>149a, [id](#), [z](#)</sup>, P. Jenni <sup>54, [id](#), [g](#)</sup>, C.E. Jessiman <sup>34, [id](#)</sup>, S. Jézéquel <sup>4, [id](#)</sup>,  
C. Jia <sup>62b, [id](#)</sup>, J. Jia <sup>145, [id](#)</sup>, X. Jia <sup>61, [id](#)</sup>, X. Jia <sup>14a, 14e, [id](#)</sup>, Z. Jia <sup>14c, [id](#)</sup>, S. Jiggins <sup>48, [id](#)</sup>, J. Jimenez Pena <sup>13, [id](#)</sup>, S. Jin <sup>14c, [id](#)</sup>,  
A. Jinaru <sup>27b, [id](#)</sup>, O. Jinnouchi <sup>154, [id](#)</sup>, P. Johansson <sup>139, [id](#)</sup>, K.A. Johns <sup>7, [id](#)</sup>, J.W. Johnson <sup>136, [id](#)</sup>, D.M. Jones <sup>32, [id](#)</sup>,  
E. Jones <sup>48, [id](#)</sup>, P. Jones <sup>32, [id](#)</sup>, R.W.L. Jones <sup>91, [id](#)</sup>, T.J. Jones <sup>92, [id](#)</sup>, H.L. Joos <sup>55, 36, [id](#)</sup>, R. Joshi <sup>119, [id](#)</sup>, J. Jovicevic <sup>15, [id](#)</sup>,  
X. Ju <sup>17a, [id](#)</sup>, J.J. Junggeburth <sup>103, [id](#)</sup>, T. Junkermann <sup>63a, [id](#)</sup>, A. Juste Rozas <sup>13, [id](#), [s](#)</sup>, M.K. Jurek <sup>87, [id](#)</sup>,  
S. Kabana <sup>137e, [id](#)</sup>, A. Kaczmarska <sup>87, [id](#)</sup>, M. Kado <sup>110, [id](#)</sup>, H. Kagan <sup>119, [id](#)</sup>, M. Kagan <sup>143, [id](#)</sup>, A. Kahn <sup>41</sup>, A. Kahn <sup>128, [id](#)</sup>,  
C. Kahra <sup>100, [id](#)</sup>, T. Kaji <sup>153, [id](#)</sup>, E. Kajomovitz <sup>150, [id](#)</sup>, N. Kakati <sup>169, [id](#)</sup>, I. Kalaitzidou <sup>54, [id](#)</sup>, C.W. Kalderon <sup>29, [id](#)</sup>,  
A. Kamenshchikov <sup>155, [id](#)</sup>, N.J. Kang <sup>136, [id](#)</sup>, D. Kar <sup>33g, [id](#)</sup>, K. Karava <sup>126, [id](#)</sup>, M.J. Kareem <sup>156b, [id](#)</sup>, E. Karentzos <sup>54, [id](#)</sup>,  
I. Karkanias <sup>152, [id](#)</sup>, O. Karkout <sup>114, [id](#)</sup>, S.N. Karpov <sup>38, [id](#)</sup>, Z.M. Karpova <sup>38, [id](#)</sup>, V. Kartvelishvili <sup>91, [id](#)</sup>,  
A.N. Karyukhin <sup>37, [id](#)</sup>, E. Kasimi <sup>152, [id](#)</sup>, J. Katzy <sup>48, [id](#)</sup>, S. Kaur <sup>34, [id](#)</sup>, K. Kawade <sup>140, [id](#)</sup>, M.P. Kawale <sup>120, [id](#)</sup>,  
C. Kawamoto <sup>88, [id](#)</sup>, T. Kawamoto <sup>62a, [id](#)</sup>, E.F. Kay <sup>36, [id](#)</sup>, F.I. Kaya <sup>158, [id](#)</sup>, S. Kazakos <sup>107, [id](#)</sup>, V.F. Kazanin <sup>37, [id](#)</sup>,

Y. Ke <sup>145, [id](#)</sup>, J.M. Keaveney <sup>33a, [id](#)</sup>, R. Keeler <sup>165, [id](#)</sup>, G.V. Kehris <sup>61, [id](#)</sup>, J.S. Keller <sup>34, [id](#)</sup>, A.S. Kelly <sup>96</sup>,  
 J.J. Kempster <sup>146, [id](#)</sup>, K.E. Kennedy <sup>41, [id](#)</sup>, P.D. Kennedy <sup>100, [id](#)</sup>, O. Kepka <sup>131, [id](#)</sup>, B.P. Kerridge <sup>167, [id](#)</sup>, S. Kersten <sup>171, [id](#)</sup>,  
 B.P. Kerševan <sup>93, [id](#)</sup>, S. Keshri <sup>66, [id](#)</sup>, L. Keszeghova <sup>28a, [id](#)</sup>, S. Ketabchi Haghghat <sup>155, [id](#)</sup>, R.A. Khan <sup>129, [id](#)</sup>,  
 M. Khandoga <sup>127, [id](#)</sup>, A. Khanov <sup>121, [id](#)</sup>, A.G. Kharlamov <sup>37, [id](#)</sup>, T. Kharlamova <sup>37, [id](#)</sup>, E.E. Khoda <sup>138, [id](#)</sup>,  
 M. Kholodenko <sup>37, [id](#)</sup>, T.J. Khoo <sup>18, [id](#)</sup>, G. Khorauli <sup>166, [id](#)</sup>, J. Khubua <sup>149b, [id](#)</sup>, Y.A.R. Khwaira <sup>66, [id](#)</sup>,  
 A. Kilgallon <sup>123, [id](#)</sup>, D.W. Kim <sup>47a,47b, [id](#)</sup>, Y.K. Kim <sup>39, [id](#)</sup>, N. Kimura <sup>96, [id](#)</sup>, M.K. Kingston <sup>55, [id](#)</sup>, A. Kirchhoff <sup>55, [id](#)</sup>,  
 C. Kirfel <sup>24, [id](#)</sup>, F. Kirfel <sup>24, [id](#)</sup>, J. Kirk <sup>134, [id](#)</sup>, A.E. Kiryunin <sup>110, [id](#)</sup>, C. Kitsaki <sup>10, [id](#)</sup>, O. Kivernyk <sup>24, [id](#)</sup>, M. Klassen <sup>63a, [id](#)</sup>,  
 C. Klein <sup>34, [id](#)</sup>, L. Klein <sup>166, [id](#)</sup>, M.H. Klein <sup>106, [id](#)</sup>, M. Klein <sup>92, [id](#)</sup>, S.B. Klein <sup>56, [id](#)</sup>, U. Klein <sup>92, [id](#)</sup>, P. Klimek <sup>36, [id](#)</sup>,  
 A. Klimentov <sup>29, [id](#)</sup>, T. Klioutchnikova <sup>36, [id](#)</sup>, P. Kluit <sup>114, [id](#)</sup>, S. Kluth <sup>110, [id](#)</sup>, E. Kneringer <sup>79, [id](#)</sup>, T.M. Knight <sup>155, [id](#)</sup>,  
 A. Knue <sup>49, [id](#)</sup>, R. Kobayashi <sup>88, [id](#)</sup>, D. Kobylanski <sup>169, [id](#)</sup>, S.F. Koch <sup>126, [id](#)</sup>, M. Kocian <sup>143, [id](#)</sup>, P. Kodyš <sup>133, [id](#)</sup>,  
 D.M. Koeck <sup>123, [id](#)</sup>, P.T. Koenig <sup>24, [id](#)</sup>, T. Koffas <sup>34, [id](#)</sup>, O. Kolay <sup>50, [id](#)</sup>, I. Koletsou <sup>4, [id](#)</sup>, T. Komarek <sup>122, [id](#)</sup>,  
 K. Köneke <sup>54, [id](#)</sup>, A.X.Y. Kong <sup>1, [id](#)</sup>, T. Kono <sup>118, [id](#)</sup>, N. Konstantinidis <sup>96, [id](#)</sup>, P. Kontaxakis <sup>56, [id](#)</sup>, B. Konya <sup>98, [id](#)</sup>,  
 R. Kopeliński <sup>68, [id](#)</sup>, S. Koperny <sup>86a, [id](#)</sup>, K. Korcyl <sup>87, [id](#)</sup>, K. Kordas <sup>152, [id](#)</sup>, G. Koren <sup>151, [id](#)</sup>, A. Korn <sup>96, [id](#)</sup>,  
 S. Korn <sup>55, [id](#)</sup>, I. Korolkov <sup>13, [id](#)</sup>, N. Korotkova <sup>37, [id](#)</sup>, B. Kortman <sup>114, [id](#)</sup>, O. Kortner <sup>110, [id](#)</sup>, S. Kortner <sup>110, [id](#)</sup>,  
 W.H. Kostecka <sup>115, [id](#)</sup>, V.V. Kostyukhin <sup>141, [id](#)</sup>, A. Kotskechagia <sup>135, [id](#)</sup>, A. Kotwal <sup>51, [id](#)</sup>, A. Koulouris <sup>36, [id](#)</sup>,  
 A. Kourkoumeli-Charalampidi <sup>73a,73b, [id](#)</sup>, C. Kourkoumelis <sup>9, [id](#)</sup>, E. Kourlitis <sup>110, [id](#)</sup>, O. Kovanda <sup>146, [id](#)</sup>,  
 R. Kowalewski <sup>165, [id](#)</sup>, W. Kozanecki <sup>135, [id](#)</sup>, A.S. Kozhin <sup>37, [id](#)</sup>, V.A. Kramarenko <sup>37, [id](#)</sup>, G. Kramberger <sup>93, [id](#)</sup>,  
 P. Kramer <sup>100, [id](#)</sup>, M.W. Krasny <sup>127, [id](#)</sup>, A. Krasznahorkay <sup>36, [id](#)</sup>, J.W. Kraus <sup>171, [id](#)</sup>, J.A. Kremer <sup>48, [id](#)</sup>, T. Kresse <sup>50, [id](#)</sup>,  
 J. Kretzschmar <sup>92, [id](#)</sup>, K. Kreul <sup>18, [id](#)</sup>, P. Krieger <sup>155, [id](#)</sup>, S. Krishnamurthy <sup>103, [id](#)</sup>, M. Krivos <sup>133, [id](#)</sup>, K. Krizka <sup>20, [id](#)</sup>,  
 K. Kroeninger <sup>49, [id](#)</sup>, H. Kroha <sup>110, [id](#)</sup>, J. Kroll <sup>131, [id](#)</sup>, J. Kroll <sup>128, [id](#)</sup>, K.S. Krowpman <sup>107, [id](#)</sup>, U. Kruchonak <sup>38, [id](#)</sup>,  
 H. Krüger <sup>24, [id](#)</sup>, N. Krumnack <sup>81</sup>, M.C. Kruse <sup>51, [id](#)</sup>, O. Kuchinskaia <sup>37, [id](#)</sup>, S. Kuday <sup>3a, [id](#)</sup>, S. Kuehn <sup>36, [id](#)</sup>,  
 R. Kuesters <sup>54, [id](#)</sup>, T. Kuhl <sup>48, [id](#)</sup>, V. Kukhtin <sup>38, [id](#)</sup>, Y. Kulchitsky <sup>37, [id](#)</sup>, S. Kuleshov <sup>137d,137b, [id](#)</sup>, M. Kumar <sup>33g, [id](#)</sup>,  
 N. Kumari <sup>48, [id](#)</sup>, P. Kumari <sup>156b, [id](#)</sup>, A. Kupco <sup>131, [id](#)</sup>, T. Kupfer <sup>49</sup>, A. Kupich <sup>37, [id](#)</sup>, O. Kuprash <sup>54, [id](#)</sup>,  
 H. Kurashige <sup>85, [id](#)</sup>, L.L. Kurchaninov <sup>156a, [id](#)</sup>, O. Kurdysh <sup>66, [id](#)</sup>, Y.A. Kurochkin <sup>37, [id](#)</sup>, A. Kurova <sup>37, [id](#)</sup>, M. Kuze <sup>154, [id](#)</sup>,  
 A.K. Kvam <sup>103, [id](#)</sup>, J. Kvita <sup>122, [id](#)</sup>, T. Kwan <sup>104, [id](#)</sup>, N.G. Kyriacou <sup>106, [id](#)</sup>, L.A.O. Laatu <sup>102, [id](#)</sup>, C. Lacasta <sup>163, [id](#)</sup>,  
 F. Lacava <sup>75a,75b, [id](#)</sup>, H. Lacker <sup>18, [id](#)</sup>, D. Lacour <sup>127, [id](#)</sup>, N.N. Lad <sup>96, [id](#)</sup>, E. Ladygin <sup>38, [id](#)</sup>, B. Laforge <sup>127, [id](#)</sup>,  
 T. Lagouri <sup>137e, [id](#)</sup>, F.Z. Lahbabi <sup>35a, [id](#)</sup>, S. Lai <sup>55, [id](#)</sup>, I.K. Lakomic <sup>86a, [id](#)</sup>, N. Lalloue <sup>60, [id](#)</sup>, J.E. Lambert <sup>165, [id](#)</sup>,  
 S. Lammers <sup>68, [id](#)</sup>, W. Lampl <sup>7, [id](#)</sup>, C. Lampoudis <sup>152, [id](#)</sup>, A.N. Lancaster <sup>115, [id](#)</sup>, E. Lançon <sup>29, [id](#)</sup>, U. Landgraf <sup>54, [id](#)</sup>,  
 M.P.J. Landon <sup>94, [id](#)</sup>, V.S. Lang <sup>54, [id](#)</sup>, R.J. Langenberg <sup>103, [id](#)</sup>, O.K.B. Langrekken <sup>125, [id](#)</sup>, A.J. Lankford <sup>160, [id](#)</sup>,  
 F. Lanni <sup>36, [id](#)</sup>, K. Lantzsch <sup>24, [id](#)</sup>, A. Lanza <sup>73a, [id](#)</sup>, A. Lapertosa <sup>57b,57a, [id](#)</sup>, J.F. Laporte <sup>135, [id](#)</sup>, T. Lari <sup>71a, [id](#)</sup>,  
 F. Lasagni Manghi <sup>23b, [id](#)</sup>, M. Lassnig <sup>36, [id](#)</sup>, V. Latonova <sup>131, [id](#)</sup>, A. Laudrain <sup>100, [id](#)</sup>, A. Laurier <sup>150, [id](#)</sup>,  
 S.D. Lawlor <sup>139, [id](#)</sup>, Z. Lawrence <sup>101, [id](#)</sup>, R. Lazaridou <sup>167</sup>, M. Lazzaroni <sup>71a,71b, [id](#)</sup>, B. Le <sup>101</sup>, E.M. Le Boulicaut <sup>51, [id](#)</sup>,  
 B. Leban <sup>93, [id](#)</sup>, A. Lebedev <sup>81, [id](#)</sup>, M. LeBlanc <sup>101, [id](#)</sup>, F. Ledroit-Guillon <sup>60, [id](#)</sup>, A.C.A. Lee <sup>96</sup>, S.C. Lee <sup>148, [id](#)</sup>,  
 S. Lee <sup>47a,47b, [id](#)</sup>, T.F. Lee <sup>92, [id](#)</sup>, L.L. Leeuw <sup>33c, [id](#)</sup>, H.P. Lefebvre <sup>95, [id](#)</sup>, M. Lefebvre <sup>165, [id](#)</sup>, C. Leggett <sup>17a, [id](#)</sup>,  
 G. Lehmann Miotto <sup>36, [id](#)</sup>, M. Leigh <sup>56, [id](#)</sup>, W.A. Leight <sup>103, [id](#)</sup>, W. Leinonen <sup>113, [id](#)</sup>, A. Leisos <sup>152, [id](#)</sup>,  
 M.A.L. Leite <sup>83c, [id](#)</sup>, C.E. Leitgeb <sup>48, [id](#)</sup>, R. Leitner <sup>133, [id](#)</sup>, K.J.C. Leney <sup>44, [id](#)</sup>, T. Lenz <sup>24, [id](#)</sup>, S. Leone <sup>74a, [id](#)</sup>,  
 C. Leonidopoulos <sup>52, [id](#)</sup>, A. Leopold <sup>144, [id](#)</sup>, C. Leroy <sup>108, [id](#)</sup>, R. Les <sup>107, [id](#)</sup>, C.G. Lester <sup>32, [id](#)</sup>, M. Levchenko <sup>37, [id](#)</sup>,  
 J. Levêque <sup>4, [id](#)</sup>, D. Levin <sup>106, [id](#)</sup>, L.J. Levinson <sup>169, [id](#)</sup>, M.P. Lewicki <sup>87, [id](#)</sup>, D.J. Lewis <sup>4, [id](#)</sup>, A. Li <sup>5, [id](#)</sup>, B. Li <sup>62b, [id](#)</sup>,  
 C. Li <sup>62a</sup>, C-Q. Li <sup>110, [id](#)</sup>, H. Li <sup>62a, [id](#)</sup>, H. Li <sup>62b, [id](#)</sup>, H. Li <sup>14c, [id](#)</sup>, H. Li <sup>14b, [id](#)</sup>, H. Li <sup>62b, [id](#)</sup>, J. Li <sup>62c, [id](#)</sup>, K. Li <sup>138, [id](#)</sup>,  
 L. Li <sup>62c, [id](#)</sup>, M. Li <sup>14a,14e, [id](#)</sup>, Q.Y. Li <sup>62a, [id](#)</sup>, S. Li <sup>14a,14e, [id](#)</sup>, S. Li <sup>62d,62c, [id](#)</sup>, T. Li <sup>5, [id](#)</sup>, X. Li <sup>104, [id](#)</sup>, Z. Li <sup>126, [id](#)</sup>, Z. Li <sup>104, [id](#)</sup>,  
 Z. Li <sup>14a,14e, [id](#)</sup>, S. Liang <sup>14a,14e</sup>, Z. Liang <sup>14a, [id](#)</sup>, M. Liberatore <sup>135, [id](#)</sup>, B. Liberti <sup>76a, [id](#)</sup>, K. Lie <sup>64c, [id](#)</sup>,  
 J. Lieber Marin <sup>83b, [id](#)</sup>, H. Lien <sup>68, [id](#)</sup>, K. Lin <sup>107, [id](#)</sup>, R.E. Lindley <sup>7, [id](#)</sup>, J.H. Lindon <sup>2, [id](#)</sup>, E. Lipeles <sup>128, [id](#)</sup>,



