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# Observation of $WWW$ production in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This Letter reports the observation of  $WWW$  production and a measurement of its cross section using  $139 \text{ fb}^{-1}$  of proton–proton collision data recorded at a center-of-mass energy of 13 TeV by the ATLAS detector at the Large Hadron Collider. Events with two same-sign leptons (electrons or muons) and at least two jets, as well as events with three leptons, are selected. A multivariate technique is then used to discriminate between signal and background events. Events from  $WWW$  production are observed with a significance of 8.0 standard deviations, where the expectation is 5.4 standard deviations. The inclusive  $WWW$  production cross section is measured to be  $820 \pm 100$  (stat.)  $\pm 80$  (syst.) fb, approximately 2.6 standard deviations from the predicted cross section of  $511 \pm 18$  fb calculated at next-to-leading-order QCD and leading-order electroweak accuracy.

Measurements of triboson production at colliders directly probe the strength of gauge boson self-interactions within the Standard Model (SM) via triple gauge couplings and quartic gauge couplings [1, 2]. Any deviations from the SM predictions would provide hints of new physics at a higher energy scale than is presently accessible [3–8]. Triboson final states are among the least-understood SM processes due to their small production cross sections. In particular, searches for the production of three  $W$  bosons ( $WWW$ ) have been performed by both the ATLAS [9, 10] and CMS [11, 12] collaborations. Using proton–proton ( $pp$ ) collisions at a center-of-mass energy ( $\sqrt{s}$ ) of 13 TeV delivered by the Large Hadron Collider (LHC) [13], the ATLAS Collaboration analyzed  $80 \text{ fb}^{-1}$  of data and provided evidence for both  $WWW$  and  $WWZ/WZZ$  production [10], and the CMS Collaboration analyzed  $137 \text{ fb}^{-1}$  of data and observed the combined production of three massive vector bosons ( $WWW$ ,  $WWZ$ ,  $WZZ$  and  $ZZZ$ ) [12].

This Letter reports the observation of  $WWW$  production and a measurement of its cross section using  $139 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  [14] taken with the ATLAS detector. At leading order (LO) in QCD,  $WWW$  production can proceed via the radiation of each  $W$  boson from a fermion, via a  $W$  boson produced in association with an intermediate  $Z/\gamma^*$  or Higgs boson that decays via the  $WW^*$  intermediate state, or via a quartic gauge coupling vertex. The analysis selection is sensitive to processes with both on-shell and off-shell  $W$  bosons decays. For simplicity all these process (including  $WH \rightarrow W WW^*$ ) are generically referred to as  $WWW$  throughout this paper. Two decay channels,  $WWW \rightarrow \ell^\pm \nu \ell^\pm \nu q \bar{q}$  and  $WWW \rightarrow \ell^\pm \nu \ell^\pm \nu \ell^\mp \bar{\nu}$  with  $\ell = e$  or  $\mu$ , are considered and are hereafter referred to as  $2\ell$  and  $3\ell$ , respectively. Events with electrons and muons produced through  $\tau$ -leptons are also included. The experimental signature of the  $2\ell$  channel consists of two same-sign charged leptons, missing transverse momentum, and two jets, while the signature of the  $3\ell$  channel consists of three charged leptons and missing transverse momentum.

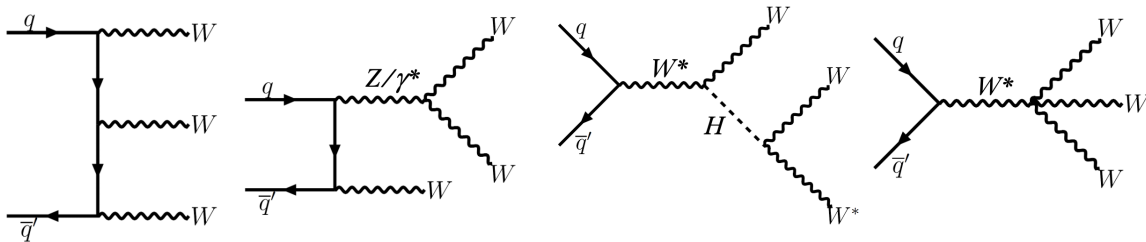


Figure 1: Representative Feynman diagrams at LO for the production of three massive  $W$  bosons, including diagrams sensitive to triple and quartic gauge couplings.

The ATLAS detector [15] is a multipurpose particle physics detector with cylindrical geometry.<sup>1</sup> It consists of an inner tracker (ID) surrounded by a superconducting solenoid, sampling electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) with three toroidal superconducting magnets. A two-level trigger system is used to select events for storage. Events used in this analysis were selected online by single-electron or single-muon triggers [16–18]. An extensive software suite [19] 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.

The proton interaction vertex with the highest  $p_{\text{T}}^2$  sum of associated ID tracks is selected as the primary

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the center of the LHC ring, and the  $y$ -axis points upwards. 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  $\eta = -\ln \tan(\theta/2)$ . Transverse momentum ( $p_{\text{T}}$ ) is defined relative to the beam axis and is calculated as  $p_{\text{T}} = p \sin \theta$  where  $p$  is the momentum.

vertex. Electrons are reconstructed from energy deposits in the EM calorimeter associated with tracks found in the ID. Muons are reconstructed by combining tracks reconstructed in the ID with tracks or track segments found in the MS. Electrons (muons) must have  $p_T > 20$  GeV and be reconstructed within  $|\eta| < 2.47$  ( $|\eta| < 2.5$ ), excluding electrons within  $1.37 < |\eta| < 1.52$ . To ensure that selected leptons originate from the primary vertex, their tracks are required to have  $|d_0/\sigma_{d_0}| < 5$  (3) for electrons (muons) and  $|z_0 \sin \theta| < 0.5$  mm for both lepton flavors, where  $d_0$  and  $\sigma_{d_0}$  are the transverse impact parameter and its uncertainty, and  $z_0$  is the longitudinal impact parameter. Electrons are required to satisfy the ‘‘Tight’’ likelihood-based identification criterion defined in Ref. [20], and muons must satisfy the ‘‘Medium’’ cut-based identification criterion defined in Ref. [21]. To reject leptons that likely originate from light-hadron decays or heavy-flavor decays, leptons are required to pass a tight isolation requirement (‘‘PLVTight’’) [22], which takes into account the energy deposits and charged-particle tracks (including the lepton track) in a cone around the lepton direction. Electrons must also satisfy a charge identification criterion based on a boosted decision tree (BDT) discriminant [23] to reduce the contamination from electrons with misidentified electric charge.

Particle-flow jets are reconstructed from tracks in the ID and topological energy clusters in the calorimeter [24]. Jet candidates are required to have  $p_T > 30$  GeV in the forward region ( $2.5 < |\eta| < 4.5$ ) and  $p_T > 20$  GeV in the central region ( $|\eta| < 2.5$ ). To reduce the effect from additional  $pp$  collisions in the same or a nearby bunch crossing (pileup), jets with  $20 \text{ GeV} < p_T < 60 \text{ GeV}$  and  $|\eta| < 2.5$  are required to pass a ‘‘jet vertex tagger’’ requirement [25]. Jets containing  $b$ -flavored hadrons (‘‘ $b$ -jets’’) are identified by a multivariate discriminant [26, 27] combining track impact parameter values with information from secondary vertices reconstructed within the jet. A working point corresponding to an 85% efficiency for identifying  $b$ -jets in  $t\bar{t}$  events is used. Procedures described in Ref. [10] that ensure the selected electron, muon, and jet candidates do not overlap are applied before the lepton ‘‘PLVTight’’ and  $|d_0/\sigma_{d_0}|$  requirements.

The missing transverse momentum, whose magnitude is denoted by  $E_T^{\text{miss}}$ , is calculated as the negative of the vector sum of the transverse momenta of all reconstructed objects associated with the primary vertex. To account for soft hadronic activity, a term including tracks associated with the primary vertex but not with any of the reconstructed objects is included in the calculation of  $E_T^{\text{miss}}$  [28].

To select candidates in the  $2\ell$  signal regions (SRs), events are required to have exactly two leptons with the same electric charge, at least two central jets, and no identified  $b$ -jets. Three final states based on the lepton flavors are considered, namely  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$ , and  $\mu^\pm \mu^\pm$ . The highest- $p_T$  lepton must have  $p_T > 27$  GeV and the dilepton invariant mass  $m_{\ell\ell}$  is required to be between 40 GeV and 400 GeV. The two highest- $p_T$  central jets are required to have  $m_{jj} < 160$  GeV and  $|\Delta\eta_{jj}| < 1.5$ , where  $m_{jj}$  is the dijet invariant mass and  $\Delta\eta_{jj}$  is the pseudorapidity separation between the two jets. The  $m_{jj}$  and  $\Delta\eta_{jj}$  selection suppresses contributions from the  $W^\pm W^\pm$  vector-boson scattering process. In the case of the  $e^\pm e^\pm$  final state, the dilepton system is required to have  $m_{\ell\ell} < 80$  GeV or  $m_{\ell\ell} > 100$  GeV. In addition, an  $E_T^{\text{miss}}$  significance [29] requirement,  $\mathcal{S}(E_T^{\text{miss}}) > 3$ , is applied to suppress contributions from the  $Z$ +jets process where the charge of one electron is misidentified. To select candidates in the  $3\ell$  SR, events are required to have exactly three leptons including at least one with  $p_T > 27$  GeV, no identified  $b$ -jets, and no same-flavor opposite-sign (SFOS) lepton pairs. Events with  $e^\pm e^\pm \mu^\mp$  and  $\mu^\pm \mu^\pm e^\mp$  final states are considered. To suppress contributions from  $WZ$ +jets production in the  $2\ell$  SRs and  $ZZ$ +jets production in the  $3\ell$  SR, events are removed if they contain additional electrons (muons) reconstructed with  $p_T > 7$  (4.5) GeV and  $|\eta| < 2.47$  (2.7) passing the loose [20] ([21]) identification requirement.

Monte Carlo (MC) simulated samples are used to model the signal  $WWW$  process, as well as contributions from other physics processes with prompt leptons. Simulated events were processed through the full ATLAS

detector simulation [30] based on GEANT4 [31]. The effects of pileup are included in the simulation.

Events with three on-shell  $W$  bosons were generated by SHERPA 2.2.2 [32, 33] with the NNPDF3.0<sub>NNLO</sub> parton distribution function (PDF) [34]. Events with an off-shell  $W$  boson through  $WH \rightarrow WWW^*$  were generated using POWHEG Box v2 [35] interfaced to PYTHIA 8.235 [36] for parton showering [37] with the NNPDF2.3<sub>LO</sub> PDF and the AZNLO set of tuned parameters [38]. Both processes are included in the signal definition and were generated at next-to-leading-order (NLO) QCD accuracy and LO electroweak accuracy with all spin correlations taken into account in the vector-boson decays. The cross section for the process with on-shell (off-shell  $WH \rightarrow WWW^*$ )  $W$  bosons is  $209 \pm 17$  fb ( $302 \pm 8$  fb). The inclusive cross section is  $\sigma^{\text{pred.}}(pp \rightarrow WWW) = 511 \pm 18$  fb. The cross sections and uncertainties used in this analysis are consistent with the latest calculations with NLO QCD and NLO electroweak corrections applied for the on-shell  $WWW$  process [39] and with next-to-next-to-next-leading-order (NNNLO) QCD and NLO electroweak corrections applied for the  $WH \rightarrow WWW^*$  process [40].

The dominant background originates from the  $WZ(\rightarrow \ell\nu\ell\ell)+\text{jets}$  process, and its contribution is estimated using simulated events generated with SHERPA 2.2.2 using the NNPDF3.0<sub>NNLO</sub> PDF. The matrix element calculations for the  $WZ$  process were performed with up to one additional parton at NLO QCD accuracy and up to three additional partons at LO QCD accuracy. To ensure proper modeling of the  $WZ$  background, the MC predictions for  $WZ + 0$  jets,  $WZ + 1$  jet, and  $WZ + \geq 2$  jets are multiplied by scale factors obtained during the fit to the data to be described later, which includes three  $WZ$  control regions (CR). These CRs are obtained by requiring exactly three leptons with one SFOS lepton pair,  $E_T^{\text{miss}}$  significance  $\mathcal{S}(E_T^{\text{miss}}) > 3$ , no  $b$ -jets identified, and a trilepton invariant mass  $110 \text{ GeV} < m_{\ell\ell\ell} < 500 \text{ GeV}$ .

The contribution from backgrounds with non-prompt leptons from hadron (including  $b$ -flavored and  $c$ -flavored hadrons) decays and jets misidentified as leptons is estimated using a data-driven method described in Ref. [41]. Lepton-like jets are defined by requiring the leptons to meet a looser selection criterion but fail the signal-lepton requirements. Compared to signal leptons, muon-like jets have  $|d_0/\sigma_{d_0}| < 10$ , and electron-like jets have the likelihood-based identification criterion loosened to “Medium” [20]. The “PLVTight” tight isolation criterion is dropped for both lepton flavors. Since the non-prompt-lepton background in the SRs comes mainly from the  $t\bar{t}$  process where one of the  $b$ -jets is misidentified as an isolated lepton, a lepton “fake factor” is determined from  $t\bar{t}$ -enriched samples selected using the same signal region criteria, except requiring one  $b$ -jet and, in the  $3\ell$  case, including events with a SFOS lepton pair with  $m_{\ell\ell} < 80 \text{ GeV}$  or  $m_{\ell\ell} > 100 \text{ GeV}$ . To estimate the non-prompt-lepton background, this fake factor is applied as a weight to events selected with the same set of criteria as the signal region but with a lepton-like jet. The non-prompt-lepton background estimate is validated by checking that the estimate agrees with the data in the  $t\bar{t}$ -enriched samples where the fake factors are measured.

The  $W\gamma/Z\gamma$  background mostly contributes to the event selection when the photon is being misidentified as an electron. This contribution (referred to as “ $\gamma$  conversions”) is evaluated using a data-driven method similar to the non-prompt-lepton background estimation by introducing electron-like photons. An electron-like photon is a reconstructed object that is like an electron except that its associated track has no hits in the innermost layer of the pixel detector. The photon fake factor is determined using  $Z\gamma \rightarrow \mu\mu\gamma$  events selected with two muons, no  $b$ -jets, and one electron or one electron-like photon. The trilepton invariant mass must satisfy  $80 \text{ GeV} < m_{e\mu\mu} < 100 \text{ GeV}$ .

The charge-flip background originates from processes in which the charge of at least one prompt electron is misidentified. The muon charge misidentification rate is found to be negligible. The electron charge misidentification rate is measured using a tag-and-probe method applied to  $Z \rightarrow e^+e^-$  events, where the two electrons have the same reconstructed charge [41]. The charge-flip background is estimated by

applying the measured electron charge misidentification rates to  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$ , and  $e^\pm e^\pm \mu^\mp$  data events that meet all signal region requirements except for the SFOS lepton pair veto requirement. This method is validated with events selected using the same set of signal region criteria as used in the  $e^\pm e^\pm$  final state, except the dilepton mass must satisfy  $80 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}$  and the  $E_T^{\text{miss}}$  significance requirement  $\mathcal{S}(E_T^{\text{miss}}) > 3$  is removed.

Other SM processes with prompt leptons include  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $tZq$ ,  $t\bar{t}H$ ,  $WWZ$ ,  $WZZ$ ,  $ZZZ$ , and  $W^\pm W^\pm jj$  production. Their contributions are estimated using simulated events normalized to the integrated luminosity of the data sample and the cross sections provided by the event generators. The  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $tZq$  processes were modeled using MADGRAPH5\_AMC@NLO 2.3.3 [42] together with PYTHIA 8.210, with up to two additional partons in the matrix-element calculations. The  $t\bar{t}H$  process was modeled using POWHEG Box v2 interfaced with PYTHIA 8.230. Other triboson processes ( $WWZ$ ,  $WZZ$ ,  $ZZZ$ ) and the strong production of  $W^\pm W^\pm jj$  were modeled using SHERPA 2.2.2. The calculations for triboson processes were performed with no extra partons at NLO QCD accuracy and up to two additional partons at LO QCD accuracy. The electroweak production of  $W^\pm W^\pm jj$  was modeled using SHERPA 2.2.11, and the calculations were performed with up to one additional parton at LO QCD accuracy. Contributions from the on-shell  $WWW$  and  $WH \rightarrow WWW^*$  processes were removed from  $W^\pm W^\pm jj$  production. Contributions from double parton scattering processes are found to be negligible.

