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## Measurement of the $ZZ$ Production Cross Section in $pp$ Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

The ATLAS Collaboration

### Abstract

The  $ZZ$  production cross section in proton–proton collisions at 13 TeV center-of-mass energy is measured using  $3.2 \text{ fb}^{-1}$  of data recorded with the ATLAS detector at the Large Hadron Collider. The considered  $Z$  boson candidates decay to an electron or muon pair of mass 66–116 GeV. The cross section is measured in a fiducial phase space reflecting the detector acceptance. It is also extrapolated to a total phase space for  $Z$  bosons in the same mass range and of all decay modes, giving  $16.7^{+2.2}_{-2.0}(\text{stat.})^{+0.9}_{-0.7}(\text{syst.})^{+1.0}_{-0.7}(\text{lumi.})$  pb. The results agree with standard model predictions.

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Studying the production of pairs of  $Z$  bosons in proton–proton ( $pp$ ) interactions at the Large Hadron Collider (LHC) tests the electroweak sector of the standard model (SM) at the highest available energies. In  $pp$  collisions at a center-of-mass energy of  $\sqrt{s} = 13$  TeV,  $ZZ$  production is dominated by quark–antiquark ( $q\bar{q}$ ) interactions, with an  $O(10\%)$  contribution from loop-induced gluon–gluon ( $gg$ ) interactions [1, 2]. The SM  $ZZ$  production can proceed via a Higgs boson propagator, although this contribution is suppressed in the region where both  $Z$  bosons are produced on-shell. As such, non-Higgs  $ZZ$  production is an important background in studies of the Higgs boson [3–5]. It is also a background in searches for new physics producing pairs of  $Z$  bosons at high invariant mass [6, 7] and sensitive to triple neutral-gauge-boson couplings, which are not allowed in the SM [8].

This Letter presents the first measurement of the  $ZZ$  production cross section in  $pp$  interactions at  $\sqrt{s} = 13$  TeV. Throughout it, “ $Z$  boson” refers to the superposition of a  $Z$  boson and virtual photon with mass in the range 66–116 GeV. The analyzed data correspond to an integrated luminosity of  $3.2 \pm 0.2 \text{ fb}^{-1}$ , collected with the ATLAS detector [9]. The uncertainty of the integrated luminosity is derived, following a methodology similar to that detailed in Ref. [10], from a preliminary calibration of the luminosity scale using a pair of  $x$ – $y$  beam-separation scans performed in June 2015. The  $ZZ$  production cross section was previously measured at  $\sqrt{s} = 7$  and 8 TeV by the ATLAS and CMS collaborations [11–13] and found to be consistent with SM predictions.

Candidate events are reconstructed in the fully leptonic  $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$  decay channel where  $\ell$  and  $\ell'$  can be an electron or a muon. The cross section  $\sigma_{ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-}^{\text{fid}}$  is found by counting candidate events, subtracting the expected contribution from background events, correcting for detector effects, and dividing by the integrated luminosity. It is measured in a fiducial phase space that corresponds closely to the experimental acceptance. In addition, an extrapolation of the cross section to a total phase space for  $Z$  bosons,  $\sigma_{ZZ}^{\text{tot}}$ , is performed. The presented cross-section measurements are inclusive with respect to additional jets. Small contributions from triboson production with two leptonically decaying  $Z$  bosons and a third hadronically decaying weak boson and contributions from double parton scattering are included in the measurement.

The fiducial phase space, which is designed to reflect the acceptance of the ATLAS detector (described below), is defined for simulated events by applying the following criteria to the final-state particle-level objects. Final-state electrons and muons are required to be prompt (i.e. to not originate from hadron or  $\tau$  decay) and their kinematics are computed including the contributions from prompt photons with a distance in  $\eta$ – $\phi$  coordinates<sup>1</sup> of  $\Delta R_{\ell,\gamma} = \sqrt{(\Delta\eta_{\ell,\gamma})^2 + (\Delta\phi_{\ell,\gamma})^2} < 0.1$  between the charged lepton and the photon, as motivated in Ref. [14]. The leptons are required to be well-separated with  $\Delta R_{\ell,\ell'} > 0.2$  between any two leptons. Each lepton must have a momentum component transverse to the beam direction  $p_T > 20$  GeV and pseudorapidity  $|\eta| < 2.7$ . Events must have exactly four leptons satisfying the above criteria forming two pairs of same-flavor oppositely charged leptons ( $\mu^+ \mu^-$  or  $e^+ e^-$ ). This gives rise to three signal channels:  $4e$ ,  $4\mu$ , and  $2e2\mu$ . Each lepton pair must have an invariant mass in the range 66–116 GeV. In the  $4e$  and  $4\mu$  channels, where there are two possible ways to form same-flavor oppositely charged lepton pairs, the combination that minimizes  $|m_{\ell\ell,a} - m_Z| + |m_{\ell\ell,b} - m_Z|$  is chosen, where  $m_{\ell\ell,a}$  and  $m_{\ell\ell,b}$  are the invariant masses of the lepton pairs and  $m_Z$  is the mass of the  $Z$  boson.

The ATLAS detector is a multipurpose particle detector with a cylindrical geometry. It consists of layers

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points to the center of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln[\tan(\theta/2)]$ .

of inner tracking detectors, calorimeters, and muon chambers. The inner detector (ID) covers the pseudorapidity range  $|\eta| < 2.5$ . The calorimeter covers the pseudorapidity range  $|\eta| < 4.9$ . Within  $|\eta| < 2.47$  the finely segmented electromagnetic calorimeter identifies electromagnetic showers and measures their energy and position, providing electron identification together with the ID. The muon spectrometer (MS) surrounds the calorimeters and provides muon identification and measurement in the region  $|\eta| < 2.7$  and triggering in the region  $|\eta| < 2.4$ .

A muon is reconstructed by matching a track (or track segment) reconstructed in the MS to a track reconstructed in the ID. Its momentum is calculated by combining the information from the two systems and correcting for energy deposited in the calorimeters. In regions of limited coverage of the MS ( $|\eta| < 0.1$ ) or outside the ID acceptance ( $2.5 < |\eta| < 2.7$ ), muons can also be reconstructed by matching calorimeter signals consistent with muons to ID tracks (calorimeter-tagged muons) or standalone in the MS [15], respectively.

An electron is reconstructed from an energy deposit (cluster) in the electromagnetic calorimeter matched to a track in the ID. Its momentum is computed from the cluster energy and the direction of the track. Electrons are distinguished from other particles using several identification criteria that rely on the shapes of electromagnetic showers as well as tracking and track-to-cluster matching quantities. The output of a likelihood function taking these quantities as input, similar to that described in Ref. [16], is used to identify electrons. Electrons sharing an ID track with a selected muon are ignored.

The leptons are required to be isolated from other particles using ID track information, and for muons also calorimeter information (since standalone muons are outside the ID acceptance). The exact requirements depend on the lepton  $p_T$  and  $\eta$  and are designed to give a uniform 99% efficiency.

Leptons are required to originate from the primary vertex, defined as the reconstructed vertex with the largest sum of the  $p_T^2$  of the associated tracks. To this end, the longitudinal impact parameter of each lepton track, calculated with respect to the vertex and multiplied by  $\sin\theta$  of the track, is required to be less than 0.5 mm. Furthermore, the significance of the transverse impact parameter calculated with respect to the beam line is required to be less than three (five) for muons (electrons). Standalone muons are exempt from both impact parameter requirements, as they do not have an ID track.

Candidate events are preselected by either a single-muon or dielectron trigger. As in the fiducial phase space described above, leptons must have  $p_T > 20$  GeV. There are slight differences from the fiducial phase space: electrons must satisfy  $|\eta| < 2.47$  due to the limited experimental acceptance, and at least one muon in the  $4\mu$  channel must satisfy  $|\eta| < 2.4$ , corresponding to the acceptance of the muon trigger. The other muons must satisfy  $|\eta| < 2.7$ . Events are ignored if more than one selected muon is calorimeter-tagged or standalone. Apart from the above differences, reconstructed candidate events are selected using exactly the same criteria that define the fiducial phase space. A total of 63 events are observed, of which 15, 30, and 18 are in the  $4e$ ,  $2e2\mu$ , and  $4\mu$  channel, respectively.

Monte-Carlo-simulated (MC) event samples are used to obtain corrections for detector effects and to estimate background contributions. The principal signal sample is generated with the POWHEG method and framework [17–19], with a diboson event generator [20, 21] used to simulate the  $ZZ$  production process at next-to-leading order (NLO).<sup>2</sup> The simulation of parton showering, of the underlying event, and of hadronization is performed with PYTHIA 8 [22, 23] using the AZNLO set of tuned parameters (tune) [24]. SHERPA [25–31] is used to generate a sample with the  $q\bar{q}$ -initiated process simulated at NLO

<sup>2</sup> Throughout this Letter, orders of calculations refer to perturbative expansions in the strong coupling constant  $\alpha_S$  unless stated otherwise.

for  $ZZ$  plus zero or one additional jet and at leading order (LO) for two or three additional jets, as well as a sample with the loop-induced  $gg$ -initiated process simulated at LO with zero or one additional jet. These are used to include the loop-induced  $gg$ -initiated production, which is not included in the POWHEG + PYTHIA 8 sample, as well as to estimate, by comparison of the various samples, a systematic uncertainty due to the choice of event generator. The CT10 NLO [32] parton distribution functions (PDFs) are used in the event generation for all samples above. Additional samples are generated to estimate the contribution from background events. Triboson events are simulated with SHERPA, using CT10 PDFs, and  $t\bar{t}Z$  events are simulated with MADGRAPH [33] interfaced with PYTHIA 8 using the NNPDF 2.3 LO PDFs [34] and the A14 tune [35].

In all MC samples, additional  $pp$  interactions occurring in the same bunch crossing as the  $ZZ$  production, or in nearby ones, are simulated with PYTHIA 8 with MSTW 2008 LO PDFs [36] and the A2 tune [37]. The samples are then passed through a simulation of the ATLAS detector [38] based on GEANT 4 [39]. Scale factors are applied to the simulated events to correct for the small differences from data in the trigger, reconstruction, identification, isolation, and impact parameter efficiencies for electrons and muons [15, 16]. Furthermore, the lepton momentum scales and resolutions are adjusted to match the data.

Background events from processes with at least four prompt leptons in the final state are estimated with the MC samples described above, including uncertainties from the cross-section values, luminosity, and reconstruction effects. Contributions of  $0.07 \pm 0.02$  events from  $ZZ$  processes where at least one  $Z$  boson decays to  $\tau$  leptons,  $0.17 \pm 0.05$  events from non-hadronic triboson processes, and  $0.30 \pm 0.09$  events from all-leptonic  $t\bar{t}Z$  processes are predicted. Events from processes with two or three prompt leptons, e.g.  $Z$ ,  $WW$ ,  $WZ$ ,  $t\bar{t}$ , and  $ZZ$  events where one  $Z$  boson decays hadronically, where associated jets or photons contain or fake a nonprompt lepton, can pass the event selection. This background contribution is estimated to be  $0.09^{+1.08}_{-0.04}$  events, using control samples and a data-driven technique described in Ref. [11]. The uncertainty is dominated by the small number of events in the control samples. It can be asymmetric due to truncation, as background contributions cannot be negative. Background from two single  $Z$  bosons produced in different  $pp$  collisions in the same bunch crossing is estimated to be negligible. The total expected number of background events is  $0.20 \pm 0.05$  ( $0.25^{+0.40}_{-0.05}$ ,  $0.17^{+1.00}_{-0.04}$ ) in the  $4e$  ( $2e2\mu$ ,  $4\mu$ ) channel, giving a total of  $0.62^{+1.08}_{-0.11}$  events.

A factor  $C_{ZZ}$  is applied to correct for detector inefficiencies and resolution effects. It relates the background-subtracted number of selected events to the number in the fiducial phase space, and is defined as the ratio of generated signal events passing the selection criteria using reconstructed objects to the number passing the fiducial criteria using generator-level objects.  $C_{ZZ}$  is determined with a combination of the POWHEG  $ZZ$  MC sample and the SHERPA loop-induced  $gg$ -initiated sample. The normalization of the latter is scaled to  $\mathcal{O}(\alpha_s^3)$  accuracy [2] in order to improve the model used to correct the measurement. The  $C_{ZZ}$  value and its total uncertainty is determined to be  $0.55 \pm 0.02$  ( $0.63 \pm 0.02$ ,  $0.81 \pm 0.03$ ) in the  $4e$  ( $2e2\mu$ ,  $4\mu$ ) channel. The dominant systematic uncertainties come from the uncertainties of the scale factors used to correct lepton reconstruction and identification efficiencies in the simulation and the choice of MC generator. Other smaller uncertainties come from the scale and resolution of the lepton momenta, PDFs, and statistical fluctuations in the MC sample. Table 1 gives a breakdown of the systematic uncertainties.

Figure 1 shows the invariant mass of the leading- $p_{T,\ell\ell}$  and the subleading- $p_{T,\ell\ell}$  lepton pair ( $\ell\ell$ ), as well as the invariant mass, transverse momentum, and rapidity of the four-lepton system. Distributions from data are compared to the signal and background expectations, with good agreement in general.

The fiducial cross section is determined using a maximum-likelihood fit to the event counts in the three signal channels. A Poisson probability function is used to parametrize the number of expected events,

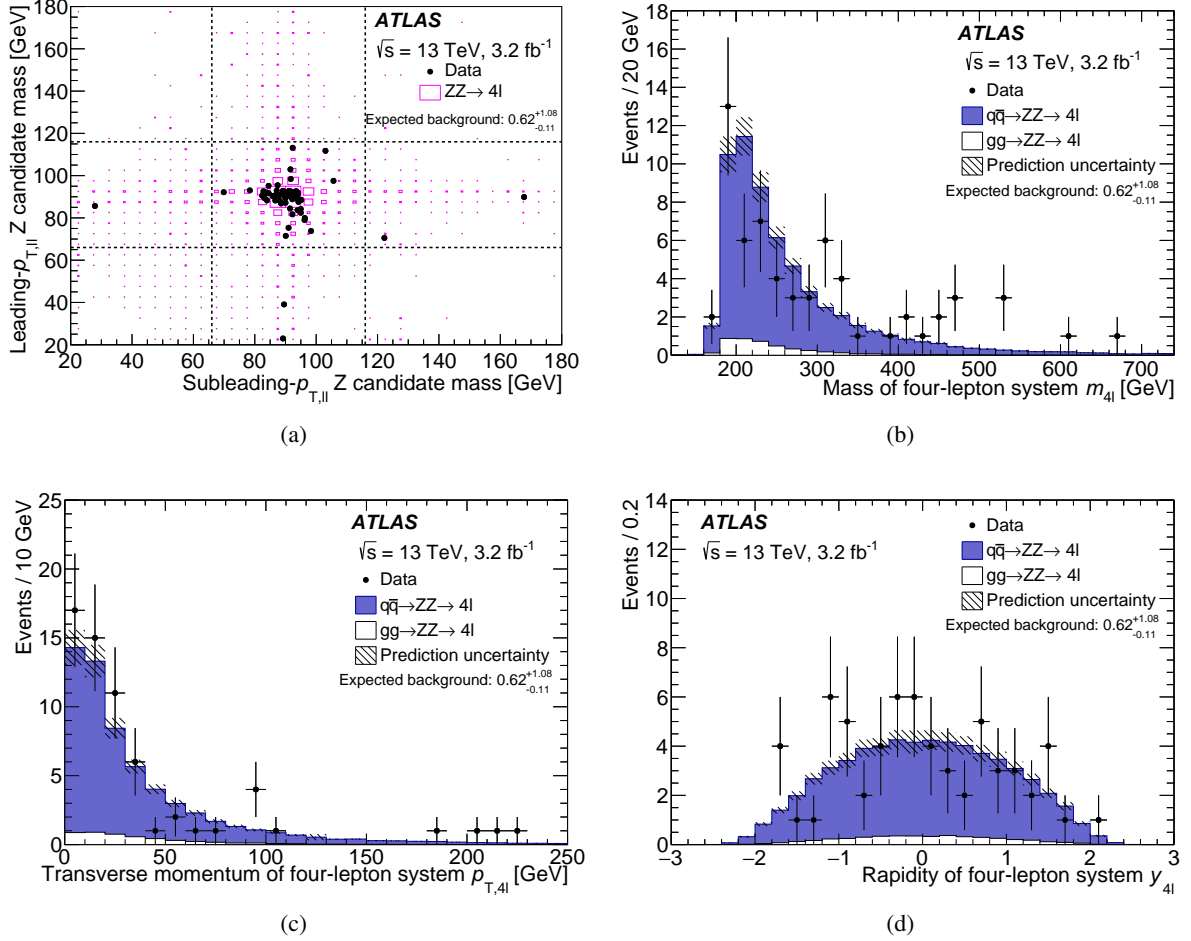


Figure 1: (a) Invariant mass  $m_{\ell\ell}$  of the leading- $p_{T,\ell\ell}$  versus the subleading- $p_{T,\ell\ell}$  lepton pair ( $\ell\ell$ ), before the requirement  $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$  is applied. The dashed lines indicate this requirement. (b) Invariant mass, (c) transverse momentum, and (d) rapidity of the four-lepton system in selected events. The points represent experimental data. The filled histograms show the signal prediction from simulation, including the  $q\bar{q}$  and loop-induced  $gg$ -initiated process. The contributions are stacked. In the simulation, the prediction from POWHEG + PYTHIA 8 combined with SHERPA is scaled to the  $\mathcal{O}(\alpha_s^2)$  prediction. The uncertainties in the simulation are from the same sources as the  $C_{ZZ}$  uncertainty. In addition, 6%  $ZZ$  cross-section uncertainty and 5% integrated-luminosity uncertainty are included. The expected background of  $0.62^{+1.08}_{-0.11}$  events is not shown as a histogram due to its small size.

Table 1: Relative uncertainties of the correction factor  $C_{ZZ}$  by signal channel, expressed in percent.

Source	$4e$	$2e2\mu$	$4\mu$
Statistical (signal samples)	0.7	0.5	0.5
Theoretical (generator, PDFs)	2.5	2.5	2.5
Experimental efficiencies	2.3	2.2	2.0
Momentum scales and resolutions	0.4	0.2	0.1
Total	3.5	3.3	3.2

multiplied by Gaussian distributions that model the nuisance parameters representing systematic uncertainties. This procedure can lead to asymmetric uncertainties as Poisson-distributed variables cannot be negative.