A. Lipniacka <sup>16, [id](#)</sup>, A. Lister <sup>164, [id](#)</sup>, J.D. Little <sup>4, [id](#)</sup>, B. Liu <sup>14a, [id](#)</sup>, B.X. Liu <sup>142, [id](#)</sup>, D. Liu <sup>62d,62c, [id](#)</sup>, J.B. Liu <sup>62a, [id](#)</sup>, J.K.K. Liu <sup>32, [id](#)</sup>, K. Liu <sup>62d,62c, [id](#)</sup>, M. Liu <sup>62a, [id](#)</sup>, M.Y. Liu <sup>62a, [id](#)</sup>, P. Liu <sup>14a, [id](#)</sup>, Q. Liu <sup>62d,138,62c, [id](#)</sup>, X. Liu <sup>62a, [id](#)</sup>, X. Liu <sup>62b, [id](#)</sup>, Y. Liu <sup>14d,14e, [id](#)</sup>, Y.L. Liu <sup>62b, [id](#)</sup>, Y.W. Liu <sup>62a, [id](#)</sup>, J. Llorente Merino <sup>142, [id](#)</sup>, S.L. Lloyd <sup>94, [id](#)</sup>, E.M. Lobodzinska <sup>48, [id](#)</sup>, P. Loch <sup>7, [id](#)</sup>, T. Lohse <sup>18, [id](#)</sup>, K. Lohwasser <sup>139, [id](#)</sup>, E. Loiacono <sup>48, [id](#)</sup>, M. Lokajicek <sup>131, [id](#),\*</sup>, J.D. Lomas <sup>20, [id](#)</sup>, J.D. Long <sup>162, [id](#)</sup>, I. Longarini <sup>160, [id](#)</sup>, L. Longo <sup>70a,70b, [id](#)</sup>, R. Longo <sup>162, [id](#)</sup>, I. Lopez Paz <sup>67, [id](#)</sup>, A. Lopez Solis <sup>48, [id](#)</sup>, N. Lorenzo Martinez <sup>4, [id](#)</sup>, A.M. Lory <sup>109, [id](#)</sup>, G. Lösckce Centeno <sup>146, [id](#)</sup>, O. Loseva <sup>37, [id](#)</sup>, X. Lou <sup>47a,47b, [id](#)</sup>, X. Lou <sup>14a,14e, [id](#)</sup>, A. Lounis <sup>66, [id](#)</sup>, J. Love <sup>6, [id](#)</sup>, P.A. Love <sup>91, [id](#)</sup>, G. Lu <sup>14a,14e, [id](#)</sup>, M. Lu <sup>80, [id](#)</sup>, S. Lu <sup>128, [id](#)</sup>, Y.J. Lu <sup>65, [id](#)</sup>, H.J. Lubatti <sup>138, [id](#)</sup>, C. Luci <sup>75a,75b, [id](#)</sup>, F.L. Lucio Alves <sup>14c, [id](#)</sup>, A. Lucotte <sup>60, [id](#)</sup>, F. Luehring <sup>68, [id](#)</sup>, I. Luise <sup>145, [id](#)</sup>, O. Lukianchuk <sup>66, [id](#)</sup>, O. Lundberg <sup>144, [id](#)</sup>, B. Lund-Jensen <sup>144, [id](#)</sup>, N.A. Luongo <sup>6, [id](#)</sup>, M.S. Lutz <sup>151, [id](#)</sup>, A.B. Lux <sup>25, [id](#)</sup>, D. Lynn <sup>29, [id](#)</sup>, H. Lyons <sup>92</sup>, R. Lysak <sup>131, [id](#)</sup>, E. Lytken <sup>98, [id](#)</sup>, V. Lyubushkin <sup>38, [id](#)</sup>, T. Lyubushkina <sup>38, [id](#)</sup>, M.M. Lyukova <sup>145, [id](#)</sup>, H. Ma <sup>29, [id](#)</sup>, K. Ma <sup>62a</sup>, L.L. Ma <sup>62b, [id](#)</sup>, W. Ma <sup>62a, [id](#)</sup>, Y. Ma <sup>121, [id](#)</sup>, D.M. Mac Donell <sup>165, [id](#)</sup>, G. Maccarrone <sup>53, [id](#)</sup>, J.C. MacDonald <sup>100, [id](#)</sup>, P.C. Machado De Abreu Farias <sup>83b, [id](#)</sup>, R. Madar <sup>40, [id](#)</sup>, W.F. Mader <sup>50, [id](#)</sup>, T. Madula <sup>96, [id](#)</sup>, J. Maeda <sup>85, [id](#)</sup>, T. Maeno <sup>29, [id](#)</sup>, H. Maguire <sup>139, [id](#)</sup>, V. Maiboroda <sup>135, [id](#)</sup>, A. Maio <sup>130a,130b,130d, [id](#)</sup>, K. Maj <sup>86a, [id](#)</sup>, O. Majersky <sup>48, [id](#)</sup>, S. Majewski <sup>123, [id](#)</sup>, N. Makovec <sup>66, [id](#)</sup>, V. Maksimovic <sup>15, [id](#)</sup>, B. Malaescu <sup>127, [id](#)</sup>, Pa. Malecki <sup>87, [id](#)</sup>, V.P. Maleev <sup>37, [id](#)</sup>, F. Malek <sup>60, [id](#)</sup>, M. Mali <sup>93, [id](#)</sup>, D. Malito <sup>95, [id](#)</sup>, U. Mallik <sup>80, [id](#)</sup>, S. Maltezos <sup>10</sup>, S. Malyukov <sup>38</sup>, J. Mamuzic <sup>13, [id](#)</sup>, G. Mancini <sup>53, [id](#)</sup>, G. Manco <sup>73a,73b, [id](#)</sup>, J.P. Mandalia <sup>94, [id](#)</sup>, I. Mandić <sup>93, [id](#)</sup>, L. Manhaes de Andrade Filho <sup>83a, [id](#)</sup>, I.M. Maniatis <sup>169, [id](#)</sup>, J. Manjarres Ramos <sup>102, [id](#),<sup>aa</sup></sup>, D.C. Mankad <sup>169, [id](#)</sup>, A. Mann <sup>109, [id](#)</sup>, B. Mansoulie <sup>135, [id](#)</sup>, S. Manzoni <sup>36, [id](#)</sup>, L. Mao <sup>62c, [id](#)</sup>, X. Mapekula <sup>33c, [id](#)</sup>, A. Marantis <sup>152, [id](#),<sup>r</sup></sup>, G. Marchiori <sup>5, [id](#)</sup>, M. Marcisovsky <sup>131, [id](#)</sup>, C. Marcon <sup>71a, [id](#)</sup>, M. Marinescu <sup>20, [id](#)</sup>, S. Marium <sup>48, [id](#)</sup>, M. Marjanovic <sup>120, [id](#)</sup>, E.J. Marshall <sup>91, [id](#)</sup>, Z. Marshall <sup>17a, [id](#)</sup>, S. Marti-Garcia <sup>163, [id](#)</sup>, T.A. Martin <sup>167, [id](#)</sup>, V.J. Martin <sup>52, [id](#)</sup>, B. Martin dit Latour <sup>16, [id](#)</sup>, L. Martinelli <sup>75a,75b, [id](#)</sup>, M. Martinez <sup>13, [id](#),<sup>s</sup></sup>, P. Martinez Agullo <sup>163, [id](#)</sup>, V.I. Martinez Outschoorn <sup>103, [id](#)</sup>, P. Martinez Suarez <sup>13, [id](#)</sup>, S. Martin-Haugh <sup>134, [id](#)</sup>, V.S. Martoiu <sup>27b, [id](#)</sup>, A.C. Martyniuk <sup>96, [id](#)</sup>, A. Marzin <sup>36, [id](#)</sup>, D. Mascione <sup>78a,78b, [id](#)</sup>, L. Masetti <sup>100, [id](#)</sup>, T. Mashimo <sup>153, [id](#)</sup>, J. Masik <sup>101, [id](#)</sup>, A.L. Maslennikov <sup>37, [id](#)</sup>, L. Massa <sup>23b, [id](#)</sup>, P. Massarotti <sup>72a,72b, [id](#)</sup>, P. Mastrandrea <sup>74a,74b, [id](#)</sup>, A. Mastroberardino <sup>43b,43a, [id](#)</sup>, T. Masubuchi <sup>153, [id](#)</sup>, T. Mathisen <sup>161, [id](#)</sup>, J. Matousek <sup>133, [id](#)</sup>, N. Matsuzawa <sup>153</sup>, J. Maurer <sup>27b, [id](#)</sup>, B. Maček <sup>93, [id](#)</sup>, D.A. Maximov <sup>37, [id](#)</sup>, R. Mazini <sup>148, [id](#)</sup>, I. Maznas <sup>152, [id](#)</sup>, M. Mazza <sup>107, [id](#)</sup>, S.M. Mazza <sup>136, [id](#)</sup>, E. Mazzeo <sup>71a,71b, [id](#)</sup>, C. Mc Ginn <sup>29, [id](#)</sup>, J.P. Mc Gowan <sup>104, [id](#)</sup>, S.P. Mc Kee <sup>106, [id](#)</sup>, C.C. McCracken <sup>164, [id](#)</sup>, E.F. McDonald <sup>105, [id](#)</sup>, A.E. McDougall <sup>114, [id](#)</sup>, J.A. MCFayden <sup>146, [id](#)</sup>, R.P. McGovern <sup>128, [id](#)</sup>, G. Mchedlidze <sup>149b, [id](#)</sup>, R.P. McKenzie <sup>33g, [id](#)</sup>, T.C. Mclachlan <sup>48, [id](#)</sup>, D.J. Mclaughlin <sup>96, [id](#)</sup>, S.J. McMahon <sup>134, [id](#)</sup>, C.M. Mcpartland <sup>92, [id](#)</sup>, R.A. McPherson <sup>165, [id](#),<sup>w</sup></sup>, S. Mehlhase <sup>109, [id](#)</sup>, A. Mehta <sup>92, [id](#)</sup>, D. Melini <sup>150, [id](#)</sup>, B.R. Mellado Garcia <sup>33g, [id](#)</sup>, A.H. Melo <sup>55, [id](#)</sup>, F. Meloni <sup>48, [id](#)</sup>, A.M. Mendes Jacques Da Costa <sup>101, [id](#)</sup>, H.Y. Meng <sup>155, [id](#)</sup>, L. Meng <sup>91, [id](#)</sup>, S. Menke <sup>110, [id](#)</sup>, M. Mentink <sup>36, [id](#)</sup>, E. Meoni <sup>43b,43a, [id](#)</sup>, G. Mercado <sup>115, [id](#)</sup>, C. Merlassino <sup>69a,69c, [id](#)</sup>, L. Merola <sup>72a,72b, [id](#)</sup>, C. Meroni <sup>71a,71b, [id](#)</sup>, G. Merz <sup>106</sup>, J. Metcalfe <sup>6, [id](#)</sup>, A.S. Mete <sup>6, [id](#)</sup>, C. Meyer <sup>68, [id](#)</sup>, J-P. Meyer <sup>135, [id](#)</sup>, R.P. Middleton <sup>134, [id](#)</sup>, L. Mijović <sup>52, [id](#)</sup>, G. Mikenberg <sup>169, [id](#)</sup>, M. Mikestikova <sup>131, [id](#)</sup>, M. Mikuž <sup>93, [id](#)</sup>, H. Mildner <sup>100, [id](#)</sup>, A. Milic <sup>36, [id](#)</sup>, C.D. Milke <sup>44, [id](#)</sup>, D.W. Miller <sup>39, [id](#)</sup>, L.S. Miller <sup>34, [id](#)</sup>, A. Milov <sup>169, [id](#)</sup>, D.A. Milstead <sup>47a,47b</sup>, T. Min <sup>14c</sup>, A.A. Minaenko <sup>37, [id](#)</sup>, I.A. Minashvili <sup>149b, [id](#)</sup>, L. Mince <sup>59, [id](#)</sup>, A.I. Mincer <sup>117, [id](#)</sup>, B. Mindur <sup>86a, [id](#)</sup>, M. Mineev <sup>38, [id](#)</sup>, Y. Mino <sup>88, [id](#)</sup>, L.M. Mir <sup>13, [id](#)</sup>, M. Miralles Lopez <sup>163, [id](#)</sup>, M. Mironova <sup>17a, [id](#)</sup>, A. Mishima <sup>153</sup>, M.C. Missio <sup>113, [id](#)</sup>, A. Mitra <sup>167, [id](#)</sup>, V.A. Mitsou <sup>163, [id](#)</sup>, Y. Mitsumori <sup>111, [id](#)</sup>, O. Miu <sup>155, [id](#)</sup>, P.S. Miyagawa <sup>94, [id](#)</sup>, T. Mkrtchyan <sup>63a, [id](#)</sup>, M. Mlinarevic <sup>96, [id](#)</sup>, T. Mlinarevic <sup>96, [id](#)</sup>, M. Mlynarikova <sup>36, [id](#)</sup>, S. Mobius <sup>19, [id](#)</sup>, P. Moder <sup>48, [id](#)</sup>, P. Mogg <sup>109, [id](#)</sup>, M.H. Mohamed Farook <sup>112, [id](#)</sup>, A.F. Mohammed <sup>14a,14e, [id](#)</sup>, S. Mohapatra <sup>41, [id](#)</sup>, G. Mokgatitswane <sup>33g, [id](#)</sup>, L. Moleri <sup>169, [id](#)</sup>, B. Mondal <sup>141, [id](#)</sup>, S. Mondal <sup>132, [id](#)</sup>, K. Mönig <sup>48, [id](#)</sup>, E. Monnier <sup>102, [id](#)</sup>, L. Monsonis Romero <sup>163</sup>, J. Montejo Berlingen <sup>13, [id](#)</sup>, M. Montella <sup>119, [id](#)</sup>, F. Montekali <sup>77a,77b, [id](#)</sup>, F. Monticelli <sup>90, [id](#)</sup>, S. Monzani <sup>69a,69c, [id](#)</sup>, N. Morange <sup>66, [id](#)</sup>, A.L. Moreira De Carvalho <sup>130a, [id](#)</sup>,