To improve the separation between signal and background, two BDTs are trained using the XGBoost [43] package and are applied separately to the  $2\ell$  and  $3\ell$  SRs. All backgrounds are included in the BDT training. Each BDT is trained with 11 variables, some of which differ between the two sets. The three variables with the highest discriminating power are:  $|m_{jj} - m_W|$ , where  $m_W$  is the pole mass of the  $W$  boson, forward jet  $p_T$ , and  $\mathcal{S}(E_T^{\text{miss}})$  for the  $2\ell$  channel, and the ratio  $\mathcal{S}(E_T^{\text{miss}})/E_T^{\text{miss}}$ ,  $p_T$  of the second highest- $p_T$  lepton, and number of jets for the  $3\ell$  channel. A  $k$ -fold cross-validation procedure is used to produce the final discriminant. Five-fold (four-fold) cross-validation BDTs are trained in the  $2\ell$  SRs ( $3\ell$  SR) and each BDT is trained on 80% (75%) of the expected signal and background events. To produce the BDT distribution used in the fit, each of the five (four) trained BDTs is applied to the 20% (25%) of the events not used to train the BDTs.

To extract the  $WWW$  inclusive cross section, a binned maximum-likelihood fit [44] is performed using the BDT distributions in the  $2\ell$  SRs ( $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$ , and  $\mu^\pm \mu^\pm$ ) and the  $3\ell$  SR as well as the  $m_{\ell\ell\ell}$  distributions in the three  $WZ$  CRs, amounting to seven distributions with 50 bins in total. The fit includes four unconstrained parameters that scale the number of events for a particular process predicted by MC simulation: the signal strength  $\mu(WWW)$  for  $WWW$  production and three scale factors for  $WZ + 0$  jets,  $WZ + 1$  jet and  $WZ + \geq 2$  jets. The ratio of on-shell  $WWW$  production to  $WH \rightarrow WWW^*$  production is determined from MC simulation and is allowed to vary within the theoretical uncertainties of the two processes.

Systematic uncertainties are included in the fit as nuisance parameters constrained by Gaussian probability density functions. Correlations between systematic uncertainties arising from common sources are maintained across processes and channels. Instrumental systematic uncertainties are related to the lepton trigger, reconstruction and identification efficiencies [21, 23], lepton isolation criteria [22], lepton energy scale and resolution [21, 45], jet energy scale and resolution [46], jet vertex tagging [47, 48],  $b$ -jet identification [26], modeling of  $E_T^{\text{miss}}$  [49] and pileup, and integrated luminosity [14, 50]. Theoretical uncertainties associated with the signal processes and the background processes with prompt leptons are evaluated using simulation. For the signal and  $WZ$  background, acceptance and distribution shape uncertainties due to the renormalization and factorization scales [51], PDFs [52], and parton showering, are also included in the simultaneous fit. The normalization uncertainties for the processes included in the

“Other” background category in Table 1 and Figure 2 are between 10% and 20% [53–56]. The fit includes the systematic uncertainties of each of the data-driven background estimates, and also the systematic uncertainties due to limited MC sample size.

The signal strength is measured to be  $\mu(WWW) = 1.61 \pm 0.25$ , where the uncertainty also includes the signal cross-section uncertainty (3.6%) affecting the predicted inclusive cross section from the signal MC samples. The three  $WZ$  scale factors are found to be  $1.12 \pm 0.11$ ,  $0.98 \pm 0.04$  and  $0.88 \pm 0.18$  for the 0-jets, 1-jet, and  $\geq 2$ -jet bins. Table 1 shows the post-fit signal and background event yields as well as the observed yield in each SR. The contribution of the  $WH$  process to the  $WWW$  yield ranges between 40% and 44% in the four SRs. All nuisance parameters remain within their one standard deviation uncertainty after the fit. Figure 2 shows a comparison between data and post-fit predictions for the BDT output score distribution in all SRs. For various post-fit kinematic distributions in the SRs, data and predictions are found to have a  $p$ -value greater than 0.05 from a  $\chi^2$  test that takes into account the systematic uncertainties and correlations used in the fit to data.

Table 1: Number of events for post-fit signal, background and data observed in the  $2\ell$  and  $3\ell$  SRs. The uncertainties shown include both the statistical and systematic contributions.

	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$3\ell$
$WWW$ signal	$28.4 \pm 4.3$	$124 \pm 19$	$82 \pm 12$	$34.8 \pm 5.2$
$WZ$	$81.1 \pm 5.7$	$346 \pm 22$	$170 \pm 10$	$16.4 \pm 1.5$
Charge-flip	$31.1 \pm 7.3$	$19 \pm 5$	-	$1.7 \pm 0.4$
$\gamma$ conversions	$60.8 \pm 8.5$	$139 \pm 15$	-	$1.5 \pm 0.1$
Non-prompt	$17.0 \pm 4.0$	$145 \pm 23$	$104 \pm 21$	$26.6 \pm 2.9$
Other	$22.3 \pm 2.4$	$100 \pm 10$	$58 \pm 6$	$8.0 \pm 0.9$
Total predicted	$241 \pm 11$	$873 \pm 22$	$415 \pm 17$	$89.0 \pm 5.4$
Data	242	885	418	79

The background-only hypothesis is rejected with an observed (expected) significance of 6.6 (4.0) standard deviations for the  $2\ell$  SRs and 4.8 (3.8) standard deviations for the  $3\ell$  SR calculated using the asymptotic approximation [57]. The combined observed (expected) significance is found to be 8.0 (5.4) standard deviations, constituting the first observation of  $WWW$  production. The signal strength is also measured separately by fitting the BDT distribution in each SR with the three  $WZ$  CRs. The values are found to be consistent:  $1.54 \pm 0.76$  for  $e^\pm e^\pm$ ,  $1.44 \pm 0.39$  for  $e^\pm \mu^\pm$ ,  $2.23 \pm 0.46$  for  $\mu^\pm \mu^\pm$ , and  $1.32 \pm 0.39$  for  $3\ell$ .

The measured inclusive  $pp \rightarrow WWW$  production cross section is calculated as the product of the measured signal strength and the cross section from MC simulation, and is found to be  $\sigma^{\text{meas.}}(pp \rightarrow WWW) = 820 \pm 100$  (stat.)  $\pm 80$  (syst.) fb. The largest systematic uncertainty contribution is 6% from data-driven estimates (mainly non-prompt background), followed by 3% from prompt-lepton-background modeling uncertainties (primarily  $WZ$  theory uncertainties).



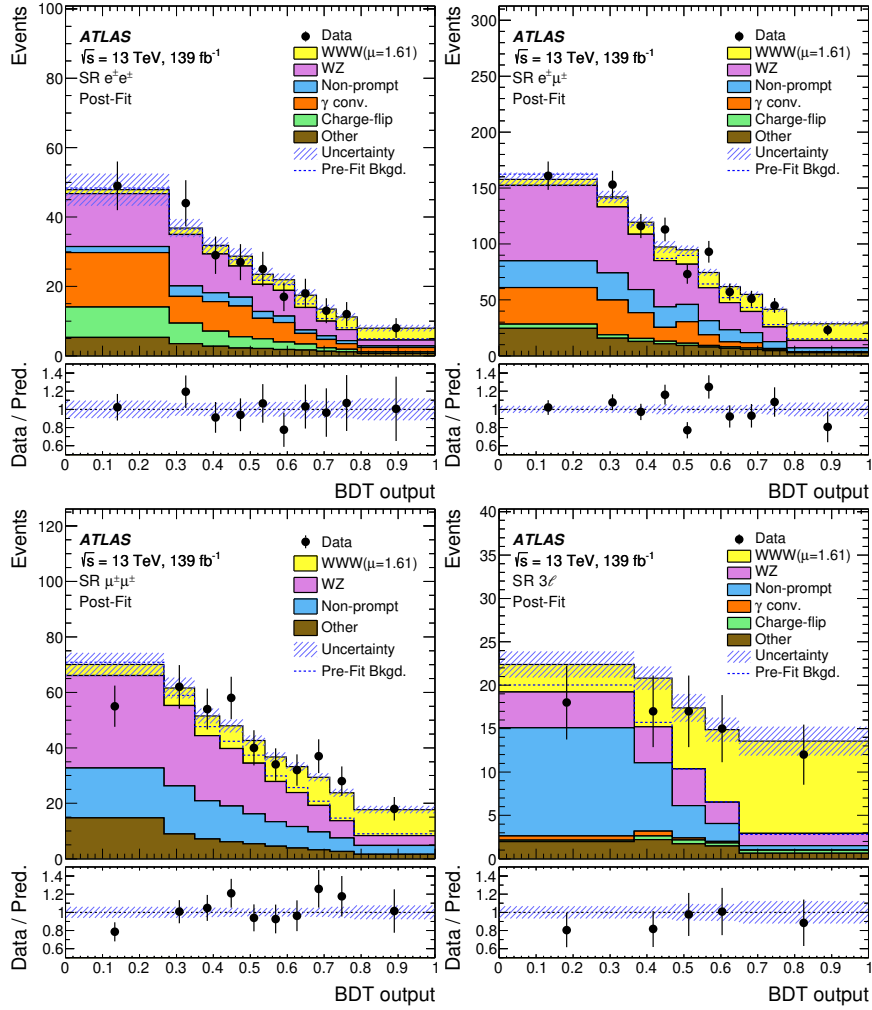


Figure 2: Post-fit BDT output distribution in the  $e^{\pm}e^{\pm}$  (top left),  $e^{\pm}\mu^{\pm}$  (top right),  $\mu^{\pm}\mu^{\pm}$  (bottom left) and  $3\ell$  (bottom right) channels. The bottom panel of each plot shows the ratio of the data to the total prediction. The uncertainty bands include both the statistical and systematic uncertainties as obtained by the fit. The signal is scaled to the fitted signal strength of 1.61.

In conclusion, the first observation of the  $pp \rightarrow WWW$  process is reported by the ATLAS experiment at the LHC. Events with two same-sign charged leptons in association with at least two jets, as well as events with three charged leptons and no same-flavor opposite-sign lepton pairs, were selected from  $139 \text{ fb}^{-1}$  of 13 TeV  $pp$  collisions. Two BDTs were trained to improve the separation between signal and background. The SM background-only hypothesis is rejected with an observed (expected) significance of 8.0 (5.4) standard deviations. The inclusive  $pp \rightarrow WWW$  production cross section is measured to be  $820 \pm 100$  (stat.)  $\pm 80$  (syst.) fb, approximately 2.6 standard deviations from the predicted cross section of  $511 \pm 18$  fb calculated at NLO QCD and LO electroweak accuracy.

## Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRf and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir IDEX and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [58].

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## The ATLAS Collaboration

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Amor Dos Santos<sup>137a</sup>, S. Amoroso<sup>46</sup>, K.R. Amos<sup>170</sup>, C.S. Amrouche<sup>54</sup>, V. Ananiev<sup>131</sup>, C. Anastopoulos<sup>146</sup>, N. Andari<sup>142</sup>, T. Andeen<sup>11</sup>, J.K. Anders<sup>19</sup>, S.Y. Andrean<sup>45a,45b</sup>, A. Andreazza<sup>68a,68b</sup>, S. Angelidakis<sup>9</sup>, A. Angerami<sup>39</sup>, A.V. Anisenkov<sup>119b,119a</sup>, A. Annovi<sup>71a</sup>, C. Antel<sup>54</sup>, M.T. Anthony<sup>146</sup>, E. Antipov<sup>127</sup>, M. Antonelli<sup>51</sup>, D.J.A. Antrim<sup>17</sup>, F. Anulli<sup>72a</sup>, M. Aoki<sup>81</sup>, J.A. Aparisi Pozo<sup>170</sup>, M.A. Aparo<sup>153</sup>, L. Aperio Bella<sup>46</sup>, N. Aranzabal<sup>36</sup>, V. Araujo Ferraz<sup>80a</sup>, C. Arcangeletti<sup>51</sup>, A.T.H. Arce<sup>49</sup>, E. Arena<sup>90</sup>, J-F. Arguin<sup>108</sup>, S. Argyropoulos<sup>52</sup>, J.-H. Arling<sup>46</sup>, A.J. Armbruster<sup>36</sup>, O. Arnaez<sup>163</sup>, H. Arnold<sup>117</sup>, Z.P. Arrubarrena Tame<sup>112</sup>, G. Artoni<sup>72a,72b</sup>, H. Asada<sup>114</sup>, K. Asai<sup>124</sup>, S. Asai<sup>160</sup>, N.A. Asbah<sup>59</sup>, E.M. Asimakopoulou<sup>168</sup>, J. Assahsah<sup>35d</sup>, K. Assamagan<sup>29</sup>, R. Astalos<sup>28a</sup>, R.J. Atkin<sup>33a</sup>, M. Atkinson<sup>169</sup>, N.B. Atlay<sup>18</sup>, H. Atmani<sup>60b</sup>, P.A. Atlasiddha<sup>104</sup>, K. Augsten<sup>139</sup>, S. Auricchio<sup>69a,69b</sup>, V.A. Austrup<sup>178</sup>, G. Avner<sup>157</sup>, G. Avolio<sup>36</sup>, M.K. Ayoub<sup>14c</sup>, G. Azuelos<sup>108,af</sup>, D. Babal<sup>28a</sup>, H. Bachacou<sup>142</sup>, K. Bachas<sup>159</sup>, A. Bachi<sup>34</sup>, F. Backman<sup>45a,45b</sup>, A. Badae<sup>59</sup>, P. Bagnaia<sup>72a,72b</sup>, M. Bahmani<sup>18</sup>, A.J. Bailey<sup>170</sup>, V.R. Bailey<sup>169</sup>, J.T. Baines<sup>141</sup>, C. Bakalis<sup>10</sup>, O.K. Baker<sup>179</sup>, P.J. Bakker<sup>117</sup>, E. Bakos<sup>15</sup>, D. 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Bartoldus<sup>150</sup>, G. Bartolini<sup>100</sup>, A.E. Barton<sup>89</sup>, P. Bartos<sup>28a</sup>, A. Basalae<sup>46</sup>, A. Basan<sup>98</sup>, M. Baselga<sup>46</sup>, I. Bashta<sup>74a,74b</sup>, A. Bassalat<sup>64,ac</sup>, M.J. Basso<sup>163</sup>, C.R. Basson<sup>99</sup>, R.L. Bates<sup>57</sup>, S. Batlamous<sup>35e</sup>, J.R. Batley<sup>32</sup>, B. Batool<sup>148</sup>, M. Battaglia<sup>143</sup>, M. Baucé<sup>72a,72b</sup>, F. Bauer<sup>142,\*</sup>, P. Bauer<sup>24</sup>, A. Bayirli<sup>21a</sup>, J.B. Beacham<sup>49</sup>, T. Beau<sup>133</sup>, P.H. Beauchemin<sup>166</sup>, F. Becherer<sup>52</sup>, P. Bechtel<sup>24</sup>, H.P. Beck<sup>19,p</sup>, K. Becker<sup>174</sup>, C. Becot<sup>46</sup>, A.J. Beddall<sup>21d</sup>, V.A. Bednyakov<sup>79</sup>, C.P. Bee<sup>152</sup>, L.J. Beemster<sup>15</sup>, T.A. Beermann<sup>36</sup>, M. Begalli<sup>80b</sup>, M. Begel<sup>29</sup>, A. Behera<sup>152</sup>, J.K. Behr<sup>46</sup>, C. 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Bhatta<sup>152</sup>, D.S. Bhattacharya<sup>173</sup>, P. Bhattarai<sup>26</sup>, V.S. Bhopatkar<sup>6</sup>, R. Bi<sup>136</sup>, R. Bi<sup>29</sup>, R.M. Bianchi<sup>136</sup>, O. Biebel<sup>112</sup>, R. Bielski<sup>129</sup>, N.V. Biesuz<sup>71a,71b</sup>, M. Biglietti<sup>74a</sup>, T.R.V. Billoud<sup>139</sup>,