The cross section measured in the fiducial phase space is also extrapolated to the total phase space, which includes a correction for QED final-state radiation effects. The extrapolation factor is obtained from the same combination of MC samples as used in the  $C_{ZZ}$  determination. The ratio of the fiducial to full phase-space cross section is  $0.39 \pm 0.02$ , in all three channels. It is corrected for the  $\sim 3\%$  increase bias introduced by the pairing algorithm in the  $4e$  and  $4\mu$  channels. The dominant systematic uncertainty comes from the difference between the nominal value and that obtained using the SHERPA samples. Smaller uncertainties are derived from PDF variations in the CT10 error set, differences between using PYTHIA 8 and HERWIG++ [40] for simulating the rest of the event, and varying the QCD renormalization and factorization scales independently by a factor of two. In order to extrapolate to the total cross section, the fiducial cross sections are divided by the ratio  $0.39 \pm 0.02$  and corrected for the leptonic branching fraction<sup>3</sup>  $(3.3658\%)^2$  [41].

The measured fiducial cross sections are shown in Table 2 and Figure 2(a) along with a comparison to  $\mathcal{O}(\alpha_S^2)$  calculations [1]. Table 2 also shows the total combined cross section. The CT10 next-to-next-to-leading order PDFs [42] and a dynamic scale equal to the mass of the four-lepton system are used in the calculation. The loop-induced  $gg$ -initiated process is included, and contributes 7.0% (5.8%) of the cross section in the fiducial (total) phase space. The predicted cross sections in the fiducial phase space are corrected for QED final-state radiation effects, which amount to a 4% reduction. The measurements agree with the SM predictions.

The theoretical predictions do not include the following effects. The loop-induced  $gg$ -initiated process calculated at  $\mathcal{O}(\alpha_S^2)$  could receive large corrections at  $\mathcal{O}(\alpha_S^3)$  of 70% [2], which would increase the prediction by 4–5%. Electroweak corrections at next-to-leading order [43, 44] are expected to reduce the cross section by 7–8% [44]. Furthermore, the contribution from double parton scattering is not accounted for, but is expected to be an effect of less than 1% [45].

The measured total cross section is compared to measurements at lower center-of-mass energies and to a prediction from MCFM [46] with the CT14 NLO PDFs [47], which is calculated at  $\mathcal{O}(\alpha_S^1)$  accuracy for the  $q\bar{q}$ -initiated process and at  $\mathcal{O}(\alpha_S^2)$  accuracy for the loop-induced  $gg$ -initiated process and is shown versus center-of-mass energy in Figure 2(b). The cross section increases by a factor of more than two with a center-of-mass energy increase from 8 TeV to 13 TeV.

<sup>3</sup> This value excludes  $\gamma^*$  contributions. Including these, the branching fraction  $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$  is about 1.01–1.02 times larger.

Table 2: Cross-section measurement results compared to the  $\mathcal{O}(\alpha_S^2)$  standard model predictions. The per-channel and combined fiducial cross sections are shown along with the combined total cross section. For experimental results, the statistical, systematic, and luminosity uncertainties are shown. For theoretical predictions, the PDF and renormalization and factorization scale uncertainties added in quadrature are shown.

	Measurement	$\mathcal{O}(\alpha_S^2)$ prediction
$\sigma_{ZZ \rightarrow e^+e^-e^+e^-}^{\text{fid}}$	$8.4^{+2.4(\text{stat.})+0.4(\text{syst.})+0.5(\text{lumi.})}_{-2.0}$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma_{ZZ \rightarrow e^+e^-\mu^+\mu^-}^{\text{fid}}$	$14.7^{+2.9(\text{stat.})+0.6(\text{syst.})+0.9(\text{lumi.})}_{-2.5}$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma_{ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-}^{\text{fid}}$	$6.8^{+1.8(\text{stat.})+0.3(\text{syst.})+0.4(\text{lumi.})}_{-1.5}$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma_{ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-}^{\text{fid}}$	$29.7^{+3.9(\text{stat.})+1.0(\text{syst.})+1.7(\text{lumi.})}_{-3.6}$ fb	$27.4^{+0.9}_{-0.8}$ fb
$\sigma_{ZZ}^{\text{tot}}$	$16.7^{+2.2(\text{stat.})+0.9(\text{syst.})+1.0(\text{lumi.})}_{-2.0}$ pb	$15.6^{+0.4}_{-0.4}$ pb

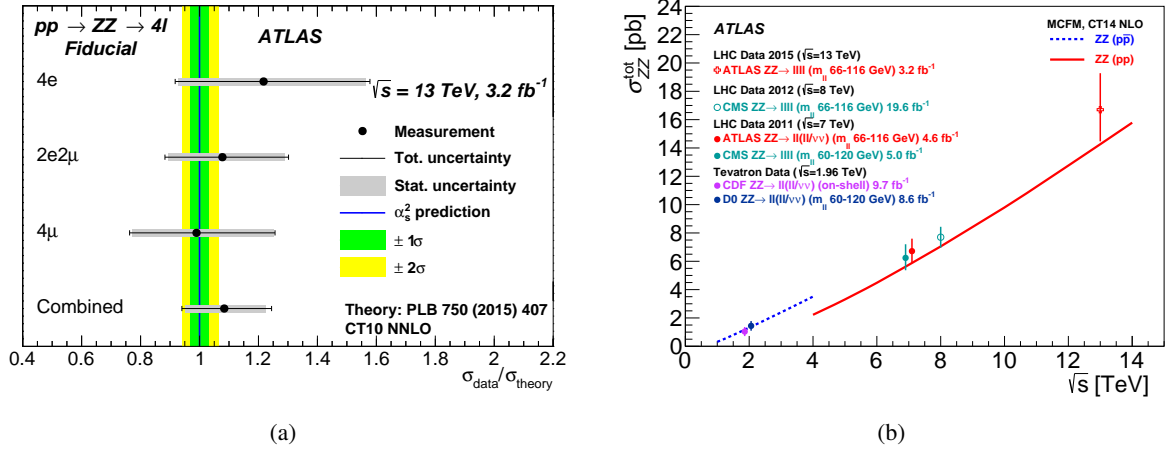


Figure 2: (a) Comparison between measured fiducial cross sections and  $\mathcal{O}(\alpha_S^2)$  predictions. (b) Total cross section compared to measurements at lower center-of-mass energies by ATLAS, CMS, CDF, and D0 [11–13, 48, 49], and to a prediction from MCFM at  $\mathcal{O}(\alpha_S^1)$  accuracy for the  $q\bar{q}$ -initiated process and at  $\mathcal{O}(\alpha_S^2)$  accuracy for the loop-induced  $gg$ -initiated process. A full  $\mathcal{O}(\alpha_S^2)$  prediction (known to improve agreement at  $\sqrt{s} = 13$  TeV) was not yet available for all the different center-of-mass energies. Some data points are shifted horizontally to improve readability. The  $ZZ$  cross section as function of  $\sqrt{s}$  in the range 130–209 GeV was also measured at the LEP 2  $e^+e^-$  collider [50].

In summary, ATLAS has measured the  $ZZ$  production cross section in  $3.2 \text{ fb}^{-1}$  of 13 TeV  $pp$  collisions at the LHC using the fully leptonic decay channel  $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ . Fiducial cross sections as well as a total cross section for  $Z$  bosons with mass 66–116 GeV have been measured and agree well with  $\mathcal{O}(\alpha_S^2)$  SM predictions.

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## The ATLAS Collaboration

G. Aad<sup>85</sup>, B. Abbott<sup>112</sup>, J. Abdallah<sup>150</sup>, O. Abdinov<sup>11</sup>, B. Abeloos<sup>116</sup>, R. Aben<sup>106</sup>, M. Abolins<sup>90</sup>, O.S. AbouZeid<sup>136</sup>, H. Abramowicz<sup>152</sup>, H. Abreu<sup>151</sup>, R. Abreu<sup>115</sup>, Y. Abulaiti<sup>145a,145b</sup>, B.S. Acharya<sup>163a,163b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>107</sup>, S. Adomeit<sup>99</sup>, T. Adye<sup>130</sup>, A.A. Affolder<sup>74</sup>, T. Agatonovic-Jovin<sup>13</sup>, J. Agricola<sup>54</sup>, J.A. Aguilar-Saavedra<sup>125a,125f</sup>, S.P. Ahlen<sup>22</sup>, F. Ahmadov<sup>65,b</sup>, G. Aielli<sup>132a,132b</sup>, H. Akerstedt<sup>145a,145b</sup>, T.P.A. Åkesson<sup>81</sup>, A.V. Akimov<sup>95</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>168</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>71</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>65</sup>, C. Alexa<sup>26b</sup>, G. Alexander<sup>152</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>112</sup>, G. Alimonti<sup>91a</sup>, L. Alio<sup>85</sup>, J. Alison<sup>31</sup>, S.P. Alkire<sup>35</sup>, B.M.M. Allbrooke<sup>148</sup>, B.W. Allen<sup>115</sup>, P.P. Allport<sup>18</sup>, A. Aloisio<sup>103a,103b</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>71</sup>, C. Alpigiani<sup>137</sup>, B. Alvarez Gonzalez<sup>30</sup>, D. Álvarez Piqueras<sup>166</sup>, M.G. Alvigi<sup>103a,103b</sup>, B.T. Amadio<sup>15</sup>, K. Amako<sup>66</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, D. Amidei<sup>89</sup>, S.P. Amor Dos Santos<sup>125a,125c</sup>, A. Amorim<sup>125a,125b</sup>, S. Amoroso<sup>30</sup>, N. Amram<sup>152</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>138</sup>, L.S. Ancu<sup>49</sup>, N. Andari<sup>107</sup>, T. Andeen<sup>31</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>30</sup>, J.K. Anders<sup>74</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>91a,91b</sup>, V. Andrei<sup>58a</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>106</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>108,c</sup>, N. Anjos<sup>12</sup>, A. Annovi<sup>123a,123b</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>97</sup>, J. Antos<sup>143b</sup>, F. Anulli<sup>131a</sup>, M. Aoki<sup>66</sup>, L. Aperio Bella<sup>18</sup>, G. Arabidze<sup>90</sup>, Y. Arai<sup>66</sup>, J.P. Araque<sup>125a</sup>, A.T.H. Arce<sup>45</sup>, F.A. Arduh<sup>71</sup>, J-F. Arguin<sup>94</sup>, S. Argyropoulos<sup>63</sup>, M. Arik<sup>19a</sup>, A.J. Armbruster<sup>30</sup>, L.J. Armitage<sup>76</sup>, O. Arnaez<sup>30</sup>, H. Arnold<sup>48</sup>, M. Arratia<sup>28</sup>, O. Arslan<sup>21</sup>, A. Artamonov<sup>96</sup>, G. Artoni<sup>119</sup>, S. Artz<sup>83</sup>, S. Asai<sup>154</sup>, N. Asbah<sup>42</sup>, A. Ashkenazi<sup>152</sup>, B. Åsman<sup>145a,145b</sup>, L. Asquith<sup>148</sup>, K. Assamagan<sup>25</sup>, R. Astalos<sup>143a</sup>, M. Atkinson<sup>164</sup>, N.B. Atlay<sup>140</sup>, K. Augsten<sup>127</sup>, G. Avolio<sup>30</sup>, B. Axen<sup>15</sup>, M.K. Ayoub<sup>116</sup>, G. Azuelos<sup>94,d</sup>, M.A. Baak<sup>30</sup>, A.E. Baas<sup>58a</sup>, M.J. Baca<sup>18</sup>, H. Bachacou<sup>135</sup>, K. Bachas<sup>73a,73b</sup>, M. Backes<sup>30</sup>, M. Backhaus<sup>30</sup>, P. Bagiacchi<sup>131a,131b</sup>, P. Bagnaia<sup>131a,131b</sup>, Y. Bai<sup>33a</sup>, J.T. Baines<sup>130</sup>, O.K. Baker<sup>175</sup>, E.M. Baldin<sup>108,c</sup>, P. Balek<sup>128</sup>, T. Balestri<sup>147</sup>, F. Balli<sup>135</sup>, W.K. Balunas<sup>121</sup>, E. Banas<sup>39</sup>, Sw. Banerjee<sup>172,e</sup>, A.A.E. Bannoura<sup>174</sup>, L. Barak<sup>30</sup>, E.L. Barberio<sup>88</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>85</sup>, T. Barillari<sup>100</sup>, M. Barisonzi<sup>163a,163b</sup>, T. Barklow<sup>142</sup>, N. Barlow<sup>28</sup>, S.L. Barnes<sup>84</sup>, B.M. Barnett<sup>130</sup>, R.M. Barnett<sup>15</sup>, Z. Barnovska<sup>5</sup>, A. Baroncelli<sup>133a</sup>, G. Barone<sup>23</sup>, A.J. Barr<sup>119</sup>, L. Barranco Navarro<sup>166</sup>, F. Barreiro<sup>82</sup>, J. Barreiro Guimarães da Costa<sup>33a</sup>, R. Bartoldus<sup>142</sup>, A.E. Barton<sup>72</sup>, P. Bartos<sup>143a</sup>, A. Basalae<sup>122</sup>, A. Bassalat<sup>116</sup>, A. Basye<sup>164</sup>, R.L. Bates<sup>53</sup>, S.J. Batista<sup>157</sup>, J.R. Batley<sup>28</sup>, M. Battaglia<sup>136</sup>, M. Bauce<sup>131a,131b</sup>, F. Bauer<sup>135</sup>, H.S. Bawa<sup>142,f</sup>, J.B. Beacham<sup>110</sup>, M.D. Beattie<sup>72</sup>, T. Beau<sup>80</sup>, P.H. Beauchemin<sup>160</sup>, R. Beccherle<sup>123a,123b</sup>, P. Bechtel<sup>21</sup>, H.P. Beck<sup>17,g</sup>, K. Becker<sup>119</sup>, M. Becker<sup>83</sup>, M. Beckingham<sup>169</sup>, C. Becot<sup>109</sup>, A.J. Beddall<sup>19e</sup>, A. Beddall<sup>19b</sup>, V.A. Bednyakov<sup>65</sup>, M. Bedognetti<sup>106</sup>, C.P. Bee<sup>147</sup>, L.J. Beemster<sup>106</sup>, T.A. Beermann<sup>30</sup>, M. Beger<sup>25</sup>, J.K. Behr<sup>119</sup>, C. Belanger-Champagne<sup>87</sup>, A.S. Bell<sup>78</sup>, W.H. Bell<sup>49</sup>, G. Bella<sup>152</sup>, L. Bellagamba<sup>20a</sup>, A. Bellerive<sup>29</sup>, M. Bellomo<sup>86</sup>, K. Belotskiy<sup>97</sup>, O. Beltramello<sup>30</sup>, N.L. Belyaev<sup>97</sup>, O. Benary<sup>152</sup>, D. Benchekroun<sup>134a</sup>, M. Bender<sup>99</sup>, K. Bendtz<sup>145a,145b</sup>, N. Benekos<sup>10</sup>, Y. Benhammou<sup>152</sup>, E. Benhar Noccioli<sup>175</sup>, J. Benitez<sup>63</sup>, J.A. Benitez Garcia<sup>158b</sup>, D.P. Benjamin<sup>45</sup>, J.R. Bensinger<sup>23</sup>, S. Bentvelsen<sup>106</sup>, L. Beresford<sup>119</sup>, M. Beretta<sup>47</sup>, D. Berge<sup>106</sup>, E. Bergeas Kuutmann<sup>165</sup>, N. Berger<sup>5</sup>, F. Berghaus<sup>168</sup>, J. Beringer<sup>15</sup>, S. Berlendis<sup>55</sup>, C. 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Black<sup>149</sup>, J.E. Black<sup>142</sup>, K.M. Black<sup>22</sup>, D. Blackburn<sup>137</sup>, R.E. Blair<sup>6</sup>, J.-B. Blanchard<sup>135</sup>, J.E. Blanco<sup>77</sup>, T. Blazek<sup>143a</sup>, I. Bloch<sup>42</sup>,