M. Moreno Llácer <sup>163, [id](#)</sup>, C. Moreno Martinez <sup>56, [id](#)</sup>, P. Morettini <sup>57b, [id](#)</sup>, S. Morgenstern <sup>36, [id](#)</sup>, M. Morii <sup>61, [id](#)</sup>, M. Morinaga <sup>153, [id](#)</sup>, A.K. Morley <sup>36, [id](#)</sup>, F. Morodei <sup>75a,75b, [id](#)</sup>, L. Morvaj <sup>36, [id](#)</sup>, P. Moschovakos <sup>36, [id](#)</sup>, B. Moser <sup>36, [id](#)</sup>, M. Mosidze <sup>149b, [id](#)</sup>, T. Moskalets <sup>54, [id](#)</sup>, P. Moskvitina <sup>113, [id](#)</sup>, J. Moss <sup>31, [id](#), [i](#)</sup>, E.J.W. Moyses <sup>103, [id](#)</sup>, O. Mtintsilana <sup>33g, [id](#)</sup>, S. Muanza <sup>102, [id](#)</sup>, J. Mueller <sup>129, [id](#)</sup>, D. Muenstermann <sup>91, [id](#)</sup>, R. Müller <sup>19, [id](#)</sup>, G.A. Mullier <sup>161, [id](#)</sup>, A.J. Mullin <sup>32</sup>, J.J. Mullin <sup>128</sup>, D.P. Mungo <sup>155, [id](#)</sup>, D. Munoz Perez <sup>163, [id](#)</sup>, F.J. Munoz Sanchez <sup>101, [id](#)</sup>, M. Murin <sup>101, [id](#)</sup>, W.J. Murray <sup>167,134, [id](#)</sup>, A. Murrone <sup>71a,71b, [id](#)</sup>, M. Muškinja <sup>17a, [id](#)</sup>, C. Mwewa <sup>29, [id](#)</sup>, A.G. Myagkov <sup>37, [id](#), [a](#)</sup>, A.J. Myers <sup>8, [id](#)</sup>, G. Myers <sup>68, [id](#)</sup>, M. Myska <sup>132, [id](#)</sup>, B.P. Nachman <sup>17a, [id](#)</sup>, O. Nackenhurst <sup>49, [id](#)</sup>, A. Nag <sup>50, [id](#)</sup>, K. Nagai <sup>126, [id](#)</sup>, K. Nagano <sup>84, [id](#)</sup>, J.L. Nagle <sup>29, [id](#), [ai](#)</sup>, E. Nagy <sup>102, [id](#)</sup>, A.M. Nairz <sup>36, [id](#)</sup>, Y. Nakahama <sup>84, [id](#)</sup>, K. Nakamura <sup>84, [id](#)</sup>, K. Nakkalil <sup>5, [id](#)</sup>, H. Nanjo <sup>124, [id](#)</sup>, R. Narayan <sup>44, [id](#)</sup>, E.A. Narayanan <sup>112, [id](#)</sup>, I. Naryshkin <sup>37, [id](#)</sup>, M. Naseri <sup>34, [id](#)</sup>, S. Nasri <sup>159, [id](#)</sup>, C. Nass <sup>24, [id](#)</sup>, G. Navarro <sup>22a, [id](#)</sup>, J. Navarro-Gonzalez <sup>163, [id](#)</sup>, R. Nayak <sup>151, [id](#)</sup>, A. Nayaz <sup>18, [id](#)</sup>, P.Y. Nechaeva <sup>37, [id](#)</sup>, F. Nechansky <sup>48, [id](#)</sup>, L. Nedic <sup>126, [id](#)</sup>, T.J. Neep <sup>20, [id](#)</sup>, A. Negri <sup>73a,73b, [id](#)</sup>, M. Negrini <sup>23b, [id](#)</sup>, C. Nellist <sup>114, [id](#)</sup>, C. Nelson <sup>104, [id](#)</sup>, K. Nelson <sup>106, [id](#)</sup>, S. Nemecek <sup>131, [id](#)</sup>, M. Nessi <sup>36, [id](#), [h](#)</sup>, M.S. Neubauer <sup>162, [id](#)</sup>, F. Neuhaus <sup>100, [id](#)</sup>, J. Neundorff <sup>48, [id](#)</sup>, R. Newhouse <sup>164, [id](#)</sup>, P.R. Newman <sup>20, [id](#)</sup>, C.W. Ng <sup>129, [id](#)</sup>, Y.W.Y. Ng <sup>48, [id](#)</sup>, B. Ngair <sup>35e, [id](#)</sup>, H.D.N. Nguyen <sup>108, [id](#)</sup>, R.B. Nickerson <sup>126, [id](#)</sup>, R. Nicolaidou <sup>135, [id](#)</sup>, J. Nielsen <sup>136, [id](#)</sup>, M. Niemeyer <sup>55, [id](#)</sup>, J. Niermann <sup>55,36, [id](#)</sup>, N. Nikiforou <sup>36, [id](#)</sup>, V. Nikolaenko <sup>37, [id](#), [a](#)</sup>, I. Nikolic-Audit <sup>127, [id](#)</sup>, K. Nikolopoulos <sup>20, [id](#)</sup>, P. Nilsson <sup>29, [id](#)</sup>, I. Ninca <sup>48, [id](#)</sup>, H.R. Nindhito <sup>56, [id](#)</sup>, G. Ninio <sup>151, [id](#)</sup>, A. Nisati <sup>75a, [id](#)</sup>, N. Nishu <sup>2, [id](#)</sup>, R. Nisius <sup>110, [id](#)</sup>, J-E. Nitschke <sup>50, [id](#)</sup>, E.K. Nkadimeng <sup>33g, [id](#)</sup>, T. Nobe <sup>153, [id](#)</sup>, D.L. Noel <sup>32, [id](#)</sup>, T. Nommensen <sup>147, [id](#)</sup>, M.B. Norfolk <sup>139, [id](#)</sup>, R.R.B. Norisam <sup>96, [id](#)</sup>, B.J. Norman <sup>34, [id](#)</sup>, M. Noury <sup>35a, [id](#)</sup>, J. Novak <sup>93, [id](#)</sup>, T. Novak <sup>48, [id](#)</sup>, L. Novotny <sup>132, [id](#)</sup>, R. Novotny <sup>112, [id](#)</sup>, L. Nozka <sup>122, [id](#)</sup>, K. Ntekas <sup>160, [id](#)</sup>, N.M.J. Nunes De Moura Junior <sup>83b, [id](#)</sup>, E. Nurse <sup>96</sup>, J. Ocariz <sup>127, [id](#)</sup>, A. Ochi <sup>85, [id](#)</sup>, I. Ochoa <sup>130a, [id](#)</sup>, S. Oerdek <sup>48, [id](#), [i](#)</sup>, J.T. Offermann <sup>39, [id](#)</sup>, A. Ogrodnik <sup>133, [id](#)</sup>, A. Oh <sup>101, [id](#)</sup>, C.C. Ohm <sup>144, [id](#)</sup>, H. Oide <sup>84, [id](#)</sup>, R. Oishi <sup>153, [id](#)</sup>, M.L. Ojeda <sup>48, [id](#)</sup>, M.W. O’Keefe <sup>92</sup>, Y. Okumura <sup>153, [id](#)</sup>, L.F. Oleiro Seabra <sup>130a, [id](#)</sup>, S.A. Olivares Pino <sup>137d, [id](#)</sup>, D. Oliveira Damazio <sup>29, [id](#)</sup>, D. Oliveira Goncalves <sup>83a, [id](#)</sup>, J.L. Oliver <sup>160, [id](#)</sup>, Ö.O. Öncel <sup>54, [id](#)</sup>, A.P. O’Neill <sup>19, [id](#)</sup>, A. Onofre <sup>130a,130c, [id](#)</sup>, P.U.E. Onyisi <sup>11, [id](#)</sup>, M.J. Oreglia <sup>39, [id](#)</sup>, G.E. Orellana <sup>90, [id](#)</sup>, D. Orestano <sup>77a,77b, [id](#)</sup>, N. Orlando <sup>13, [id](#)</sup>, R.S. Orr <sup>155, [id](#)</sup>, V. O’Shea <sup>59, [id](#)</sup>, L.M. Osojnak <sup>128, [id](#)</sup>, R. Ospanov <sup>62a, [id](#)</sup>, G. Otero y Garzon <sup>30, [id](#)</sup>, H. Otono <sup>89, [id](#)</sup>, P.S. Ott <sup>63a, [id](#)</sup>, G.J. Ottino <sup>17a, [id](#)</sup>, M. Ouchrif <sup>35d, [id](#)</sup>, J. Ouellette <sup>29, [id](#)</sup>, F. Ould-Saada <sup>125, [id](#)</sup>, M. Owen <sup>59, [id](#)</sup>, R.E. Owen <sup>134, [id](#)</sup>, K.Y. Oyulmaz <sup>21a, [id](#)</sup>, V.E. Ozcan <sup>21a, [id](#)</sup>, F. Ozturk <sup>87, [id](#)</sup>, N. Ozturk <sup>8, [id](#)</sup>, S. Ozturk <sup>82, [id](#)</sup>, H.A. Pacey <sup>126, [id](#)</sup>, A. Pacheco Pages <sup>13, [id](#)</sup>, C. Padilla Aranda <sup>13, [id](#)</sup>, G. Padovano <sup>75a,75b, [id](#)</sup>, S. Pagan Griso <sup>17a, [id](#)</sup>, G. Palacino <sup>68, [id](#)</sup>, A. Palazzo <sup>70a,70b, [id](#)</sup>, S. Palestini <sup>36, [id](#)</sup>, J. Pan <sup>172, [id](#)</sup>, T. Pan <sup>64a, [id](#)</sup>, D.K. Panchal <sup>11, [id](#)</sup>, C.E. Pandini <sup>114, [id](#)</sup>, J.G. Panduro Vazquez <sup>95, [id](#)</sup>, H.D. Pandya <sup>1, [id](#)</sup>, H. Pang <sup>14b, [id](#)</sup>, P. Pani <sup>48, [id](#)</sup>, G. Panizzo <sup>69a,69c, [id](#)</sup>, L. Paolozzi <sup>56, [id](#)</sup>, C. Papadatos <sup>108, [id](#)</sup>, S. Parajuli <sup>44, [id](#)</sup>, A. Paramonov <sup>6, [id](#)</sup>, C. Paraskevopoulos <sup>10, [id](#)</sup>, D. Paredes Hernandez <sup>64b, [id](#)</sup>, K.R. Park <sup>41, [id](#)</sup>, T.H. Park <sup>155, [id](#)</sup>, M.A. Parker <sup>32, [id](#)</sup>, F. Parodi <sup>57b,57a, [id](#)</sup>, E.W. Parrish <sup>115, [id](#)</sup>, V.A. Parrish <sup>52, [id](#)</sup>, J.A. Parsons <sup>41, [id](#)</sup>, U. Parzefall <sup>54, [id](#)</sup>, B. Pascual Dias <sup>108, [id](#)</sup>, L. Pascual Dominguez <sup>151, [id](#)</sup>, E. Pasqualucci <sup>75a, [id](#)</sup>, S. Passaggio <sup>57b, [id](#)</sup>, F. Pastore <sup>95, [id](#)</sup>, P. Pasuwan <sup>47a,47b, [id](#)</sup>, P. Patel <sup>87, [id](#)</sup>, U.M. Patel <sup>51, [id](#)</sup>, J.R. Pater <sup>101, [id](#)</sup>, T. Pauly <sup>36, [id](#)</sup>, J. Pearkes <sup>143, [id](#)</sup>, M. Pedersen <sup>125, [id](#)</sup>, R. Pedro <sup>130a, [id](#)</sup>, S.V. Peleganchuk <sup>37, [id](#)</sup>, O. Penc <sup>36, [id](#)</sup>, E.A. Pender <sup>52, [id](#)</sup>, K.E. Pinski <sup>109, [id](#)</sup>, M. Penzin <sup>37, [id](#)</sup>, B.S. Peralva <sup>83d, [id](#)</sup>, A.P. Pereira Peixoto <sup>60, [id](#)</sup>, L. Pereira Sanchez <sup>47a,47b, [id](#)</sup>, D.V. Perepelitsa <sup>29, [id](#), [ai](#)</sup>, E. Perez Codina <sup>156a, [id](#)</sup>, M. Perganti <sup>10, [id](#)</sup>, L. Perini <sup>71a,71b, [id](#), [\\*](#)</sup>, H. Pernegger <sup>36, [id](#)</sup>, O. Perrin <sup>40, [id](#)</sup>, K. Peters <sup>48, [id](#)</sup>, R.F.Y. Peters <sup>101, [id](#)</sup>, B.A. Petersen <sup>36, [id](#)</sup>, T.C. Petersen <sup>42, [id](#)</sup>, E. Petit <sup>102, [id](#)</sup>, V. Petousis <sup>132, [id](#)</sup>, C. Petridou <sup>152, [id](#), [e](#)</sup>, A. Petrukhin <sup>141, [id](#)</sup>, M. Pettee <sup>17a, [id](#)</sup>, N.E. Pettersson <sup>36, [id](#)</sup>, A. Petukhov <sup>37, [id](#)</sup>, K. Petukhova <sup>133, [id](#)</sup>, R. Pezoa <sup>137f, [id](#)</sup>, L. Pezzotti <sup>36, [id](#)</sup>, G. Pezzullo <sup>172, [id](#)</sup>, T.M. Pham <sup>170, [id](#)</sup>, T. Pham <sup>105, [id](#)</sup>, P.W. Phillips <sup>134, [id](#)</sup>, G. Piacquadio <sup>145, [id](#)</sup>, E. Pianori <sup>17a, [id](#)</sup>, F. Piazza <sup>123, [id](#)</sup>, R. Piegaia <sup>30, [id](#)</sup>, D. Pietreanu <sup>27b, [id](#)</sup>, A.D. Pilkington <sup>101, [id](#)</sup>, M. Pinamonti <sup>69a,69c, [id](#)</sup>,