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G.A. Bird<sup>20,141</sup>, M. Birman<sup>176</sup>, T. Bisanz<sup>36</sup>, J.P. Biswal<sup>2</sup>, D. Biswas<sup>177,j</sup>, A. Bitadze<sup>99</sup>, K. Bjørke<sup>131</sup>,  
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E.V. Bouhova-Thacker<sup>89</sup>, D. Boumediene<sup>38</sup>, R. Bouquet<sup>133</sup>, A. Boveia<sup>125</sup>, J. Boyd<sup>36</sup>, D. Boye<sup>29</sup>,  
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S. Burdin<sup>90</sup>, C.D. Burgard<sup>46</sup>, A.M. Burger<sup>127</sup>, B. Burghgrave<sup>8</sup>, J.T.P. Burr<sup>32</sup>, C.D. Burton<sup>11</sup>,  
J.C. Burzynski<sup>149</sup>, E.L. Busch<sup>39</sup>, V. Büscher<sup>98</sup>, P.J. Bussey<sup>57</sup>, J.M. Butler<sup>25</sup>, C.M. Buttar<sup>57</sup>,  
J.M. Butterworth<sup>94</sup>, W. Buttinger<sup>141</sup>, C.J. Buxo Vazquez<sup>105</sup>, A.R. Buzykaev<sup>119b,119a</sup>, G. Cabras<sup>23b</sup>,  
S. Cabrera Urbán<sup>170</sup>, D. Caforio<sup>56</sup>, H. Cai<sup>136</sup>, V.M.M. Cairo<sup>150</sup>, O. Cakir<sup>3a</sup>, N. Calace<sup>36</sup>, P. Calafiura<sup>17</sup>,  
G. Calderini<sup>133</sup>, P. Calfayan<sup>65</sup>, G. Callea<sup>57</sup>, L.P. Caloba<sup>80b</sup>, D. Calvet<sup>38</sup>, S. Calvet<sup>38</sup>, T.P. Calvet<sup>100</sup>,  
M. Calvetti<sup>71a,71b</sup>, R. Camacho Toro<sup>133</sup>, S. Camarda<sup>36</sup>, D. Camarero Munoz<sup>97</sup>, P. Camarri<sup>73a,73b</sup>,  
M.T. Camerlingo<sup>74a,74b</sup>, D. Cameron<sup>131</sup>, C. Camincher<sup>172</sup>, M. Campanelli<sup>94</sup>, A. Camplani<sup>40</sup>,  
V. Canale<sup>69a,69b</sup>, A. Canesse<sup>102</sup>, M. Cano Bret<sup>77</sup>, J. Cantero<sup>97</sup>, Y. Cao<sup>169</sup>, F. Capocasa<sup>26</sup>, M. Capua<sup>41b,41a</sup>,  
A. Carbone<sup>68a,68b</sup>, R. Cardarelli<sup>73a</sup>, J.C.J. Cardenas<sup>8</sup>, F. Cardillo<sup>170</sup>, G. Carducci<sup>41b,41a</sup>, T. Carli<sup>36</sup>,  
G. Carlino<sup>69a</sup>, B.T. Carlson<sup>136</sup>, E.M. Carlson<sup>172,164a</sup>, L. Carminati<sup>68a,68b</sup>, M. Carnesale<sup>72a,72b</sup>, S. Caron<sup>116</sup>,  
E. Carquin<sup>144f</sup>, S. Carrá<sup>46</sup>, G. Carratta<sup>23b,23a</sup>, J.W.S. Carter<sup>163</sup>, T.M. Carter<sup>50</sup>, D. Casadei<sup>33c</sup>,  
M.P. Casado<sup>13,g</sup>, A.F. Casha<sup>163</sup>, E.G. Castiglia<sup>179</sup>, F.L. Castillo<sup>61a</sup>, L. Castillo Garcia<sup>13</sup>,  
V. Castillo Gimenez<sup>170</sup>, N.F. Castro<sup>137a,137e</sup>, A. Catinaccio<sup>36</sup>, J.R. Catmore<sup>131</sup>, V. Cavaliere<sup>29</sup>,  
N. Cavalli<sup>23b,23a</sup>, V. Cavasinni<sup>71a,71b</sup>, E. Celebi<sup>21a</sup>, F. Celli<sup>132</sup>, M.S. Centonze<sup>67a,67b</sup>, K. Cerny<sup>128</sup>,  
A.S. Cerqueira<sup>80a</sup>, A. Cerri<sup>153</sup>, L. Cerrito<sup>73a,73b</sup>, F. Cerutti<sup>17</sup>, A. Cervelli<sup>23b</sup>, S.A. Cetin<sup>21d</sup>, Z. Chadi<sup>35a</sup>,  
D. Chakraborty<sup>118</sup>, M. Chala<sup>137f</sup>, J. Chan<sup>177</sup>, W.S. Chan<sup>117</sup>, W.Y. Chan<sup>90</sup>, J.D. Chapman<sup>32</sup>,  
B. Chargeishvili<sup>156b</sup>, D.G. Charlton<sup>20</sup>, T.P. Charman<sup>92</sup>, M. Chatterjee<sup>19</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>164a</sup>,  
G.A. Chelkov<sup>79,aa</sup>, A. Chen<sup>104</sup>, B. Chen<sup>158</sup>, B. Chen<sup>172</sup>, C. Chen<sup>60a</sup>, H. Chen<sup>14c</sup>, H. Chen<sup>29</sup>, J. Chen<sup>60c</sup>,  
J. Chen<sup>26</sup>, S. Chen<sup>134</sup>, S.J. Chen<sup>14c</sup>, X. Chen<sup>60c</sup>, X. Chen<sup>14b</sup>, Y. Chen<sup>60a</sup>, C.L. Cheng<sup>177</sup>, H.C. Cheng<sup>62a</sup>,  
A. Cheplakov<sup>79</sup>, E. Cheremushkina<sup>46</sup>, E. Cherepanova<sup>79</sup>, R. Cherkaoui El Moursli<sup>35e</sup>, E. Cheu<sup>7</sup>,  
K. Cheung<sup>63</sup>, L. Chevalier<sup>142</sup>, V. Chiarella<sup>51</sup>, G. Chiarelli<sup>71a</sup>, G. Chiodini<sup>67a</sup>, A.S. Chisholm<sup>20</sup>,  
A. Chitan<sup>27b</sup>, Y.H. Chiu<sup>172</sup>, M.V. Chizhov<sup>79</sup>, K. Choi<sup>11</sup>, A.R. Chomont<sup>72a,72b</sup>, Y. Chou<sup>101</sup>, Y.S. Chow<sup>117</sup>,  
T. Chowdhury<sup>33g</sup>, L.D. Christopher<sup>33g</sup>, M.C. Chu<sup>62a</sup>, X. Chu<sup>14a,14d</sup>, J. Chudoba<sup>138</sup>, J.J. Chwastowski<sup>84</sup>,  
D. Cieri<sup>113</sup>, K.M. Ciesla<sup>84</sup>, V. Cindro<sup>91</sup>, A. Ciocio<sup>17</sup>, F. Ciotto<sup>69a,69b</sup>, Z.H. Citron<sup>176,k</sup>, M. Citterio<sup>68a</sup>,  
D.A. Ciubotaru<sup>27b</sup>, B.M. Ciungu<sup>163</sup>, A. Clark<sup>54</sup>, P.J. Clark<sup>50</sup>, J.M. Clavijo Columbie<sup>46</sup>, S.E. Clawson<sup>99</sup>,  
C. Clement<sup>45a,45b</sup>, L. Clissa<sup>23b,23a</sup>, Y. Coadou<sup>100</sup>, M. Cobal<sup>66a,66c</sup>, A. Coccaro<sup>55b</sup>, R.F. Coelho Barrue<sup>137a</sup>,  
R. Coelho Lopes De Sa<sup>101</sup>, S. Coelli<sup>68a</sup>, H. Cohen<sup>158</sup>, A.E.C. Coimbra<sup>36</sup>, B. Cole<sup>39</sup>, J. Collot<sup>58</sup>,  
P. Conde Muñio<sup>137a,137g</sup>, S.H. Connell<sup>33c</sup>, I.A. Connelly<sup>57</sup>, E.I. Conroy<sup>132</sup>, F. Conventi<sup>69a,ag</sup>,  
H.G. Cooke<sup>20</sup>, A.M. Cooper-Sarkar<sup>132</sup>, F. Cormier<sup>171</sup>, L.D. Corpe<sup>36</sup>, M. Corradi<sup>72a,72b</sup>, E.E. Corrigan<sup>96</sup>,  
F. Corriveau<sup>102,v</sup>, M.J. Costa<sup>170</sup>, F. Costanza<sup>4</sup>, D. Costanzo<sup>146</sup>, B.M. Cote<sup>125</sup>, G. Cowan<sup>93</sup>, J.W. Cowley<sup>32</sup>,  
K. Cranmer<sup>123</sup>, S. Crépe-Renaudin<sup>58</sup>, F. Crescioli<sup>133</sup>, M. Cristinziani<sup>148</sup>, M. Cristoforetti<sup>75a,75b</sup>,  
V. Croft<sup>166</sup>, G. Crosetti<sup>41b,41a</sup>, A. Cueto<sup>36</sup>, T. Cuhadar Donszelmann<sup>167</sup>, H. Cui<sup>14a,14d</sup>, Z. Cui<sup>7</sup>,  
A.R. Cukierman<sup>150</sup>, W.R. Cunningham<sup>57</sup>, F. Curcio<sup>41b,41a</sup>, P. Czodrowski<sup>36</sup>, M.M. Czurylo<sup>61b</sup>,



M.J. Da Cunha Sargedas De Sousa<sup>60a</sup>, J.V. Da Fonseca Pinto<sup>80b</sup>, C. Da Via<sup>99</sup>, W. Dabrowski<sup>83a</sup>, T. Dado<sup>47</sup>,  
S. Dahbi<sup>33g</sup>, T. Dai<sup>104</sup>, C. Dallapiccola<sup>101</sup>, M. Dam<sup>40</sup>, G. D'amen<sup>29</sup>, V. D'Amico<sup>74a,74b</sup>, J. Damp<sup>98</sup>,  
J.R. Dandoy<sup>134</sup>, M.F. Daneri<sup>30</sup>, M. Danninger<sup>149</sup>, V. Dao<sup>36</sup>, G. Darbo<sup>55b</sup>, S. Darmora<sup>6</sup>, A. Dattagupta<sup>129</sup>,  
S. D'Auria<sup>68a,68b</sup>, C. David<sup>164b</sup>, T. Davidek<sup>140</sup>, D.R. Davis<sup>49</sup>, B. Davis-Purcell<sup>34</sup>, I. Dawson<sup>92</sup>, K. De<sup>8</sup>,  
R. De Asmundis<sup>69a</sup>, M. De Beurs<sup>117</sup>, S. De Castro<sup>23b,23a</sup>, N. De Groot<sup>116</sup>, P. de Jong<sup>117</sup>, H. De la Torre<sup>105</sup>,  
A. De Maria<sup>14c</sup>, A. De Salvo<sup>72a</sup>, U. De Sanctis<sup>73a,73b</sup>, M. De Santis<sup>73a,73b</sup>, A. De Santo<sup>153</sup>,  
J.B. De Vivie De Regie<sup>58</sup>, D.V. Dedovich<sup>79</sup>, J. Degens<sup>117</sup>, A.M. Deiana<sup>42</sup>, J. Del Peso<sup>97</sup>, F. Del Rio<sup>61a</sup>,  
F. Deliot<sup>142</sup>, C.M. Delitzsch<sup>47</sup>, M. Della Pietra<sup>69a,69b</sup>, D. Della Volpe<sup>54</sup>, A. Dell'Acqua<sup>36</sup>,  
L. Dell'Asta<sup>68a,68b</sup>, M. Delmastro<sup>4</sup>, P.A. Delsart<sup>58</sup>, S. Demers<sup>179</sup>, M. Demichev<sup>79</sup>, S.P. Denisov<sup>120</sup>,  
L. D'Eramo<sup>118</sup>, D. Derendarz<sup>84</sup>, F. Derue<sup>133</sup>, P. Dervan<sup>90</sup>, K. Desch<sup>24</sup>, K. Dette<sup>163</sup>, C. Deutsch<sup>24</sup>,  
P.O. Deviveiros<sup>36</sup>, F.A. Di Bello<sup>72a,72b</sup>, A. Di Ciaccio<sup>73a,73b</sup>, L. Di Ciaccio<sup>4</sup>, A. Di Domenico<sup>72a,72b</sup>,  
C. Di Donato<sup>69a,69b</sup>, A. Di Girolamo<sup>36</sup>, G. Di Gregorio<sup>71a,71b</sup>, A. Di Luca<sup>75a,75b,b</sup>, B. Di Micco<sup>74a,74b</sup>,  
R. Di Nardo<sup>74a,74b</sup>, C. Diaconu<sup>100</sup>, F.A. Dias<sup>117</sup>, T. Dias Do Vale<sup>149</sup>, M.A. Diaz<sup>144a</sup>, F.G. Diaz Capriles<sup>24</sup>,  
M. Didenko<sup>170</sup>, E.B. Diehl<sup>104</sup>, S. Díez Cornell<sup>46</sup>, C. Diez Pardos<sup>148</sup>, C. Dimitriadi<sup>24,168</sup>, A. Dimitrievska<sup>17</sup>,  
W. Ding<sup>14b</sup>, J. Dingfelder<sup>24</sup>, I-M. Dinu<sup>27b</sup>, S.J. Dittmeier<sup>61b</sup>, F. Dittus<sup>36</sup>, F. Djama<sup>100</sup>, T. Djobava<sup>156b</sup>,  
J.I. Djuvsland<sup>16</sup>, D. Dodsworth<sup>26</sup>, C. Doglioni<sup>99,96</sup>, J. Dolejsi<sup>140</sup>, Z. Dolezal<sup>140</sup>, M. Donadelli<sup>80c</sup>,  
B. Dong<sup>60c</sup>, J. Donini<sup>38</sup>, A. D'onofrio<sup>14c</sup>, M. D'Onofrio<sup>90</sup>, J. Dopke<sup>141</sup>, A. Doria<sup>69a</sup>, M.T. Dova<sup>88</sup>,  
A.T. Doyle<sup>57</sup>, E. Drechsler<sup>149</sup>, E. Dreyer<sup>176</sup>, A.S. Drobac<sup>166</sup>, D. Du<sup>60a</sup>, T.A. du Pree<sup>117</sup>, F. Dubinin<sup>109</sup>,  
M. Dubovsky<sup>28a</sup>, E. Duchovni<sup>176</sup>, G. Duckeck<sup>112</sup>, O.A. Ducu<sup>36,27b</sup>, D. Duda<sup>113</sup>, A. Dudarev<sup>36</sup>,  
M. D'uffizi<sup>99</sup>, L. Duflot<sup>64</sup>, M. Dührssen<sup>36</sup>, C. Dülsen<sup>178</sup>, A.E. Dumitriu<sup>27b</sup>, M. Dunford<sup>61a</sup>, S. Dungs<sup>47</sup>,  
K. Dunne<sup>45a,45b</sup>, A. Duperrin<sup>100</sup>, H. Duran Yildiz<sup>3a</sup>, M. Düren<sup>56</sup>, A. Durglishvili<sup>156b</sup>, B. Dutta<sup>46</sup>,  
B.L. Dwyer<sup>118</sup>, G.I. Dyckes<sup>17</sup>, M. Dyndal<sup>83a</sup>, S. Dysch<sup>99</sup>, B.S. Dziedzic<sup>84</sup>, B. Eckerova<sup>28a</sup>,  
M.G. Eggleston<sup>49</sup>, E. Egidio Purcino De Souza<sup>80b</sup>, L.F. Ehrke<sup>54</sup>, G. Eigen<sup>16</sup>, K. Einsweiler<sup>17</sup>, T. Ekelof<sup>168</sup>,  
Y. El Ghazali<sup>35b</sup>, H. El Jarrari<sup>35e</sup>, A. El Moussaouy<sup>35a</sup>, V. Ellajosyula<sup>168</sup>, M. Ellert<sup>168</sup>, F. Ellinghaus<sup>178</sup>,  
A.A. Elliot<sup>92</sup>, N. Ellis<sup>36</sup>, J. Elmsheuser<sup>29</sup>, M. Elsing<sup>36</sup>, D. Emelianov<sup>141</sup>, A. Emerman<sup>39</sup>, Y. Enari<sup>160</sup>,  
I. Ene<sup>17</sup>, J. Erdmann<sup>47</sup>, A. Ereditato<sup>19</sup>, P.A. Erland<sup>84</sup>, M. Errenst<sup>178</sup>, M. Escalier<sup>64</sup>, C. Escobar<sup>170</sup>,  
E. Etzion<sup>158</sup>, G. Evans<sup>137a</sup>, H. Evans<sup>65</sup>, M.O. Evans<sup>153</sup>, A. Ezhilov<sup>135</sup>, S. Ezzarqtouni<sup>35a</sup>, F. Fabbri<sup>57</sup>,  
L. Fabbri<sup>23b,23a</sup>, G. Facini<sup>174</sup>, V. Fadeyev<sup>143</sup>, R.M. Fakhruddinov<sup>120</sup>, S. Falciano<sup>72a</sup>, P.J. Falke<sup>24</sup>, S. Falke<sup>36</sup>,  
J. Faltova<sup>140</sup>, Y. Fan<sup>14a</sup>, Y. Fang<sup>14a</sup>, G. Fanourakis<sup>44</sup>, M. Fanti<sup>68a,68b</sup>, M. Faraj<sup>60c</sup>, A. Farbin<sup>8</sup>, A. Farilla<sup>74a</sup>,  
E.M. Farina<sup>70a,70b</sup>, T. Farooque<sup>105</sup>, S.M. Farrington<sup>50</sup>, F. Fassi<sup>35e</sup>, D. Fassouliotis<sup>9</sup>,  
M. Fauci Giannelli<sup>73a,73b</sup>, W.J. Fawcett<sup>32</sup>, L. Fayard<sup>64</sup>, O.L. Fedin<sup>135,o</sup>, G. Fedotov<sup>135</sup>, M. Feickert<sup>169</sup>,  
L. Feligioni<sup>100</sup>, A. Fell<sup>146</sup>, D.E. Fellers<sup>129</sup>, C. Feng<sup>60b</sup>, M. Feng<sup>14b</sup>, M.J. Fenton<sup>167</sup>, A.B. Fenyuk<sup>120</sup>,  
S.W. Ferguson<sup>43</sup>, J.A. Fernandez Pretel<sup>52</sup>, J. Ferrando<sup>46</sup>, A. Ferrari<sup>168</sup>, P. Ferrari<sup>117</sup>, R. Ferrari<sup>70a</sup>,  
D. Ferrere<sup>54</sup>, C. Ferretti<sup>104</sup>, F. Fiedler<sup>98</sup>, A. Filipčič<sup>91</sup>, F. Filthaut<sup>116</sup>, M.C.N. Fiolhais<sup>137a,137c,a</sup>,  
L. Fiorini<sup>170</sup>, F. Fischer<sup>148</sup>, W.C. Fisher<sup>105</sup>, T. Fitschen<sup>20,64</sup>, I. Fleck<sup>148</sup>, P. Fleischmann<sup>104</sup>, T. Flick<sup>178</sup>,  
L. Flores<sup>134</sup>, M. Flores<sup>33d</sup>, L.R. Flores Castillo<sup>62a</sup>, F.M. Follega<sup>75a,75b</sup>, N. Fomin<sup>16</sup>, J.H. Foo<sup>163</sup>,  
B.C. Forland<sup>65</sup>, A. Formica<sup>142</sup>, A.C. Forti<sup>99</sup>, E. Fortin<sup>100</sup>, A.W. Fortman<sup>59</sup>, M.G. Foti<sup>17</sup>, L. Fountas<sup>9</sup>,  
D. Fournier<sup>64</sup>, H. Fox<sup>89</sup>, P. Francavilla<sup>71a,71b</sup>, S. Francescato<sup>59</sup>, M. Franchini<sup>23b,23a</sup>, S. Franchino<sup>61a</sup>,  
D. Francis<sup>36</sup>, L. Franco<sup>4</sup>, L. Franconi<sup>19</sup>, M. Franklin<sup>59</sup>, G. Frattari<sup>72a,72b</sup>, A.C. Freegard<sup>92</sup>,  
P.M. Freeman<sup>20</sup>, W.S. Freund<sup>80b</sup>, E.M. Freundlich<sup>47</sup>, D. Froidevaux<sup>36</sup>, J.A. Frost<sup>132</sup>, Y. Fu<sup>60a</sup>,  
M. Fujimoto<sup>124</sup>, E. Fullana Torregrosa<sup>170</sup>, J. Fuster<sup>170</sup>, A. Gabrielli<sup>23b,23a</sup>, A. Gabrielli<sup>36</sup>, P. Gadow<sup>46</sup>,  
G. Gagliardi<sup>55b,55a</sup>, L.G. Gagnon<sup>17</sup>, G.E. Gallardo<sup>132</sup>, E.J. Gallas<sup>132</sup>, B.J. Gallop<sup>141</sup>, R. Gamboa Goni<sup>92</sup>,  
K.K. Gan<sup>125</sup>, S. Ganguly<sup>160</sup>, J. Gao<sup>60a</sup>, Y. Gao<sup>50</sup>, F.M. Garay Walls<sup>144a,144b</sup>, B. Garcia<sup>29</sup>, C. García<sup>170</sup>,  
J.E. García Navarro<sup>170</sup>, J.A. García Pascual<sup>14a</sup>, M. Garcia-Sciveres<sup>17</sup>, R.W. Gardner<sup>37</sup>, D. Garg<sup>77</sup>,  
R.B. Garg<sup>150</sup>, S. Gargiulo<sup>52</sup>, C.A. Garner<sup>163</sup>, V. Garonne<sup>29</sup>, S.J. Gasiorowski<sup>145</sup>, P. Gaspar<sup>80b</sup>,  
G. Gaudio<sup>70a</sup>, P. Gauzzi<sup>72a,72b</sup>, I.L. Gavrilenko<sup>109</sup>, A. Gavriluyuk<sup>121</sup>, C. Gay<sup>171</sup>, G. Gaycken<sup>46</sup>,  
E.N. Gazis<sup>10</sup>, A.A. Geanta<sup>27b</sup>, C.M. Gee<sup>143</sup>, J. Geisen<sup>96</sup>, M. Geisen<sup>98</sup>, C. Gemme<sup>55b</sup>, M.H. Genest<sup>58</sup>,