C. Blocker<sup>23</sup>, W. Blum<sup>83,\*</sup>, U. Blumenschein<sup>54</sup>, S. Blunier<sup>32a</sup>, G.J. Bobbink<sup>106</sup>, V.S. Bobrovnikov<sup>108,c</sup>, S.S. Bocchetta<sup>81</sup>, A. Bocci<sup>45</sup>, C. Bock<sup>99</sup>, M. Boehler<sup>48</sup>, D. Boerner<sup>174</sup>, J.A. Bogaerts<sup>30</sup>, D. Bogavac<sup>13</sup>, A.G. Bogdanchikov<sup>108</sup>, C. Bohm<sup>145a</sup>, V. Boisvert<sup>77</sup>, T. Bold<sup>38a</sup>, V. Boldea<sup>26b</sup>, A.S. Boldyrev<sup>98</sup>, M. Bomben<sup>80</sup>, M. Bona<sup>76</sup>, M. Boonekamp<sup>135</sup>, A. Borisov<sup>129</sup>, G. Borissov<sup>72</sup>, J. Bortfeldt<sup>99</sup>, D. Bortoletto<sup>119</sup>, V. Bortolotto<sup>60a,60b,60c</sup>, K. Bos<sup>106</sup>, D. Boscherini<sup>20a</sup>, M. Bosman<sup>12</sup>, J.D. Bossio Sola<sup>27</sup>, J. Boudreau<sup>124</sup>, J. Bouffard<sup>2</sup>, E.V. Bouhova-Thacker<sup>72</sup>, D. Boumediene<sup>34</sup>, C. Bourdarios<sup>116</sup>, N. Bousson<sup>113</sup>, S.K. Boutle<sup>53</sup>, A. Boveia<sup>30</sup>, J. Boyd<sup>30</sup>, I.R. Boyko<sup>65</sup>, J. Bracinik<sup>18</sup>, A. Brandt<sup>8</sup>, G. Brandt<sup>54</sup>, O. Brandt<sup>58a</sup>, U. Bratzler<sup>155</sup>, B. Brau<sup>86</sup>, J.E. Brau<sup>115</sup>, H.M. Braun<sup>174,\*</sup>, W.D. Breaden Madden<sup>53</sup>, K. Brendlinger<sup>121</sup>, A.J. Brennan<sup>88</sup>, L. Brenner<sup>106</sup>, R. Brenner<sup>165</sup>, S. Bressler<sup>171</sup>, T.M. Bristow<sup>46</sup>, D. Britton<sup>53</sup>, D. Britzger<sup>42</sup>, F.M. Brochu<sup>28</sup>, I. Brock<sup>21</sup>, R. Brock<sup>90</sup>, G. Brooijmans<sup>35</sup>, T. Brooks<sup>77</sup>, W.K. Brooks<sup>32b</sup>, J. Brosamer<sup>15</sup>, E. Brost<sup>115</sup>, J.H. Broughton<sup>18</sup>, P.A. Bruckman de Renstrom<sup>39</sup>, D. Bruncko<sup>143b</sup>, R. Bruneliere<sup>48</sup>, A. Bruni<sup>20a</sup>, G. Bruni<sup>20a</sup>, B.H. Brunt<sup>28</sup>, M. Bruschi<sup>20a</sup>, N. Bruscino<sup>21</sup>, P. Bryant<sup>31</sup>, L. Bryngemark<sup>81</sup>, T. Buanes<sup>14</sup>, Q. Buat<sup>141</sup>, P. Buchholz<sup>140</sup>, A.G. Buckley<sup>53</sup>, I.A. Budagov<sup>65</sup>, F. Buehrer<sup>48</sup>, M.K. Bugge<sup>118</sup>, O. Bulekov<sup>97</sup>, D. Bullock<sup>8</sup>, H. Burckhart<sup>30</sup>, S. Burdin<sup>74</sup>, C.D. Burgard<sup>48</sup>, B. Burghgrave<sup>107</sup>, K. Burka<sup>39</sup>, S. Burke<sup>130</sup>, I. Burmeister<sup>43</sup>, E. Busato<sup>34</sup>, D. Büscher<sup>48</sup>, V. Büscher<sup>83</sup>, P. Bussey<sup>53</sup>, J.M. Butler<sup>22</sup>, A.I. Butt<sup>3</sup>, C.M. Buttar<sup>53</sup>, J.M. Butterworth<sup>78</sup>, P. Butti<sup>106</sup>, W. Buttinger<sup>25</sup>, A. Buzatu<sup>53</sup>, A.R. Buzykaev<sup>108,c</sup>, S. Cabrera Urbán<sup>166</sup>, D. Caforio<sup>127</sup>, V.M. Cairo<sup>37a,37b</sup>, O. Cakir<sup>4a</sup>, N. Calace<sup>49</sup>, P. Calafiura<sup>15</sup>, A. Calandri<sup>85</sup>, G. Calderini<sup>80</sup>, P. Calfayan<sup>99</sup>, L.P. Caloba<sup>24a</sup>, D. Calvet<sup>34</sup>, S. Calvet<sup>34</sup>, T.P. Calvet<sup>85</sup>, R. Camacho Toro<sup>31</sup>, S. Camarda<sup>42</sup>, P. Camarri<sup>132a,132b</sup>, D. Cameron<sup>118</sup>, R. Caminal Armadans<sup>164</sup>, C. Camincher<sup>55</sup>, S. Campana<sup>30</sup>, M. Campanelli<sup>78</sup>, A. Campoverde<sup>147</sup>, V. Canale<sup>103a,103b</sup>, A. Canepa<sup>158a</sup>, M. Cano Bret<sup>33e</sup>, J. Cantero<sup>82</sup>, R. Cantrill<sup>125a</sup>, T. Cao<sup>40</sup>, M.D.M. Capeans Garrido<sup>30</sup>, I. Caprini<sup>26b</sup>, M. Caprini<sup>26b</sup>, M. Capua<sup>37a,37b</sup>, R. Caputo<sup>83</sup>, R.M. Carbone<sup>35</sup>, R. Cardarelli<sup>132a</sup>, F. Cardillo<sup>48</sup>, T. Carli<sup>30</sup>, G. Carlino<sup>103a</sup>, L. Carminati<sup>91a,91b</sup>, S. Caron<sup>105</sup>, E. Carquin<sup>32a</sup>, G.D. Carrillo-Montoya<sup>30</sup>, J.R. Carter<sup>28</sup>, J. Carvalho<sup>125a,125c</sup>, D. Casadei<sup>78</sup>, M.P. Casado<sup>12,h</sup>, M. Casolino<sup>12</sup>, D.W. Casper<sup>162</sup>, E. Castaneda-Miranda<sup>144a</sup>, A. Castelli<sup>106</sup>, V. Castillo Gimenez<sup>166</sup>, N.F. Castro<sup>125a,i</sup>, A. Catinaccio<sup>30</sup>, J.R. Catmore<sup>118</sup>, A. Cattai<sup>30</sup>, J. Caudron<sup>83</sup>, V. Cavaliere<sup>164</sup>, D. Cavalli<sup>91a</sup>, M. Cavalli-Sforza<sup>12</sup>, V. Cavasinni<sup>123a,123b</sup>, F. Ceradini<sup>133a,133b</sup>, L. Cerda Alberich<sup>166</sup>, B.C. Cerio<sup>45</sup>, A.S. Cerqueira<sup>24b</sup>, A. Cerri<sup>148</sup>, L. Cerrito<sup>76</sup>, F. Cerutti<sup>15</sup>, M. Cerv<sup>30</sup>, A. Cervelli<sup>17</sup>, S.A. Cetin<sup>19d</sup>, A. Chafaq<sup>134a</sup>, D. Chakraborty<sup>107</sup>, I. Chalupkova<sup>128</sup>, S.K. Chan<sup>57</sup>, Y.L. Chan<sup>60a</sup>, P. Chang<sup>164</sup>, J.D. Chapman<sup>28</sup>, D.G. Charlton<sup>18</sup>, A. Chatterjee<sup>49</sup>, C.C. Chau<sup>157</sup>, C.A. Chavez Barajas<sup>148</sup>, S. Che<sup>110</sup>, S. Cheatham<sup>72</sup>, A. Chegwidan<sup>90</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>158a</sup>, G.A. Chelkov<sup>65,j</sup>, M.A. Chelstowska<sup>89</sup>, C. Chen<sup>64</sup>, H. Chen<sup>25</sup>, K. Chen<sup>147</sup>, S. Chen<sup>33c</sup>, S. Chen<sup>154</sup>, X. Chen<sup>33f</sup>, Y. Chen<sup>67</sup>, H.C. Cheng<sup>89</sup>, Y. Cheng<sup>31</sup>, A. Cheplakov<sup>65</sup>, E. Cheremushkina<sup>129</sup>, R. Cherkaoui El Moursli<sup>134e</sup>, V. Chernyatin<sup>25,\*</sup>, E. Cheu<sup>7</sup>, L. Chevalier<sup>135</sup>, V. Chiarella<sup>47</sup>, G. Chiarelli<sup>123a,123b</sup>, G. Chiodini<sup>73a</sup>, A.S. Chisholm<sup>18</sup>, A. Chitan<sup>26b</sup>, M.V. Chizhov<sup>65</sup>, K. Choi<sup>61</sup>, S. Chouridou<sup>9</sup>, B.K.B. Chow<sup>99</sup>, V. Christodoulou<sup>78</sup>, D. Chromek-Burckhart<sup>30</sup>, J. Chudoba<sup>126</sup>, A.J. Chuinard<sup>87</sup>, J.J. Chwastowski<sup>39</sup>, L. Chytka<sup>114</sup>, G. Ciapetti<sup>131a,131b</sup>, A.K. Ciftci<sup>4a</sup>, D. Cinca<sup>53</sup>, V. Cindro<sup>75</sup>, I.A. Cioara<sup>21</sup>, A. Ciocio<sup>15</sup>, F. Ciotto<sup>103a,103b</sup>, Z.H. Citron<sup>171</sup>, M. Ciubancan<sup>26b</sup>, A. Clark<sup>49</sup>, B.L. Clark<sup>57</sup>, P.J. Clark<sup>46</sup>, R.N. Clarke<sup>15</sup>, C. Clement<sup>145a,145b</sup>, Y. Coadou<sup>85</sup>, M. Cobal<sup>163a,163c</sup>, A. Coccaro<sup>49</sup>, J. Cochran<sup>64</sup>, L. Coffey<sup>23</sup>, L. Colasurdo<sup>105</sup>, B. Cole<sup>35</sup>, S. Cole<sup>107</sup>, A.P. Colijn<sup>106</sup>, J. Collot<sup>55</sup>, T. Colombo<sup>30</sup>, G. Compostella<sup>100</sup>, P. Conde Muiño<sup>125a,125b</sup>, E. Coniavitis<sup>48</sup>, S.H. Connell<sup>144b</sup>, I.A. Connelly<sup>77</sup>, V. Consorti<sup>48</sup>, S. Constantinescu<sup>26b</sup>, C. Conta<sup>120a,120b</sup>, G. Conti<sup>30</sup>, F. Conventi<sup>103a,k</sup>, M. Cooke<sup>15</sup>, B.D. Cooper<sup>78</sup>, A.M. Cooper-Sarkar<sup>119</sup>, T. Cornelissen<sup>174</sup>, M. Corradi<sup>131a,131b</sup>, F. Corriveau<sup>87,l</sup>, A. Corso-Radu<sup>162</sup>, A. Cortes-Gonzalez<sup>12</sup>, G. Cortiana<sup>100</sup>, G. Costa<sup>91a</sup>, M.J. Costa<sup>166</sup>, D. Costanzo<sup>138</sup>, G. Cottin<sup>28</sup>, G. Cowan<sup>77</sup>, B.E. Cox<sup>84</sup>, K. Cranmer<sup>109</sup>, S.J. Crawley<sup>53</sup>, G. Cree<sup>29</sup>, S. Crépe-Renaudin<sup>55</sup>, F. Crescioli<sup>80</sup>, W.A. Cribbs<sup>145a,145b</sup>, M. Crispin Ortuzar<sup>119</sup>, M. Cristinziani<sup>21</sup>, V. Croft<sup>105</sup>, G. Crosetti<sup>37a,37b</sup>,

T. Cuhadar Donszelmann<sup>138</sup>, J. Cummings<sup>175</sup>, M. Curatolo<sup>47</sup>, J. Cúth<sup>83</sup>, C. Cuthbert<sup>149</sup>, H. Czirr<sup>140</sup>, P. Czodrowski<sup>3</sup>, S. D'Auria<sup>53</sup>, M. D'Onofrio<sup>74</sup>, M.J. Da Cunha Sargedas De Sousa<sup>125a,125b</sup>, C. Da Via<sup>84</sup>, W. Dabrowski<sup>38a</sup>, T. Dai<sup>89</sup>, O. Dale<sup>14</sup>, F. Dallaire<sup>94</sup>, C. Dallapiccola<sup>86</sup>, M. Dam<sup>36</sup>, J.R. Dandoy<sup>31</sup>, N.P. Dang<sup>48</sup>, A.C. Daniells<sup>18</sup>, N.S. Dann<sup>84</sup>, M. Danning<sup>167</sup>, M. Dano Hoffmann<sup>135</sup>, V. Dao<sup>48</sup>, G. Darbo<sup>50a</sup>, S. Darmora<sup>8</sup>, J. Dassoulas<sup>3</sup>, A. Dattagupta<sup>61</sup>, W. Davey<sup>21</sup>, C. David<sup>168</sup>, T. Davidek<sup>128</sup>, M. Davies<sup>152</sup>, P. Davison<sup>78</sup>, Y. Davygora<sup>58a</sup>, E. Dawe<sup>88</sup>, I. Dawson<sup>138</sup>, R.K. Daya-Ishmukhametova<sup>86</sup>, K. De<sup>8</sup>, R. de Asmundis<sup>103a</sup>, A. De Benedetti<sup>112</sup>, S. De Castro<sup>20a,20b</sup>, S. De Cecco<sup>80</sup>, N. De Groot<sup>105</sup>, P. de Jong<sup>106</sup>, H. De la Torre<sup>82</sup>, F. De Lorenzi<sup>64</sup>, D. De Pedis<sup>131a</sup>, A. De Salvo<sup>131a</sup>, U. De Sanctis<sup>148</sup>, A. De Santo<sup>148</sup>, J.B. De Vivie De Regie<sup>116</sup>, W.J. Dearnaley<sup>72</sup>, R. Debbe<sup>25</sup>, C. Debenedetti<sup>136</sup>, D.V. Dedovich<sup>65</sup>, I. Deigaard<sup>106</sup>, J. Del Peso<sup>82</sup>, T. Del Prete<sup>123a,123b</sup>, D. Delgove<sup>116</sup>, F. Deliot<sup>135</sup>, C.M. Delitzsch<sup>49</sup>, M. Deliyergiyev<sup>75</sup>, A. Dell'Acqua<sup>30</sup>, L. Dell'Asta<sup>22</sup>, M. Dell'Orso<sup>123a,123b</sup>, M. Della Pietra<sup>103a,k</sup>, D. della Volpe<sup>49</sup>, M. Delmastro<sup>5</sup>, P.A. Delsart<sup>55</sup>, C. Deluca<sup>106</sup>, D.A. DeMarco<sup>157</sup>, S. Demers<sup>175</sup>, M. Demichev<sup>65</sup>, A. Demilly<sup>80</sup>, S.P. Denisov<sup>129</sup>, D. Denysiuk<sup>135</sup>, D. Derendarz<sup>39</sup>, J.E. Derkaoui<sup>134d</sup>, F. Derue<sup>80</sup>, P. Dervan<sup>74</sup>, K. Desch<sup>21</sup>, C. Deterre<sup>42</sup>, K. Dette<sup>43</sup>, P.O. Deviveiros<sup>30</sup>, A. Dewhurst<sup>130</sup>, S. Dhaliwal<sup>23</sup>, A. Di Ciaccio<sup>132a,132b</sup>, L. Di Ciaccio<sup>5</sup>, W.K. Di Clemente<sup>121</sup>, A. Di Domenico<sup>131a,131b</sup>, C. Di Donato<sup>131a,131b</sup>, A. Di Girolamo<sup>30</sup>, B. Di Girolamo<sup>30</sup>, A. Di Mattia<sup>151</sup>, B. Di Micco<sup>133a,133b</sup>, R. Di Nardo<sup>47</sup>, A. Di Simone<sup>48</sup>, R. Di Sipio<sup>157</sup>, D. Di Valentino<sup>29</sup>, C. Diaconu<sup>85</sup>, M. Diamond<sup>157</sup>, F.A. Dias<sup>46</sup>, M.A. Diaz<sup>32a</sup>, E.B. Diehl<sup>89</sup>, J. Dietrich<sup>16</sup>, S. Diglio<sup>85</sup>, A. Dimitrievska<sup>13</sup>, J. Dingfelder<sup>21</sup>, P. Dita<sup>26b</sup>, S. Dita<sup>26b</sup>, F. Dittus<sup>30</sup>, F. Djama<sup>85</sup>, T. Djobava<sup>51b</sup>, J.I. Djuvsland<sup>58a</sup>, M.A.B. do Vale<sup>24c</sup>, D. Dobos<sup>30</sup>, M. Dobre<sup>26b</sup>, C. Dogliani<sup>81</sup>, T. Dohmae<sup>154</sup>, J. Dolejsi<sup>128</sup>, Z. Dolezal<sup>128</sup>, B.A. Dolgoshein<sup>97,\*</sup>, M. Donadelli<sup>24d</sup>, S. Donati<sup>123a,123b</sup>, P. Dondero<sup>120a,120b</sup>, J. Donini<sup>34</sup>, J. Dopke<sup>130</sup>, A. Doria<sup>103a</sup>, M.T. Dova<sup>71</sup>, A.T. Doyle<sup>53</sup>, E. Drechsler<sup>54</sup>, M. Dris<sup>10</sup>, Y. Du<sup>33d</sup>, J. Duarte-Camperderros<sup>152</sup>, E. Duchovni<sup>171</sup>, G. Duckeck<sup>99</sup>, O.A. Ducu<sup>26b</sup>, D. Duda<sup>106</sup>, A. Dudarev<sup>30</sup>, L. Dufflot<sup>116</sup>, L. Duguid<sup>77</sup>, M. Dührssen<sup>30</sup>, M. Dunford<sup>58a</sup>, H. Duran Yildiz<sup>4a</sup>, M. Düren<sup>52</sup>, A. Durglishvili<sup>51b</sup>, D. Duschinger<sup>44</sup>, B. Dutta<sup>42</sup>, M. Dyndal<sup>38a</sup>, C. Eckardt<sup>42</sup>, K.M. Ecker<sup>100</sup>, R.C. Edgar<sup>89</sup>, W. Edson<sup>2</sup>, N.C. Edwards<sup>46</sup>, T. Eifert<sup>30</sup>, G. Eigen<sup>14</sup>, K. Einsweiler<sup>15</sup>, T. Ekelof<sup>165</sup>, M. El Kacimi<sup>134c</sup>, V. Ellajosyula<sup>85</sup>, M. Ellert<sup>165</sup>, S. Elles<sup>5</sup>, F. Ellinghaus<sup>174</sup>, A.A. Elliot<sup>168</sup>, N. Ellis<sup>30</sup>, J. Elmsheuser<sup>99</sup>, M. Elsing<sup>30</sup>, D. Emelianov<sup>130</sup>, Y. Enari<sup>154</sup>, O.C. Endner<sup>83</sup>, M. Endo<sup>117</sup>, J.S. Ennis<sup>169</sup>, J. Erdmann<sup>43</sup>, A. Ereditato<sup>17</sup>, G. Ernis<sup>174</sup>, J. Ernst<sup>2</sup>, M. Ernst<sup>25</sup>, S. Errede<sup>164</sup>, E. Ertel<sup>83</sup>, M. Escalier<sup>116</sup>, H. Esch<sup>43</sup>, C. Escobar<sup>124</sup>, B. Esposito<sup>47</sup>, A.I. Etienne<sup>135</sup>, E. Etzion<sup>152</sup>, H. Evans<sup>61</sup>, A. Ezhilov<sup>122</sup>, L. Fabbri<sup>20a,20b</sup>, G. Facini<sup>31</sup>, R.M. Fakhruddinov<sup>129</sup>, S. Falciano<sup>131a</sup>, R.J. Falla<sup>78</sup>, J. Faltova<sup>128</sup>, Y. Fang<sup>33a</sup>, M. Fanti<sup>91a,91b</sup>, A. Farbin<sup>8</sup>, A. Farilla<sup>133a</sup>, C. Farina<sup>124</sup>, T. Farooque<sup>12</sup>, S. Farrell<sup>15</sup>, S.M. Farrington<sup>169</sup>, P. Farthouat<sup>30</sup>, F. Fassi<sup>134e</sup>, P. Fassnacht<sup>30</sup>, D. Fassouliotis<sup>9</sup>, M. Fauci Giannelli<sup>77</sup>, A. Favareto<sup>50a,50b</sup>, L. Fayard<sup>116</sup>, O.L. Fedin<sup>122,m</sup>, W. Fedorko<sup>167</sup>, S. Feigl<sup>118</sup>, L. Felgioni<sup>85</sup>, C. Feng<sup>33d</sup>, E.J. Feng<sup>30</sup>, H. Feng<sup>89</sup>, A.B. Fenyuk<sup>129</sup>, L. Feremenga<sup>8</sup>, P. Fernandez Martinez<sup>166</sup>, S. Fernandez Perez<sup>12</sup>, J. Ferrando<sup>53</sup>, A. Ferrari<sup>165</sup>, P. Ferrari<sup>106</sup>, R. Ferrari<sup>120a</sup>, D.E. Ferreira de Lima<sup>53</sup>, A. Ferrer<sup>166</sup>, D. Ferrere<sup>49</sup>, C. Ferretti<sup>89</sup>, A. Ferretto Parodi<sup>50a,50b</sup>, F. Fiedler<sup>83</sup>, A. Filipčič<sup>75</sup>, M. Filipuzzi<sup>42</sup>, F. Filthaut<sup>105</sup>, M. Fincke-Keeler<sup>168</sup>, K.D. Finelli<sup>149</sup>, M.C.N. Fiolhais<sup>125a,125c</sup>, L. Fiorini<sup>166</sup>, A. Firan<sup>40</sup>, A. Fischer<sup>2</sup>, C. Fischer<sup>12</sup>, J. Fischer<sup>174</sup>, W.C. Fisher<sup>90</sup>, N. Flaschel<sup>42</sup>, I. Fleck<sup>140</sup>, P. Fleischmann<sup>89</sup>, G.T. Fletcher<sup>138</sup>, G. Fletcher<sup>76</sup>, R.R.M. Fletcher<sup>121</sup>, T. Flick<sup>174</sup>, A. Floderus<sup>81</sup>, L.R. Flores Castillo<sup>60a</sup>, M.J. Flowerdew<sup>100</sup>, G.T. Forcolin<sup>84</sup>, A. Formica<sup>135</sup>, A. Forti<sup>84</sup>, D. Fournier<sup>116</sup>, H. Fox<sup>72</sup>, S. Fracchia<sup>12</sup>, P. Francavilla<sup>80</sup>, M. Franchini<sup>20a,20b</sup>, D. Francis<sup>30</sup>, L. Franconi<sup>118</sup>, M. Franklin<sup>57</sup>, M. Frate<sup>162</sup>, M. Fraternali<sup>120a,120b</sup>, D. Freeborn<sup>78</sup>, S.M. Fressard-Batraneanu<sup>30</sup>, F. Friedrich<sup>44</sup>, D. Froidevaux<sup>30</sup>, J.A. Frost<sup>119</sup>, C. Fukunaga<sup>155</sup>, E. Fullana Torregrosa<sup>83</sup>, T. Fusayasu<sup>101</sup>, J. Fuster<sup>166</sup>, C. Gabaldon<sup>55</sup>, O. Gabizon<sup>174</sup>, A. Gabrielli<sup>20a,20b</sup>, A. Gabrielli<sup>15</sup>, G.P. Gach<sup>38a</sup>, S. Gadatsch<sup>30</sup>, S. Gadomski<sup>49</sup>, G. Gagliardi<sup>50a,50b</sup>, P. Gagnon<sup>61</sup>, C. Galea<sup>105</sup>, B. Galhardo<sup>125a,125c</sup>, E.J. Gallas<sup>119</sup>, B.J. Gallop<sup>130</sup>, P. Gallus<sup>127</sup>, G. Galster<sup>36</sup>, K.K. Gan<sup>110</sup>, J. Gao<sup>33b,85</sup>, Y. Gao<sup>46</sup>, Y.S. Gao<sup>142,f</sup>, F.M. Garay Walls<sup>46</sup>, C. García<sup>166</sup>,