J.L. Pinfold <sup>2, [id](#)</sup>, B.C. Pinheiro Pereira <sup>130a, [id](#)</sup>, A.E. Pinto Pinoargote <sup>100,135, [id](#)</sup>, L. Pintucci <sup>69a,69c, [id](#)</sup>,  
K.M. Piper <sup>146, [id](#)</sup>, A. Pirttikoski <sup>56, [id](#)</sup>, D.A. Pizzi <sup>34, [id](#)</sup>, L. Pizzimento <sup>64b, [id](#)</sup>, A. Pizzini <sup>114, [id](#)</sup>, M.-A. Pleier <sup>29, [id](#)</sup>,  
V. Plesanovs <sup>54, [id](#)</sup>, V. Pleskot <sup>133, [id](#)</sup>, E. Plotnikova <sup>38, [id](#)</sup>, G. Poddar <sup>4, [id](#)</sup>, R. Poettgen <sup>98, [id](#)</sup>, L. Poggioli <sup>127, [id](#)</sup>,  
I. Pokharel <sup>55, [id](#)</sup>, S. Polacek <sup>133, [id](#)</sup>, G. Polesello <sup>73a, [id](#)</sup>, A. Poley <sup>142,156a, [id](#)</sup>, R. Polifka <sup>132, [id](#)</sup>, A. Polini <sup>23b, [id](#)</sup>,  
C.S. Pollard <sup>167, [id](#)</sup>, Z.B. Pollock <sup>119, [id](#)</sup>, V. Polychronakos <sup>29, [id](#)</sup>, E. Pompa Pacchi <sup>75a,75b, [id](#)</sup>, D. Ponomarenko <sup>113, [id](#)</sup>,  
L. Pontecorvo <sup>36, [id](#)</sup>, S. Popa <sup>27a, [id](#)</sup>, G.A. Popeneciu <sup>27d, [id](#)</sup>, A. Poreba <sup>36, [id](#)</sup>, D.M. Portillo Quintero <sup>156a, [id](#)</sup>,  
S. Pospisil <sup>132, [id](#)</sup>, M.A. Postill <sup>139, [id](#)</sup>, P. Postolache <sup>27c, [id](#)</sup>, K. Potamianos <sup>167, [id](#)</sup>, P.A. Potepa <sup>86a, [id](#)</sup>, I.N. Potrap <sup>38, [id](#)</sup>,  
C.J. Potter <sup>32, [id](#)</sup>, H. Potti <sup>1, [id](#)</sup>, T. Poulsen <sup>48, [id](#)</sup>, J. Poveda <sup>163, [id](#)</sup>, M.E. Pozo Astigarraga <sup>36, [id](#)</sup>,  
A. Prades Ibanez <sup>163, [id](#)</sup>, J. Pretel <sup>54, [id](#)</sup>, D. Price <sup>101, [id](#)</sup>, M. Primavera <sup>70a, [id](#)</sup>, M.A. Principe Martin <sup>99, [id](#)</sup>,  
R. Privara <sup>122, [id](#)</sup>, T. Procter <sup>59, [id](#)</sup>, M.L. Proffitt <sup>138, [id](#)</sup>, N. Proklova <sup>128, [id](#)</sup>, K. Prokofiev <sup>64c, [id](#)</sup>, G. Proto <sup>110, [id](#)</sup>,  
S. Protopopescu <sup>29, [id](#)</sup>, J. Proudfoot <sup>6, [id](#)</sup>, M. Przybycien <sup>86a, [id](#)</sup>, W.W. Przygoda <sup>86b, [id](#)</sup>, J.E. Puddefoot <sup>139, [id](#)</sup>,  
D. Pudzha <sup>37, [id](#)</sup>, D. Pyatiizbyantseva <sup>37, [id](#)</sup>, J. Qian <sup>106, [id](#)</sup>, D. Qichen <sup>101, [id](#)</sup>, Y. Qin <sup>101, [id](#)</sup>, T. Qiu <sup>52, [id](#)</sup>, A. Quadt <sup>55, [id](#)</sup>,  
M. Queitsch-Maitland <sup>101, [id](#)</sup>, G. Quetant <sup>56, [id](#)</sup>, R.P. Quinn <sup>164, [id](#)</sup>, G. Rabanal Bolanos <sup>61, [id](#)</sup>, D. Rafanoharana <sup>54, [id](#)</sup>,  
F. Ragusa <sup>71a,71b, [id](#)</sup>, J.L. Rainbolt <sup>39, [id](#)</sup>, J.A. Raine <sup>56, [id](#)</sup>, S. Rajagopalan <sup>29, [id](#)</sup>, E. Ramakoti <sup>37, [id](#)</sup>,  
I.A. Ramirez-Berend <sup>34, [id](#)</sup>, K. Ran <sup>48,14e, [id](#)</sup>, N.P. Rapheeha <sup>33g, [id](#)</sup>, H. Rasheed <sup>27b, [id](#)</sup>, V. Raskina <sup>127, [id](#)</sup>,  
D.F. Rassloff <sup>63a, [id](#)</sup>, A. Rastogi <sup>17a, [id](#)</sup>, S. Rave <sup>100, [id](#)</sup>, B. Ravina <sup>55, [id](#)</sup>, I. Ravinovich <sup>169, [id](#)</sup>, M. Raymond <sup>36, [id](#)</sup>,  
A.L. Read <sup>125, [id](#)</sup>, N.P. Readioff <sup>139, [id](#)</sup>, D.M. Rebuffi <sup>73a,73b, [id](#)</sup>, G. Redlinger <sup>29, [id](#)</sup>, A.S. Reed <sup>110, [id](#)</sup>, K. Reeves <sup>26, [id](#)</sup>,  
J.A. Reidelsturz <sup>171, [id](#)</sup>, D. Reikher <sup>151, [id](#)</sup>, A. Rej <sup>49, [id](#)</sup>, C. Rembser <sup>36, [id](#)</sup>, A. Renardi <sup>48, [id](#)</sup>, M. Renda <sup>27b, [id](#)</sup>,  
M.B. Rendel <sup>110, [id](#)</sup>, F. Renner <sup>48, [id](#)</sup>, A.G. Rennie <sup>160, [id](#)</sup>, A.L. Rescia <sup>48, [id](#)</sup>, S. Resconi <sup>71a, [id](#)</sup>, M. Ressegotti <sup>57b,57a, [id](#)</sup>,  
S. Rettie <sup>36, [id](#)</sup>, J.G. Reyes Rivera <sup>107, [id](#)</sup>, E. Reynolds <sup>17a, [id](#)</sup>, O.L. Rezanova <sup>37, [id](#)</sup>, P. Reznicek <sup>133, [id](#)</sup>, N. Ribaric <sup>91, [id](#)</sup>,  
E. Ricci <sup>78a,78b, [id](#)</sup>, R. Richter <sup>110, [id](#)</sup>, S. Richter <sup>47a,47b, [id](#)</sup>, E. Richter-Was <sup>86b, [id](#)</sup>, M. Ridel <sup>127, [id](#)</sup>, S. Ridouani <sup>35d, [id](#)</sup>,  
P. Rieck <sup>117, [id](#)</sup>, P. Riedler <sup>36, [id](#)</sup>, E.M. Riefel <sup>47a,47b, [id](#)</sup>, J.O. Rieger <sup>114, [id](#)</sup>, M. Rijssenbeek <sup>145, [id](#)</sup>, A. Rimoldi <sup>73a,73b, [id](#)</sup>,  
M. Rimoldi <sup>36, [id](#)</sup>, L. Rinaldi <sup>23b,23a, [id](#)</sup>, T.T. Rinn <sup>29, [id](#)</sup>, M.P. Rinnagel <sup>109, [id](#)</sup>, G. Ripellino <sup>161, [id](#)</sup>, I. Riu <sup>13, [id](#)</sup>,  
P. Rivadeneira <sup>48, [id](#)</sup>, J.C. Rivera Vergara <sup>165, [id](#)</sup>, F. Rizatdinova <sup>121, [id](#)</sup>, E. Rizvi <sup>94, [id](#)</sup>, B.A. Roberts <sup>167, [id](#)</sup>,  
B.R. Roberts <sup>17a, [id](#)</sup>, S.H. Robertson <sup>104, [id](#),w</sup>, D. Robinson <sup>32, [id](#)</sup>, C.M. Robles Gajardo <sup>137f</sup>, M. Robles Manzano <sup>100, [id](#)</sup>,  
A. Robson <sup>59, [id](#)</sup>, A. Rocchi <sup>76a,76b, [id](#)</sup>, C. Roda <sup>74a,74b, [id](#)</sup>, S. Rodriguez Bosca <sup>63a, [id](#)</sup>, Y. Rodriguez Garcia <sup>22a, [id](#)</sup>,  
A. Rodriguez Rodriguez <sup>54, [id](#)</sup>, A.M. Rodríguez Vera <sup>156b, [id](#)</sup>, S. Roe <sup>36, [id](#)</sup>, J.T. Roemer <sup>160, [id](#)</sup>, A.R. Roepe-Gier <sup>136, [id](#)</sup>,  
J. Roggel <sup>171, [id](#)</sup>, O. Røhne <sup>125, [id](#)</sup>, R.A. Rojas <sup>103, [id](#)</sup>, C.P.A. Roland <sup>127, [id](#)</sup>, J. Roloff <sup>29, [id](#)</sup>, A. Romaniouk <sup>37, [id](#)</sup>,  
E. Romano <sup>73a,73b, [id](#)</sup>, M. Romano <sup>23b, [id](#)</sup>, A.C. Romero Hernandez <sup>162, [id](#)</sup>, N. Rompotis <sup>92, [id](#)</sup>, L. Roos <sup>127, [id](#)</sup>,  
S. Rosati <sup>75a, [id](#)</sup>, B.J. Rosser <sup>39, [id](#)</sup>, E. Rossi <sup>126, [id](#)</sup>, E. Rossi <sup>72a,72b, [id](#)</sup>, L.P. Rossi <sup>57b, [id](#)</sup>, L. Rossini <sup>54, [id](#)</sup>, R. Rosten <sup>119, [id](#)</sup>,  
M. Rotaru <sup>27b, [id](#)</sup>, B. Rottler <sup>54, [id](#)</sup>, C. Rougier <sup>102, [id](#),aa</sup>, D. Rousseau <sup>66, [id](#)</sup>, D. Rousso <sup>32, [id](#)</sup>, A. Roy <sup>162, [id](#)</sup>,  
S. Roy-Garand <sup>155, [id](#)</sup>, A. Rozanov <sup>102, [id](#)</sup>, Z.M.A. Rozario <sup>59, [id](#)</sup>, Y. Rozen <sup>150, [id](#)</sup>, X. Ruan <sup>33g, [id](#)</sup>,  
A. Rubio Jimenez <sup>163, [id](#)</sup>, A.J. Ruby <sup>92, [id](#)</sup>, V.H. Ruelas Rivera <sup>18, [id](#)</sup>, T.A. Ruggeri <sup>1, [id](#)</sup>, A. Ruggiero <sup>126, [id](#)</sup>,  
A. Ruiz-Martinez <sup>163, [id](#)</sup>, A. Rummeler <sup>36, [id](#)</sup>, Z. Rurikova <sup>54, [id](#)</sup>, N.A. Rusakovich <sup>38, [id](#)</sup>, H.L. Russell <sup>165, [id](#)</sup>,  
G. Russo <sup>75a,75b, [id](#)</sup>, J.P. Rutherford <sup>7, [id](#)</sup>, S. Rutherford Colmenares <sup>32, [id](#)</sup>, K. Rybacki <sup>91, [id](#)</sup>, M. Rybar <sup>133, [id](#)</sup>,  
E.B. Rye <sup>125, [id](#)</sup>, A. Ryzhov <sup>44, [id](#)</sup>, J.A. Sabater Iglesias <sup>56, [id](#)</sup>, P. Sabatini <sup>163, [id](#)</sup>, H.F-W. Sadrozinski <sup>136, [id](#)</sup>,  
F. Safai Tehrani <sup>75a, [id](#)</sup>, B. Safarzadeh Samani <sup>134, [id](#)</sup>, M. Safdari <sup>143, [id](#)</sup>, S. Saha <sup>165, [id](#)</sup>, M. Sahinsoy <sup>110, [id](#)</sup>,  
A. Saibel <sup>163, [id](#)</sup>, M. Saimpert <sup>135, [id](#)</sup>, M. Saito <sup>153, [id](#)</sup>, T. Saito <sup>153, [id](#)</sup>, D. Salamani <sup>36, [id](#)</sup>, A. Salnikov <sup>143, [id](#)</sup>,  
J. Salt <sup>163, [id](#)</sup>, A. Salvador Salas <sup>151, [id](#)</sup>, D. Salvatore <sup>43b,43a, [id](#)</sup>, F. Salvatore <sup>146, [id](#)</sup>, A. Salzburger <sup>36, [id](#)</sup>,  
D. Sammel <sup>54, [id](#)</sup>, D. Sampsonidis <sup>152, [id](#),e</sup>, D. Sampsonidou <sup>123, [id](#)</sup>, J. Sánchez <sup>163, [id](#)</sup>, A. Sanchez Pineda <sup>4, [id](#)</sup>,  
V. Sanchez Sebastian <sup>163, [id](#)</sup>, H. Sandaker <sup>125, [id](#)</sup>, C.O. Sander <sup>48, [id](#)</sup>, J.A. Sandesara <sup>103, [id](#)</sup>, M. Sandhoff <sup>171, [id](#)</sup>,  
C. Sandoval <sup>22b, [id](#)</sup>, D.P.C. Sankey <sup>134, [id](#)</sup>, T. Sano <sup>88, [id](#)</sup>, A. Sansoni <sup>53, [id](#)</sup>, L. Santi <sup>75a,75b, [id](#)</sup>, C. Santoni <sup>40, [id](#)</sup>,