S. Gentile<sup>72a,72b</sup>, S. George<sup>93</sup>, W.F. George<sup>20</sup>, T. Geralis<sup>44</sup>, L.O. Gerlach<sup>53</sup>, P. Gessinger-Befurt<sup>36</sup>,  
 M. Ghasemi Bostanabad<sup>172</sup>, A. Ghosh<sup>167</sup>, A. Ghosh<sup>7</sup>, B. Giacobbe<sup>23b</sup>, S. Giagu<sup>72a,72b</sup>, N. Giangiacomi<sup>163</sup>,  
 P. Giannetti<sup>71a</sup>, A. Giannini<sup>60a</sup>, S.M. Gibson<sup>93</sup>, M. Gignac<sup>143</sup>, D.T. Gil<sup>83b</sup>, B.J. Gilbert<sup>39</sup>, D. Gillberg<sup>34</sup>,  
 G. Gilles<sup>117</sup>, N.E.K. Gillwald<sup>46</sup>, L. Ginabat<sup>133</sup>, D.M. Gingrich<sup>2,af</sup>, M.P. Giordani<sup>66a,66c</sup>, P.F. Giraud<sup>142</sup>,  
 G. Giugliarelli<sup>66a,66c</sup>, D. Giugni<sup>68a</sup>, F. Giuli<sup>73a,73b</sup>, I. Gkialas<sup>9,h</sup>, P. Gkountoumis<sup>10</sup>, L.K. Gladilin<sup>111</sup>,  
 C. Glasman<sup>97</sup>, G.R. Gledhill<sup>129</sup>, M. Glisic<sup>129</sup>, I. Gnesi<sup>41b,d</sup>, Y. Go<sup>29</sup>, M. Goblirsch-Kolb<sup>26</sup>, D. Godin<sup>108</sup>,  
 S. Goldfarb<sup>103</sup>, T. Golling<sup>54</sup>, D. Golubkov<sup>120</sup>, J.P. Gombas<sup>105</sup>, A. Gomes<sup>137a,137b</sup>, R. Goncalves Gama<sup>53</sup>,  
 R. Gonçalves<sup>137a,137c</sup>, G. Gonella<sup>129</sup>, L. Gonella<sup>20</sup>, A. Gongadze<sup>79</sup>, F. Gonnella<sup>20</sup>, J.L. Gonski<sup>39</sup>,  
 S. González de la Hoz<sup>170</sup>, S. Gonzalez Fernandez<sup>13</sup>, R. Gonzalez Lopez<sup>90</sup>, C. Gonzalez Renteria<sup>17</sup>,  
 R. Gonzalez Suarez<sup>168</sup>, S. Gonzalez-Sevilla<sup>54</sup>, G.R. Gonzalvo Rodriguez<sup>170</sup>, R.Y. González Andana<sup>50</sup>,  
 L. Goossens<sup>36</sup>, N.A. Gorasia<sup>20</sup>, P.A. Gorbounov<sup>121</sup>, H.A. Gordon<sup>29</sup>, B. Gorini<sup>36</sup>, E. Gorini<sup>67a,67b</sup>,  
 A. Gorišek<sup>91</sup>, A.T. Goshaw<sup>49</sup>, M.I. Gostkin<sup>79</sup>, C.A. Gottardo<sup>116</sup>, M. Gouighri<sup>35b</sup>, V. Goumarre<sup>46</sup>,  
 A.G. Goussiou<sup>145</sup>, N. Govender<sup>33c</sup>, C. Goy<sup>4</sup>, I. Grabowska-Bold<sup>83a</sup>, K. Graham<sup>34</sup>, E. Gramstad<sup>131</sup>,  
 S. Grancagnolo<sup>18</sup>, M. Grandi<sup>153</sup>, V. Gratchev<sup>135</sup>, P.M. Gravila<sup>27f</sup>, F.G. Gravill<sup>67a,67b</sup>, H.M. Gray<sup>17</sup>,  
 C. Greife<sup>24</sup>, I.M. Gregor<sup>46</sup>, P. Grenier<sup>150</sup>, K. Grevtsov<sup>46</sup>, C. Grieco<sup>13</sup>, A.A. Grillo<sup>143</sup>, K. Grimm<sup>31,1</sup>,  
 S. Grinstein<sup>13,t</sup>, J.-F. Grivaz<sup>64</sup>, S. Groh<sup>98</sup>, E. Gross<sup>176</sup>, J. Grosse-Knetter<sup>53</sup>, C. Grud<sup>104</sup>, A. Grummer<sup>115</sup>,  
 J.C. Grundy<sup>132</sup>, L. Guan<sup>104</sup>, W. Guan<sup>177</sup>, C. Gubbels<sup>171</sup>, J.G.R. Guerrero Rojas<sup>170</sup>, F. Guescini<sup>113</sup>,  
 D. Guest<sup>18</sup>, R. Gugel<sup>98</sup>, A. Guida<sup>46</sup>, T. Guillemin<sup>4</sup>, S. Guindon<sup>36</sup>, F. Guo<sup>14a</sup>, J. Guo<sup>60c</sup>, L. Guo<sup>64</sup>,  
 Y. Guo<sup>104</sup>, R. Gupta<sup>46</sup>, S. Gurbuz<sup>24</sup>, G. Gustavino<sup>36</sup>, M. Guth<sup>54</sup>, P. Gutierrez<sup>126</sup>,  
 L.F. Gutierrez Zagazeta<sup>134</sup>, C. Gutschow<sup>94</sup>, C. Guyot<sup>142</sup>, C. Gwenlan<sup>132</sup>, C.B. Gwilliam<sup>90</sup>,  
 E.S. Haaland<sup>131</sup>, A. Haas<sup>123</sup>, M. Habedank<sup>46</sup>, C. Haber<sup>17</sup>, H.K. Hadavand<sup>8</sup>, A. Hadeef<sup>98</sup>, S. Hadzic<sup>113</sup>,  
 M. Haleem<sup>173</sup>, J. Haley<sup>127</sup>, J.J. Hall<sup>146</sup>, G.D. Hallewell<sup>100</sup>, L. Halser<sup>19</sup>, K. Hamano<sup>172</sup>, H. Hamdaoui<sup>35e</sup>,  
 M. Hamer<sup>24</sup>, G.N. Hamity<sup>50</sup>, J. Han<sup>60b</sup>, K. Han<sup>60a</sup>, L. Han<sup>14c</sup>, L. Han<sup>60a</sup>, S. Han<sup>17</sup>, Y.F. Han<sup>163</sup>,  
 K. Hanagaki<sup>81,r</sup>, M. Hance<sup>143</sup>, D.A. Hangal<sup>39</sup>, M.D. Hank<sup>37</sup>, R. Hankache<sup>99</sup>, E. Hansen<sup>96</sup>, J.B. Hansen<sup>40</sup>,  
 J.D. Hansen<sup>40</sup>, P.H. Hansen<sup>40</sup>, K. Hara<sup>165</sup>, D. Harada<sup>54</sup>, T. Harenberg<sup>178</sup>, S. Harkusha<sup>106</sup>, Y.T. Harris<sup>132</sup>,  
 P.F. Harrison<sup>174</sup>, N.M. Hartman<sup>150</sup>, N.M. Hartmann<sup>112</sup>, Y. Hasegawa<sup>147</sup>, A. Hasib<sup>50</sup>, S. Haug<sup>19</sup>,  
 R. Hauser<sup>105</sup>, M. Havranek<sup>139</sup>, C.M. Hawkes<sup>20</sup>, R.J. Hawkins<sup>36</sup>, S. Hayashida<sup>114</sup>, D. Hayden<sup>105</sup>,  
 C. Hayes<sup>104</sup>, R.L. Hayes<sup>171</sup>, C.P. Hays<sup>132</sup>, J.M. Hays<sup>92</sup>, H.S. Hayward<sup>90</sup>, F. He<sup>60a</sup>, Y. He<sup>161</sup>, Y. He<sup>133</sup>,  
 M.P. Heath<sup>50</sup>, V. Hedberg<sup>96</sup>, A.L. Heggelund<sup>131</sup>, N.D. Hehir<sup>92</sup>, C. Heidegger<sup>52</sup>, K.K. Heidegger<sup>52</sup>,  
 W.D. Heidorn<sup>78</sup>, J. Heilman<sup>34</sup>, S. Heim<sup>46</sup>, T. Heim<sup>17</sup>, B. Heinemann<sup>46,ad</sup>, J.G. Heinlein<sup>134</sup>,  
 J.J. Heinrich<sup>129</sup>, L. Heinrich<sup>36</sup>, J. Hejbal<sup>138</sup>, L. Helary<sup>46</sup>, A. Held<sup>123</sup>, C.M. Helling<sup>143</sup>, S. Hellman<sup>45a,45b</sup>,  
 C. Helsen<sup>36</sup>, R.C.W. Henderson<sup>89</sup>, L. Henkelmann<sup>32</sup>, A.M. Henriques Correia<sup>36</sup>, H. Herde<sup>150</sup>,  
 Y. Hernández Jiménez<sup>152</sup>, H. Herr<sup>98</sup>, M.G. Herrmann<sup>112</sup>, T. Herrmann<sup>48</sup>, G. Herten<sup>52</sup>, R. Hertenberger<sup>112</sup>,  
 L. Hervas<sup>36</sup>, N.P. Hessey<sup>164a</sup>, H. Hibi<sup>82</sup>, E. Higón-Rodríguez<sup>170</sup>, S.J. Hillier<sup>20</sup>, I. Hinchliffe<sup>17</sup>,  
 F. Hinterkeuser<sup>24</sup>, M. Hirose<sup>130</sup>, S. Hirose<sup>165</sup>, D. Hirschbuehl<sup>178</sup>, B. Hiti<sup>91</sup>, O. Hladik<sup>138</sup>, J. Hobbs<sup>152</sup>,  
 R. Hobincu<sup>27e</sup>, N. Hod<sup>176</sup>, M.C. Hodgkinson<sup>146</sup>, B.H. Hodgkinson<sup>32</sup>, A. Hoecker<sup>36</sup>, J. Hofer<sup>46</sup>, D. Hohn<sup>52</sup>,  
 T. Holm<sup>24</sup>, M. Holzbock<sup>113</sup>, L.B.A.H. Hommels<sup>32</sup>, B.P. Honan<sup>99</sup>, J. Hong<sup>60c</sup>, T.M. Hong<sup>136</sup>, Y. Hong<sup>53</sup>,  
 J.C. Honig<sup>52</sup>, A. Hönle<sup>113</sup>, B.H. Hooberman<sup>169</sup>, W.H. Hopkins<sup>6</sup>, Y. Horii<sup>114</sup>, L.A. Horyn<sup>37</sup>, S. Hou<sup>155</sup>,  
 J. Howarth<sup>57</sup>, J. Hoya<sup>88</sup>, M. Hrabovsky<sup>128</sup>, A. Hrynevich<sup>107</sup>, T. Hryn'ova<sup>4</sup>, P.J. Hsu<sup>63</sup>, S.-C. Hsu<sup>145</sup>,  
 Q. Hu<sup>39</sup>, S. Hu<sup>60c</sup>, Y.F. Hu<sup>14a,14d,ah</sup>, D.P. Huang<sup>94</sup>, X. Huang<sup>14c</sup>, Y. Huang<sup>60a</sup>, Y. Huang<sup>14a</sup>, Z. Hubacek<sup>139</sup>,  
 M. Huebner<sup>24</sup>, F. Huegging<sup>24</sup>, T.B. Huffman<sup>132</sup>, M. Huhtinen<sup>36</sup>, S.K. Huiberts<sup>16</sup>, R. Hulsken<sup>58</sup>,  
 N. Huseynov<sup>12,z</sup>, J. Huston<sup>105</sup>, J. Huth<sup>59</sup>, R. Hyneman<sup>150</sup>, S. Hyrych<sup>28a</sup>, G. Iacobucci<sup>54</sup>, G. Iakovidis<sup>29</sup>,  
 I. Ibragimov<sup>148</sup>, L. Iconomidou-Fayard<sup>64</sup>, P. Iengo<sup>36</sup>, R. Iguchi<sup>160</sup>, T. Iizawa<sup>54</sup>, Y. Ikegami<sup>81</sup>, A. Ilg<sup>19</sup>,  
 N. Ilic<sup>163</sup>, H. Imam<sup>35a</sup>, T. Ingebretsen Carlson<sup>45a,45b</sup>, G. Introzzi<sup>70a,70b</sup>, M. Iodice<sup>74a</sup>, V. Ippolito<sup>72a,72b</sup>,  
 M. Ishino<sup>160</sup>, W. Islam<sup>177</sup>, C. Issever<sup>18,46</sup>, S. Istin<sup>21a,ai</sup>, H. Ito<sup>175</sup>, J.M. Iturbe Ponce<sup>62a</sup>, R. Iuppa<sup>75a,75b</sup>,  
 A. Ivina<sup>176</sup>, J.M. Izen<sup>43</sup>, V. Izzo<sup>69a</sup>, P. Jacka<sup>138</sup>, P. Jackson<sup>1</sup>, R.M. Jacobs<sup>46</sup>, B.P. Jaeger<sup>149</sup>, C.S. Jagfeld<sup>112</sup>,  
 G. Jäkel<sup>178</sup>, K. Jakobs<sup>52</sup>, T. Jakoubek<sup>176</sup>, J. Jamieson<sup>57</sup>, K.W. Janas<sup>83a</sup>, G. Jarlskog<sup>96</sup>, A.E. Jaspán<sup>90</sup>,