J.E. García Navarro<sup>166</sup>, M. Garcia-Sciveres<sup>15</sup>, R.W. Gardner<sup>31</sup>, N. Garelli<sup>142</sup>, V. Garonne<sup>118</sup>,  
 A. Gascon Bravo<sup>42</sup>, C. Gatti<sup>47</sup>, A. Gaudiello<sup>50a,50b</sup>, G. Gaudio<sup>120a</sup>, B. Gaur<sup>140</sup>, L. Gauthier<sup>94</sup>,  
 I.L. Gavrilenko<sup>95</sup>, C. Gay<sup>167</sup>, G. Gaycken<sup>21</sup>, E.N. Gazis<sup>10</sup>, Z. Gecse<sup>167</sup>, C.N.P. Gee<sup>130</sup>,  
 Ch. Geich-Gimbel<sup>21</sup>, M.P. Geisler<sup>58a</sup>, C. Gemme<sup>50a</sup>, M.H. Genest<sup>55</sup>, C. Geng<sup>33b,n</sup>, S. Gentile<sup>131a,131b</sup>,  
 S. George<sup>77</sup>, D. Gerbaudo<sup>162</sup>, A. Gershon<sup>152</sup>, S. Ghasemi<sup>140</sup>, H. Ghazlane<sup>134b</sup>, B. Giacobbe<sup>20a</sup>,  
 S. Giagu<sup>131a,131b</sup>, P. Giannetti<sup>123a,123b</sup>, B. Gibbard<sup>25</sup>, S.M. Gibson<sup>77</sup>, M. Gignac<sup>167</sup>, M. Gilchriese<sup>15</sup>,  
 T.P.S. Gillam<sup>28</sup>, D. Gillberg<sup>29</sup>, G. Gilles<sup>174</sup>, D.M. Gingrich<sup>3,d</sup>, N. Giokaris<sup>9</sup>, M.P. Giordani<sup>163a,163c</sup>,  
 F.M. Giorgi<sup>20a</sup>, F.M. Giorgi<sup>16</sup>, P.F. Giraud<sup>135</sup>, P. Giromini<sup>57</sup>, D. Giugni<sup>91a</sup>, C. Giuliani<sup>100</sup>, M. Giulini<sup>58b</sup>,  
 B.K. Gjelsten<sup>118</sup>, S. Gkaitatzis<sup>153</sup>, I. Gkialas<sup>153</sup>, E.L. Gkoukousis<sup>116</sup>, L.K. Gladilin<sup>98</sup>, C. Glasman<sup>82</sup>,  
 J. Glatzer<sup>30</sup>, P.C.F. Glaysheer<sup>46</sup>, A. Glazov<sup>42</sup>, M. Goblirsch-Kolb<sup>100</sup>, J. Godlewski<sup>39</sup>, S. Goldfarb<sup>89</sup>,  
 T. Golling<sup>49</sup>, D. Golubkov<sup>129</sup>, A. Gomes<sup>125a,125b,125d</sup>, R. Gonçalo<sup>125a</sup>,  
 J. Goncalves Pinto Firmino Da Costa<sup>135</sup>, L. Gonella<sup>18</sup>, A. Gongadze<sup>65</sup>, S. González de la Hoz<sup>166</sup>,  
 G. Gonzalez Parra<sup>12</sup>, S. Gonzalez-Sevilla<sup>49</sup>, L. Goossens<sup>30</sup>, P.A. Gorbounov<sup>96</sup>, H.A. Gordon<sup>25</sup>,  
 I. Gorelov<sup>104</sup>, B. Gorini<sup>30</sup>, E. Gorini<sup>73a,73b</sup>, A. Gorišek<sup>75</sup>, E. Gornicki<sup>39</sup>, A.T. Goshaw<sup>45</sup>, C. Gössling<sup>43</sup>,  
 M.I. Gostkin<sup>65</sup>, C.R. Goudet<sup>116</sup>, D. Goujdami<sup>134c</sup>, A.G. Goussiou<sup>137</sup>, N. Govender<sup>144b</sup>, E. Gozani<sup>151</sup>,  
 L. Graber<sup>54</sup>, I. Grabowska-Bold<sup>38a</sup>, P.O.J. Gradin<sup>165</sup>, P. Grafström<sup>20a,20b</sup>, J. Gramling<sup>49</sup>, E. Gramstad<sup>118</sup>,  
 S. Grancagnolo<sup>16</sup>, V. Gratchev<sup>122</sup>, H.M. Gray<sup>30</sup>, E. Graziani<sup>133a</sup>, Z.D. Greenwood<sup>79,o</sup>, C. Greife<sup>21</sup>,  
 K. Gregersen<sup>78</sup>, I.M. Gregor<sup>42</sup>, P. Grenier<sup>142</sup>, K. Grevtsov<sup>5</sup>, J. Griffiths<sup>8</sup>, A.A. Grillo<sup>136</sup>, K. Grimm<sup>72</sup>,  
 S. Grinstein<sup>12,p</sup>, Ph. Gris<sup>34</sup>, J.-F. Grivaz<sup>116</sup>, S. Groh<sup>83</sup>, J.P. Grohs<sup>44</sup>, E. Gross<sup>171</sup>, J. Grosse-Knetter<sup>54</sup>,  
 G.C. Grossi<sup>79</sup>, Z.J. Grout<sup>148</sup>, L. Guan<sup>89</sup>, W. Guan<sup>172</sup>, J. Guenther<sup>127</sup>, F. Guescini<sup>49</sup>, D. Guest<sup>162</sup>,  
 O. Gueta<sup>152</sup>, E. Guido<sup>50a,50b</sup>, T. Guillemin<sup>5</sup>, S. Guindon<sup>2</sup>, U. Gul<sup>53</sup>, C. Gumpert<sup>30</sup>, J. Guo<sup>33e</sup>,  
 Y. Guo<sup>33b,n</sup>, S. Gupta<sup>119</sup>, G. Gustavino<sup>131a,131b</sup>, P. Gutierrez<sup>112</sup>, N.G. Gutierrez Ortiz<sup>78</sup>, C. Gutschow<sup>44</sup>,  
 C. Guyot<sup>135</sup>, C. Gwenlan<sup>119</sup>, C.B. Gwilliam<sup>74</sup>, A. Haas<sup>109</sup>, C. Haber<sup>15</sup>, H.K. Hadavand<sup>8</sup>, N. Haddad<sup>134e</sup>,  
 A. Hader<sup>85</sup>, P. Haefner<sup>21</sup>, S. Hageböck<sup>21</sup>, Z. Hajduk<sup>39</sup>, H. Hakobyan<sup>176,\*</sup>, M. Haleem<sup>42</sup>, J. Haley<sup>113</sup>,  
 D. Hall<sup>119</sup>, G. Halladjian<sup>90</sup>, G.D. Hallowell<sup>85</sup>, K. Hamacher<sup>174</sup>, P. Hamal<sup>114</sup>, K. Hamano<sup>168</sup>,  
 A. Hamilton<sup>144a</sup>, G.N. Hamity<sup>138</sup>, P.G. Hamnett<sup>42</sup>, L. Han<sup>33b</sup>, K. Hanagaki<sup>66,q</sup>, K. Hanawa<sup>154</sup>,  
 M. Hance<sup>136</sup>, B. Haney<sup>121</sup>, P. Hanke<sup>58a</sup>, R. Hanna<sup>135</sup>, J.B. Hansen<sup>36</sup>, J.D. Hansen<sup>36</sup>, M.C. Hansen<sup>21</sup>,  
 P.H. Hansen<sup>36</sup>, K. Hara<sup>159</sup>, A.S. Hard<sup>172</sup>, T. Harenberg<sup>174</sup>, F. Hariri<sup>116</sup>, S. Harkusha<sup>92</sup>,  
 R.D. Harrington<sup>46</sup>, P.F. Harrison<sup>169</sup>, F. Hartjes<sup>106</sup>, M. Hasegawa<sup>67</sup>, Y. Hasegawa<sup>139</sup>, A. Hasib<sup>112</sup>,  
 S. Hassani<sup>135</sup>, S. Haug<sup>17</sup>, R. Hauser<sup>90</sup>, L. Hauswald<sup>44</sup>, M. Havranek<sup>126</sup>, C.M. Hawkes<sup>18</sup>,  
 R.J. Hawkings<sup>30</sup>, A.D. Hawkins<sup>81</sup>, D. Hayden<sup>90</sup>, C.P. Hays<sup>119</sup>, J.M. Hays<sup>76</sup>, H.S. Hayward<sup>74</sup>,  
 S.J. Haywood<sup>130</sup>, S.J. Head<sup>18</sup>, T. Heck<sup>83</sup>, V. Hedberg<sup>81</sup>, L. Heelan<sup>8</sup>, S. Heim<sup>121</sup>, T. Heim<sup>15</sup>,  
 B. Heinemann<sup>15</sup>, J.J. Heinrich<sup>99</sup>, L. Heinrich<sup>109</sup>, C. Heinz<sup>52</sup>, J. Hejbal<sup>126</sup>, L. Helary<sup>22</sup>,  
 S. Hellman<sup>145a,145b</sup>, C. Helsen<sup>30</sup>, J. Henderson<sup>119</sup>, R.C.W. Henderson<sup>72</sup>, Y. Heng<sup>172</sup>, S. Henkelmann<sup>167</sup>,  
 A.M. Henriques Correia<sup>30</sup>, S. Henrot-Versille<sup>116</sup>, G.H. Herbert<sup>16</sup>, Y. Hernández Jiménez<sup>166</sup>, G. Herten<sup>48</sup>,  
 R. Hertenberger<sup>99</sup>, L. Hervas<sup>30</sup>, G.G. Hesketh<sup>78</sup>, N.P. Hessey<sup>106</sup>, J.W. Hetherly<sup>40</sup>, R. Hickling<sup>76</sup>,  
 E. Higón-Rodríguez<sup>166</sup>, E. Hill<sup>168</sup>, J.C. Hill<sup>28</sup>, K.H. Hiller<sup>42</sup>, S.J. Hillier<sup>18</sup>, I. Hinchliffe<sup>15</sup>, E. Hines<sup>121</sup>,  
 R.R. Hinman<sup>15</sup>, M. Hirose<sup>156</sup>, D. Hirschbuehl<sup>174</sup>, J. Hobbs<sup>147</sup>, N. Hod<sup>106</sup>, M.C. Hodgkinson<sup>138</sup>,  
 P. Hodgson<sup>138</sup>, A. Hoecker<sup>30</sup>, M.R. Hoefkamp<sup>104</sup>, F. Hoenig<sup>99</sup>, M. Hohlfeld<sup>83</sup>, D. Hohn<sup>21</sup>,  
 T.R. Holmes<sup>15</sup>, M. Homann<sup>43</sup>, T.M. Hong<sup>124</sup>, B.H. Hooberman<sup>164</sup>, W.H. Hopkins<sup>115</sup>, Y. Horii<sup>102</sup>,  
 A.J. Horton<sup>141</sup>, J.-Y. Hostachy<sup>55</sup>, S. Hou<sup>150</sup>, A. Hoummada<sup>134a</sup>, J. Howard<sup>119</sup>, J. Howarth<sup>42</sup>,  
 M. Hrabovsky<sup>114</sup>, I. Hristova<sup>16</sup>, J. Hrivnac<sup>116</sup>, T. Hryn'ova<sup>5</sup>, A. Hrynevich<sup>93</sup>, C. Hsu<sup>144c</sup>, P.J. Hsu<sup>150,r</sup>,  
 S.-C. Hsu<sup>137</sup>, D. Hu<sup>35</sup>, Q. Hu<sup>33b</sup>, Y. Huang<sup>42</sup>, Z. Hubacek<sup>127</sup>, F. Hubaut<sup>85</sup>, F. Huegging<sup>21</sup>,  
 T.B. Huffman<sup>119</sup>, E.W. Hughes<sup>35</sup>, G. Hughes<sup>72</sup>, M. Huhtinen<sup>30</sup>, T.A. Hülsing<sup>83</sup>, N. Huseynov<sup>65,b</sup>,  
 J. Huston<sup>90</sup>, J. Huth<sup>57</sup>, G. Iacobucci<sup>49</sup>, G. Iakovidis<sup>25</sup>, I. Ibragimov<sup>140</sup>, L. Iconomidou-Fayard<sup>116</sup>,  
 E. Ideal<sup>175</sup>, Z. Idrissi<sup>134e</sup>, P. Iengo<sup>30</sup>, O. Igonkina<sup>106</sup>, T. Iizawa<sup>170</sup>, Y. Ikegami<sup>66</sup>, M. Ikeno<sup>66</sup>,  
 Y. Ilchenko<sup>31,s</sup>, D. Iliadis<sup>153</sup>, N. Ilic<sup>142</sup>, T. Ince<sup>100</sup>, G. Introzzi<sup>120a,120b</sup>, P. Ioannou<sup>9,\*</sup>, M. Iodice<sup>133a</sup>,