H. Santos <sup>130a,130b, [id](#)</sup>, S.N. Santpur <sup>17a, [id](#)</sup>, A. Santra <sup>169, [id](#)</sup>, K.A. Saoucha <sup>116b, [id](#)</sup>, J.G. Saraiva <sup>130a,130d, [id](#)</sup>,  
 J. Sardain <sup>7, [id](#)</sup>, O. Sasaki <sup>84, [id](#)</sup>, K. Sato <sup>157, [id](#)</sup>, C. Sauer <sup>63b</sup>, F. Sauerburger <sup>54, [id](#)</sup>, E. Sauvan <sup>4, [id](#)</sup>, P. Savard <sup>155, [id](#), [af](#)</sup>,  
 R. Sawada <sup>153, [id](#)</sup>, C. Sawyer <sup>134, [id](#)</sup>, L. Sawyer <sup>97, [id](#)</sup>, I. Sayago Galvan <sup>163</sup>, C. Sbarra <sup>23b, [id](#)</sup>, A. Sbrizzi <sup>23b,23a, [id](#)</sup>,  
 T. Scanlon <sup>96, [id](#)</sup>, J. Schaarschmidt <sup>138, [id](#)</sup>, P. Schacht <sup>110, [id](#)</sup>, U. Schäfer <sup>100, [id](#)</sup>, A.C. Schaffer <sup>66,44, [id](#)</sup>, D. Schaile <sup>109, [id](#)</sup>,  
 R.D. Schamberger <sup>145, [id](#)</sup>, C. Scharf <sup>18, [id](#)</sup>, M.M. Schefer <sup>19, [id](#)</sup>, V.A. Schegelsky <sup>37, [id](#)</sup>, D. Scheirich <sup>133, [id](#)</sup>,  
 F. Schenck <sup>18, [id](#)</sup>, M. Schernau <sup>160, [id](#)</sup>, C. Scheulen <sup>55, [id](#)</sup>, C. Schiavi <sup>57b,57a, [id](#)</sup>, E.J. Schioppa <sup>70a,70b, [id](#)</sup>,  
 M. Schioppa <sup>43b,43a, [id](#)</sup>, B. Schlag <sup>143, [id](#), [n](#)</sup>, K.E. Schleicher <sup>54, [id](#)</sup>, S. Schlenker <sup>36, [id](#)</sup>, J. Schmeing <sup>171, [id](#)</sup>,  
 M.A. Schmidt <sup>171, [id](#)</sup>, K. Schmieden <sup>100, [id](#)</sup>, C. Schmitt <sup>100, [id](#)</sup>, N. Schmitt <sup>100, [id](#)</sup>, S. Schmitt <sup>48, [id](#)</sup>, L. Schoeffel <sup>135, [id](#)</sup>,  
 A. Schoening <sup>63b, [id](#)</sup>, P.G. Scholer <sup>54, [id](#)</sup>, E. Schopf <sup>126, [id](#)</sup>, M. Schott <sup>100, [id](#)</sup>, J. Schovancova <sup>36, [id](#)</sup>, S. Schramm <sup>56, [id](#)</sup>,  
 F. Schroeder <sup>171, [id](#)</sup>, T. Schroer <sup>56, [id](#)</sup>, H-C. Schultz-Coulon <sup>63a, [id](#)</sup>, M. Schumacher <sup>54, [id](#)</sup>, B.A. Schumm <sup>136, [id](#)</sup>,  
 Ph. Schune <sup>135, [id](#)</sup>, A.J. Schuy <sup>138, [id](#)</sup>, H.R. Schwartz <sup>136, [id](#)</sup>, A. Schwartzman <sup>143, [id](#)</sup>, T.A. Schwarz <sup>106, [id](#)</sup>,  
 Ph. Schwemling <sup>135, [id](#)</sup>, R. Schwienhorst <sup>107, [id](#)</sup>, A. Sciandra <sup>136, [id](#)</sup>, G. Sciolla <sup>26, [id](#)</sup>, F. Scuri <sup>74a, [id](#)</sup>,  
 C.D. Sebastiani <sup>92, [id](#)</sup>, K. Sedlaczek <sup>115, [id](#)</sup>, P. Seema <sup>18, [id](#)</sup>, S.C. Seidel <sup>112, [id](#)</sup>, A. Seiden <sup>136, [id](#)</sup>, B.D. Seidlitz <sup>41, [id](#)</sup>,  
 C. Seitz <sup>48, [id](#)</sup>, J.M. Seixas <sup>83b, [id](#)</sup>, G. Sekhniaidze <sup>72a, [id](#)</sup>, S.J. Sekula <sup>44, [id](#)</sup>, L. Selem <sup>60, [id](#)</sup>, N. Semprini-Cesari <sup>23b,23a, [id](#)</sup>,  
 D. Sengupta <sup>56, [id](#)</sup>, V. Senthilkumar <sup>163, [id](#)</sup>, L. Serin <sup>66, [id](#)</sup>, L. Serkin <sup>69a,69b, [id](#)</sup>, M. Sessa <sup>76a,76b, [id](#)</sup>, H. Severini <sup>120, [id](#)</sup>,  
 F. Sforza <sup>57b,57a, [id](#)</sup>, A. Sfyrlla <sup>56, [id](#)</sup>, E. Shabalina <sup>55, [id](#)</sup>, R. Shaheen <sup>144, [id](#)</sup>, J.D. Shahinian <sup>128, [id](#)</sup>,  
 D. Shaked Renous <sup>169, [id](#)</sup>, L.Y. Shan <sup>14a, [id](#)</sup>, M. Shapiro <sup>17a, [id](#)</sup>, A. Sharma <sup>36, [id](#)</sup>, A.S. Sharma <sup>164, [id](#)</sup>, P. Sharma <sup>80, [id](#)</sup>,  
 S. Sharma <sup>48, [id](#)</sup>, P.B. Shatalov <sup>37, [id](#)</sup>, K. Shaw <sup>146, [id](#)</sup>, S.M. Shaw <sup>101, [id](#)</sup>, A. Shcherbakova <sup>37, [id](#)</sup>, Q. Shen <sup>62c,5, [id](#)</sup>,  
 D.J. Sheppard <sup>142, [id](#)</sup>, P. Sherwood <sup>96, [id](#)</sup>, L. Shi <sup>96, [id](#)</sup>, X. Shi <sup>14a, [id](#)</sup>, C.O. Shimmin <sup>172, [id](#)</sup>, J.D. Shinner <sup>95, [id](#)</sup>,  
 I.P.J. Shipsey <sup>126, [id](#)</sup>, S. Shirabe <sup>56, [id](#), [h](#)</sup>, M. Shiyakova <sup>38, [id](#), [u](#)</sup>, J. Shlomi <sup>169, [id](#)</sup>, M.J. Shochet <sup>39, [id](#)</sup>, J. Shojaii <sup>105, [id](#)</sup>,  
 D.R. Shope <sup>125, [id](#)</sup>, B. Shrestha <sup>120, [id](#)</sup>, S. Shrestha <sup>119, [id](#), [aj](#)</sup>, E.M. Shrif <sup>33g, [id](#)</sup>, M.J. Shroff <sup>165, [id](#)</sup>, P. Sicho <sup>131, [id](#)</sup>,  
 A.M. Sickles <sup>162, [id](#)</sup>, E. Sideras Haddad <sup>33g, [id](#)</sup>, A. Sidoti <sup>23b, [id](#)</sup>, F. Siegert <sup>50, [id](#)</sup>, Dj. Sijacki <sup>15, [id](#)</sup>, F. Sili <sup>90, [id](#)</sup>,  
 J.M. Silva <sup>20, [id](#)</sup>, M.V. Silva Oliveira <sup>29, [id](#)</sup>, S.B. Silverstein <sup>47a, [id](#)</sup>, S. Simion <sup>66</sup>, R. Simoniello <sup>36, [id](#)</sup>,  
 E.L. Simpson <sup>59, [id](#)</sup>, H. Simpson <sup>146, [id](#)</sup>, L.R. Simpson <sup>106, [id](#)</sup>, N.D. Simpson <sup>98</sup>, S. Simsek <sup>82, [id](#)</sup>, S. Sindhu <sup>55, [id](#)</sup>,  
 P. Sinervo <sup>155, [id](#)</sup>, S. Singh <sup>155, [id](#)</sup>, S. Sinha <sup>48, [id](#)</sup>, S. Sinha <sup>101, [id](#)</sup>, M. Sioli <sup>23b,23a, [id](#)</sup>, I. Siral <sup>36, [id](#)</sup>, E. Sitnikova <sup>48, [id](#)</sup>,  
 S.Yu. Sivoklokov <sup>37, [id](#), [\\*](#)</sup>, J. Sjölin <sup>47a,47b, [id](#)</sup>, A. Skaf <sup>55, [id](#)</sup>, E. Skorda <sup>20, [id](#)</sup>, P. Skubic <sup>120, [id](#)</sup>, M. Slawinska <sup>87, [id](#)</sup>,  
 V. Smakhtin <sup>169</sup>, B.H. Smart <sup>134, [id](#)</sup>, J. Smiesko <sup>36, [id](#)</sup>, S.Yu. Smirnov <sup>37, [id](#)</sup>, Y. Smirnov <sup>37, [id](#)</sup>, L.N. Smirnova <sup>37, [id](#), [a](#)</sup>,  
 O. Smirnova <sup>98, [id](#)</sup>, A.C. Smith <sup>41, [id](#)</sup>, E.A. Smith <sup>39, [id](#)</sup>, H.A. Smith <sup>126, [id](#)</sup>, J.L. Smith <sup>92, [id](#)</sup>, R. Smith <sup>143</sup>,  
 M. Smizanska <sup>91, [id](#)</sup>, K. Smolek <sup>132, [id](#)</sup>, A.A. Snesev <sup>37, [id](#)</sup>, S.R. Snider <sup>155, [id](#)</sup>, H.L. Snoek <sup>114, [id](#)</sup>, S. Snyder <sup>29, [id](#)</sup>,  
 R. Sobie <sup>165, [id](#), [w](#)</sup>, A. Soffer <sup>151, [id](#)</sup>, C.A. Solans Sanchez <sup>36, [id](#)</sup>, E.Yu. Soldatov <sup>37, [id](#)</sup>, U. Soldevila <sup>163, [id](#)</sup>,  
 A.A. Solodkov <sup>37, [id](#)</sup>, S. Solomon <sup>26, [id](#)</sup>, A. Soloshenko <sup>38, [id](#)</sup>, K. Solovieva <sup>54, [id](#)</sup>, O.V. Solovyanov <sup>40, [id](#)</sup>,  
 V. Solovyev <sup>37, [id](#)</sup>, P. Sommer <sup>36, [id](#)</sup>, A. Sonay <sup>13, [id](#)</sup>, W.Y. Song <sup>156b, [id](#)</sup>, J.M. Sonneveld <sup>114, [id](#)</sup>, A. Sopczak <sup>132, [id](#)</sup>,  
 A.L. Soppio <sup>96, [id](#)</sup>, F. Sopkova <sup>28b, [id](#)</sup>, I.R. Sotarriva Alvarez <sup>154, [id](#)</sup>, V. Sothilingam <sup>63a</sup>, O.J. Soto Sandoval <sup>137c,137b, [id](#)</sup>,  
 S. Sottocornola <sup>68, [id](#)</sup>, R. Soualah <sup>116b, [id](#)</sup>, Z. Soumami <sup>35c, [id](#)</sup>, D. South <sup>48, [id](#)</sup>, N. Soybelman <sup>169, [id](#)</sup>,  
 S. Spagnolo <sup>70a,70b, [id](#)</sup>, M. Spalla <sup>110, [id](#)</sup>, D. Sperlich <sup>54, [id](#)</sup>, G. Spigo <sup>36, [id](#)</sup>, S. Spinali <sup>91, [id](#)</sup>, D.P. Spiteri <sup>59, [id](#)</sup>,  
 M. Spousta <sup>133, [id](#)</sup>, E.J. Staats <sup>34, [id](#)</sup>, A. Stabile <sup>71a,71b, [id](#)</sup>, R. Stamen <sup>63a, [id](#)</sup>, A. Stampekis <sup>20, [id](#)</sup>, M. Standke <sup>24, [id](#)</sup>,  
 E. Stanecka <sup>87, [id](#)</sup>, M.V. Stange <sup>50, [id](#)</sup>, B. Stanislaus <sup>17a, [id](#)</sup>, M.M. Stanitzki <sup>48, [id](#)</sup>, B. Stapf <sup>48, [id](#)</sup>, E.A. Starchenko <sup>37, [id](#)</sup>,  
 G.H. Stark <sup>136, [id](#)</sup>, J. Stark <sup>102, [id](#), [aa](#)</sup>, D.M. Starcko <sup>156b</sup>, P. Staroba <sup>131, [id](#)</sup>, P. Starovoitov <sup>63a, [id](#)</sup>, S. Stärz <sup>104, [id](#)</sup>,  
 R. Staszewski <sup>87, [id](#)</sup>, G. Stavropoulos <sup>46, [id](#)</sup>, J. Steentoft <sup>161, [id](#)</sup>, P. Steinberg <sup>29, [id](#)</sup>, B. Stelzer <sup>142,156a, [id](#)</sup>,  
 H.J. Stelzer <sup>129, [id](#)</sup>, O. Stelzer-Chilton <sup>156a, [id](#)</sup>, H. Stenzel <sup>58, [id](#)</sup>, T.J. Stevenson <sup>146, [id](#)</sup>, G.A. Stewart <sup>36, [id](#)</sup>,  
 J.R. Stewart <sup>121, [id](#)</sup>, M.C. Stockton <sup>36, [id](#)</sup>, G. Stoicea <sup>27b, [id](#)</sup>, M. Stolarski <sup>130a, [id](#)</sup>, S. Stonjek <sup>110, [id](#)</sup>, A. Straessner <sup>50, [id](#)</sup>,  
 J. Strandberg <sup>144, [id](#)</sup>, S. Strandberg <sup>47a,47b, [id](#)</sup>, M. Stratmann <sup>171, [id](#)</sup>, M. Strauss <sup>120, [id](#)</sup>, T. Strebler <sup>102, [id](#)</sup>,