T. Javůrek<sup>36</sup>, M. Javurkova<sup>101</sup>, F. Jeanneau<sup>142</sup>, L. Jeanty<sup>129</sup>, J. Jejelava<sup>156a,w</sup>, P. Jenni<sup>52,e</sup>, S. Jézéquel<sup>4</sup>,  
 J. Jia<sup>152</sup>, Z. Jia<sup>14c</sup>, Y. Jiang<sup>60a</sup>, S. Jiggins<sup>50</sup>, J. Jimenez Pena<sup>113</sup>, S. Jin<sup>14c</sup>, A. Jinaru<sup>27b</sup>, O. Jinnouchi<sup>161</sup>,  
 H. Jivan<sup>33g</sup>, P. Johansson<sup>146</sup>, K.A. Johns<sup>7</sup>, C.A. Johnson<sup>65</sup>, D.M. Jones<sup>32</sup>, E. Jones<sup>174</sup>, R.W.L. Jones<sup>89</sup>,  
 T.J. Jones<sup>90</sup>, J. Jovicevic<sup>15</sup>, X. Ju<sup>17</sup>, J.J. Junggeburth<sup>36</sup>, A. Juste Rozas<sup>13,t</sup>, S. Kabana<sup>144e</sup>,  
 A. Kaczmarzka<sup>84</sup>, M. Kado<sup>72a,72b</sup>, H. Kagan<sup>125</sup>, M. Kagan<sup>150</sup>, A. Kahn<sup>39</sup>, A. Kahn<sup>134</sup>, C. Kahra<sup>98</sup>,  
 T. Kaji<sup>175</sup>, E. Kajomovitz<sup>157</sup>, N. Kakati<sup>176</sup>, C.W. Kalderon<sup>29</sup>, A. Kamenshchikov<sup>163</sup>, N.J. Kang<sup>143</sup>,  
 Y. Kano<sup>114</sup>, D. Kar<sup>33g</sup>, K. Karava<sup>132</sup>, M.J. Kareem<sup>164b</sup>, E. Karentzos<sup>52</sup>, I. Karkanas<sup>159</sup>, S.N. Karpov<sup>79</sup>,  
 Z.M. Karpova<sup>79</sup>, V. Kartvelishvili<sup>89</sup>, A.N. Karyukhin<sup>120</sup>, E. Kasimi<sup>159</sup>, C. Kato<sup>60d</sup>, J. Katzy<sup>46</sup>, S. Kaur<sup>34</sup>,  
 K. Kawade<sup>147</sup>, K. Kawagoe<sup>87</sup>, T. Kawaguchi<sup>114</sup>, T. Kawamoto<sup>142</sup>, G. Kawamura<sup>53</sup>, E.F. Kay<sup>172</sup>,  
 F.I. Kaya<sup>166</sup>, S. Kazakos<sup>13</sup>, V.F. Kazanin<sup>119b,119a</sup>, Y. Ke<sup>152</sup>, J.M. Keaveney<sup>33a</sup>, R. Keeler<sup>172</sup>, J.S. Keller<sup>34</sup>,  
 A.S. Kelly<sup>94</sup>, D. Kelsey<sup>153</sup>, J.J. Kempster<sup>20</sup>, J. Kendrick<sup>20</sup>, K.E. Kennedy<sup>39</sup>, O. Kepka<sup>138</sup>, S. Kersten<sup>178</sup>,  
 B.P. Kerševan<sup>91</sup>, S. Ketabchi Haghighat<sup>163</sup>, M. Khandoga<sup>133</sup>, A. Khanov<sup>127</sup>, A.G. Kharlamov<sup>119b,119a</sup>,  
 T. Kharlamova<sup>119b,119a</sup>, E.E. Khoda<sup>145</sup>, T.J. Khoo<sup>18</sup>, G. Khoriali<sup>173</sup>, E. Khramov<sup>79</sup>, J. Khubua<sup>156b</sup>,  
 M. Kiehn<sup>36</sup>, A. Kilgallon<sup>129</sup>, E. Kim<sup>161</sup>, Y.K. Kim<sup>37</sup>, N. Kimura<sup>94</sup>, A. Kirchhoff<sup>53</sup>, D. Kirchmeier<sup>48</sup>,  
 C. Kirfel<sup>24</sup>, J. Kirk<sup>141</sup>, A.E. Kiryunin<sup>113</sup>, T. Kishimoto<sup>160</sup>, D.P. Kisliuk<sup>163</sup>, C. Kitsaki<sup>10</sup>, O. Kivernyk<sup>24</sup>,  
 M. Klassen<sup>61a</sup>, C. Klein<sup>34</sup>, L. Klein<sup>173</sup>, M.H. Klein<sup>104</sup>, M. Klein<sup>90</sup>, U. Klein<sup>90</sup>, P. Klimek<sup>36</sup>,  
 A. Klimentov<sup>29</sup>, F. Klimpel<sup>113</sup>, T. Klingl<sup>24</sup>, T. Klioutchnikova<sup>36</sup>, F.F. Klitzner<sup>112</sup>, P. Kluit<sup>117</sup>, S. Kluth<sup>113</sup>,  
 E. Kneringer<sup>76</sup>, T.M. Knight<sup>163</sup>, A. Knue<sup>52</sup>, D. Kobayashi<sup>87</sup>, R. Kobayashi<sup>85</sup>, M. Kocian<sup>150</sup>, T. Kodama<sup>160</sup>,  
 P. Kodys<sup>140</sup>, D.M. Koeck<sup>153</sup>, P.T. Koenig<sup>24</sup>, T. Koffas<sup>34</sup>, N.M. Köhler<sup>36</sup>, M. Kolb<sup>142</sup>, I. Koletsou<sup>4</sup>,  
 T. Komarek<sup>128</sup>, K. Köneke<sup>52</sup>, A.X.Y. Kong<sup>1</sup>, T. Kono<sup>124</sup>, V. Konstantinides<sup>94</sup>, N. Konstantinidis<sup>94</sup>,  
 B. Konya<sup>96</sup>, R. Kopeliansky<sup>65</sup>, S. Koperny<sup>83a</sup>, K. Korcyl<sup>84</sup>, K. Kordas<sup>159</sup>, G. Koren<sup>158</sup>, A. Korn<sup>94</sup>,  
 S. Korn<sup>53</sup>, I. Korolkov<sup>13</sup>, N. Korotkova<sup>111</sup>, B. Kortman<sup>117</sup>, O. Kortner<sup>113</sup>, S. Kortner<sup>113</sup>, W.H. Kostecka<sup>118</sup>,  
 V.V. Kostyukhin<sup>148,162</sup>, A. Kotsokechagia<sup>64</sup>, A. Kotwal<sup>49</sup>, A. Koulouris<sup>36</sup>,  
 A. Kourkoumeli-Charalampidi<sup>70a,70b</sup>, C. Kourkoumelis<sup>9</sup>, E. Kourlitis<sup>6</sup>, O. Kovanda<sup>153</sup>, R. Kowalewski<sup>172</sup>,  
 W. Kozanecki<sup>142</sup>, A.S. Kozhin<sup>120</sup>, V.A. Kramarenko<sup>111</sup>, G. Kramberger<sup>91</sup>, P. Kramer<sup>98</sup>, M.W. Krasny<sup>133</sup>,  
 A. Krasznahorkay<sup>36</sup>, J.A. Kremer<sup>98</sup>, J. Kretschmar<sup>90</sup>, K. Kreul<sup>18</sup>, P. Krieger<sup>163</sup>, F. Krieter<sup>112</sup>,  
 S. Krishnamurthy<sup>101</sup>, A. Krishnan<sup>61b</sup>, M. Krivos<sup>140</sup>, K. Krizka<sup>17</sup>, K. Kroeninger<sup>47</sup>, H. Kroha<sup>113</sup>,  
 J. Kroll<sup>138</sup>, J. Kroll<sup>134</sup>, K.S. Krowpman<sup>105</sup>, U. Kruchonak<sup>79</sup>, H. Krüger<sup>24</sup>, N. Krumnack<sup>78</sup>, M.C. Kruse<sup>49</sup>,  
 J.A. Krzysiak<sup>84</sup>, A. Kubota<sup>161</sup>, O. Kuchinskaia<sup>162</sup>, S. Kuday<sup>3a</sup>, D. Kuechler<sup>46</sup>, J.T. Kuechler<sup>46</sup>, S. Kuehn<sup>36</sup>,  
 T. Kuhl<sup>46</sup>, V. Kukhtin<sup>79</sup>, Y. Kulchitsky<sup>106,z</sup>, S. Kuleshov<sup>144d,144b</sup>, M. Kumar<sup>33g</sup>, N. Kumari<sup>100</sup>, M. Kuna<sup>58</sup>,  
 A. Kupco<sup>138</sup>, T. Kupfer<sup>47</sup>, O. Kuprash<sup>52</sup>, H. Kurashige<sup>82</sup>, L.L. Kurchaninov<sup>164a</sup>, Y.A. Kurochkin<sup>106</sup>,  
 A. Kurova<sup>110</sup>, E.S. Kuwertz<sup>36</sup>, M. Kuze<sup>161</sup>, A.K. Kvam<sup>145</sup>, J. Kvita<sup>128</sup>, T. Kwan<sup>102</sup>, K.W. Kwok<sup>62a</sup>,  
 C. Lacasta<sup>170</sup>, F. Lacava<sup>72a,72b</sup>, H. Lacker<sup>18</sup>, D. Lacour<sup>133</sup>, N.N. Lad<sup>94</sup>, E. Ladygin<sup>79</sup>, B. Laforge<sup>133</sup>,  
 T. Lagouri<sup>144e</sup>, S. Lai<sup>53</sup>, I.K. Lakomic<sup>83a</sup>, N. Lalloue<sup>58</sup>, J.E. Lambert<sup>126</sup>, S. Lammers<sup>65</sup>, W. Lampl<sup>7</sup>,  
 C. Lampoudis<sup>159</sup>, E. Lançon<sup>29</sup>, U. Landgraf<sup>52</sup>, M.P.J. Landon<sup>92</sup>, V.S. Lang<sup>52</sup>, J.C. Lange<sup>53</sup>,  
 R.J. Langenberg<sup>101</sup>, A.J. Lankford<sup>167</sup>, F. Lanni<sup>29</sup>, K. Lantzsche<sup>24</sup>, A. Lanza<sup>70a</sup>, A. Lapertosa<sup>55b,55a</sup>,  
 J.F. Laporte<sup>142</sup>, T. Lari<sup>68a</sup>, F. Lasagni Manghi<sup>23b</sup>, M. Lassnig<sup>36</sup>, V. Latonova<sup>138</sup>, T.S. Lau<sup>62a</sup>,  
 A. Laudrain<sup>98</sup>, A. Laurier<sup>34</sup>, M. Lavorgna<sup>69a,69b</sup>, S.D. Lawlor<sup>93</sup>, Z. Lawrence<sup>99</sup>, M. Lazzaroni<sup>68a,68b</sup>,  
 B. Le<sup>99</sup>, B. Leban<sup>91</sup>, A. Lebedev<sup>78</sup>, M. LeBlanc<sup>36</sup>, T. LeCompte<sup>150</sup>, F. Ledroit-Guillon<sup>58</sup>, A.C.A. Lee<sup>94</sup>,  
 G.R. Lee<sup>16</sup>, L. Lee<sup>59</sup>, S.C. Lee<sup>155</sup>, L.L. Leeuw<sup>33c</sup>, B. Lefebvre<sup>164a</sup>, H.P. Lefebvre<sup>93</sup>, M. Lefebvre<sup>172</sup>,  
 C. Leggett<sup>17</sup>, K. Lehmann<sup>149</sup>, G. Lehmann Miotto<sup>36</sup>, W.A. Leight<sup>101</sup>, A. Leisos<sup>159,s</sup>, M.A.L. Leite<sup>80c</sup>,  
 C.E. Leitgeb<sup>46</sup>, R. Leitner<sup>140</sup>, K.J.C. Leney<sup>42</sup>, T. Lenz<sup>24</sup>, S. Leone<sup>71a</sup>, C. Leonidopoulos<sup>50</sup>, A. Leopold<sup>151</sup>,  
 C. Leroy<sup>108</sup>, R. Les<sup>105</sup>, C.G. Lester<sup>32</sup>, M. Levchenko<sup>135</sup>, J. Levêque<sup>4</sup>, D. Levin<sup>104</sup>, L.J. Levinson<sup>176</sup>,  
 D.J. Lewis<sup>20</sup>, B. Li<sup>14b</sup>, B. Li<sup>60b</sup>, C. Li<sup>60a</sup>, C-Q. Li<sup>60c,60d</sup>, H. Li<sup>60a</sup>, H. Li<sup>60b</sup>, H. Li<sup>60c</sup>, J. Li<sup>60c</sup>, K. Li<sup>145</sup>,  
 L. Li<sup>60c</sup>, M. Li<sup>14a,14d</sup>, Q.Y. Li<sup>60a</sup>, S. Li<sup>60d,60c,c</sup>, T. Li<sup>60b</sup>, X. Li<sup>46</sup>, Z. Li<sup>60b</sup>, Z. Li<sup>132</sup>, Z. Li<sup>102</sup>, Z. Li<sup>90</sup>,  
 Z. Liang<sup>14a</sup>, M. Liberatore<sup>46</sup>, B. Liberti<sup>73a</sup>, K. Lie<sup>62c</sup>, J. Lieber Marin<sup>80b</sup>, K. Lin<sup>105</sup>, R.A. Linck<sup>65</sup>,  
 R.E. Lindley<sup>7</sup>, J.H. Lindon<sup>2</sup>, A. Linss<sup>46</sup>, E. Lipeles<sup>134</sup>, A. Lipniacka<sup>16</sup>, T.M. Liss<sup>169,ae</sup>, A. Lister<sup>171</sup>,