K. Iordanidou<sup>35</sup>, V. Ippolito<sup>57</sup>, A. Irlles Quiles<sup>166</sup>, C. Isaksson<sup>165</sup>, M. Ishino<sup>68</sup>, M. Ishitsuka<sup>156</sup>,  
 R. Ishmukhametov<sup>110</sup>, C. Issever<sup>119</sup>, S. Istin<sup>19a</sup>, F. Ito<sup>159</sup>, J.M. Iturbe Ponce<sup>84</sup>, R. Iuppa<sup>132a,132b</sup>,  
 J. Ivarsson<sup>81</sup>, W. Iwanski<sup>39</sup>, H. Iwasaki<sup>66</sup>, J.M. Izen<sup>41</sup>, V. Izzo<sup>103a</sup>, S. Jabbar<sup>3</sup>, B. Jackson<sup>121</sup>,  
 M. Jackson<sup>74</sup>, P. Jackson<sup>1</sup>, V. Jain<sup>2</sup>, K.B. Jakobi<sup>83</sup>, K. Jakobs<sup>48</sup>, S. Jakobsen<sup>30</sup>, T. Jakoubek<sup>126</sup>,  
 D.O. Jamin<sup>113</sup>, D.K. Jana<sup>79</sup>, E. Jansen<sup>78</sup>, R. Jansky<sup>62</sup>, J. Janssen<sup>21</sup>, M. Janus<sup>54</sup>, G. Jarlskog<sup>81</sup>,  
 N. Javadov<sup>65,b</sup>, T. Javůrek<sup>48</sup>, F. Jeanneau<sup>135</sup>, L. Jeanty<sup>15</sup>, J. Jejelava<sup>51a,t</sup>, G.-Y. Jeng<sup>149</sup>, D. Jennens<sup>88</sup>,  
 P. Jenni<sup>48,u</sup>, J. Jentzsch<sup>43</sup>, C. Jeske<sup>169</sup>, S. Jézéquel<sup>5</sup>, H. Ji<sup>172</sup>, J. Jia<sup>147</sup>, H. Jiang<sup>64</sup>, Y. Jiang<sup>33b</sup>,  
 S. Jiggins<sup>78</sup>, J. Jimenez Pena<sup>166</sup>, S. Jin<sup>33a</sup>, A. Jinaru<sup>26b</sup>, O. Jinnouchi<sup>156</sup>, P. Johansson<sup>138</sup>, K.A. Johns<sup>7</sup>,  
 W.J. Johnson<sup>137</sup>, K. Jon-And<sup>145a,145b</sup>, G. Jones<sup>169</sup>, R.W.L. Jones<sup>72</sup>, S. Jones<sup>7</sup>, T.J. Jones<sup>74</sup>,  
 J. Jongmanns<sup>58a</sup>, P.M. Jorge<sup>125a,125b</sup>, J. Jovicevic<sup>158a</sup>, X. Ju<sup>172</sup>, A. Juste Rozas<sup>12,p</sup>, M.K. Köhler<sup>171</sup>,  
 A. Kaczmarska<sup>39</sup>, M. Kado<sup>116</sup>, H. Kagan<sup>110</sup>, M. Kagan<sup>142</sup>, S.J. Kahn<sup>85</sup>, E. Kajomovitz<sup>45</sup>,  
 C.W. Kalderon<sup>119</sup>, A. Kaluza<sup>83</sup>, S. Kama<sup>40</sup>, A. Kamenshchikov<sup>129</sup>, N. Kanaya<sup>154</sup>, S. Kaneti<sup>28</sup>,  
 V.A. Kantserov<sup>97</sup>, J. Kanzaki<sup>66</sup>, B. Kaplan<sup>109</sup>, L.S. Kaplan<sup>172</sup>, A. Kapliy<sup>31</sup>, D. Kar<sup>144c</sup>, K. Karakostas<sup>10</sup>,  
 A. Karamaoun<sup>3</sup>, N. Karastathis<sup>10,106</sup>, M.J. Kareem<sup>54</sup>, E. Karentzos<sup>10</sup>, M. Karnevskiy<sup>83</sup>, S.N. Karpov<sup>65</sup>,  
 Z.M. Karpova<sup>65</sup>, K. Karthik<sup>109</sup>, V. Kartvelishvili<sup>72</sup>, A.N. Karyukhin<sup>129</sup>, K. Kasahara<sup>159</sup>, L. Kashif<sup>72</sup>,  
 R.D. Kass<sup>110</sup>, A. Kastanas<sup>14</sup>, Y. Kataoka<sup>154</sup>, C. Kato<sup>154</sup>, A. Katre<sup>49</sup>, J. Katzy<sup>42</sup>, K. Kawade<sup>102</sup>,  
 K. Kawagoe<sup>70</sup>, T. Kawamoto<sup>154</sup>, G. Kawamura<sup>54</sup>, S. Kazama<sup>154</sup>, V.F. Kazanin<sup>108,c</sup>, R. Keeler<sup>168</sup>,  
 R. Kehoe<sup>40</sup>, J.S. Keller<sup>42</sup>, J.J. Kempster<sup>77</sup>, H. Keoshkerian<sup>84</sup>, O. Kepka<sup>126</sup>, B.P. Kerševan<sup>75</sup>,  
 S. Kersten<sup>174</sup>, R.A. Keyes<sup>87</sup>, F. Khalil-zada<sup>11</sup>, H. Khandanyan<sup>145a,145b</sup>, A. Khanov<sup>113</sup>,  
 A.G. Kharlamov<sup>108,c</sup>, T.J. Khoo<sup>28</sup>, V. Khovanskiy<sup>96</sup>, E. Khramov<sup>65</sup>, J. Khubua<sup>51b,v</sup>, S. Kido<sup>67</sup>,  
 H.Y. Kim<sup>8</sup>, S.H. Kim<sup>159</sup>, Y.K. Kim<sup>31</sup>, N. Kimura<sup>153</sup>, O.M. Kind<sup>16</sup>, B.T. King<sup>74</sup>, M. King<sup>166</sup>,  
 S.B. King<sup>167</sup>, J. Kirk<sup>130</sup>, A.E. Kiryunin<sup>100</sup>, T. Kishimoto<sup>67</sup>, D. Kisielewska<sup>38a</sup>, F. Kiss<sup>48</sup>, K. Kiuchi<sup>159</sup>,  
 O. Kivernyk<sup>135</sup>, E. Kladiva<sup>143b</sup>, M.H. Klein<sup>35</sup>, M. Klein<sup>74</sup>, U. Klein<sup>74</sup>, K. Kleinknecht<sup>83</sup>,  
 P. Klimek<sup>145a,145b</sup>, A. Klimentov<sup>25</sup>, R. Klingenberg<sup>43</sup>, J.A. Klinger<sup>138</sup>, T. Klioutchnikova<sup>30</sup>,  
 E.-E. Kluge<sup>58a</sup>, P. Kluit<sup>106</sup>, S. Kluth<sup>100</sup>, J. Knapik<sup>39</sup>, E. Kneringer<sup>62</sup>, E.B.F.G. Knoops<sup>85</sup>, A. Knue<sup>53</sup>,  
 A. Kobayashi<sup>154</sup>, D. Kobayashi<sup>156</sup>, T. Kobayashi<sup>154</sup>, M. Kobel<sup>44</sup>, M. Kocian<sup>142</sup>, P. Kodys<sup>128</sup>, T. Koffas<sup>29</sup>,  
 E. Koffeman<sup>106</sup>, L.A. Kogan<sup>119</sup>, T. Kohriki<sup>66</sup>, T. Koi<sup>142</sup>, H. Kolanoski<sup>16</sup>, M. Kolb<sup>58b</sup>, I. Koletsou<sup>5</sup>,  
 A.A. Komar<sup>95,\*</sup>, Y. Komori<sup>154</sup>, T. Kondo<sup>66</sup>, N. Kondrashova<sup>42</sup>, K. Köneke<sup>48</sup>, A.C. König<sup>105</sup>,  
 T. Kono<sup>66,w</sup>, R. Konoplich<sup>109,x</sup>, N. Konstantinidis<sup>78</sup>, R. Kopeliansky<sup>61</sup>, S. Koperny<sup>38a</sup>, L. Köpke<sup>83</sup>,  
 A.K. Kopp<sup>48</sup>, K. Korcyl<sup>39</sup>, K. Kordas<sup>153</sup>, A. Korn<sup>78</sup>, A.A. Korol<sup>108,c</sup>, I. Korolkov<sup>12</sup>, E.V. Korolkova<sup>138</sup>,  
 O. Kortner<sup>100</sup>, S. Kortner<sup>100</sup>, T. Kosek<sup>128</sup>, V.V. Kostyukhin<sup>21</sup>, V.M. Kotov<sup>65</sup>, A. Kotwal<sup>45</sup>,  
 A. Kourkoumeli-Charalampidi<sup>153</sup>, C. Kourkoumelis<sup>9</sup>, V. Kouskoura<sup>25</sup>, A. Koutsman<sup>158a</sup>,  
 A.B. Kowalewska<sup>39</sup>, R. Kowalewski<sup>168</sup>, T.Z. Kowalski<sup>38a</sup>, W. Kozanecki<sup>135</sup>, A.S. Kozhin<sup>129</sup>,  
 V.A. Kramarenko<sup>98</sup>, G. Kramberger<sup>75</sup>, D. Krasnopevtsev<sup>97</sup>, M.W. Krasny<sup>80</sup>, A. Krasznahorkay<sup>30</sup>,  
 J.K. Kraus<sup>21</sup>, A. Kravchenko<sup>25</sup>, M. Kretz<sup>58c</sup>, J. Kretzschmar<sup>74</sup>, K. Kreutzfeldt<sup>52</sup>, P. Krieger<sup>157</sup>,  
 K. Krizka<sup>31</sup>, K. Kroeninger<sup>43</sup>, H. Kroha<sup>100</sup>, J. Kroll<sup>121</sup>, J. Kroseberg<sup>21</sup>, J. Krstic<sup>13</sup>, U. Kruchonak<sup>65</sup>,  
 H. Krüger<sup>21</sup>, N. Krumnack<sup>64</sup>, A. Kruse<sup>172</sup>, M.C. Kruse<sup>45</sup>, M. Kruskal<sup>22</sup>, T. Kubota<sup>88</sup>, H. Kucuk<sup>78</sup>,  
 S. Kудay<sup>4b</sup>, J.T. Kuechler<sup>174</sup>, S. Kuehn<sup>48</sup>, A. Kugel<sup>58c</sup>, F. Kuger<sup>173</sup>, A. Kuhl<sup>136</sup>, T. Kuhl<sup>42</sup>, V. Kukhtin<sup>65</sup>,  
 R. Kukla<sup>135</sup>, Y. Kulchitsky<sup>92</sup>, S. Kuleshov<sup>32b</sup>, M. Kuna<sup>131a,131b</sup>, T. Kunigo<sup>68</sup>, A. Kupco<sup>126</sup>,  
 H. Kurashige<sup>67</sup>, Y.A. Kurochkin<sup>92</sup>, V. Kus<sup>126</sup>, E.S. Kuwertz<sup>168</sup>, M. Kuze<sup>156</sup>, J. Kvita<sup>114</sup>, T. Kwan<sup>168</sup>,  
 D. Kyriazopoulos<sup>138</sup>, A. La Rosa<sup>100</sup>, J.L. La Rosa Navarro<sup>24d</sup>, L. La Rotonda<sup>37a,37b</sup>, C. Lacasta<sup>166</sup>,  
 F. Lacava<sup>131a,131b</sup>, J. Lacey<sup>29</sup>, H. Lacker<sup>16</sup>, D. Lacour<sup>80</sup>, V.R. Lacuesta<sup>166</sup>, E. Ladygin<sup>65</sup>, R. Lafaye<sup>5</sup>,  
 B. Laforge<sup>80</sup>, T. Lagouri<sup>175</sup>, S. Lai<sup>54</sup>, S. Lammers<sup>61</sup>, W. Lampl<sup>7</sup>, E. Lançon<sup>135</sup>, U. Landgraf<sup>48</sup>,  
 M.P.J. Landon<sup>76</sup>, V.S. Lang<sup>58a</sup>, J.C. Lange<sup>12</sup>, A.J. Lankford<sup>162</sup>, F. Lanni<sup>25</sup>, K. Lantzsch<sup>21</sup>, A. Lanza<sup>120a</sup>,  
 S. Laplace<sup>80</sup>, C. Lapoire<sup>30</sup>, J.F. Laporte<sup>135</sup>, T. Lari<sup>91a</sup>, F. Lasagni Manghi<sup>20a,20b</sup>, M. Lassnig<sup>30</sup>,  
 P. Laurelli<sup>47</sup>, W. Lavrijsen<sup>15</sup>, A.T. Law<sup>136</sup>, P. Laycock<sup>74</sup>, T. Lazovich<sup>57</sup>, O. Le Dortz<sup>80</sup>, E. Le Guirriec<sup>85</sup>,  
 E. Le Menedeu<sup>12</sup>, E.P. Le Quilleuc<sup>135</sup>, M. LeBlanc<sup>168</sup>, T. LeCompte<sup>6</sup>, F. Ledroit-Guillon<sup>55</sup>, C.A. Lee<sup>25</sup>,

S.C. Lee<sup>150</sup>, L. Lee<sup>1</sup>, G. Lefebvre<sup>80</sup>, M. Lefebvre<sup>168</sup>, F. Legger<sup>99</sup>, C. Leggett<sup>15</sup>, A. Lehan<sup>74</sup>,  
 G. Lehmann Miotto<sup>30</sup>, X. Lei<sup>7</sup>, W.A. Leight<sup>29</sup>, A. Leisos<sup>153,y</sup>, A.G. Leister<sup>175</sup>, M.A.L. Leite<sup>24d</sup>,  
 R. Leitner<sup>128</sup>, D. Lellouch<sup>171</sup>, B. Lemmer<sup>54</sup>, K.J.C. Leney<sup>78</sup>, T. Lenz<sup>21</sup>, B. Lenzi<sup>30</sup>, R. Leone<sup>7</sup>,  
 S. Leone<sup>123a,123b</sup>, C. Leonidopoulos<sup>46</sup>, S. Leontsinis<sup>10</sup>, C. Leroy<sup>94</sup>, A.A.J. Lesage<sup>135</sup>, C.G. Lester<sup>28</sup>,  
 M. Levchenko<sup>122</sup>, J. Levêque<sup>5</sup>, D. Levin<sup>89</sup>, L.J. Levinson<sup>171</sup>, M. Levy<sup>18</sup>, A.M. Leyko<sup>21</sup>, M. Leyton<sup>41</sup>,  
 B. Li<sup>33b,z</sup>, H. Li<sup>147</sup>, H.L. Li<sup>31</sup>, L. Li<sup>45</sup>, L. Li<sup>33e</sup>, Q. Li<sup>33a</sup>, S. Li<sup>45</sup>, X. Li<sup>84</sup>, Y. Li<sup>140</sup>, Z. Liang<sup>136</sup>,  
 H. Liao<sup>34</sup>, B. Liberti<sup>132a</sup>, A. Liblong<sup>157</sup>, P. Lichard<sup>30</sup>, K. Lie<sup>164</sup>, J. Liebal<sup>21</sup>, W. Liebig<sup>14</sup>, C. Limbach<sup>21</sup>,  
 A. Limosani<sup>149</sup>, S.C. Lin<sup>150,aa</sup>, T.H. Lin<sup>83</sup>, B.E. Lindquist<sup>147</sup>, E. Lipeles<sup>121</sup>, A. Lipniacka<sup>14</sup>,  
 M. Lisovyi<sup>58b</sup>, T.M. Liss<sup>164</sup>, D. Lissauer<sup>25</sup>, A. Lister<sup>167</sup>, A.M. Litke<sup>136</sup>, B. Liu<sup>150,ab</sup>, D. Liu<sup>150</sup>, H. Liu<sup>89</sup>,  
 H. Liu<sup>25</sup>, J. Liu<sup>85</sup>, J.B. Liu<sup>33b</sup>, K. Liu<sup>85</sup>, L. Liu<sup>164</sup>, M. Liu<sup>45</sup>, M. Liu<sup>33b</sup>, Y.L. Liu<sup>33b</sup>, Y. Liu<sup>33b</sup>,  
 M. Livan<sup>120a,120b</sup>, A. Lleres<sup>55</sup>, J. Llorente Merino<sup>82</sup>, S.L. Lloyd<sup>76</sup>, F. Lo Sterzo<sup>150</sup>, E. Lobodzinska<sup>42</sup>,  
 P. Loch<sup>7</sup>, W.S. Lockman<sup>136</sup>, F.K. Loebinger<sup>84</sup>, A.E. Loevschall-Jensen<sup>36</sup>, K.M. Loew<sup>23</sup>, A. Loginov<sup>175</sup>,  
 T. Lohse<sup>16</sup>, K. Lohwasser<sup>42</sup>, M. Lokajicek<sup>126</sup>, B.A. Long<sup>22</sup>, J.D. Long<sup>164</sup>, R.E. Long<sup>72</sup>, L. Longo<sup>73a,73b</sup>,  
 K.A. Looper<sup>110</sup>, L. Lopes<sup>125a</sup>, D. Lopez Mateos<sup>57</sup>, B. Lopez Paredes<sup>138</sup>, I. Lopez Paz<sup>12</sup>,  
 A. Lopez Solis<sup>80</sup>, J. Lorenz<sup>99</sup>, N. Lorenzo Martinez<sup>61</sup>, M. Losada<sup>161</sup>, P.J. Lösel<sup>99</sup>, X. Lou<sup>33a</sup>,  
 A. Lounis<sup>116</sup>, J. Love<sup>6</sup>, P.A. Love<sup>72</sup>, H. Lu<sup>60a</sup>, N. Lu<sup>89</sup>, H.J. Lubatti<sup>137</sup>, C. Luci<sup>131a,131b</sup>, A. Lucotte<sup>55</sup>,  
 C. Luedtke<sup>48</sup>, F. Luehring<sup>61</sup>, W. Lukas<sup>62</sup>, L. Luminari<sup>131a</sup>, O. Lundberg<sup>145a,145b</sup>, B. Lund-Jensen<sup>146</sup>,  
 D. Lynn<sup>25</sup>, R. Lysak<sup>126</sup>, E. Lytken<sup>81</sup>, H. Ma<sup>25</sup>, L.L. Ma<sup>33d</sup>, G. Maccarrone<sup>47</sup>, A. Macchiolo<sup>100</sup>,  
 C.M. Macdonald<sup>138</sup>, B. Maček<sup>75</sup>, J. Machado Miguens<sup>121,125b</sup>, D. Madaffari<sup>85</sup>, R. Madar<sup>34</sup>,  
 H.J. Maddocks<sup>165</sup>, W.F. Mader<sup>44</sup>, A. Madsen<sup>42</sup>, J. Maeda<sup>67</sup>, S. Maeland<sup>14</sup>, T. Maeno<sup>25</sup>, A. Maevskiy<sup>98</sup>,  
 E. Magradze<sup>54</sup>, J. Mahlstedt<sup>106</sup>, C. Maiani<sup>116</sup>, C. Maidantchik<sup>24a</sup>, A.A. Maier<sup>100</sup>, T. Maier<sup>99</sup>,  
 A. Maio<sup>125a,125b,125d</sup>, S. Majewski<sup>115</sup>, Y. Makida<sup>66</sup>, N. Makovec<sup>116</sup>, B. Malaescu<sup>80</sup>, Pa. Malecki<sup>39</sup>,  
 V.P. Maleev<sup>122</sup>, F. Malek<sup>55</sup>, U. Mallik<sup>63</sup>, D. Malon<sup>6</sup>, C. Malone<sup>142</sup>, S. Maltezos<sup>10</sup>, V.M. Malyshev<sup>108</sup>,  
 S. Malyukov<sup>30</sup>, J. Mamuzic<sup>42</sup>, G. Mancini<sup>47</sup>, B. Mandelli<sup>30</sup>, L. Mandelli<sup>91a</sup>, I. Mandić<sup>75</sup>,  
 J. Maneira<sup>125a,125b</sup>, L. Manhaes de Andrade Filho<sup>24b</sup>, J. Manjarres Ramos<sup>158b</sup>, A. Mann<sup>99</sup>,  
 B. Mansoulie<sup>135</sup>, R. Mantifel<sup>87</sup>, M. Mantoani<sup>54</sup>, S. Manzoni<sup>91a,91b</sup>, L. Mapelli<sup>30</sup>, G. Marceca<sup>27</sup>,  
 L. March<sup>49</sup>, G. Marchiori<sup>80</sup>, M. Marcisovsky<sup>126</sup>, M. Marjanovic<sup>13</sup>, D.E. Marley<sup>89</sup>, F. Marroquim<sup>24a</sup>,  
 S.P. Marsden<sup>84</sup>, Z. Marshall<sup>15</sup>, L.F. Marti<sup>17</sup>, S. Marti-Garcia<sup>166</sup>, B. Martin<sup>90</sup>, T.A. Martin<sup>169</sup>,  
 V.J. Martin<sup>46</sup>, B. Martin dit Latour<sup>14</sup>, M. Martinez<sup>12,p</sup>, S. Martin-Haugh<sup>130</sup>, V.S. Martoiu<sup>26b</sup>,  
 A.C. Martyniuk<sup>78</sup>, M. Marx<sup>137</sup>, F. Marzano<sup>131a</sup>, A. Marzin<sup>30</sup>, L. Masetti<sup>83</sup>, T. Mashimo<sup>154</sup>,  
 R. Mashinistov<sup>95</sup>, J. Masik<sup>84</sup>, A.L. Maslennikov<sup>108,c</sup>, I. Massa<sup>20a,20b</sup>, L. Massa<sup>20a,20b</sup>, P. Mastrandrea<sup>5</sup>,  
 A. Mastroberardino<sup>37a,37b</sup>, T. Masubuchi<sup>154</sup>, P. Mättig<sup>174</sup>, J. Mattmann<sup>83</sup>, J. Maurer<sup>26b</sup>, S.J. Maxfield<sup>74</sup>,  
 D.A. Maximov<sup>108,c</sup>, R. Mazini<sup>150</sup>, S.M. Mazza<sup>91a,91b</sup>, N.C. Mc Fadden<sup>104</sup>, G. Mc Goldrick<sup>157</sup>,  
 S.P. Mc Kee<sup>89</sup>, A. McCarn<sup>89</sup>, R.L. McCarthy<sup>147</sup>, T.G. McCarthy<sup>29</sup>, L.I. McClymont<sup>78</sup>,  
 K.W. McFarlane<sup>56,\*</sup>, J.A. Mcfayden<sup>78</sup>, G. Mchedlidze<sup>54</sup>, S.J. McMahon<sup>130</sup>, R.A. McPherson<sup>168,l</sup>,  
 M. Medinnis<sup>42</sup>, S. Meehan<sup>137</sup>, S. Mehlhase<sup>99</sup>, A. Mehta<sup>74</sup>, K. Meier<sup>58a</sup>, C. Meineck<sup>99</sup>, B. Meirose<sup>41</sup>,  
 B.R. Mellado Garcia<sup>144c</sup>, F. Meloni<sup>17</sup>, A. Mengarelli<sup>20a,20b</sup>, S. Menke<sup>100</sup>, E. Meoni<sup>160</sup>, K.M. Mercurio<sup>57</sup>,  
 S. Mergelmeyer<sup>16</sup>, P. Mermod<sup>49</sup>, L. Merola<sup>103a,103b</sup>, C. Meroni<sup>91a</sup>, F.S. Merritt<sup>31</sup>, A. Messina<sup>131a,131b</sup>,  
 J. Metcalfe<sup>6</sup>, A.S. Mete<sup>162</sup>, C. Meyer<sup>83</sup>, C. Meyer<sup>121</sup>, J-P. Meyer<sup>135</sup>, J. Meyer<sup>106</sup>,  
 H. Meyer Zu Theenhausen<sup>58a</sup>, R.P. Middleton<sup>130</sup>, S. Miglioranza<sup>163a,163c</sup>, L. Mijović<sup>21</sup>, G. Mikenberg<sup>171</sup>,  
 M. Mikestikova<sup>126</sup>, M. Mikuz<sup>75</sup>, M. Milesi<sup>88</sup>, A. Milic<sup>30</sup>, D.W. Miller<sup>31</sup>, C. Mills<sup>46</sup>, A. Milov<sup>171</sup>,  
 D.A. Milstead<sup>145a,145b</sup>, A.A. Minaenko<sup>129</sup>, Y. Minami<sup>154</sup>, I.A. Minashvili<sup>65</sup>, A.I. Mincer<sup>109</sup>,  
 B. Mindur<sup>38a</sup>, M. Mineev<sup>65</sup>, Y. Ming<sup>172</sup>, L.M. Mir<sup>12</sup>, K.P. Mistry<sup>121</sup>, T. Mitani<sup>170</sup>, J. Mitrevski<sup>99</sup>,  
 V.A. Mitsou<sup>166</sup>, A. Miucci<sup>49</sup>, P.S. Miyagawa<sup>138</sup>, J.U. Mjörnmark<sup>81</sup>, T. Moa<sup>145a,145b</sup>, K. Mochizuki<sup>85</sup>,  
 S. Mohapatra<sup>35</sup>, W. Mohr<sup>48</sup>, S. Molander<sup>145a,145b</sup>, R. Moles-Valls<sup>21</sup>, R. Monden<sup>68</sup>, M.C. Mondragon<sup>90</sup>,  
 K. Mönig<sup>42</sup>, J. Monk<sup>36</sup>, E. Monnier<sup>85</sup>, A. Montalbano<sup>147</sup>, J. Montejo Berlingen<sup>30</sup>, F. Monticelli<sup>71</sup>,  
 S. Monzani<sup>91a,91b</sup>, R.W. Moore<sup>3</sup>, N. Morange<sup>116</sup>, D. Moreno<sup>161</sup>, M. Moreno Llácer<sup>54</sup>, P. Morettini<sup>50a</sup>,