P. Strizenec<sup>28b,ib</sup>, R. Ströhmer<sup>166,ib</sup>, D.M. Strom<sup>123,ib</sup>, R. Stroynowski<sup>44,ib</sup>, A. Strubig<sup>47a,47b,ib</sup>, S.A. Stucci<sup>29,ib</sup>, B. Stugu<sup>16,ib</sup>, J. Stupak<sup>120,ib</sup>, N.A. Styles<sup>48,ib</sup>, D. Su<sup>143,ib</sup>, S. Su<sup>62a,ib</sup>, W. Su<sup>62d,ib</sup>, X. Su<sup>62a,66,ib</sup>, K. Sugizaki<sup>153,ib</sup>, V.V. Sulin<sup>37,ib</sup>, M.J. Sullivan<sup>92,ib</sup>, D.M.S. Sultan<sup>78a,78b,ib</sup>, L. Sultanaliev<sup>37,ib</sup>, S. Sultansoy<sup>3b,ib</sup>, T. Sumida<sup>88,ib</sup>, S. Sun<sup>106,ib</sup>, S. Sun<sup>170,ib</sup>, O. Sunneborn Gudnadottir<sup>161,ib</sup>, N. Sur<sup>102,ib</sup>, M.R. Sutton<sup>146,ib</sup>, H. Suzuki<sup>157,ib</sup>, M. Svatos<sup>131,ib</sup>, M. Swiatlowski<sup>156a,ib</sup>, T. Swirski<sup>166,ib</sup>, I. Sykora<sup>28a,ib</sup>, M. Sykora<sup>133,ib</sup>, T. Sykora<sup>133,ib</sup>, D. Ta<sup>100,ib</sup>, K. Tackmann<sup>48,ib,r</sup>, A. Taffard<sup>160,ib</sup>, R. Tafirout<sup>156a,ib</sup>, J.S. Tafoya Vargas<sup>66,ib</sup>, E.P. Takeva<sup>52,ib</sup>, Y. Takubo<sup>84,ib</sup>, M. Talby<sup>102,ib</sup>, A.A. Talyshev<sup>37,ib</sup>, K.C. Tam<sup>64b,ib</sup>, N.M. Tamir<sup>151</sup>, A. Tanaka<sup>153,ib</sup>, J. Tanaka<sup>153,ib</sup>, R. Tanaka<sup>66,ib</sup>, M. Tanasini<sup>57b,57a,ib</sup>, Z. Tao<sup>164,ib</sup>, S. Tapia Araya<sup>137f,ib</sup>, S. Tapprogge<sup>100,ib</sup>, A. Tarek Abouelfadl Mohamed<sup>107,ib</sup>, S. Tarem<sup>150,ib</sup>, K. Tariq<sup>14a,ib</sup>, G. Tarna<sup>102,27b,ib</sup>, G.F. Tartarelli<sup>71a,ib</sup>, P. Tas<sup>133,ib</sup>, M. Tasevsky<sup>131,ib</sup>, E. Tassi<sup>43b,43a,ib</sup>, A.C. Tate<sup>162,ib</sup>, G. Tateno<sup>153,ib</sup>, Y. Tayalati<sup>35e,ib,v</sup>, G.N. Taylor<sup>105,ib</sup>, W. Taylor<sup>156b,ib</sup>, A.S. Tee<sup>170,ib</sup>, R. Teixeira De Lima<sup>143,ib</sup>, P. Teixeira-Dias<sup>95,ib</sup>, J.J. Teoh<sup>155,ib</sup>, K. Terashi<sup>153,ib</sup>, J. Terron<sup>99,ib</sup>, S. Terzo<sup>13,ib</sup>, M. Testa<sup>53,ib</sup>, R.J. Teuscher<sup>155,ib,w</sup>, A. Thaler<sup>79,ib</sup>, O. Theiner<sup>56,ib</sup>, N. Themistokleous<sup>52,ib</sup>, T. Theveneaux-Pelzer<sup>102,ib</sup>, O. Thielmann<sup>171,ib</sup>, D.W. Thomas<sup>95</sup>, J.P. Thomas<sup>20,ib</sup>, E.A. Thompson<sup>17a,ib</sup>, P.D. Thompson<sup>20,ib</sup>, E. Thomson<sup>128,ib</sup>, Y. Tian<sup>55,ib</sup>, V. Tikhomirov<sup>37,ib,a</sup>, Yu.A. Tikhonov<sup>37,ib</sup>, S. Timoshenko<sup>37</sup>, D. Timoshyn<sup>133,ib</sup>, E.X.L. Ting<sup>1,ib</sup>, P. Tipton<sup>172,ib</sup>, S.H. Tlou<sup>33g,ib</sup>, A. Tmourji<sup>40,ib</sup>, K. Todome<sup>154,ib</sup>, S. Todorova-Nova<sup>133,ib</sup>, S. Todt<sup>50</sup>, M. Togawa<sup>84,ib</sup>, J. Tojo<sup>89,ib</sup>, S. Tokár<sup>28a,ib</sup>, K. Tokushuku<sup>84,ib</sup>, O. Toldaiev<sup>68,ib</sup>, R. Tombs<sup>32,ib</sup>, M. Tomoto<sup>84,111,ib</sup>, L. Tompkins<sup>143,ib,n</sup>, K.W. Topolnicki<sup>86b,ib</sup>, E. Torrence<sup>123,ib</sup>, H. Torres<sup>102,ib,aa</sup>, E. Torrón Pastor<sup>163,ib</sup>, M. Toscani<sup>30,ib</sup>, C. Toscirri<sup>39,ib</sup>, M. Tost<sup>11,ib</sup>, D.R. Tovey<sup>139,ib</sup>, A. Traeet<sup>16</sup>, I.S. Trandafir<sup>27b,ib</sup>, T. Trefzger<sup>166,ib</sup>, A. Tricoli<sup>29,ib</sup>, I.M. Trigger<sup>156a,ib</sup>, S. Trincaz-Duvoid<sup>127,ib</sup>, D.A. Trischuk<sup>26,ib</sup>, B. Trocmé<sup>60,ib</sup>, C. Troncon<sup>71a,ib</sup>, L. Truong<sup>33c,ib</sup>, M. Trzebinski<sup>87,ib</sup>, A. Trzupek<sup>87,ib</sup>, F. Tsai<sup>145,ib</sup>, M. Tsai<sup>106,ib</sup>, A. Tsiamis<sup>152,ib,e</sup>, P.V. Tsiarehka<sup>37</sup>, S. Tsigaridas<sup>156a,ib</sup>, A. Tsigotis<sup>152,ib,r</sup>, V. Tsiskaridze<sup>155,ib</sup>, E.G. Tskhadadze<sup>149a,ib</sup>, M. Tsopoulou<sup>152,ib,e</sup>, Y. Tsujikawa<sup>88,ib</sup>, I.I. Tsukerman<sup>37,ib</sup>, V. Tsulaia<sup>17a,ib</sup>, S. Tsuno<sup>84,ib</sup>, K. Tsurii<sup>118,ib</sup>, D. Tsybychev<sup>145,ib</sup>, Y. Tu<sup>64b,ib</sup>, A. Tudorache<sup>27b,ib</sup>, V. Tudorache<sup>27b,ib</sup>, A.N. Tuna<sup>61,ib</sup>, S. Turchikhin<sup>57b,57a,ib</sup>, I. Turk Cakir<sup>3a,ib</sup>, R. Turra<sup>71a,ib</sup>, T. Turtuvshin<sup>38,ib,x</sup>, P.M. Tuts<sup>41,ib</sup>, S. Tzamarias<sup>152,ib,e</sup>, P. Tzanis<sup>10,ib</sup>, E. Tzovara<sup>100,ib</sup>, F. Ukegawa<sup>157,ib</sup>, P.A. Ulloa Poblete<sup>137c,137b,ib</sup>, E.N. Umaka<sup>29,ib</sup>, G. Unal<sup>36,ib</sup>, M. Unal<sup>11,ib</sup>, A. Undrus<sup>29,ib</sup>, G. Unel<sup>160,ib</sup>, J. Urban<sup>28b,ib</sup>, P. Urquijo<sup>105,ib</sup>, P. Urrejola<sup>137a,ib</sup>, G. Usai<sup>8,ib</sup>, R. Ushioda<sup>154,ib</sup>, M. Usman<sup>108,ib</sup>, Z. Uysal<sup>21b,ib</sup>, V. Vacek<sup>132,ib</sup>, B. Vachon<sup>104,ib</sup>, K.O.H. Vadla<sup>125,ib</sup>, T. Vafeiadis<sup>36,ib</sup>, A. Vaitkus<sup>96,ib</sup>, C. Valderanis<sup>109,ib</sup>, E. Valdes Santurio<sup>47a,47b,ib</sup>, M. Valente<sup>156a,ib</sup>, S. Valentinetti<sup>23b,23a,ib</sup>, A. Valero<sup>163,ib</sup>, E. Valiente Moreno<sup>163,ib</sup>, A. Vallier<sup>102,ib,aa</sup>, J.A. Valls Ferrer<sup>163,ib</sup>, D.R. Van Arneeman<sup>114,ib</sup>, T.R. Van Daalen<sup>138,ib</sup>, A. Van Der Graaf<sup>49,ib</sup>, P. Van Gemmeren<sup>6,ib</sup>, M. Van Rijnbach<sup>125,36,ib</sup>, S. Van Stroud<sup>96,ib</sup>, I. Van Vulpen<sup>114,ib</sup>, M. Vanadia<sup>76a,76b,ib</sup>, W. Vandelli<sup>36,ib</sup>, M. Vandenbroucke<sup>135,ib</sup>, E.R. Vandewall<sup>121,ib</sup>, D. Vannicola<sup>151,ib</sup>, L. Vannoli<sup>57b,57a,ib</sup>, R. Vari<sup>75a,ib</sup>, E.W. Varnes<sup>7,ib</sup>, C. Varni<sup>17b,ib</sup>, T. Varol<sup>148,ib</sup>, D. Varouchas<sup>66,ib</sup>, L. Varriale<sup>163,ib</sup>, K.E. Varvell<sup>147,ib</sup>, M.E. Vasile<sup>27b,ib</sup>, L. Vaslin<sup>84</sup>, G.A. Vasquez<sup>165,ib</sup>, A. Vasyukov<sup>38,ib</sup>, F. Vazeille<sup>40,ib</sup>, T. Vazquez Schroeder<sup>36,ib</sup>, J. Veatch<sup>31,ib</sup>, V. Vecchio<sup>101,ib</sup>, M.J. Veen<sup>103,ib</sup>, I. Veliscek<sup>126,ib</sup>, L.M. Veloce<sup>155,ib</sup>, F. Veloso<sup>130a,130c,ib</sup>, S. Veneziano<sup>75a,ib</sup>, A. Ventura<sup>70a,70b,ib</sup>, S. Ventura Gonzalez<sup>135,ib</sup>, A. Verbytskyi<sup>110,ib</sup>, M. Verducci<sup>74a,74b,ib</sup>, C. Vergis<sup>24,ib</sup>, M. Verissimo De Araujo<sup>83b,ib</sup>, W. Verkerke<sup>114,ib</sup>, J.C. Vermeulen<sup>114,ib</sup>, C. Vernieri<sup>143,ib</sup>, M. Vessella<sup>103,ib</sup>, M.C. Vetterli<sup>142,ib,af</sup>, A. Vgenopoulos<sup>152,ib,e</sup>, N. Viaux Maira<sup>137f,ib</sup>, T. Vickey<sup>139,ib</sup>, O.E. Vickey Boeriu<sup>139,ib</sup>, G.H.A. Viehhauser<sup>126,ib</sup>, L. Vigani<sup>63b,ib</sup>, M. Villa<sup>23b,23a,ib</sup>, M. Villaplana Perez<sup>163,ib</sup>, E.M. Villhauer<sup>52</sup>, E. Vilucchi<sup>53,ib</sup>, M.G. Vincker<sup>34,ib</sup>, G.S. Virdee<sup>20,ib</sup>, A. Vishwakarma<sup>52,ib</sup>, A. Visibile<sup>114</sup>, C. Vittori<sup>36,ib</sup>, I. Vivarelli<sup>146,ib</sup>, E. Voevodina<sup>110,ib</sup>, F. Vogel<sup>109,ib</sup>,