J.D. Little<sup>4</sup>, B. Liu<sup>14a</sup>, B.X. Liu<sup>149</sup>, D. Liu<sup>60d,60c</sup>, J.B. Liu<sup>60a</sup>, J.K.K. Liu<sup>32</sup>, K. Liu<sup>60d,60c</sup>, M. Liu<sup>60a</sup>, M.Y. Liu<sup>60a</sup>, P. Liu<sup>14a</sup>, Q. Liu<sup>60d,145,60c</sup>, X. Liu<sup>60a</sup>, Y. Liu<sup>46</sup>, Y. Liu<sup>14c,14d</sup>, Y.L. Liu<sup>104</sup>, Y.W. Liu<sup>60a</sup>, M. Livan<sup>70a,70b</sup>, J. Llorente Merino<sup>149</sup>, S.L. Lloyd<sup>92</sup>, E.M. Lobodzinska<sup>46</sup>, P. Loch<sup>7</sup>, S. Loffredo<sup>73a,73b</sup>, T. Lohse<sup>18</sup>, K. Lohwasser<sup>146</sup>, M. Lokajicek<sup>138</sup>, J.D. Long<sup>169</sup>, I. Longarini<sup>72a,72b</sup>, L. Longo<sup>67a,67b</sup>, R. Longo<sup>169</sup>, I. Lopez Paz<sup>36</sup>, A. Lopez Solis<sup>46</sup>, J. Lorenz<sup>112</sup>, N. Lorenzo Martinez<sup>4</sup>, A.M. Lory<sup>112</sup>, A. Lösle<sup>52</sup>, X. Lou<sup>45a,45b</sup>, X. Lou<sup>14a</sup>, A. Lounis<sup>64</sup>, J. Love<sup>6</sup>, P.A. Love<sup>89</sup>, J.J. Lozano Bahilo<sup>170</sup>, G. Lu<sup>14a</sup>, M. Lu<sup>77</sup>, S. Lu<sup>134</sup>, Y.J. Lu<sup>63</sup>, H.J. Lubatti<sup>145</sup>, C. Luci<sup>72a,72b</sup>, F.L. Lucio Alves<sup>14c</sup>, A. Lucotte<sup>58</sup>, F. Luehring<sup>65</sup>, I. Luise<sup>152</sup>, O. Lundberg<sup>151</sup>, B. Lund-Jensen<sup>151</sup>, N.A. Luongo<sup>129</sup>, M.S. Lutz<sup>158</sup>, D. Lynn<sup>29</sup>, H. Lyons<sup>90</sup>, R. Lysak<sup>138</sup>, E. Lytken<sup>96</sup>, F. Lyu<sup>14a</sup>, V. Lyubushkin<sup>79</sup>, T. Lyubushkina<sup>79</sup>, H. Ma<sup>29</sup>, L.L. Ma<sup>60b</sup>, Y. Ma<sup>94</sup>, D.M. Mac Donell<sup>172</sup>, G. Maccarrone<sup>51</sup>, J.C. MacDonald<sup>146</sup>, R. Madar<sup>38</sup>, W.F. Mader<sup>48</sup>, J. Maeda<sup>82</sup>, T. Maeno<sup>29</sup>, M. Maerker<sup>48</sup>, V. Magerl<sup>52</sup>, J. Magro<sup>66a,66c</sup>, D.J. Mahon<sup>39</sup>, C. Maidantchik<sup>80b</sup>, A. Maio<sup>137a,137b,137d</sup>, K. Maj<sup>83a</sup>, O. Majersky<sup>28a</sup>, S. Majewski<sup>129</sup>, N. Makovec<sup>64</sup>, V. Maksimovic<sup>15</sup>, B. Malaescu<sup>133</sup>, Pa. Malecki<sup>84</sup>, V.P. Maleev<sup>135</sup>, F. Malek<sup>58</sup>, D. Malito<sup>41b,41a</sup>, U. Mallik<sup>77</sup>, C. Malone<sup>32</sup>, S. Maltezos<sup>10</sup>, S. Malyukov<sup>79</sup>, J. Mamuzic<sup>170</sup>, G. Mancini<sup>51</sup>, J.P. Mandalia<sup>92</sup>, I. Mandić<sup>91</sup>, L. Manhaes de Andrade Filho<sup>80a</sup>, I.M. Maniatis<sup>159</sup>, M. Manisha<sup>142</sup>, J. Manjarres Ramos<sup>48</sup>, D.C. Mankad<sup>176</sup>, K.H. Mankinen<sup>96</sup>, A. Mann<sup>112</sup>, A. Manousos<sup>76</sup>, B. Mansoulie<sup>142</sup>, S. Manzoni<sup>36</sup>, A. Marantis<sup>159,s</sup>, G. Marchiori<sup>5</sup>, M. Marcisovsky<sup>138</sup>, L. Marcoccia<sup>73a,73b</sup>, C. Marcon<sup>96</sup>, M. Marinescu<sup>20</sup>, M. Marjanovic<sup>126</sup>, Z. Marshall<sup>17</sup>, S. Marti-Garcia<sup>170</sup>, T.A. Martin<sup>174</sup>, V.J. Martin<sup>50</sup>, B. Martin dit Latour<sup>16</sup>, L. Martinelli<sup>72a,72b</sup>, M. Martinez<sup>13,t</sup>, P. Martinez Agullo<sup>170</sup>, V.I. Martinez Outschoorn<sup>101</sup>, P. Martinez Suarez<sup>13</sup>, S. Martin-Haugh<sup>141</sup>, V.S. Martoiu<sup>27b</sup>, A.C. Martyniuk<sup>94</sup>, A. Marzin<sup>36</sup>, S.R. Maschek<sup>113</sup>, L. Masetti<sup>98</sup>, T. Mashimo<sup>160</sup>, J. Masik<sup>99</sup>, A.L. Maslennikov<sup>119b,119a</sup>, L. Massa<sup>23b</sup>, P. Massarotti<sup>69a,69b</sup>, P. Mastrandrea<sup>71a,71b</sup>, A. Mastroberardino<sup>41b,41a</sup>, T. Masubuchi<sup>160</sup>, T. Mathisen<sup>168</sup>, A. Matic<sup>112</sup>, N. Matsuzawa<sup>160</sup>, J. Maurer<sup>27b</sup>, B. Maček<sup>91</sup>, D.A. Maximov<sup>119b,119a</sup>, R. Mazini<sup>155</sup>, I. Maznas<sup>159</sup>, M. Mazza<sup>105</sup>, S.M. Mazza<sup>143</sup>, C. Mc Ginn<sup>29</sup>, J.P. Mc Gowan<sup>102</sup>, S.P. Mc Kee<sup>104</sup>, T.G. McCarthy<sup>113</sup>, W.P. McCormack<sup>17</sup>, E.F. McDonald<sup>103</sup>, A.E. McDougall<sup>117</sup>, J.A. Mcfayden<sup>153</sup>, G. Mchedlidze<sup>156b</sup>, M.A. McKay<sup>42</sup>, R.P. Mckenzie<sup>33g</sup>, D.J. McLaughlin<sup>94</sup>, K.D. McLean<sup>172</sup>, S.J. McMahon<sup>141</sup>, P.C. McNamara<sup>103</sup>, R.A. McPherson<sup>172,v</sup>, J.E. Mdhluli<sup>33g</sup>, S. Meehan<sup>36</sup>, T. Megy<sup>38</sup>, S. Mehlhase<sup>112</sup>, A. Mehta<sup>90</sup>, B. Meirose<sup>43</sup>, D. Melini<sup>157</sup>, B.R. Mellado Garcia<sup>33g</sup>, A.H. Melo<sup>53</sup>, F. Meloni<sup>46</sup>, A. Melzer<sup>24</sup>, E.D. Mendes Gouveia<sup>137a</sup>, A.M. Mendes Jacques Da Costa<sup>20</sup>, H.Y. Meng<sup>163</sup>, L. Meng<sup>89</sup>, S. Menke<sup>113</sup>, M. Mentink<sup>36</sup>, E. Meoni<sup>41b,41a</sup>, C. Merlassino<sup>132</sup>, L. Merola<sup>69a,69b</sup>, C. Meroni<sup>68a</sup>, G. Merz<sup>104</sup>, O. Meshkov<sup>109,111</sup>, J.K.R. Meshreki<sup>148</sup>, J. Metcalfe<sup>6</sup>, A.S. Mete<sup>6</sup>, C. Meyer<sup>65</sup>, J-P. Meyer<sup>142</sup>, M. Michetti<sup>18</sup>, R.P. Middleton<sup>141</sup>, L. Mijovic<sup>50</sup>, G. Mikenberg<sup>176</sup>, M. Mikestikova<sup>138</sup>, M. Mikuz<sup>91</sup>, H. Mildner<sup>146</sup>, A. Milic<sup>163</sup>, C.D. Milke<sup>42</sup>, D.W. Miller<sup>37</sup>, L.S. Miller<sup>34</sup>, A. Milov<sup>176</sup>, D.A. Milstead<sup>45a,45b</sup>, T. Min<sup>14c</sup>, A.A. Minaenko<sup>120</sup>, I.A. Minashvili<sup>156b</sup>, L. Mince<sup>57</sup>, A.I. Mincer<sup>123</sup>, B. Mindur<sup>83a</sup>, M. Mineev<sup>79</sup>, Y. Minegishi<sup>160</sup>, Y. Mino<sup>85</sup>, L.M. Mir<sup>13</sup>, M. Miralles Lopez<sup>170</sup>, M. Mironova<sup>132</sup>, T. Mitani<sup>175</sup>, A. Mitra<sup>174</sup>, V.A. Mitsou<sup>170</sup>, O. Miu<sup>163</sup>, P.S. Miyagawa<sup>92</sup>, Y. Miyazaki<sup>87</sup>, A. Mizukami<sup>81</sup>, J.U. Mjörnmark<sup>96</sup>, T. Mkrtchyan<sup>61a</sup>, M. Mlynarikova<sup>118</sup>, T. Moa<sup>45a,45b</sup>, S. Mobius<sup>53</sup>, K. Mochizuki<sup>108</sup>, P. Moder<sup>46</sup>, P. Mogg<sup>112</sup>, A.F. Mohammed<sup>14a</sup>, S. Mohapatra<sup>39</sup>, G. Mokgatitswane<sup>33g</sup>, B. Mondal<sup>148</sup>, S. Mondal<sup>139</sup>, K. Mönig<sup>46</sup>, E. Monnier<sup>100</sup>, L. Monsonis Romero<sup>170</sup>, J. Montejo Berlingen<sup>36</sup>, M. Montella<sup>125</sup>, F. Monticelli<sup>88</sup>, N. Morange<sup>64</sup>, A.L. Moreira De Carvalho<sup>137a</sup>, M. Moreno Llácer<sup>170</sup>, C. Moreno Martinez<sup>13</sup>, P. Morettini<sup>55b</sup>, S. Morgenstern<sup>174</sup>, D. Mori<sup>149</sup>, M. Morii<sup>59</sup>, M. Morinaga<sup>160</sup>, V. Morisbak<sup>131</sup>, A.K. Morley<sup>36</sup>, A.P. Morris<sup>94</sup>, L. Morvaj<sup>36</sup>, P. Moschovakos<sup>36</sup>, B. Moser<sup>117</sup>, M. Mosidze<sup>156b</sup>, T. Moskalets<sup>52</sup>, P. Moskvitina<sup>116</sup>, J. Moss<sup>31,m</sup>, E.J.W. Moyses<sup>101</sup>, S. Muanza<sup>100</sup>, J. Mueller<sup>136</sup>, R. Mueller<sup>19</sup>, D. Muenstermann<sup>89</sup>, G.A. Mullier<sup>96</sup>, J.J. Mullin<sup>134</sup>, D.P. Mungo<sup>68a,68b</sup>, J.L. Munoz Martinez<sup>13</sup>, F.J. Munoz Sanchez<sup>99</sup>, M. Murin<sup>99</sup>, W.J. Murray<sup>174,141</sup>, A. Murrone<sup>68a,68b</sup>, J.M. Muse<sup>126</sup>, M. Muškinja<sup>17</sup>, C. Mwewa<sup>29</sup>, A.G. Myagkov<sup>120,aa</sup>, A.J. Myers<sup>8</sup>, A.A. Myers<sup>136</sup>, G. Myers<sup>65</sup>, M. Myska<sup>139</sup>, B.P. Nachman<sup>17</sup>, O. Nackenhorst<sup>47</sup>, A.Nag Nag<sup>48</sup>, K. Nagai<sup>132</sup>, K. Nagano<sup>81</sup>, J.L. Nagle<sup>29</sup>,