D. Mori<sup>141</sup>, T. Mori<sup>154</sup>, M. Morii<sup>57</sup>, M. Morinaga<sup>154</sup>, V. Morisbak<sup>118</sup>, S. Moritz<sup>83</sup>, A.K. Morley<sup>149</sup>,  
 G. Mornacchi<sup>30</sup>, J.D. Morris<sup>76</sup>, S.S. Mortensen<sup>36</sup>, L. Morvaj<sup>147</sup>, M. Mosidze<sup>51b</sup>, J. Moss<sup>142</sup>,  
 K. Motohashi<sup>156</sup>, R. Mount<sup>142</sup>, E. Mountricha<sup>25</sup>, S.V. Mouraviev<sup>95,\*</sup>, E.J.W. Moyses<sup>86</sup>, S. Muanza<sup>85</sup>,  
 R.D. Mudd<sup>18</sup>, F. Mueller<sup>100</sup>, J. Mueller<sup>124</sup>, R.S.P. Mueller<sup>99</sup>, T. Mueller<sup>28</sup>, D. Muenstermann<sup>72</sup>,  
 P. Mullen<sup>53</sup>, G.A. Mullier<sup>17</sup>, F.J. Munoz Sanchez<sup>84</sup>, J.A. Murillo Quijada<sup>18</sup>, W.J. Murray<sup>169,130</sup>,  
 H. Musheghyan<sup>54</sup>, A.G. Myagkov<sup>129.ac</sup>, M. Myska<sup>127</sup>, B.P. Nachman<sup>142</sup>, O. Nackenhorst<sup>49</sup>, J. Nadal<sup>54</sup>,  
 K. Nagai<sup>119</sup>, R. Nagai<sup>66,w</sup>, Y. Nagai<sup>85</sup>, K. Nagano<sup>66</sup>, Y. Nagasaka<sup>59</sup>, K. Nagata<sup>159</sup>, M. Nagel<sup>100</sup>,  
 E. Nagy<sup>85</sup>, A.M. Nairz<sup>30</sup>, Y. Nakahama<sup>30</sup>, K. Nakamura<sup>66</sup>, T. Nakamura<sup>154</sup>, I. Nakano<sup>111</sup>,  
 H. Namasivayam<sup>41</sup>, R.F. Naranjo Garcia<sup>42</sup>, R. Narayan<sup>31</sup>, D.I. Narrias Villar<sup>58a</sup>, I. Naryshkin<sup>122</sup>,  
 T. Naumann<sup>42</sup>, G. Navarro<sup>161</sup>, R. Nayyar<sup>7</sup>, H.A. Neal<sup>89</sup>, P.Yu. Nechaeva<sup>95</sup>, T.J. Neep<sup>84</sup>, P.D. Nef<sup>142</sup>,  
 A. Negri<sup>120a,120b</sup>, M. Negrini<sup>20a</sup>, S. Nektarijevic<sup>105</sup>, C. Nellist<sup>116</sup>, A. Nelson<sup>162</sup>, S. Nemecek<sup>126</sup>,  
 P. Nemethy<sup>109</sup>, A.A. Nepomuceno<sup>24a</sup>, M. Nessi<sup>30.ad</sup>, M.S. Neubauer<sup>164</sup>, M. Neumann<sup>174</sup>,  
 R.M. Neves<sup>109</sup>, P. Nevski<sup>25</sup>, P.R. Newman<sup>18</sup>, D.H. Nguyen<sup>6</sup>, R.B. Nickerson<sup>119</sup>, R. Nicolaidou<sup>135</sup>,  
 B. Nicquevert<sup>30</sup>, J. Nielsen<sup>136</sup>, A. Nikiforov<sup>16</sup>, V. Nikolaenko<sup>129.ac</sup>, I. Nikolic-Audit<sup>80</sup>,  
 K. Nikolopoulos<sup>18</sup>, J.K. Nilsen<sup>118</sup>, P. Nilsson<sup>25</sup>, Y. Ninomiya<sup>154</sup>, A. Nisati<sup>131a</sup>, R. Nisius<sup>100</sup>, T. Nobe<sup>154</sup>,  
 L. Nodulman<sup>6</sup>, M. Nomachi<sup>117</sup>, I. Nomidis<sup>29</sup>, T. Nooney<sup>76</sup>, S. Norberg<sup>112</sup>, M. Nordberg<sup>30</sup>,  
 O. Novgorodova<sup>44</sup>, S. Nowak<sup>100</sup>, M. Nozaki<sup>66</sup>, L. Nozka<sup>114</sup>, K. Ntekas<sup>10</sup>, E. Nurse<sup>78</sup>, F. Nuti<sup>88</sup>,  
 F. O'grady<sup>7</sup>, D.C. O'Neil<sup>141</sup>, A.A. O'Rourke<sup>42</sup>, V. O'Shea<sup>53</sup>, F.G. Oakham<sup>29.d</sup>, H. Oberlack<sup>100</sup>,  
 T. Obermann<sup>21</sup>, J. Ocariz<sup>80</sup>, A. Ochi<sup>67</sup>, I. Ochoa<sup>35</sup>, J.P. Ochoa-Ricoux<sup>32a</sup>, S. Oda<sup>70</sup>, S. Odaka<sup>66</sup>,  
 H. Ogren<sup>61</sup>, A. Oh<sup>84</sup>, S.H. Oh<sup>45</sup>, C.C. Ohm<sup>15</sup>, H. Ohman<sup>165</sup>, H. Oide<sup>30</sup>, H. Okawa<sup>159</sup>, Y. Okumura<sup>31</sup>,  
 T. Okuyama<sup>66</sup>, A. Olariu<sup>26b</sup>, L.F. Oleiro Seabra<sup>125a</sup>, S.A. Olivares Pino<sup>46</sup>, D. Oliveira Damazio<sup>25</sup>,  
 A. Olszewski<sup>39</sup>, J. Olszowska<sup>39</sup>, A. Onofre<sup>125a,125e</sup>, K. Onogi<sup>102</sup>, P.U.E. Onyisi<sup>31,s</sup>, C.J. Oram<sup>158a</sup>,  
 M.J. Oreglia<sup>31</sup>, Y. Oren<sup>152</sup>, D. Orestano<sup>133a,133b</sup>, N. Orlando<sup>60b</sup>, R.S. Orr<sup>157</sup>, B. Osculati<sup>50a,50b</sup>,  
 R. Ospanov<sup>84</sup>, G. Otero y Garzon<sup>27</sup>, H. Otono<sup>70</sup>, M. Ouchrif<sup>134d</sup>, F. Ould-Saada<sup>118</sup>, A. Ouraou<sup>135</sup>,  
 K.P. Oussoren<sup>106</sup>, Q. Ouyang<sup>33a</sup>, A. Ovcharova<sup>15</sup>, M. Owen<sup>53</sup>, R.E. Owen<sup>18</sup>, V.E. Ozcan<sup>19a</sup>, N. Ozturk<sup>8</sup>,  
 K. Pachal<sup>141</sup>, A. Pacheco Pages<sup>12</sup>, C. Padilla Aranda<sup>12</sup>, M. Pagáčová<sup>48</sup>, S. Pagan Griso<sup>15</sup>, F. Paige<sup>25</sup>,  
 P. Pais<sup>86</sup>, K. Pajchel<sup>118</sup>, G. Palacino<sup>158b</sup>, S. Palestini<sup>30</sup>, M. Palka<sup>38b</sup>, D. Pallin<sup>34</sup>, A. Palma<sup>125a,125b</sup>,  
 E.St. Panagiotopoulou<sup>10</sup>, C.E. Pandini<sup>80</sup>, J.G. Panduro Vazquez<sup>77</sup>, P. Pani<sup>145a,145b</sup>, S. Panitkin<sup>25</sup>,  
 D. Pantea<sup>26b</sup>, L. Paolozzi<sup>49</sup>, Th.D. Papadopoulou<sup>10</sup>, K. Papageorgiou<sup>153</sup>, A. Paramonov<sup>6</sup>,  
 D. Paredes Hernandez<sup>175</sup>, M.A. Parker<sup>28</sup>, K.A. Parker<sup>138</sup>, F. Parodi<sup>50a,50b</sup>, J.A. Parsons<sup>35</sup>, U. Parzefall<sup>48</sup>,  
 V. Pascuzzi<sup>157</sup>, E. Pasqualucci<sup>131a</sup>, S. Passaggio<sup>50a</sup>, F. Pastore<sup>133a,133b,\*</sup>, Fr. Pastore<sup>77</sup>, G. Pásztor<sup>29</sup>,  
 S. Pataria<sup>174</sup>, N.D. Patel<sup>149</sup>, J.R. Pater<sup>84</sup>, T. Pauly<sup>30</sup>, J. Pearce<sup>168</sup>, B. Pearson<sup>112</sup>, L.E. Pedersen<sup>36</sup>,  
 M. Pedersen<sup>118</sup>, S. Pedraza Lopez<sup>166</sup>, R. Pedro<sup>125a,125b</sup>, S.V. Peleganchuk<sup>108,c</sup>, D. Pelikan<sup>165</sup>, O. Penc<sup>126</sup>,  
 C. Peng<sup>33a</sup>, H. Peng<sup>33b</sup>, J. Penwell<sup>61</sup>, B.S. Peralva<sup>24b</sup>, D.V. Perepelitsa<sup>25</sup>, E. Perez Codina<sup>158a</sup>,  
 L. Perini<sup>91a,91b</sup>, H. Pernegger<sup>30</sup>, S. Perrella<sup>103a,103b</sup>, R. Peschke<sup>42</sup>, V.D. Peshekhonov<sup>65</sup>, K. Peters<sup>30</sup>,  
 R.F.Y. Peters<sup>84</sup>, B.A. Petersen<sup>30</sup>, T.C. Petersen<sup>36</sup>, E. Petit<sup>55</sup>, A. Petridis<sup>1</sup>, C. Petridou<sup>153</sup>, P. Petroff<sup>116</sup>,  
 E. Petrolo<sup>131a</sup>, M. Petrov<sup>119</sup>, F. Petrucci<sup>133a,133b</sup>, N.E. Pettersson<sup>156</sup>, A. Peyaud<sup>135</sup>, R. Pezoa<sup>32b</sup>,  
 P.W. Phillips<sup>130</sup>, G. Piacquadio<sup>142</sup>, E. Pianori<sup>169</sup>, A. Picazio<sup>86</sup>, E. Piccaro<sup>76</sup>, M. Piccinini<sup>20a,20b</sup>,  
 M.A. Pickering<sup>119</sup>, R. Piegaia<sup>27</sup>, J.E. Pilcher<sup>31</sup>, A.D. Pilkington<sup>84</sup>, A.W.J. Pin<sup>84</sup>, J. Pina<sup>125a,125b,125d</sup>,  
 M. Pinamonti<sup>163a,163c,ae</sup>, J.L. Pinfold<sup>3</sup>, A. Pingel<sup>36</sup>, S. Pires<sup>80</sup>, H. Pirumov<sup>42</sup>, M. Pitt<sup>171</sup>, L. Plazak<sup>143a</sup>,  
 M.-A. Pleier<sup>25</sup>, V. Pleskot<sup>83</sup>, E. Plotnikova<sup>65</sup>, P. Plucinski<sup>145a,145b</sup>, D. Pluth<sup>64</sup>, R. Poettgen<sup>145a,145b</sup>,  
 L. Poggioli<sup>116</sup>, D. Pohl<sup>21</sup>, G. Polesello<sup>120a</sup>, A. Poley<sup>42</sup>, A. Policicchio<sup>37a,37b</sup>, R. Polifka<sup>157</sup>, A. Polini<sup>20a</sup>,  
 C.S. Pollard<sup>53</sup>, V. Polychronakos<sup>25</sup>, K. Pommès<sup>30</sup>, L. Pontecorvo<sup>131a</sup>, B.G. Pope<sup>90</sup>, G.A. Popeneciu<sup>26c</sup>,  
 D.S. Popovic<sup>13</sup>, A. Poppleton<sup>30</sup>, S. Pospisil<sup>127</sup>, K. Potamianos<sup>15</sup>, I.N. Potrap<sup>65</sup>, C.J. Potter<sup>28</sup>,  
 C.T. Potter<sup>115</sup>, G. Poulard<sup>30</sup>, J. Poveda<sup>30</sup>, V. Pozdnyakov<sup>65</sup>, M.E. Pozo Astigarraga<sup>30</sup>, P. Pralavorio<sup>85</sup>,  
 A. Pranko<sup>15</sup>, S. Prell<sup>64</sup>, D. Price<sup>84</sup>, L.E. Price<sup>6</sup>, M. Primavera<sup>73a</sup>, S. Prince<sup>87</sup>, M. Proissl<sup>46</sup>,  
 K. Prokofiev<sup>60c</sup>, F. Prokoshin<sup>32b</sup>, S. Protopopescu<sup>25</sup>, J. Proudfoot<sup>6</sup>, M. Przybycien<sup>38a</sup>, D. Puudu<sup>133a,133b</sup>,