J.C. Voigt<sup>50, [id](#)</sup>, P. Vokac<sup>132, [id](#)</sup>, Yu. Volkotrub<sup>86a, [id](#)</sup>, J. Von Ahnen<sup>48, [id](#)</sup>, E. Von Toerne<sup>24, [id](#)</sup>, B. Vormwald<sup>36, [id](#)</sup>, V. Vorobel<sup>133, [id](#)</sup>, K. Vorobev<sup>37, [id](#)</sup>, M. Vos<sup>163, [id](#)</sup>, K. Voss<sup>141, [id](#)</sup>, J.H. Vosseveld<sup>92, [id](#)</sup>, M. Vozak<sup>114, [id](#)</sup>, L. Vozdecky<sup>94, [id](#)</sup>, N. Vranjes<sup>15, [id](#)</sup>, M. Vranjes Milosavljevic<sup>15, [id](#)</sup>, M. Vreeswijk<sup>114, [id](#)</sup>, R. Vuillermet<sup>36, [id](#)</sup>, O. Vujanovic<sup>100, [id](#)</sup>, I. Vukotic<sup>39, [id](#)</sup>, S. Wada<sup>157, [id](#)</sup>, C. Wagner<sup>103</sup>, J.M. Wagner<sup>17a, [id](#)</sup>, W. Wagner<sup>171, [id](#)</sup>, S. Wahdan<sup>171, [id](#)</sup>, H. Wahlberg<sup>90, [id](#)</sup>, M. Wakida<sup>111, [id](#)</sup>, J. Walder<sup>134, [id](#)</sup>, R. Walker<sup>109, [id](#)</sup>, W. Walkowiak<sup>141, [id](#)</sup>, A. Wall<sup>128, [id](#)</sup>, T. Wamorkar<sup>6, [id](#)</sup>, A.Z. Wang<sup>136, [id](#)</sup>, C. Wang<sup>100, [id](#)</sup>, C. Wang<sup>62c, [id](#)</sup>, H. Wang<sup>17a, [id](#)</sup>, J. Wang<sup>64a, [id](#)</sup>, R.-J. Wang<sup>100, [id](#)</sup>, R. Wang<sup>61, [id](#)</sup>, R. Wang<sup>6, [id](#)</sup>, S.M. Wang<sup>148, [id](#)</sup>, S. Wang<sup>62b, [id](#)</sup>, T. Wang<sup>62a, [id](#)</sup>, W.T. Wang<sup>80, [id](#)</sup>, W. Wang<sup>14a, [id](#)</sup>, X. Wang<sup>14c, [id](#)</sup>, X. Wang<sup>162, [id](#)</sup>, X. Wang<sup>62c, [id](#)</sup>, Y. Wang<sup>62d, [id](#)</sup>, Y. Wang<sup>14c, [id](#)</sup>, Z. Wang<sup>106, [id](#)</sup>, Z. Wang<sup>62d,51,62c, [id](#)</sup>, Z. Wang<sup>106, [id](#)</sup>, A. Warburton<sup>104, [id](#)</sup>, R.J. Ward<sup>20, [id](#)</sup>, N. Warrack<sup>59, [id](#)</sup>, A.T. Watson<sup>20, [id](#)</sup>, H. Watson<sup>59, [id](#)</sup>, M.F. Watson<sup>20, [id](#)</sup>, E. Watton<sup>59,134, [id](#)</sup>, G. Watts<sup>138, [id](#)</sup>, B.M. Waugh<sup>96, [id](#)</sup>, C. Weber<sup>29, [id](#)</sup>, H.A. Weber<sup>18, [id](#)</sup>, M.S. Weber<sup>19, [id](#)</sup>, S.M. Weber<sup>63a, [id](#)</sup>, C. Wei<sup>62a, [id](#)</sup>, Y. Wei<sup>126, [id](#)</sup>, A.R. Weidberg<sup>126, [id](#)</sup>, E.J. Weik<sup>117, [id](#)</sup>, J. Weingarten<sup>49, [id](#)</sup>, M. Weirich<sup>100, [id](#)</sup>, C. Weiser<sup>54, [id](#)</sup>, C.J. Wells<sup>48, [id](#)</sup>, T. Wenaus<sup>29, [id](#)</sup>, B. Wendland<sup>49, [id](#)</sup>, T. Wengler<sup>36, [id](#)</sup>, N.S. Wenke<sup>110</sup>, N. Vermes<sup>24, [id](#)</sup>, M. Wessels<sup>63a, [id](#)</sup>, A.M. Wharton<sup>91, [id](#)</sup>, A.S. White<sup>61, [id](#)</sup>, A. White<sup>8, [id](#)</sup>, M.J. White<sup>1, [id](#)</sup>, D. Whiteson<sup>160, [id](#)</sup>, L. Wickremasinghe<sup>124, [id](#)</sup>, W. Wiedenmann<sup>170, [id](#)</sup>, C. Wiel<sup>50, [id](#)</sup>, M. Wielers<sup>134, [id](#)</sup>, C. Wiglesworth<sup>42, [id](#)</sup>, D.J. Wilbern<sup>120</sup>, H.G. Wilkens<sup>36, [id](#)</sup>, D.M. Williams<sup>41, [id](#)</sup>, H.H. Williams<sup>128</sup>, S. Williams<sup>32, [id](#)</sup>, S. Willocq<sup>103, [id](#)</sup>, B.J. Wilson<sup>101, [id](#)</sup>, P.J. Windischhofer<sup>39, [id](#)</sup>, F.I. Winkel<sup>30, [id](#)</sup>, F. Winklmeier<sup>123, [id](#)</sup>, B.T. Winter<sup>54, [id](#)</sup>, J.K. Winter<sup>101, [id](#)</sup>, M. Wittgen<sup>143</sup>, M. Wobisch<sup>97, [id](#)</sup>, Z. Wolffs<sup>114, [id](#)</sup>, J. Wollrath<sup>160</sup>, M.W. Wolter<sup>87, [id](#)</sup>, H. Wolters<sup>130a,130c, [id](#)</sup>, A.F. Wongel<sup>48, [id](#)</sup>, E.L. Woodward<sup>41, [id](#)</sup>, S.D. Worm<sup>48, [id](#)</sup>, B.K. Wosiek<sup>87, [id](#)</sup>, K.W. Woźniak<sup>87, [id](#)</sup>, S. Wozniowski<sup>55, [id](#)</sup>, K. Wraight<sup>59, [id](#)</sup>, C. Wu<sup>20, [id](#)</sup>, J. Wu<sup>14a,14e, [id](#)</sup>, M. Wu<sup>64a, [id](#)</sup>, M. Wu<sup>113, [id](#)</sup>, S.L. Wu<sup>170, [id](#)</sup>, X. Wu<sup>56, [id](#)</sup>, Y. Wu<sup>62a, [id](#)</sup>, Z. Wu<sup>135, [id](#)</sup>, J. Wuerzinger<sup>110, [id](#)</sup>,<sup>ad</sup> T.R. Wyatt<sup>101, [id](#)</sup>, B.M. Wynne<sup>52, [id](#)</sup>, S. Xella<sup>42, [id](#)</sup>, L. Xia<sup>14c, [id](#)</sup>, M. Xia<sup>14b, [id](#)</sup>, J. Xiang<sup>64c, [id](#)</sup>, M. Xie<sup>62a, [id](#)</sup>, X. Xie<sup>62a, [id](#)</sup>, S. Xin<sup>14a,14e, [id](#)</sup>, A. Xiong<sup>123, [id](#)</sup>, J. Xiong<sup>17a, [id](#)</sup>, D. Xu<sup>14a, [id](#)</sup>, H. Xu<sup>62a, [id](#)</sup>, L. Xu<sup>62a, [id](#)</sup>, R. Xu<sup>128, [id](#)</sup>, T. Xu<sup>106, [id](#)</sup>, Y. Xu<sup>14b, [id](#)</sup>, Z. Xu<sup>52, [id](#)</sup>, Z. Xu<sup>14c</sup>, B. Yabsley<sup>147, [id](#)</sup>, S. Yacoob<sup>33a, [id](#)</sup>, Y. Yamaguchi<sup>154, [id](#)</sup>, E. Yamashita<sup>153, [id](#)</sup>, H. Yamauchi<sup>157, [id](#)</sup>, T. Yamazaki<sup>17a, [id](#)</sup>, Y. Yamazaki<sup>85, [id](#)</sup>, J. Yan<sup>62c</sup>, S. Yan<sup>126, [id](#)</sup>, Z. Yan<sup>25, [id](#)</sup>, H.J. Yang<sup>62c,62d, [id](#)</sup>, H.T. Yang<sup>62a, [id](#)</sup>, S. Yang<sup>62a, [id](#)</sup>, T. Yang<sup>64c, [id](#)</sup>, X. Yang<sup>36, [id](#)</sup>, X. Yang<sup>14a, [id](#)</sup>, Y. Yang<sup>44, [id](#)</sup>, Y. Yang<sup>62a</sup>, Z. Yang<sup>62a, [id](#)</sup>, W-M. Yao<sup>17a, [id](#)</sup>, Y.C. Yap<sup>48, [id](#)</sup>, H. Ye<sup>14c, [id](#)</sup>, H. Ye<sup>55, [id](#)</sup>, J. Ye<sup>14a, [id](#)</sup>, S. Ye<sup>29, [id](#)</sup>, X. Ye<sup>62a, [id](#)</sup>, Y. Yeh<sup>96, [id](#)</sup>, I. Yeletsikh<sup>38, [id](#)</sup>, B.K. Yeo<sup>17b, [id](#)</sup>, M.R. Yexley<sup>96, [id](#)</sup>, P. Yin<sup>41, [id](#)</sup>, K. Yorita<sup>168, [id](#)</sup>, S. Younas<sup>27b, [id](#)</sup>, C.J.S. Young<sup>36, [id](#)</sup>, C. Young<sup>143, [id](#)</sup>, C. Yu<sup>14a,14e, [id](#)</sup>,<sup>ah</sup> Y. Yu<sup>62a, [id](#)</sup>, M. Yuan<sup>106, [id](#)</sup>, R. Yuan<sup>62b, [id](#)</sup>, L. Yue<sup>96, [id](#)</sup>, M. Zaazoua<sup>62a, [id](#)</sup>, B. Zabinski<sup>87, [id](#)</sup>, E. Zaid<sup>52</sup>, Z.K. Zak<sup>87, [id](#)</sup>, T. Zakareishvili<sup>149b, [id](#)</sup>, N. Zakharchuk<sup>34, [id](#)</sup>, S. Zambito<sup>56, [id](#)</sup>, J.A. Zamora Saa<sup>137d,137b, [id](#)</sup>, J. Zang<sup>153, [id](#)</sup>, D. Zanzi<sup>54, [id](#)</sup>, O. Zaplatilek<sup>132, [id](#)</sup>, C. Zeitnitz<sup>171, [id](#)</sup>, H. Zeng<sup>14a, [id](#)</sup>, J.C. Zeng<sup>162, [id](#)</sup>, D.T. Zenger Jr<sup>26, [id](#)</sup>, O. Zenin<sup>37, [id](#)</sup>, T. Ženiš<sup>28a, [id](#)</sup>, S. Zenz<sup>94, [id](#)</sup>, S. Zerradi<sup>35a, [id](#)</sup>, D. Zerwas<sup>66, [id](#)</sup>, M. Zhai<sup>14a,14e, [id](#)</sup>, B. Zhang<sup>14c, [id](#)</sup>, D.F. Zhang<sup>139, [id](#)</sup>, J. Zhang<sup>62b, [id](#)</sup>, J. Zhang<sup>6, [id](#)</sup>, K. Zhang<sup>14a,14e, [id](#)</sup>, L. Zhang<sup>14c, [id](#)</sup>, P. Zhang<sup>14a,14e, [id](#)</sup>, R. Zhang<sup>170, [id](#)</sup>, S. Zhang<sup>106, [id](#)</sup>, S. Zhang<sup>44, [id](#)</sup>, T. Zhang<sup>153, [id](#)</sup>, X. Zhang<sup>62c, [id](#)</sup>, X. Zhang<sup>62b, [id](#)</sup>, Y. Zhang<sup>62c,5, [id](#)</sup>, Y. Zhang<sup>96, [id](#)</sup>, Y. Zhang<sup>14c, [id](#)</sup>, Z. Zhang<sup>17a, [id](#)</sup>, Z. Zhang<sup>66, [id](#)</sup>, H. Zhao<sup>138, [id](#)</sup>, T. Zhao<sup>62b, [id](#)</sup>, Y. Zhao<sup>136, [id](#)</sup>, Z. Zhao<sup>62a, [id](#)</sup>, A. Zhemchugov<sup>38, [id](#)</sup>, J. Zheng<sup>14c, [id](#)</sup>, K. Zheng<sup>162, [id](#)</sup>, X. Zheng<sup>62a, [id](#)</sup>, Z. Zheng<sup>143, [id](#)</sup>, D. Zhong<sup>162, [id](#)</sup>, B. Zhou<sup>106, [id](#)</sup>, H. Zhou<sup>7, [id](#)</sup>, N. Zhou<sup>62c, [id](#)</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>62b, [id](#)</sup>, J. Zhu<sup>106, [id](#)</sup>, Y. Zhu<sup>62c, [id](#)</sup>, Y. Zhu<sup>62a, [id](#)</sup>, X. Zhuang<sup>14a, [id](#)</sup>, K. Zhukov<sup>37, [id](#)</sup>, V. Zhulanov<sup>37, [id](#)</sup>, N.I. Zimine<sup>38, [id](#)</sup>, J. Zinsser<sup>63b, [id](#)</sup>, M. Ziolkowski<sup>141, [id](#)</sup>, L. Živković<sup>15, [id](#)</sup>, A. Zoccoli<sup>23b,23a, [id](#)</sup>, K. Zoch<sup>61, [id](#)</sup>, T.G. Zorbas<sup>139, [id](#)</sup>, O. Zormpa<sup>46, [id](#)</sup>, W. Zou<sup>41, [id](#)</sup>, L. Zwalinski<sup>36, [id](#)</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide; Australia<sup>2</sup> Department of Physics, University of Alberta, Edmonton AB; Canada<sup>3</sup> (a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye<sup>4</sup> LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France