E. Nagy<sup>100</sup>, A.M. Nairz<sup>36</sup>, Y. Nakahama<sup>81</sup>, K. Nakamura<sup>81</sup>, H. Nanjo<sup>130</sup>, F. Napolitano<sup>61a</sup>, R. Narayan<sup>42</sup>,  
 E.A. Narayanan<sup>115</sup>, I. Naryshkin<sup>135</sup>, M. Naseri<sup>34</sup>, C. Nass<sup>24</sup>, G. Navarro<sup>22a</sup>, J. Navarro-Gonzalez<sup>170</sup>,  
 R. Nayak<sup>158</sup>, P.Y. Nechaeva<sup>109</sup>, F. Nechansky<sup>46</sup>, T.J. Neep<sup>20</sup>, A. Negri<sup>70a,70b</sup>, M. Negrini<sup>23b</sup>, C. Nellist<sup>116</sup>,  
 C. Nelson<sup>102</sup>, K. Nelson<sup>104</sup>, S. Nemecek<sup>138</sup>, M. Nessi<sup>36,f</sup>, M.S. Neubauer<sup>169</sup>, F. Neuhaus<sup>98</sup>, J. Neundorff<sup>46</sup>,  
 R. Newhouse<sup>171</sup>, P.R. Newman<sup>20</sup>, C.W. Ng<sup>136</sup>, Y.S. Ng<sup>18</sup>, Y.W.Y. Ng<sup>167</sup>, B. Ngair<sup>35e</sup>, H.D.N. Nguyen<sup>108</sup>,  
 R.B. Nickerson<sup>132</sup>, R. Nicolaidou<sup>142</sup>, D.S. Nielsen<sup>40</sup>, J. Nielsen<sup>143</sup>, M. Niemeyer<sup>53</sup>, N. Nikiforou<sup>11</sup>,  
 V. Nikolaenko<sup>120,aa</sup>, I. Nikolic-Audit<sup>133</sup>, K. Nikolopoulos<sup>20</sup>, P. Nilsson<sup>29</sup>, H.R. Nindhito<sup>54</sup>, A. Nisati<sup>72a</sup>,  
 N. Nishu<sup>2</sup>, R. Nisius<sup>113</sup>, S.J. Noacco Rosende<sup>88</sup>, T. Nobe<sup>160</sup>, D.L. Noel<sup>32</sup>, Y. Noguchi<sup>85</sup>, I. Nomidis<sup>133</sup>,  
 M.A. Nomura<sup>29</sup>, M.B. Norfolk<sup>146</sup>, R.R.B. Norisam<sup>94</sup>, J. Novak<sup>91</sup>, T. Novak<sup>46</sup>, O. Novgorodova<sup>48</sup>,  
 L. Novotny<sup>139</sup>, R. Novotny<sup>115</sup>, L. Nozka<sup>128</sup>, K. Ntekas<sup>167</sup>, E. Nurse<sup>94</sup>, F.G. Oakham<sup>34,af</sup>, J. Ocariz<sup>133</sup>,  
 A. Ochi<sup>82</sup>, I. Ochoa<sup>137a</sup>, J.P. Ochoa-Ricoux<sup>144a</sup>, S. Oda<sup>87</sup>, S. Odaka<sup>81</sup>, S. Oerdek<sup>168</sup>, A. Ogrodnik<sup>83a</sup>,  
 A. Oh<sup>99</sup>, C.C. Ohm<sup>151</sup>, H. Oide<sup>161</sup>, R. Oishi<sup>160</sup>, M.L. Ojeda<sup>46</sup>, Y. Okazaki<sup>85</sup>, M.W. O'Keefe<sup>90</sup>,  
 Y. Okumura<sup>160</sup>, A. Olariu<sup>27b</sup>, L.F. Oleiro Seabra<sup>137a</sup>, S.A. Olivares Pino<sup>144e</sup>, D. Oliveira Damazio<sup>29</sup>,  
 D. Oliveira Goncalves<sup>80a</sup>, J.L. Oliver<sup>167</sup>, M.J.R. Olsson<sup>167</sup>, A. Olszewski<sup>84</sup>, J. Olszowska<sup>84</sup>, Ö.O. Öncel<sup>52</sup>,  
 D.C. O'Neil<sup>149</sup>, A.P. O'Neill<sup>19</sup>, A. Onofre<sup>137a,137e</sup>, P.U.E. Onyisi<sup>11</sup>, R.G. Oreamuno Madriz<sup>118</sup>,  
 M.J. Oreglia<sup>37</sup>, G.E. Orellana<sup>88</sup>, D. Orestano<sup>74a,74b</sup>, N. Orlando<sup>13</sup>, R.S. Orr<sup>163</sup>, V. O'Shea<sup>57</sup>,  
 R. Ospanov<sup>60a</sup>, G. Otero y Garzon<sup>30</sup>, H. Otono<sup>87</sup>, P.S. Ott<sup>61a</sup>, G.J. Ottino<sup>17</sup>, M. Ouchrif<sup>35d</sup>, J. Ouellette<sup>29</sup>,  
 F. Ould-Saada<sup>131</sup>, M. Owen<sup>57</sup>, R.E. Owen<sup>141</sup>, K.Y. Oyulmaz<sup>21a</sup>, V.E. Ozcan<sup>21a</sup>, N. Ozturk<sup>8</sup>, S. Ozturk<sup>21d</sup>,  
 J. Pacalt<sup>128</sup>, H.A. Pacey<sup>32</sup>, K. Pachal<sup>49</sup>, A. Pacheco Pages<sup>13</sup>, C. Padilla Aranda<sup>13</sup>, S. Pagan Griso<sup>17</sup>,  
 G. Palacino<sup>65</sup>, S. Palazzo<sup>50</sup>, S. Palestini<sup>36</sup>, M. Palka<sup>83b</sup>, J. Pan<sup>179</sup>, D.K. Panchal<sup>11</sup>, C.E. Pandini<sup>117</sup>,  
 J.G. Panduro Vazquez<sup>93</sup>, P. Pani<sup>46</sup>, G. Panizzo<sup>66a,66c</sup>, L. Paolozzi<sup>54</sup>, C. Papadatos<sup>108</sup>, S. Parajuli<sup>42</sup>,  
 A. Paramonov<sup>6</sup>, C. Paraskevopoulos<sup>10</sup>, D. Paredes Hernandez<sup>62b</sup>, B. Parida<sup>176</sup>, T.H. Park<sup>163</sup>, A.J. Parker<sup>31</sup>,  
 M.A. Parker<sup>32</sup>, F. Parodi<sup>55b,55a</sup>, E.W. Parrish<sup>118</sup>, V.A. Parrish<sup>50</sup>, J.A. Parsons<sup>39</sup>, U. Parzefall<sup>52</sup>,  
 B. Pascual Dias<sup>108</sup>, L. Pascual Dominguez<sup>158</sup>, V.R. Pascuzzi<sup>17</sup>, F. Pasquali<sup>117</sup>, E. Pasqualucci<sup>72a</sup>,  
 S. Passaggio<sup>55b</sup>, F. Pastore<sup>93</sup>, P. Pasuwan<sup>45a,45b</sup>, J.R. Pater<sup>99</sup>, A. Pathak<sup>177</sup>, J. Patton<sup>90</sup>, T. Pauly<sup>36</sup>,  
 J. Pearkes<sup>150</sup>, M. Pedersen<sup>131</sup>, R. Pedro<sup>137a</sup>, S.V. Peleganchuk<sup>119b,119a</sup>, O. Penc<sup>138</sup>, C. Peng<sup>62b</sup>, H. Peng<sup>60a</sup>,  
 M. Penzin<sup>162</sup>, B.S. Peralva<sup>80a</sup>, A.P. Pereira Peixoto<sup>58</sup>, L. Pereira Sanchez<sup>45a,45b</sup>, D.V. Perepelitsa<sup>29</sup>,  
 E. Perez Codina<sup>164a</sup>, M. Perganti<sup>10</sup>, L. Perini<sup>68a,68b</sup>, H. Pernegger<sup>36</sup>, S. Perrella<sup>36</sup>, A. Perrevoort<sup>116</sup>,  
 K. Peters<sup>46</sup>, R.F.Y. Peters<sup>99</sup>, B.A. Petersen<sup>36</sup>, T.C. Petersen<sup>40</sup>, E. Petit<sup>100</sup>, V. Petousis<sup>139</sup>, C. Petridou<sup>159</sup>,  
 A. Petrukhin<sup>148</sup>, M. Pettee<sup>17</sup>, N.E. Pettersson<sup>36</sup>, K. Petukhova<sup>140</sup>, A. Peyaud<sup>142</sup>, R. Pezoa<sup>144f</sup>, L. Pezzotti<sup>36</sup>,  
 G. Pezzullo<sup>179</sup>, T. Pham<sup>103</sup>, P.W. Phillips<sup>141</sup>, M.W. Phipps<sup>169</sup>, G. Piacquadio<sup>152</sup>, E. Pianori<sup>17</sup>,  
 F. Piazza<sup>68a,68b</sup>, R. Piegaia<sup>30</sup>, D. Pietreanu<sup>27b</sup>, A.D. Pilkington<sup>99</sup>, M. Pinamonti<sup>66a,66c</sup>, J.L. Pinfold<sup>2</sup>,  
 C. Pitman Donaldson<sup>94</sup>, D.A. Pizzi<sup>34</sup>, L. Pizzimento<sup>73a,73b</sup>, A. Pizzini<sup>117</sup>, M.-A. Pleier<sup>29</sup>, V. Plesanovs<sup>52</sup>,  
 V. Pleskot<sup>140</sup>, E. Plotnikova<sup>79</sup>, G. Poddar<sup>4</sup>, R. Poettgen<sup>96</sup>, R. Poggi<sup>54</sup>, L. Poggioli<sup>133</sup>, I. Pogrebnyak<sup>105</sup>,  
 D. Pohl<sup>24</sup>, I. Pokharel<sup>53</sup>, S. Polacek<sup>140</sup>, G. Polesello<sup>70a</sup>, A. Poley<sup>149,164a</sup>, R. Polifka<sup>139</sup>, A. Polini<sup>23b</sup>,  
 C.S. Pollard<sup>132</sup>, Z.B. Pollock<sup>125</sup>, V. Polychronakos<sup>29</sup>, D. Ponomarenko<sup>110</sup>, L. Pontecorvo<sup>36</sup>, S. Popa<sup>27a</sup>,  
 G.A. Popeneciu<sup>27d</sup>, L. Portales<sup>4</sup>, D.M. Portillo Quintero<sup>164a</sup>, S. Pospisil<sup>139</sup>, P. Postolache<sup>27c</sup>,  
 K. Potamianos<sup>132</sup>, I.N. Potrap<sup>79</sup>, C.J. Potter<sup>32</sup>, H. Potti<sup>1</sup>, T. Poulsen<sup>46</sup>, J. Poveda<sup>170</sup>, G. Pownall<sup>46</sup>,  
 M.E. Pozo Astigarraga<sup>36</sup>, A. Prades Ibanez<sup>170</sup>, P. Pralavorio<sup>100</sup>, M.M. Prapa<sup>44</sup>, D. Price<sup>99</sup>,  
 M. Primavera<sup>67a</sup>, M.A. Principe Martin<sup>97</sup>, M.L. Proffitt<sup>145</sup>, N. Proklova<sup>110</sup>, K. Prokofiev<sup>62c</sup>, F. Prokoshin<sup>79</sup>,  
 G. Proto<sup>73a,73b</sup>, S. Protopopescu<sup>29</sup>, J. Proudfoot<sup>6</sup>, M. Przybycien<sup>83a</sup>, D. Pudzha<sup>135</sup>, P. Puzo<sup>64</sup>,  
 D. Pyatiizbyantseva<sup>110</sup>, J. Qian<sup>104</sup>, Y. Qin<sup>99</sup>, T. Qiu<sup>92</sup>, A. Quadt<sup>53</sup>, M. Queitsch-Maitland<sup>24</sup>,  
 G. Rabanal Bolanos<sup>59</sup>, D. Rafanoharana<sup>52</sup>, F. Ragusa<sup>68a,68b</sup>, J.A. Raine<sup>54</sup>, S. Rajagopalan<sup>29</sup>, K. Ran<sup>14a,14d</sup>,  
 V. Raskina<sup>133</sup>, D.F. Rassloff<sup>61a</sup>, S. Rave<sup>98</sup>, B. Ravina<sup>57</sup>, I. Ravinovich<sup>176</sup>, M. Raymond<sup>36</sup>, A.L. Read<sup>131</sup>,  
 N.P. Readioff<sup>146</sup>, D.M. Rebuzzi<sup>70a,70b</sup>, G. Redlinger<sup>29</sup>, K. Reeves<sup>43</sup>, D. Reikher<sup>158</sup>, A. Reiss<sup>98</sup>, A. Rej<sup>148</sup>,  
 C. Rembser<sup>36</sup>, A. Renardi<sup>46</sup>, M. Renda<sup>27b</sup>, M.B. Rendel<sup>113</sup>, A.G. Rennie<sup>57</sup>, S. Resconi<sup>68a</sup>,  
 M. Ressegotti<sup>55b,55a</sup>, E.D. Resseguie<sup>17</sup>, S. Rettie<sup>94</sup>, B. Reynolds<sup>125</sup>, E. Reynolds<sup>17</sup>, M. Rezaei Estabragh<sup>178</sup>,

O.L. Rezanova<sup>119b,119a</sup>, P. Reznicek<sup>140</sup>, E. Ricci<sup>75a,75b</sup>, R. Richter<sup>113</sup>, S. Richter<sup>45a,45b</sup>, E. Richter-Was<sup>83b</sup>,  
 M. Ridel<sup>133</sup>, P. Rieck<sup>123</sup>, P. Riedler<sup>36</sup>, M. Rijssenbeek<sup>152</sup>, A. Rimoldi<sup>70a,70b</sup>, M. Rimoldi<sup>46</sup>,  
 L. Rinaldi<sup>23b,23a</sup>, T.T. Rinn<sup>169</sup>, M.P. Rinnagel<sup>112</sup>, G. Ripellino<sup>151</sup>, I. Riu<sup>13</sup>, P. Rivadeneira<sup>46</sup>,  
 J.C. Rivera Vergara<sup>172</sup>, F. Rizatdinova<sup>127</sup>, E. Rizvi<sup>92</sup>, C. Rizzi<sup>54</sup>, B.A. Roberts<sup>174</sup>, B.R. Roberts<sup>17</sup>,  
 S.H. Robertson<sup>102,v</sup>, M. Robin<sup>46</sup>, D. Robinson<sup>32</sup>, C.M. Robles Gajardo<sup>144f</sup>, M. Robles Manzano<sup>98</sup>,  
 A. Robson<sup>57</sup>, A. Rocchi<sup>73a,73b</sup>, C. Roda<sup>71a,71b</sup>, S. Rodriguez Bosca<sup>61a</sup>, Y. Rodriguez Garcia<sup>22a</sup>,  
 A. Rodriguez Rodriguez<sup>52</sup>, A.M. Rodriguez Vera<sup>164b</sup>, S. Roe<sup>36</sup>, J.T. Roemer<sup>167</sup>, A.R. Roepe<sup>126</sup>,  
 J. Roggel<sup>178</sup>, O. Røhne<sup>131</sup>, R.A. Rojas<sup>172</sup>, B. Roland<sup>52</sup>, C.P.A. Roland<sup>65</sup>, J. Roloff<sup>29</sup>, A. Romaniouk<sup>110</sup>,  
 M. Romano<sup>23b</sup>, A.C. Romero Hernandez<sup>169</sup>, N. Rompotis<sup>90</sup>, M. Ronzani<sup>123</sup>, L. Roos<sup>133</sup>, S. Rosati<sup>72a</sup>,  
 B.J. Rosser<sup>134</sup>, E. Rossi<sup>163</sup>, E. Rossi<sup>4</sup>, E. Rossi<sup>69a,69b</sup>, L.P. Rossi<sup>55b</sup>, L. Rossini<sup>46</sup>, R. Rosten<sup>125</sup>,  
 M. Rotaru<sup>27b</sup>, B. Rottler<sup>52</sup>, D. Rousseau<sup>64</sup>, D. Rouso<sup>32</sup>, G. Rovelli<sup>70a,70b</sup>, A. Roy<sup>169</sup>, A. Rozanov<sup>100</sup>,  
 Y. Rozen<sup>157</sup>, X. Ruan<sup>33g</sup>, A.J. Ruby<sup>90</sup>, T.A. Ruggeri<sup>1</sup>, F. Rühr<sup>52</sup>, A. Ruiz-Martinez<sup>170</sup>, A. Rummler<sup>36</sup>,  
 Z. Rurikova<sup>52</sup>, N.A. Rusakovich<sup>79</sup>, H.L. Russell<sup>172</sup>, L. Rustige<sup>38</sup>, J.P. Rutherford<sup>7</sup>, E.M. Rüttinger<sup>146</sup>,  
 K. Rybacki<sup>89</sup>, M. Rybar<sup>140</sup>, E.B. Rye<sup>131</sup>, A. Ryzhov<sup>120</sup>, J.A. Sabater Iglesias<sup>54</sup>, P. Sabatini<sup>170</sup>,  
 L. Sabetta<sup>72a,72b</sup>, H.F-W. Sadrozinski<sup>143</sup>, R. Sadykov<sup>79</sup>, F. Safai Tehrani<sup>72a</sup>, B. Safarzadeh Samani<sup>153</sup>,  
 M. Safdari<sup>150</sup>, S. Saha<sup>102</sup>, M. Sahinsoy<sup>113</sup>, A. Sahu<sup>178</sup>, M. Saimpert<sup>142</sup>, M. Saito<sup>160</sup>, T. Saito<sup>160</sup>,  
 D. Salamani<sup>36</sup>, G. Salamanna<sup>74a,74b</sup>, A. Salnikov<sup>150</sup>, J. Salt<sup>170</sup>, A. Salvador Salas<sup>13</sup>, D. Salvatore<sup>41b,41a</sup>,  
 F. Salvatore<sup>153</sup>, A. Salzburger<sup>36</sup>, D. Sammel<sup>52</sup>, D. Sampsonidis<sup>159</sup>, D. Sampsonidou<sup>60d,60c</sup>, J. Sánchez<sup>170</sup>,  
 A. Sanchez Pineda<sup>4</sup>, V. Sanchez Sebastian<sup>170</sup>, H. Sandaker<sup>131</sup>, C.O. Sander<sup>46</sup>, I.G. Sanderswood<sup>89</sup>,  
 J.A. Sandesara<sup>101</sup>, M. Sandhoff<sup>178</sup>, C. Sandoval<sup>22b</sup>, D.P.C. Sankey<sup>141</sup>, A. Sansoni<sup>51</sup>, C. Santoni<sup>38</sup>,  
 H. Santos<sup>137a,137b</sup>, S.N. Santpur<sup>17</sup>, A. Santra<sup>176</sup>, K.A. Saoucha<sup>146</sup>, A. Saprnov<sup>79</sup>, J.G. Saraiva<sup>137a,137d</sup>,  
 J. Sardain<sup>100</sup>, O. Sasaki<sup>81</sup>, K. Sato<sup>165</sup>, C. Sauer<sup>61b</sup>, F. Sauerburger<sup>52</sup>, E. Sauvan<sup>4</sup>, P. Savard<sup>163,af</sup>,  
 R. Sawada<sup>160</sup>, C. Sawyer<sup>141</sup>, L. Sawyer<sup>95</sup>, I. Sayago Galvan<sup>170</sup>, C. Sbarra<sup>23b</sup>, A. Sbrizzi<sup>23b,23a</sup>,  
 T. Scanlon<sup>94</sup>, J. Schaarschmidt<sup>145</sup>, P. Schacht<sup>113</sup>, D. Schaefer<sup>37</sup>, U. Schäfer<sup>98</sup>, A.C. Schaffer<sup>64</sup>,  
 D. Schaile<sup>112</sup>, R.D. Schamberger<sup>152</sup>, E. Schanet<sup>112</sup>, C. Scharf<sup>18</sup>, N. Scharmberg<sup>99</sup>, V.A. Schegelsky<sup>135</sup>,  
 D. Scheirich<sup>140</sup>, F. Schenck<sup>18</sup>, M. Schernau<sup>167</sup>, C. Scheulen<sup>53</sup>, C. Schiavi<sup>55b,55a</sup>, Z.M. Schillaci<sup>26</sup>,  
 E.J. Schioppa<sup>67a,67b</sup>, M. Schioppa<sup>41b,41a</sup>, B. Schlag<sup>98</sup>, K.E. Schleicher<sup>52</sup>, S. Schlenker<sup>36</sup>, K. Schmieden<sup>98</sup>,  
 C. Schmitt<sup>98</sup>, S. Schmitt<sup>46</sup>, L. Schoeffel<sup>142</sup>, A. Schoening<sup>61b</sup>, P.G. Scholer<sup>52</sup>, E. Schopf<sup>132</sup>, M. Schott<sup>98</sup>,  
 J. Schovancova<sup>36</sup>, S. Schramm<sup>54</sup>, F. Schroeder<sup>178</sup>, H-C. Schultz-Coulon<sup>61a</sup>, M. Schumacher<sup>52</sup>,  
 B.A. Schumm<sup>143</sup>, Ph. Schune<sup>142</sup>, A. Schwartzman<sup>150</sup>, T.A. Schwarz<sup>104</sup>, Ph. Schwemling<sup>142</sup>,  
 R. Schwienhorst<sup>105</sup>, A. Sciandra<sup>143</sup>, G. Sciolla<sup>26</sup>, F. Scuri<sup>71a</sup>, F. Scutti<sup>103</sup>, C.D. Sebastiani<sup>90</sup>,  
 K. Sedlaczek<sup>47</sup>, P. Seema<sup>18</sup>, S.C. Seidel<sup>115</sup>, A. Seiden<sup>143</sup>, B.D. Seidlitz<sup>29</sup>, T. Seiss<sup>37</sup>, C. Seitz<sup>46</sup>,  
 J.M. Seixas<sup>80b</sup>, G. Sekhniaidze<sup>69a</sup>, S.J. Sekula<sup>42</sup>, L. Selem<sup>4</sup>, N. Semprini-Cesari<sup>23b,23a</sup>, S. Sen<sup>49</sup>,  
 L. Serin<sup>64</sup>, L. Serkin<sup>66a,66b</sup>, M. Sessa<sup>74a,74b</sup>, H. Severini<sup>126</sup>, S. Sevova<sup>150</sup>, F. Sforza<sup>55b,55a</sup>, A. Sfyrla<sup>54</sup>,  
 E. Shabalina<sup>53</sup>, R. Shaheen<sup>151</sup>, J.D. Shahinian<sup>134</sup>, N.W. Shaikh<sup>45a,45b</sup>, D. Shaked Renous<sup>176</sup>, L.Y. Shan<sup>14a</sup>,  
 M. Shapiro<sup>17</sup>, A. Sharma<sup>36</sup>, A.S. Sharma<sup>1</sup>, S. Sharma<sup>46</sup>, P.B. Shatalov<sup>121</sup>, K. Shaw<sup>153</sup>, S.M. Shaw<sup>99</sup>,  
 P. Sherwood<sup>94</sup>, L. Shi<sup>94</sup>, C.O. Shimmin<sup>179</sup>, Y. Shimogama<sup>175</sup>, J.D. Shinner<sup>93</sup>, I.P.J. Shipsey<sup>132</sup>,  
 S. Shirabe<sup>54</sup>, M. Shiyakova<sup>79</sup>, J. Shlomi<sup>176</sup>, M.J. Shochet<sup>37</sup>, J. Shojaii<sup>103</sup>, D.R. Shope<sup>151</sup>, S. Shrestha<sup>125</sup>,  
 E.M. Shrif<sup>33g</sup>, M.J. Shroff<sup>172</sup>, P. Sicho<sup>138</sup>, A.M. Sickles<sup>169</sup>, E. Sideras Haddad<sup>33g</sup>, O. Sidiropoulou<sup>36</sup>,  
 A. Sidoti<sup>23b</sup>, F. Siegert<sup>48</sup>, Dj. Sijacki<sup>15</sup>, F. Sili<sup>88</sup>, J.M. Silva<sup>20</sup>, M.V. Silva Oliveira<sup>36</sup>, S.B. Silverstein<sup>45a</sup>,  
 S. Simion<sup>64</sup>, R. Simoniello<sup>36</sup>, N.D. Simpson<sup>96</sup>, S. Simsek<sup>21a</sup>, S. Sindhu<sup>53</sup>, P. Sinervo<sup>163</sup>, V. Sinetckii<sup>111</sup>,  
 S. Singh<sup>149</sup>, S. Singh<sup>163</sup>, S. Sinha<sup>46</sup>, S. Sinha<sup>33g</sup>, M. Sioli<sup>23b,23a</sup>, I. Siral<sup>129</sup>, S.Yu. Sivoklov<sup>111</sup>,  
 J. Sjölin<sup>45a,45b</sup>, A. Skaf<sup>53</sup>, E. Skorda<sup>96</sup>, P. Skubic<sup>126</sup>, M. Slawinska<sup>84</sup>, V. Smakhtin<sup>176</sup>, B.H. Smart<sup>141</sup>,  
 J. Smiesko<sup>140</sup>, S.Yu. Smirnov<sup>110</sup>, Y. Smirnov<sup>110</sup>, L.N. Smirnova<sup>111,q</sup>, O. Smirnova<sup>96</sup>, E.A. Smith<sup>37</sup>,  
 H.A. Smith<sup>132</sup>, R. Smith<sup>150</sup>, M. Smizanska<sup>89</sup>, K. Smolek<sup>139</sup>, A. Smykiewicz<sup>84</sup>, A.A. Snesarev<sup>109</sup>,  
 H.L. Snoek<sup>117</sup>, S. Snyder<sup>29</sup>, R. Sobie<sup>172,v</sup>, A. Soffer<sup>158</sup>, C.A. Solans Sanchez<sup>36</sup>, E.Yu. Soldatov<sup>110</sup>,  
 U. Soldevila<sup>170</sup>, A.A. Solodkov<sup>120</sup>, S. Solomon<sup>52</sup>, A. Soloshenko<sup>79</sup>, K. Solovieva<sup>52</sup>, O.V. Solovyanov<sup>120</sup>,