D. Puldon<sup>147</sup>, M. Purohit<sup>25,af</sup>, P. Puzo<sup>116</sup>, J. Qian<sup>89</sup>, G. Qin<sup>53</sup>, Y. Qin<sup>84</sup>, A. Quadt<sup>54</sup>, D.R. Quarrie<sup>15</sup>,  
 W.B. Quayle<sup>163a,163b</sup>, M. Queitsch-Maitland<sup>84</sup>, D. Quilty<sup>53</sup>, S. Raddum<sup>118</sup>, V. Radeka<sup>25</sup>, V. Radescu<sup>42</sup>,  
 S.K. Radhakrishnan<sup>147</sup>, P. Radloff<sup>115</sup>, P. Rados<sup>88</sup>, F. Ragusa<sup>91a,91b</sup>, G. Rahal<sup>177</sup>, S. Rajagopalan<sup>25</sup>,  
 M. Rammensee<sup>30</sup>, C. Rangel-Smith<sup>165</sup>, M.G. Ratti<sup>91a,91b</sup>, F. Rauscher<sup>99</sup>, S. Rave<sup>83</sup>, T. Ravenscroft<sup>53</sup>,  
 M. Raymond<sup>30</sup>, A.L. Read<sup>118</sup>, N.P. Readioff<sup>74</sup>, D.M. Rebuzzi<sup>120a,120b</sup>, A. Redelbach<sup>173</sup>, G. Redlinger<sup>25</sup>,  
 R. Reece<sup>136</sup>, K. Reeves<sup>41</sup>, L. Rehnisch<sup>16</sup>, J. Reichert<sup>121</sup>, H. Reisin<sup>27</sup>, C. Rembser<sup>30</sup>, H. Ren<sup>33a</sup>,  
 M. Rescigno<sup>131a</sup>, S. Resconi<sup>91a</sup>, O.L. Rezanova<sup>108,c</sup>, P. Reznicek<sup>128</sup>, R. Rezvani<sup>94</sup>, R. Richter<sup>100</sup>,  
 S. Richter<sup>78</sup>, E. Richter-Was<sup>38b</sup>, O. Ricken<sup>21</sup>, M. Ridel<sup>80</sup>, P. Rieck<sup>16</sup>, C.J. Riegel<sup>174</sup>, J. Rieger<sup>54</sup>,  
 O. Rifki<sup>112</sup>, M. Rijssenbeek<sup>147</sup>, A. Rimoldi<sup>120a,120b</sup>, L. Rinaldi<sup>20a</sup>, B. Ristić<sup>49</sup>, E. Ritsch<sup>30</sup>, I. Riu<sup>12</sup>,  
 F. Rizatdinova<sup>113</sup>, E. Rizvi<sup>76</sup>, S.H. Robertson<sup>87,l</sup>, A. Robichaud-Veronneau<sup>87</sup>, D. Robinson<sup>28</sup>,  
 J.E.M. Robinson<sup>42</sup>, A. Robson<sup>53</sup>, C. Roda<sup>123a,123b</sup>, Y. Rodina<sup>85</sup>, A. Rodriguez Perez<sup>12</sup>,  
 D. Rodriguez Rodriguez<sup>166</sup>, S. Roe<sup>30</sup>, C.S. Rogan<sup>57</sup>, O. Røhne<sup>118</sup>, A. Romaniouk<sup>97</sup>, M. Romano<sup>20a,20b</sup>,  
 S.M. Romano Saez<sup>34</sup>, E. Romero Adam<sup>166</sup>, N. Rompotis<sup>137</sup>, M. Ronzani<sup>48</sup>, L. Roos<sup>80</sup>, E. Ros<sup>166</sup>,  
 S. Rosati<sup>131a</sup>, K. Rosbach<sup>48</sup>, P. Rose<sup>136</sup>, O. Rosenthal<sup>140</sup>, V. Rossetti<sup>145a,145b</sup>, E. Rossi<sup>103a,103b</sup>,  
 L.P. Rossi<sup>50a</sup>, J.H.N. Rosten<sup>28</sup>, R. Rosten<sup>137</sup>, M. Rotaru<sup>26b</sup>, I. Roth<sup>171</sup>, J. Rothberg<sup>137</sup>, D. Rousseau<sup>116</sup>,  
 C.R. Royon<sup>135</sup>, A. Rozanov<sup>85</sup>, Y. Rozen<sup>151</sup>, X. Ruan<sup>144c</sup>, F. Rubbo<sup>142</sup>, I. Rubinskiy<sup>42</sup>, V.I. Rud<sup>98</sup>,  
 M.S. Rudolph<sup>157</sup>, F. Rühr<sup>48</sup>, A. Ruiz-Martinez<sup>30</sup>, Z. Rurikova<sup>48</sup>, N.A. Rusakovich<sup>65</sup>, A. Ruschke<sup>99</sup>,  
 H.L. Russell<sup>137</sup>, J.P. Rutherford<sup>7</sup>, N. Ruthmann<sup>30</sup>, Y.F. Ryabov<sup>122</sup>, M. Rybar<sup>164</sup>, G. Rybkin<sup>116</sup>, S. Ryu<sup>6</sup>,  
 A. Ryzhov<sup>129</sup>, A.F. Saavedra<sup>149</sup>, G. Sabato<sup>106</sup>, S. Sacerdoti<sup>27</sup>, H.F-W. Sadrozinski<sup>136</sup>, R. Sadykov<sup>65</sup>,  
 F. Safai Tehrani<sup>131a</sup>, P. Saha<sup>107</sup>, M. Sahinsoy<sup>58a</sup>, M. Saimpert<sup>135</sup>, T. Saito<sup>154</sup>, H. Sakamoto<sup>154</sup>,  
 Y. Sakurai<sup>170</sup>, G. Salamanna<sup>133a,133b</sup>, A. Salamon<sup>132a,132b</sup>, J.E. Salazar Loyola<sup>32b</sup>, D. Salek<sup>106</sup>,  
 P.H. Sales De Bruin<sup>137</sup>, D. Salihagic<sup>100</sup>, A. Salnikov<sup>142</sup>, J. Salt<sup>166</sup>, D. Salvatore<sup>37a,37b</sup>, F. Salvatore<sup>148</sup>,  
 A. Salvucci<sup>60a</sup>, A. Salzburger<sup>30</sup>, D. Sammel<sup>48</sup>, D. Sampsonidis<sup>153</sup>, A. Sanchez<sup>103a,103b</sup>, J. Sánchez<sup>166</sup>,  
 V. Sanchez Martinez<sup>166</sup>, H. Sandaker<sup>118</sup>, R.L. Sandbach<sup>76</sup>, H.G. Sander<sup>83</sup>, M.P. Sanders<sup>99</sup>,  
 M. Sandhoff<sup>174</sup>, C. Sandoval<sup>161</sup>, R. Sandstroem<sup>100</sup>, D.P.C. Sankey<sup>130</sup>, M. Sannino<sup>50a,50b</sup>, A. Sansoni<sup>47</sup>,  
 C. Santoni<sup>34</sup>, R. Santonico<sup>132a,132b</sup>, H. Santos<sup>125a</sup>, I. Santoyo Castillo<sup>148</sup>, K. Sapp<sup>124</sup>, A. Saponov<sup>65</sup>,  
 J.G. Saraiva<sup>125a,125d</sup>, B. Sarrazin<sup>21</sup>, O. Sasaki<sup>66</sup>, Y. Sasaki<sup>154</sup>, K. Sato<sup>159</sup>, G. Sauvage<sup>5,\*</sup>, E. Sauvan<sup>5</sup>,  
 G. Savage<sup>77</sup>, P. Savard<sup>157,d</sup>, C. Sawyer<sup>130</sup>, L. Sawyer<sup>79,o</sup>, J. Saxon<sup>31</sup>, C. Sbarra<sup>20a</sup>, A. Sbrizzi<sup>20a,20b</sup>,  
 T. Scanlon<sup>78</sup>, D.A. Scannicchio<sup>162</sup>, M. Scarcella<sup>149</sup>, V. Scarfone<sup>37a,37b</sup>, J. Schaarschmidt<sup>171</sup>,  
 P. Schacht<sup>100</sup>, D. Schaefer<sup>30</sup>, R. Schaefer<sup>42</sup>, J. Schaeffer<sup>83</sup>, S. Schaepe<sup>21</sup>, S. Schaezel<sup>58b</sup>, U. Schäfer<sup>83</sup>,  
 A.C. Schaffer<sup>116</sup>, D. Schaile<sup>99</sup>, R.D. Schamberger<sup>147</sup>, V. Scharf<sup>58a</sup>, V.A. Schegelsky<sup>122</sup>, D. Scheirich<sup>128</sup>,  
 M. Schernau<sup>162</sup>, C. Schiavi<sup>50a,50b</sup>, C. Schillo<sup>48</sup>, M. Schioppa<sup>37a,37b</sup>, S. Schlenker<sup>30</sup>, K. Schmieden<sup>30</sup>,  
 C. Schmitt<sup>83</sup>, S. Schmitt<sup>42</sup>, S. Schmitz<sup>83</sup>, B. Schneider<sup>158a</sup>, Y.J. Schnellbach<sup>74</sup>, U. Schnoor<sup>48</sup>,  
 L. Schoeffel<sup>135</sup>, A. Schoening<sup>58b</sup>, B.D. Schoenrock<sup>90</sup>, E. Schopf<sup>21</sup>, A.L.S. Schorlemmer<sup>43</sup>, M. Schott<sup>83</sup>,  
 D. Schouten<sup>158a</sup>, J. Schovancova<sup>8</sup>, S. Schramm<sup>49</sup>, M. Schreyer<sup>173</sup>, N. Schuh<sup>83</sup>, M.J. Schultens<sup>21</sup>,  
 H.-C. Schultz-Coulon<sup>58a</sup>, H. Schulz<sup>16</sup>, M. Schumacher<sup>48</sup>, B.A. Schumm<sup>136</sup>, Ph. Schune<sup>135</sup>,  
 C. Schwanenberger<sup>84</sup>, A. Schwartzman<sup>142</sup>, T.A. Schwarz<sup>89</sup>, Ph. Schwegler<sup>100</sup>, H. Schweiger<sup>84</sup>,  
 Ph. Schwemling<sup>135</sup>, R. Schwienhorst<sup>90</sup>, J. Schwindling<sup>135</sup>, T. Schwindt<sup>21</sup>, G. Sciolla<sup>23</sup>, F. Scuri<sup>123a,123b</sup>,  
 F. Scutti<sup>88</sup>, J. Searcy<sup>89</sup>, P. Seema<sup>21</sup>, S.C. Seidel<sup>104</sup>, A. Seiden<sup>136</sup>, F. Seifert<sup>127</sup>, J.M. Seixas<sup>24a</sup>,  
 G. Sekhniaidze<sup>103a</sup>, K. Sekhon<sup>89</sup>, S.J. Sekula<sup>40</sup>, D.M. Seliverstov<sup>122,\*</sup>, N. Semprini-Cesari<sup>20a,20b</sup>,  
 C. Serfon<sup>30</sup>, L. Serin<sup>116</sup>, L. Serkin<sup>163a,163b</sup>, M. Sessa<sup>133a,133b</sup>, R. Seuster<sup>158a</sup>, H. Severini<sup>112</sup>, T. Sfiligoi<sup>75</sup>,  
 F. Sforza<sup>30</sup>, A. Sfyrla<sup>49</sup>, E. Shabalina<sup>54</sup>, N.W. Shaikh<sup>145a,145b</sup>, L.Y. Shan<sup>33a</sup>, R. Shang<sup>164</sup>, J.T. Shank<sup>22</sup>,  
 M. Shapiro<sup>15</sup>, P.B. Shatalov<sup>96</sup>, K. Shaw<sup>163a,163b</sup>, S.M. Shaw<sup>84</sup>, A. Shcherbakova<sup>145a,145b</sup>, C.Y. Shehu<sup>148</sup>,  
 P. Sherwood<sup>78</sup>, L. Shi<sup>150,ag</sup>, S. Shimizu<sup>67</sup>, C.O. Shimmin<sup>162</sup>, M. Shimojima<sup>101</sup>, M. Shiyakova<sup>65,ah</sup>,  
 A. Shmeleva<sup>95</sup>, D. Shoaleh Saadi<sup>94</sup>, M.J. Shochet<sup>31</sup>, S. Shojaii<sup>91a,91b</sup>, S. Shrestha<sup>110</sup>, E. Shulga<sup>97</sup>,  
 M.A. Shupe<sup>7</sup>, P. Sicho<sup>126</sup>, P.E. Sidebo<sup>146</sup>, O. Sidiropoulou<sup>173</sup>, D. Sidorov<sup>113</sup>, A. Sidoti<sup>20a,20b</sup>,  
 F. Siegert<sup>44</sup>, Dj. Sijacki<sup>13</sup>, J. Silva<sup>125a,125d</sup>, S.B. Silverstein<sup>145a</sup>, V. Simak<sup>127</sup>, O. Simard<sup>5</sup>, Lj. Simic<sup>13</sup>,