- <sup>5</sup> APC, Université Paris Cité, CNRS/IN2P3, Paris; France
- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America
- <sup>7</sup> Department of Physics, University of Arizona, Tucson AZ; United States of America
- <sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington TX; United States of America
- <sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens; Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou; Greece
- <sup>11</sup> Department of Physics, University of Texas at Austin, Austin TX; United States of America
- <sup>12</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
- <sup>13</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain
- <sup>14</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Physics Department, Tsinghua University, Beijing; <sup>(c)</sup> Department of Physics, Nanjing University, Nanjing; <sup>(d)</sup> School of Science, Shenzhen Campus of Sun Yat-sen University; <sup>(e)</sup> University of Chinese Academy of Science (UCAS), Beijing; China
- <sup>15</sup> Institute of Physics, University of Belgrade, Belgrade; Serbia
- <sup>16</sup> Department for Physics and Technology, University of Bergen, Bergen; Norway
- <sup>17</sup> <sup>(a)</sup> Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; <sup>(b)</sup> University of California, Berkeley CA; United States of America
- <sup>18</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
- <sup>19</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
- <sup>20</sup> School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
- <sup>21</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(c)</sup> Department of Physics, Istanbul University, Istanbul; Türkiye
- <sup>22</sup> <sup>(a)</sup> Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; <sup>(b)</sup> Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
- <sup>23</sup> <sup>(a)</sup> Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; <sup>(b)</sup> INFN Sezione di Bologna; Italy
- <sup>24</sup> Physikalisches Institut, Universität Bonn, Bonn; Germany
- <sup>25</sup> Department of Physics, Boston University, Boston MA; United States of America
- <sup>26</sup> Department of Physics, Brandeis University, Waltham MA; United States of America
- <sup>27</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov; <sup>(b)</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; <sup>(d)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; <sup>(e)</sup> National University of Science and Technology Politehnica, Bucharest; <sup>(f)</sup> West University in Timisoara, Timisoara; <sup>(g)</sup> Faculty of Physics, University of Bucharest, Bucharest; Romania
- <sup>28</sup> <sup>(a)</sup> Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
- <sup>29</sup> Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
- <sup>30</sup> Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
- <sup>31</sup> California State University, CA; United States of America
- <sup>32</sup> Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- <sup>33</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> iThemba Labs, Western Cape; <sup>(c)</sup> Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;
- <sup>34</sup> National Institute of Physics, University of the Philippines Diliman (Philippines); <sup>(d)</sup> University of South Africa, Department of Physics, Pretoria; <sup>(e)</sup> University of Zululand, KwaDlangezwa;
- <sup>35</sup> School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- <sup>36</sup> Department of Physics, Carleton University, Ottawa ON; Canada
- <sup>37</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; <sup>(b)</sup> Faculté des Sciences, Université Ibn-Tofail, Kénitra; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; <sup>(d)</sup> LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V, Rabat;
- <sup>38</sup> Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
- <sup>39</sup> CERN, Geneva; Switzerland
- <sup>40</sup> Affiliated with an institute covered by a cooperation agreement with CERN
- <sup>41</sup> Affiliated with an international laboratory covered by a cooperation agreement with CERN
- <sup>42</sup> Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- <sup>43</sup> LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- <sup>44</sup> Nevis Laboratory, Columbia University, Irvington NY; United States of America
- <sup>45</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- <sup>46</sup> <sup>(a)</sup> Dipartimento di Fisica, Università della Calabria, Rende; <sup>(b)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- <sup>47</sup> Physics Department, Southern Methodist University, Dallas TX; United States of America
- <sup>48</sup> Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- <sup>49</sup> National Centre for Scientific Research “Demokritos”, Agia Paraskevi; Greece
- <sup>50</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> Oskar Klein Centre, Stockholm; Sweden
- <sup>51</sup> Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- <sup>52</sup> Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- <sup>53</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- <sup>54</sup> Department of Physics, Duke University, Durham NC; United States of America
- <sup>55</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
- <sup>56</sup> INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- <sup>57</sup> Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- <sup>58</sup> II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- <sup>59</sup> Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- <sup>60</sup> <sup>(a)</sup> Dipartimento di Fisica, Università di Genova, Genova; <sup>(b)</sup> INFN Sezione di Genova; Italy
- <sup>61</sup> II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- <sup>62</sup> SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- <sup>63</sup> LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- <sup>64</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- <sup>65</sup> <sup>(a)</sup> Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; <sup>(b)</sup> Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; <sup>(c)</sup> School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; <sup>(d)</sup> Tsung-Dao Lee Institute, Shanghai; <sup>(e)</sup> School of Physics and Microelectronics, Zhengzhou University; China
- <sup>66</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- <sup>67</sup> <sup>(a)</sup> Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
- <sup>68</sup> Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- <sup>69</sup> IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- <sup>70</sup> Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
- <sup>71</sup> Department of Physics, Indiana University, Bloomington IN; United States of America
- <sup>72</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- <sup>73</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- <sup>74</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano; Italy
- <sup>75</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli; Italy

- 73 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- 74 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- 75 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
- 76 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- 77 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- 78 <sup>(a)</sup> INFN-TIFPA; <sup>(b)</sup> Università degli Studi di Trento, Trento; Italy
- 79 Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
- 80 University of Iowa, Iowa City IA; United States of America
- 81 Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- 82 İstinye University, Sariyer, Istanbul; Türkiye
- 83 <sup>(a)</sup> Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; <sup>(b)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(c)</sup> Instituto de Física, Universidade de São Paulo, São Paulo; <sup>(d)</sup> Rio de Janeiro State University, Rio de Janeiro; Brazil
- 84 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- 85 Graduate School of Science, Kobe University, Kobe; Japan
- 86 <sup>(a)</sup> AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
- 87 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- 88 Faculty of Science, Kyoto University, Kyoto; Japan
- 89 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
- 90 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
- 91 Physics Department, Lancaster University, Lancaster; United Kingdom
- 92 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
- 93 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
- 94 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
- 95 Department of Physics, Royal Holloway University of London, Egham; United Kingdom
- 96 Department of Physics and Astronomy, University College London, London; United Kingdom
- 97 Louisiana Tech University, Ruston LA; United States of America
- 98 Fysiska institutionen, Lunds universitet, Lund; Sweden
- 99 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
- 100 Institut für Physik, Universität Mainz, Mainz; Germany
- 101 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
- 102 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
- 103 Department of Physics, University of Massachusetts, Amherst MA; United States of America
- 104 Department of Physics, McGill University, Montreal QC; Canada
- 105 School of Physics, University of Melbourne, Victoria; Australia
- 106 Department of Physics, University of Michigan, Ann Arbor MI; United States of America
- 107 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
- 108 Group of Particle Physics, University of Montreal, Montreal QC; Canada
- 109 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
- 110 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
- 111 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
- 112 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
- 113 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
- 114 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
- 115 Department of Physics, Northern Illinois University, DeKalb IL; United States of America
- 116 <sup>(a)</sup> New York University Abu Dhabi, Abu Dhabi; <sup>(b)</sup> University of Sharjah, Sharjah; United Arab Emirates
- 117 Department of Physics, New York University, New York NY; United States of America
- 118 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
- 119 Ohio State University, Columbus OH; United States of America
- 120 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
- 121 Department of Physics, Oklahoma State University, Stillwater OK; United States of America
- 122 Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
- 123 Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
- 124 Graduate School of Science, Osaka University, Osaka; Japan
- 125 Department of Physics, University of Oslo, Oslo; Norway
- 126 Department of Physics, Oxford University, Oxford; United Kingdom
- 127 LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
- 128 Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
- 129 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
- 130 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- 131 Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- 132 Czech Technical University in Prague, Prague; Czech Republic
- 133 Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- 134 Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- 135 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- 136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- 137 <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; <sup>(c)</sup> Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; <sup>(d)</sup> Universidad Andres Bello, Department of Physics, Santiago; <sup>(e)</sup> Instituto de Alta Investigación, Universidad de Tarapacá, Arica; <sup>(f)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- 138 Department of Physics, University of Washington, Seattle WA; United States of America
- 139 Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- 140 Department of Physics, Shinshu University, Nagano; Japan
- 141 Department Physik, Universität Siegen, Siegen; Germany
- 142 Department of Physics, Simon Fraser University, Burnaby BC; Canada
- 143 SLAC National Accelerator Laboratory, Stanford CA; United States of America
- 144 Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- 145 Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- 146 Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- 147 School of Physics, University of Sydney, Sydney; Australia



<sup>148</sup> *Institute of Physics, Academia Sinica, Taipei; Taiwan*

<sup>149</sup> <sup>(a)</sup> *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* <sup>(b)</sup> *High Energy Physics Institute, Tbilisi State University, Tbilisi;* <sup>(c)</sup> *University of Georgia, Tbilisi;*  
*Georgia*

<sup>150</sup> *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*

<sup>151</sup> *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*

<sup>152</sup> *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*

<sup>153</sup> *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*

<sup>154</sup> *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*

<sup>155</sup> *Department of Physics, University of Toronto, Toronto ON; Canada*

<sup>156</sup> <sup>(a)</sup> *TRIUMF, Vancouver BC;* <sup>(b)</sup> *Department of Physics and Astronomy, York University, Toronto ON; Canada*

<sup>157</sup> *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*

<sup>158</sup> *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*

<sup>159</sup> *United Arab Emirates University, Al Ain; United Arab Emirates*

<sup>160</sup> *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*

<sup>161</sup> *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*

<sup>162</sup> *Department of Physics, University of Illinois, Urbana IL; United States of America*

<sup>163</sup> *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain*

<sup>164</sup> *Department of Physics, University of British Columbia, Vancouver BC; Canada*

<sup>165</sup> *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*

<sup>166</sup> *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*

<sup>167</sup> *Department of Physics, University of Warwick, Coventry; United Kingdom*

<sup>168</sup> *Waseda University, Tokyo; Japan*

<sup>169</sup> *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel*

<sup>170</sup> *Department of Physics, University of Wisconsin, Madison WI; United States of America*

<sup>171</sup> *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*

<sup>172</sup> *Department of Physics, Yale University, New Haven CT; United States of America*

<sup>a</sup> Also Affiliated with an institute covered by a cooperation agreement with CERN.

<sup>b</sup> Also at An-Najah National University, Nablus; Palestine.

<sup>c</sup> Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

<sup>d</sup> Also at Center for High Energy Physics, Peking University; China.

<sup>e</sup> Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.

<sup>f</sup> Also at Centro Studi e Ricerche Enrico Fermi; Italy.

<sup>g</sup> Also at CERN, Geneva; Switzerland.

<sup>h</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

<sup>i</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

<sup>j</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

<sup>k</sup> Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.

<sup>l</sup> Also at Department of Physics, California State University, Sacramento; United States of America.

<sup>m</sup> Also at Department of Physics, King's College London, London; United Kingdom.

<sup>n</sup> Also at Department of Physics, Stanford University, Stanford CA; United States of America.

<sup>o</sup> Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

<sup>p</sup> Also at Department of Physics, University of Thessaly; Greece.

<sup>q</sup> Also at Department of Physics, Westmont College, Santa Barbara; United States of America.

<sup>r</sup> Also at Hellenic Open University, Patras; Greece.

<sup>s</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

<sup>t</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.

<sup>u</sup> Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.

<sup>v</sup> Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

<sup>w</sup> Also at Institute of Particle Physics (IPP); Canada.

<sup>x</sup> Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.

<sup>y</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

<sup>z</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

<sup>aa</sup> Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.

<sup>ab</sup> Also at Lawrence Livermore National Laboratory, Livermore; United States of America.

<sup>ac</sup> Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.

<sup>ad</sup> Also at Technical University of Munich, Munich; Germany.

<sup>ae</sup> Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.

<sup>af</sup> Also at TRIUMF, Vancouver BC; Canada.

<sup>ag</sup> Also at Università di Napoli Parthenope, Napoli; Italy.

<sup>ah</sup> Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.

<sup>ai</sup> Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.

<sup>aj</sup> Also at Washington College, Chestertown, MD; United States of America.

<sup>ak</sup> Also at Yeditepe University, Physics Department, Istanbul; Türkiye.

\* Deceased.