V. Solovyev<sup>135</sup>, P. Sommer<sup>146</sup>, H. Son<sup>166</sup>, A. Sonay<sup>13</sup>, W.Y. Song<sup>164b</sup>, A. Sopczak<sup>139</sup>, A.L. Sopio<sup>94</sup>, F. Sopkova<sup>28b</sup>, V. Sothilingam<sup>61a</sup>, S. Sottocornola<sup>70a,70b</sup>, R. Soualah<sup>122c</sup>, A.M. Soukharev<sup>119b,119a</sup>, Z. Soumami<sup>35e</sup>, D. South<sup>46</sup>, S. Spagnolo<sup>67a,67b</sup>, M. Spalla<sup>113</sup>, M. Spangenberg<sup>174</sup>, F. Spanò<sup>93</sup>, D. Sperlich<sup>52</sup>, G. Spigo<sup>36</sup>, M. Spina<sup>153</sup>, S. Spinali<sup>89</sup>, D.P. Spiteri<sup>57</sup>, M. Spousta<sup>140</sup>, E.J. Staats<sup>34</sup>, A. Stabile<sup>68a,68b</sup>, R. Stamen<sup>61a</sup>, M. Stamenkovic<sup>117</sup>, A. Stampekis<sup>20</sup>, M. Standke<sup>24</sup>, E. Stanecka<sup>84</sup>, B. Stanislaus<sup>17</sup>, M.M. Stanitzki<sup>46</sup>, M. Stankaityte<sup>132</sup>, B. Stapf<sup>46</sup>, E.A. Starchenko<sup>120</sup>, G.H. Stark<sup>143</sup>, J. Stark<sup>100</sup>, D.M. Starke<sup>164b</sup>, P. Staroba<sup>138</sup>, P. Starovoitov<sup>61a</sup>, S. Stärz<sup>102</sup>, R. Staszewski<sup>84</sup>, G. Stavropoulos<sup>44</sup>, J. Steentoft<sup>168</sup>, P. Steinberg<sup>29</sup>, A.L. Steinhebel<sup>129</sup>, B. Stelzer<sup>149,164a</sup>, H.J. Stelzer<sup>136</sup>, O. Stelzer-Chilton<sup>164a</sup>, H. Stenzel<sup>56</sup>, T.J. Stevenson<sup>153</sup>, G.A. Stewart<sup>36</sup>, M.C. Stockton<sup>36</sup>, G. Stoicea<sup>27b</sup>, M. Stolarski<sup>137a</sup>, S. Stonjek<sup>113</sup>, A. Straessner<sup>48</sup>, J. Strandberg<sup>151</sup>, S. Strandberg<sup>45a,45b</sup>, M. Strauss<sup>126</sup>, T. Strebler<sup>100</sup>, P. Strizenec<sup>28b</sup>, R. Ströhmer<sup>173</sup>, D.M. Strom<sup>129</sup>, L.R. Strom<sup>46</sup>, R. Stroynowski<sup>42</sup>, A. Strubig<sup>45a,45b</sup>, S.A. Stucci<sup>29</sup>, B. Stugu<sup>16</sup>, J. Stupak<sup>126</sup>, N.A. Styles<sup>46</sup>, D. Su<sup>150</sup>, S. Su<sup>60a</sup>, W. Su<sup>60d,145,60c</sup>, X. Su<sup>60a,64</sup>, K. Sugizaki<sup>160</sup>, V.V. Sulin<sup>109</sup>, M.J. Sullivan<sup>90</sup>, D.M.S. Sultan<sup>75a,75b</sup>, L. Sultanaliyeva<sup>109</sup>, S. Sultansoy<sup>3b</sup>, T. Sumida<sup>85</sup>, S. Sun<sup>104</sup>, S. Sun<sup>177</sup>, O. Sunneborn Gudnadottir<sup>168</sup>, M.R. Sutton<sup>153</sup>, M. Svatos<sup>138</sup>, M. Swiatlowski<sup>164a</sup>, T. Swirski<sup>173</sup>, I. Sykora<sup>28a</sup>, M. Sykora<sup>140</sup>, T. Sykora<sup>140</sup>, D. Ta<sup>98</sup>, K. Tackmann<sup>46,u</sup>, A. Taffard<sup>167</sup>, R. Tafirout<sup>164a</sup>, R.H.M. Taibah<sup>133</sup>, R. Takashima<sup>86</sup>, K. Takeda<sup>82</sup>, E.P. Takeva<sup>50</sup>, Y. Takubo<sup>81</sup>, M. Talby<sup>100</sup>, A.A. Talyshev<sup>119b,119a</sup>, K.C. Tam<sup>62b</sup>, N.M. Tamir<sup>158</sup>, A. Tanaka<sup>160</sup>, J. Tanaka<sup>160</sup>, R. Tanaka<sup>64</sup>, J. Tang<sup>60c</sup>, Z. Tao<sup>171</sup>, S. Tapia Araya<sup>78</sup>, S. Tapprogge<sup>98</sup>, A. Tarek Abouelfadl Mohamed<sup>105</sup>, S. Tarem<sup>157</sup>, K. Tariq<sup>60b</sup>, G. Tarna<sup>27b</sup>, G.F. Tartarelli<sup>68a</sup>, P. Tas<sup>140</sup>, M. Tasevsky<sup>138</sup>, E. Tassi<sup>41b,41a</sup>, G. Tateno<sup>160</sup>, Y. Tayalati<sup>35e</sup>, G.N. Taylor<sup>103</sup>, W. Taylor<sup>164b</sup>, H. Teagle<sup>90</sup>, A.S. Tee<sup>177</sup>, R. Teixeira De Lima<sup>150</sup>, P. Teixeira-Dias<sup>93</sup>, J.J. Teoh<sup>117</sup>, K. Terashi<sup>160</sup>, J. Terron<sup>97</sup>, S. Terzo<sup>13</sup>, M. Testa<sup>51</sup>, R.J. Teuscher<sup>163,v</sup>, N. Themistokleous<sup>50</sup>, T. Thevenaux-Pelzer<sup>18</sup>, O. Thielmann<sup>178</sup>, D.W. Thomas<sup>93</sup>, J.P. Thomas<sup>20</sup>, E.A. Thompson<sup>46</sup>, P.D. Thompson<sup>20</sup>, E. Thomson<sup>134</sup>, E.J. Thorpe<sup>92</sup>, Y. Tian<sup>53</sup>, V.O. Tikhomirov<sup>109,ab</sup>, Yu.A. Tikhonov<sup>119b,119a</sup>, S. Timoshenko<sup>110</sup>, E.X.L. Ting<sup>1</sup>, P. Tipton<sup>179</sup>, S. Tisserant<sup>100</sup>, S.H. Tlou<sup>33g</sup>, A. Tmourji<sup>38</sup>, K. Todome<sup>23b,23a</sup>, S. Todorova-Nova<sup>140</sup>, S. Todt<sup>48</sup>, M. Togawa<sup>81</sup>, J. Tojo<sup>87</sup>, S. Tokár<sup>28a</sup>, K. Tokushuku<sup>81</sup>, R. Tombs<sup>32</sup>, M. Tomoto<sup>81,114</sup>, L. Tompkins<sup>150</sup>, P. Tornambe<sup>101</sup>, E. Torrence<sup>129</sup>, H. Torres<sup>48</sup>, E. Torró Pastor<sup>170</sup>, M. Toscani<sup>30</sup>, C. Toscirci<sup>37</sup>, D.R. Tovey<sup>146</sup>, A. Traeet<sup>16</sup>, I.S. Trandafir<sup>27b</sup>, C.J. Treado<sup>123</sup>, T. Trefzger<sup>173</sup>, A. Tricoli<sup>29</sup>, I.M. Trigger<sup>164a</sup>, S. Trincaz-Duvoid<sup>133</sup>, D.A. Trischuk<sup>171</sup>, W. Trischuk<sup>163</sup>, B. Trocmé<sup>58</sup>, A. Trofymov<sup>64</sup>, C. Troncon<sup>68a</sup>, F. Trovato<sup>153</sup>, L. Truong<sup>33c</sup>, M. Trzebinski<sup>84</sup>, A. Trzupek<sup>84</sup>, F. Tsai<sup>152</sup>, M. Tsai<sup>104</sup>, A. Tsiamis<sup>159</sup>, P.V. Tsiarehka<sup>106</sup>, A. Tsirigotis<sup>159,s</sup>, V. Tsiskaridze<sup>152</sup>, E.G. Tskhadadze<sup>156a</sup>, M. Tsopoulou<sup>159</sup>, Y. Tsujikawa<sup>85</sup>, I.I. Tsukerman<sup>121</sup>, V. Tsulaia<sup>17</sup>, S. Tsuno<sup>81</sup>, O. Tsur<sup>157</sup>, D. Tsybychev<sup>152</sup>, Y. Tu<sup>62b</sup>, A. Tudorache<sup>27b</sup>, V. Tudorache<sup>27b</sup>, A.N. Tuna<sup>36</sup>, S. Turchikhin<sup>79</sup>, I. Turk Cakir<sup>3a</sup>, R. Turra<sup>68a</sup>, P.M. Tuts<sup>39</sup>, S. Tzamarias<sup>159</sup>, P. Tzanis<sup>10</sup>, E. Tzovara<sup>98</sup>, K. Uchida<sup>160</sup>, F. Ukegawa<sup>165</sup>, P.A. Ulloa Poblete<sup>144c</sup>, G. Unal<sup>36</sup>, M. Unal<sup>11</sup>, A. Undrus<sup>29</sup>, G. Unel<sup>167</sup>, K. Uno<sup>160</sup>, J. Urban<sup>28b</sup>, P. Urquijo<sup>103</sup>, G. Usai<sup>8</sup>, R. Ushioda<sup>161</sup>, M. Usman<sup>108</sup>, Z. Uysal<sup>21b</sup>, V. Vacek<sup>139</sup>, B. Vachon<sup>102</sup>, K.O.H. Vadla<sup>131</sup>, T. Vafeiadis<sup>36</sup>, C. Valderanis<sup>112</sup>, E. Valdes Santurio<sup>45a,45b</sup>, M. Valente<sup>164a</sup>, S. Valentinetti<sup>23b,23a</sup>, A. Valero<sup>170</sup>, A. Vallier<sup>100</sup>, J.A. Valls Ferrer<sup>170</sup>, T.R. Van Daalen<sup>145</sup>, P. Van Gemmeren<sup>6</sup>, S. Van Stroud<sup>94</sup>, I. Van Vulpen<sup>117</sup>, M. Vanadia<sup>73a,73b</sup>, W. Vandelli<sup>36</sup>, M. Vandenbroucke<sup>142</sup>, E.R. Vandewall<sup>127</sup>, D. Vannicola<sup>158</sup>, L. Vannoli<sup>55b,55a</sup>, R. Vari<sup>72a</sup>, E.W. Varnes<sup>7</sup>, C. Varni<sup>17</sup>, T. Varol<sup>155</sup>, D. Varouchas<sup>64</sup>, K.E. Varvell<sup>154</sup>, M.E. Vasile<sup>27b</sup>, L. Vaslin<sup>38</sup>, G.A. Vasquez<sup>172</sup>, F. Vazeille<sup>38</sup>, D. Vazquez Furelos<sup>13</sup>, T. Vazquez Schroeder<sup>36</sup>, J. Veatch<sup>53</sup>, V. Vecchio<sup>99</sup>, M.J. Veen<sup>117</sup>, I. Veliscek<sup>132</sup>, L.M. Veloce<sup>163</sup>, F. Veloso<sup>137a,137c</sup>, S. Veneziano<sup>72a</sup>, A. Ventura<sup>67a,67b</sup>, A. Verbytskyi<sup>113</sup>, M. Verducci<sup>71a,71b</sup>, C. Vergis<sup>24</sup>, M. Verissimo De Araujo<sup>80b</sup>, W. Verkerke<sup>117</sup>, J.C. Vermeulen<sup>117</sup>, C. Vernieri<sup>150</sup>, P.J. Verschuur<sup>93</sup>, M. Vessella<sup>101</sup>, M.L. Vesterbacka<sup>123</sup>, M.C. Vetterli<sup>149,af</sup>, A. Vgenopoulos<sup>159</sup>, N. Viaux Maira<sup>144f</sup>, T. Vickey<sup>146</sup>, O.E. Vickey Boeriu<sup>146</sup>, G.H.A. Viehhauser<sup>132</sup>, L. Vignani<sup>61b</sup>, M. Villa<sup>23b,23a</sup>, M. Villaplana Perez<sup>170</sup>, E.M. Villhauer<sup>50</sup>, E. Vilucchi<sup>51</sup>, M.G. Vincter<sup>34</sup>, G.S. Virdee<sup>20</sup>,

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