S. Simion<sup>116</sup>, E. Simioni<sup>83</sup>, B. Simmons<sup>78</sup>, D. Simon<sup>34</sup>, M. Simon<sup>83</sup>, P. Sinervo<sup>157</sup>, N.B. Sinev<sup>115</sup>,  
 M. Sioli<sup>20a,20b</sup>, G. Siragusa<sup>173</sup>, S.Yu. Sivoklov<sup>98</sup>, J. Sjölin<sup>145a,145b</sup>, T.B. Sjursen<sup>14</sup>, M.B. Skinner<sup>72</sup>,  
 H.P. Skottowe<sup>57</sup>, P. Skubic<sup>112</sup>, M. Slater<sup>18</sup>, T. Slavicek<sup>127</sup>, M. Slawinska<sup>106</sup>, K. Sliwa<sup>160</sup>,  
 V. Smakhtin<sup>171</sup>, B.H. Smart<sup>5</sup>, L. Smestad<sup>14</sup>, S.Yu. Smirnov<sup>97</sup>, Y. Smirnov<sup>97</sup>, L.N. Smirnova<sup>98,ai</sup>,  
 O. Smirnova<sup>81</sup>, M.N.K. Smith<sup>35</sup>, R.W. Smith<sup>35</sup>, M. Smizanska<sup>72</sup>, K. Smolek<sup>127</sup>, A.A. Snesarev<sup>95</sup>,  
 G. Snidero<sup>76</sup>, S. Snyder<sup>25</sup>, R. Sobie<sup>168,l</sup>, F. Socher<sup>44</sup>, A. Soffer<sup>152</sup>, D.A. Soh<sup>150,ag</sup>, G. Sokhrannyi<sup>75</sup>,  
 C.A. Solans Sanchez<sup>30</sup>, M. Solar<sup>127</sup>, E.Yu. Soldatov<sup>97</sup>, U. Soldevila<sup>166</sup>, A.A. Solodkov<sup>129</sup>,  
 A. Soloshenko<sup>65</sup>, O.V. Solovyanov<sup>129</sup>, V. Solovyev<sup>122</sup>, P. Sommer<sup>48</sup>, H.Y. Song<sup>33b,z</sup>, N. Soni<sup>1</sup>,  
 A. Sood<sup>15</sup>, A. Sopczak<sup>127</sup>, V. Sopko<sup>127</sup>, V. Sorin<sup>12</sup>, D. Sosa<sup>58b</sup>, C.L. Sotiropoulou<sup>123a,123b</sup>,  
 R. Soualah<sup>163a,163c</sup>, A.M. Soukharev<sup>108,c</sup>, D. South<sup>42</sup>, B.C. Sowden<sup>77</sup>, S. Spagnolo<sup>73a,73b</sup>,  
 M. Spalla<sup>123a,123b</sup>, M. Spangenberg<sup>169</sup>, F. Spanò<sup>77</sup>, D. Sperlich<sup>16</sup>, F. Spettel<sup>100</sup>, R. Spighi<sup>20a</sup>, G. Spigo<sup>30</sup>,  
 L.A. Spiller<sup>88</sup>, M. Spousta<sup>128</sup>, R.D. St. Denis<sup>53,\*</sup>, A. Stabile<sup>91a</sup>, S. Staerz<sup>30</sup>, J. Stahlman<sup>121</sup>,  
 R. Stamen<sup>58a</sup>, S. Stamm<sup>16</sup>, E. Stanecka<sup>39</sup>, R.W. Stanek<sup>6</sup>, C. Stanescu<sup>133a</sup>, M. Stanescu-Bellu<sup>42</sup>,  
 M.M. Stanitzki<sup>42</sup>, S. Stapnes<sup>118</sup>, E.A. Starchenko<sup>129</sup>, G.H. Stark<sup>31</sup>, J. Stark<sup>55</sup>, P. Staroba<sup>126</sup>,  
 P. Starovoitov<sup>58a</sup>, R. Staszewski<sup>39</sup>, P. Steinberg<sup>25</sup>, B. Stelzer<sup>141</sup>, H.J. Stelzer<sup>30</sup>, O. Stelzer-Chilton<sup>158a</sup>,  
 H. Stenzel<sup>52</sup>, G.A. Stewart<sup>53</sup>, J.A. Stillings<sup>21</sup>, M.C. Stockton<sup>87</sup>, M. Stoebe<sup>87</sup>, G. Stoica<sup>26b</sup>, P. Stolte<sup>54</sup>,  
 S. Stonjek<sup>100</sup>, A.R. Stradling<sup>8</sup>, A. Straessner<sup>44</sup>, M.E. Stramaglia<sup>17</sup>, J. Strandberg<sup>146</sup>,  
 S. Strandberg<sup>145a,145b</sup>, A. Strandlie<sup>118</sup>, M. Strauss<sup>112</sup>, P. Strizenec<sup>143b</sup>, R. Ströhmer<sup>173</sup>, D.M. Strom<sup>115</sup>,  
 R. Stroynowski<sup>40</sup>, A. Strubig<sup>105</sup>, S.A. Stucci<sup>17</sup>, B. Stugu<sup>14</sup>, N.A. Styles<sup>42</sup>, D. Su<sup>142</sup>, J. Su<sup>124</sup>,  
 R. Subramaniam<sup>79</sup>, S. Suchek<sup>58a</sup>, Y. Sugaya<sup>117</sup>, M. Suk<sup>127</sup>, V.V. Sulin<sup>95</sup>, S. Sultansoy<sup>4c</sup>, T. Sumida<sup>68</sup>,  
 S. Sun<sup>57</sup>, X. Sun<sup>33a</sup>, J.E. Sundermann<sup>48</sup>, K. Suruliz<sup>148</sup>, G. Susinno<sup>37a,37b</sup>, M.R. Sutton<sup>148</sup>, S. Suzuki<sup>66</sup>,  
 M. Svatos<sup>126</sup>, M. Swiatlowski<sup>31</sup>, I. Sykora<sup>143a</sup>, T. Sykora<sup>128</sup>, D. Ta<sup>48</sup>, C. Taccini<sup>133a,133b</sup>, K. Tackmann<sup>42</sup>,  
 J. Taenzer<sup>157</sup>, A. Taffard<sup>162</sup>, R. Tafirout<sup>158a</sup>, N. Taiblum<sup>152</sup>, H. Takai<sup>25</sup>, R. Takashima<sup>69</sup>, H. Takeda<sup>67</sup>,  
 T. Takeshita<sup>139</sup>, Y. Takubo<sup>66</sup>, M. Talby<sup>85</sup>, A.A. Talyshv<sup>108,c</sup>, J.Y.C. Tam<sup>173</sup>, K.G. Tan<sup>88</sup>, J. Tanaka<sup>154</sup>,  
 R. Tanaka<sup>116</sup>, S. Tanaka<sup>66</sup>, B.B. Tannenwald<sup>110</sup>, S. Tapia Araya<sup>32b</sup>, S. Tapprogge<sup>83</sup>, S. Tarem<sup>151</sup>,  
 G.F. Tartarelli<sup>91a</sup>, P. Tas<sup>128</sup>, M. Tasevsky<sup>126</sup>, T. Tashiro<sup>68</sup>, E. Tassi<sup>37a,37b</sup>, A. Tavares Delgado<sup>125a,125b</sup>,  
 Y. Tayalati<sup>134d</sup>, A.C. Taylor<sup>104</sup>, G.N. Taylor<sup>88</sup>, P.T.E. Taylor<sup>88</sup>, W. Taylor<sup>158b</sup>, F.A. Teischinger<sup>30</sup>,  
 P. Teixeira-Dias<sup>77</sup>, K.K. Temming<sup>48</sup>, D. Temple<sup>141</sup>, H. Ten Kate<sup>30</sup>, P.K. Teng<sup>150</sup>, J.J. Teoh<sup>117</sup>,  
 F. Tepel<sup>174</sup>, S. Terada<sup>66</sup>, K. Terashi<sup>154</sup>, J. Terron<sup>82</sup>, S. Terzo<sup>100</sup>, M. Testa<sup>47</sup>, R.J. Teuscher<sup>157,l</sup>,  
 T. Thevenaux-Pelzer<sup>85</sup>, J.P. Thomas<sup>18</sup>, J. Thomas-Wilsker<sup>77</sup>, E.N. Thompson<sup>35</sup>, P.D. Thompson<sup>18</sup>,  
 R.J. Thompson<sup>84</sup>, A.S. Thompson<sup>53</sup>, L.A. Thomsen<sup>175</sup>, E. Thomson<sup>121</sup>, M. Thomson<sup>28</sup>, M.J. Tibbetts<sup>15</sup>,  
 R.E. Ticse Torres<sup>85</sup>, V.O. Tikhomirov<sup>95,aj</sup>, Yu.A. Tikhonov<sup>108,c</sup>, S. Timoshenko<sup>97</sup>, E. Tiouchichine<sup>85</sup>,  
 P. Tipton<sup>175</sup>, S. Tisserant<sup>85</sup>, K. Todome<sup>156</sup>, T. Todorov<sup>5,\*</sup>, S. Todorova-Nova<sup>128</sup>, J. Tojo<sup>70</sup>, S. Tokár<sup>143a</sup>,  
 K. Tokushuku<sup>66</sup>, E. Tolley<sup>57</sup>, L. Tomlinson<sup>84</sup>, M. Tomoto<sup>102</sup>, L. Tompkins<sup>142,ak</sup>, K. Toms<sup>104</sup>, B. Tong<sup>57</sup>,  
 E. Torrence<sup>115</sup>, H. Torres<sup>141</sup>, E. Torró Pastor<sup>137</sup>, J. Toth<sup>85,al</sup>, F. Touchard<sup>85</sup>, D.R. Tovey<sup>138</sup>,  
 T. Trefzger<sup>173</sup>, L. Tremblet<sup>30</sup>, A. Tricoli<sup>30</sup>, I.M. Trigger<sup>158a</sup>, S. Trincaz-Duvoid<sup>80</sup>, M.F. Tripiana<sup>12</sup>,  
 W. Trischuk<sup>157</sup>, B. Trocmé<sup>55</sup>, A. Trofymov<sup>42</sup>, C. Troncon<sup>91a</sup>, M. Trotter-McDonald<sup>15</sup>, M. Trovatelli<sup>168</sup>,  
 L. Truong<sup>163a,163b</sup>, M. Trzebinski<sup>39</sup>, A. Trzupek<sup>39</sup>, J.C-L. Tseng<sup>119</sup>, P.V. Tsiarshka<sup>92</sup>, G. Tsipolitis<sup>10</sup>,  
 N. Tsirintanis<sup>9</sup>, S. Tsiskaridze<sup>12</sup>, V. Tsiskaridze<sup>48</sup>, E.G. Tskhadadze<sup>51a</sup>, K.M. Tsui<sup>60a</sup>, I.I. Tsukerman<sup>96</sup>,  
 V. Tsulaia<sup>15</sup>, S. Tsuno<sup>66</sup>, D. Tsybychev<sup>147</sup>, A. Tudorache<sup>26b</sup>, V. Tudorache<sup>26b</sup>, A.N. Tuna<sup>57</sup>,  
 S.A. Tuppuri<sup>20a,20b</sup>, S. Turchikhin<sup>98,ai</sup>, D. Turecek<sup>127</sup>, D. Turgeman<sup>171</sup>, R. Turra<sup>91a,91b</sup>, A.J. Turvey<sup>40</sup>,  
 P.M. Tuts<sup>35</sup>, M. Tylmad<sup>145a,145b</sup>, M. Tyndel<sup>130</sup>, I. Ueda<sup>154</sup>, R. Ueno<sup>29</sup>, M. Ughetto<sup>145a,145b</sup>,  
 F. Ukegawa<sup>159</sup>, G. Unal<sup>30</sup>, A. Undrus<sup>25</sup>, G. Unel<sup>162</sup>, F.C. Ungaro<sup>88</sup>, Y. Unno<sup>66</sup>, C. Unverdorben<sup>99</sup>,  
 J. Urban<sup>143b</sup>, P. Urquijo<sup>88</sup>, P. Urrejola<sup>83</sup>, G. Usai<sup>8</sup>, A. Usanova<sup>62</sup>, L. Vacavant<sup>85</sup>, V. Vacek<sup>127</sup>,  
 B. Vachon<sup>87</sup>, C. Valderanis<sup>83</sup>, E. Valdes Santurio<sup>145a,145b</sup>, N. Valencic<sup>106</sup>, S. Valentinetti<sup>20a,20b</sup>,  
 A. Valero<sup>166</sup>, L. Valery<sup>12</sup>, S. Valkar<sup>128</sup>, S. Vallecorsa<sup>49</sup>, J.A. Valls Ferrer<sup>166</sup>, W. Van Den Wollenberg<sup>106</sup>,  
 P.C. Van Der Deijl<sup>106</sup>, R. van der Geer<sup>106</sup>, H. van der Graaf<sup>106</sup>, N. van Eldik<sup>151</sup>, P. van Gemmeren<sup>6</sup>,

J. Van Nieuwkoop<sup>141</sup>, I. van Vulpen<sup>106</sup>, M.C. van Woerden<sup>30</sup>, M. Vanadia<sup>131a,131b</sup>, W. Vandelli<sup>30</sup>, R. Vanguri<sup>121</sup>, A. Vaniachine<sup>6</sup>, P. Vankov<sup>106</sup>, G. Vardanyan<sup>176</sup>, R. Vari<sup>131a</sup>, E.W. Varnes<sup>7</sup>, T. Varol<sup>40</sup>, D. Varouchas<sup>80</sup>, A. Vartapetian<sup>8</sup>, K.E. Varvell<sup>149</sup>, F. Vazeille<sup>34</sup>, T. Vazquez Schroeder<sup>87</sup>, J. Veatch<sup>7</sup>, L.M. Veloce<sup>157</sup>, F. Veloso<sup>125a,125c</sup>, S. Veneziano<sup>131a</sup>, A. Ventura<sup>73a,73b</sup>, M. Venturi<sup>168</sup>, N. Venturi<sup>157</sup>, A. Venturini<sup>23</sup>, V. Vercesi<sup>120a</sup>, M. Verducci<sup>131a,131b</sup>, W. Verkerke<sup>106</sup>, J.C. Vermeulen<sup>106</sup>, A. Vest<sup>44,am</sup>, M.C. Vetterli<sup>141,d</sup>, O. Viazlo<sup>81</sup>, I. Vichou<sup>164</sup>, T. Vickey<sup>138</sup>, O.E. Vickey Boeriu<sup>138</sup>, G.H.A. Viehhauser<sup>119</sup>, S. Viel<sup>15</sup>, R. Vigne<sup>62</sup>, M. Villa<sup>20a,20b</sup>, M. Villaplana Perez<sup>91a,91b</sup>, E. Vilucchi<sup>47</sup>, M.G. Vincter<sup>29</sup>, V.B. Vinogradov<sup>65</sup>, I. Vivarelli<sup>148</sup>, S. Vlachos<sup>10</sup>, M. Vlasak<sup>127</sup>, M. Vogel<sup>174</sup>, P. Vokac<sup>127</sup>, G. Volpi<sup>123a,123b</sup>, M. Volpi<sup>88</sup>, H. von der Schmitt<sup>100</sup>, E. von Toerne<sup>21</sup>, V. Vorobel<sup>128</sup>, K. Vorobev<sup>97</sup>, M. Vos<sup>166</sup>, R. Voss<sup>30</sup>, J.H. Vosseveld<sup>74</sup>, N. Vranjes<sup>13</sup>, M. Vranjes Milosavljevic<sup>13</sup>, V. Vrba<sup>126</sup>, M. Vreeswijk<sup>106</sup>, R. Vuillermet<sup>30</sup>, I. Vukotic<sup>31</sup>, Z. Vykydal<sup>127</sup>, P. Wagner<sup>21</sup>, W. Wagner<sup>174</sup>, H. Wahlberg<sup>71</sup>, S. Wahrmund<sup>44</sup>, J. Wakabayashi<sup>102</sup>, J. Walder<sup>72</sup>, R. Walker<sup>99</sup>, W. Walkowiak<sup>140</sup>, V. Wallangen<sup>145a,145b</sup>, C. Wang<sup>150</sup>, C. Wang<sup>33d,85</sup>, F. Wang<sup>172</sup>, H. Wang<sup>15</sup>, H. Wang<sup>40</sup>, J. Wang<sup>42</sup>, J. Wang<sup>149</sup>, K. Wang<sup>87</sup>, R. Wang<sup>6</sup>, S.M. Wang<sup>150</sup>, T. Wang<sup>21</sup>, T. Wang<sup>35</sup>, X. Wang<sup>175</sup>, C. Wanotayaroj<sup>115</sup>, A. Warburton<sup>87</sup>, C.P. Ward<sup>28</sup>, D.R. Wardrope<sup>78</sup>, A. Washbrook<sup>46</sup>, P.M. Watkins<sup>18</sup>, A.T. Watson<sup>18</sup>, I.J. Watson<sup>149</sup>, M.F. Watson<sup>18</sup>, G. Watts<sup>137</sup>, S. Watts<sup>84</sup>, B.M. Waugh<sup>78</sup>, S. Webb<sup>83</sup>, M.S. Weber<sup>17</sup>, S.W. Weber<sup>173</sup>, J.S. Webster<sup>6</sup>, A.R. Weidberg<sup>119</sup>, B. Weinert<sup>61</sup>, J. Weingarten<sup>54</sup>, C. Weiser<sup>48</sup>, H. Weits<sup>106</sup>, P.S. Wells<sup>30</sup>, T. Wenaus<sup>25</sup>, T. Wengler<sup>30</sup>, S. Wenig<sup>30</sup>, N. Wermes<sup>21</sup>, M. Werner<sup>48</sup>, P. Werner<sup>30</sup>, M. Wessels<sup>58a</sup>, J. Wetter<sup>160</sup>, K. Whalen<sup>115</sup>, A.M. Wharton<sup>72</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>32b</sup>, S. White<sup>123a,123b</sup>, D. Whiteson<sup>162</sup>, F.J. Wickens<sup>130</sup>, W. Wiedenmann<sup>172</sup>, M. Wielers<sup>130</sup>, P. Wienemann<sup>21</sup>, C. Wiglesworth<sup>36</sup>, L.A.M. Wiik-Fuchs<sup>21</sup>, A. Wildauer<sup>100</sup>, H.G. Wilkens<sup>30</sup>, H.H. Williams<sup>121</sup>, S. Williams<sup>106</sup>, C. Willis<sup>90</sup>, S. Willocq<sup>86</sup>, J.A. Wilson<sup>18</sup>, I. Wingerter-Seez<sup>5</sup>, F. Winklmeier<sup>115</sup>, O.J. Winston<sup>148</sup>, B.T. Winter<sup>21</sup>, M. Wittgen<sup>142</sup>, J. Wittkowski<sup>99</sup>, A. Wolf<sup>83</sup>, S.J. Wollstadt<sup>83</sup>, M.W. Wolter<sup>39</sup>, H. Wolters<sup>125a,125c</sup>, B.K. Wosiek<sup>39</sup>, J. Wotschack<sup>30</sup>, M.J. Woudstra<sup>84</sup>, K.W. Wozniak<sup>39</sup>, M. Wu<sup>55</sup>, M. Wu<sup>31</sup>, S.L. Wu<sup>172</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>89</sup>, T.R. Wyatt<sup>84</sup>, B.M. Wynne<sup>46</sup>, S. Xella<sup>36</sup>, D. Xu<sup>33a</sup>, L. Xu<sup>25</sup>, B. Yabsley<sup>149</sup>, S. Yacoub<sup>144a</sup>, R. Yakabe<sup>67</sup>, D. Yamaguchi<sup>156</sup>, Y. Yamaguchi<sup>117</sup>, A. Yamamoto<sup>66</sup>, S. Yamamoto<sup>154</sup>, T. Yamanaka<sup>154</sup>, K. Yamauchi<sup>102</sup>, Y. Yamazaki<sup>67</sup>, Z. Yan<sup>22</sup>, H. Yang<sup>33e</sup>, H. Yang<sup>172</sup>, Y. Yang<sup>150</sup>, Z. Yang<sup>14</sup>, W-M. Yao<sup>15</sup>, Y.C. Yap<sup>80</sup>, Y. Yasu<sup>66</sup>, E. Yatsenko<sup>5</sup>, K.H. Yau Wong<sup>21</sup>, J. Ye<sup>40</sup>, S. Ye<sup>25</sup>, I. Yeletsikh<sup>65</sup>, A.L. Yen<sup>57</sup>, E. Yildirim<sup>42</sup>, K. Yorita<sup>170</sup>, R. Yoshida<sup>6</sup>, K. Yoshihara<sup>121</sup>, C. Young<sup>142</sup>, C.J.S. Young<sup>30</sup>, S. Youssef<sup>22</sup>, D.R. Yu<sup>15</sup>, J. Yu<sup>8</sup>, J.M. Yu<sup>89</sup>, J. Yu<sup>64</sup>, L. Yuan<sup>67</sup>, S.P.Y. Yuen<sup>21</sup>, I. Yusuf<sup>28,an</sup>, B. Zabinski<sup>39</sup>, R. Zaidan<sup>33d</sup>, A.M. Zaitsev<sup>129,ac</sup>, N. Zakharchuk<sup>42</sup>, J. Zalieckas<sup>14</sup>, A. Zaman<sup>147</sup>, S. Zambito<sup>57</sup>, L. Zanello<sup>131a,131b</sup>, D. Zanzi<sup>88</sup>, C. Zeitnitz<sup>174</sup>, M. Zeman<sup>127</sup>, A. Zemla<sup>38a</sup>, J.C. Zeng<sup>164</sup>, Q. Zeng<sup>142</sup>, K. Zengel<sup>23</sup>, O. Zenin<sup>129</sup>, T. Ženiš<sup>143a</sup>, D. Zerwas<sup>116</sup>, D. Zhang<sup>89</sup>, F. Zhang<sup>172</sup>, G. Zhang<sup>33b,z</sup>, H. Zhang<sup>33c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>48</sup>, R. Zhang<sup>21</sup>, R. Zhang<sup>33b,ao</sup>, X. Zhang<sup>33d</sup>, Z. Zhang<sup>116</sup>, X. Zhao<sup>40</sup>, Y. Zhao<sup>33d,116</sup>, Z. Zhao<sup>33b</sup>, A. Zhemchugov<sup>65</sup>, J. Zhong<sup>119</sup>, B. Zhou<sup>89</sup>, C. Zhou<sup>45</sup>, L. Zhou<sup>35</sup>, L. Zhou<sup>40</sup>, M. Zhou<sup>147</sup>, N. Zhou<sup>33f</sup>, C.G. Zhu<sup>33d</sup>, H. Zhu<sup>33a</sup>, J. Zhu<sup>89</sup>, Y. Zhu<sup>33b</sup>, X. Zhuang<sup>33a</sup>, K. Zhukov<sup>95</sup>, A. Zibell<sup>173</sup>, D. Zieminska<sup>61</sup>, N.I. Zimine<sup>65</sup>, C. Zimmermann<sup>83</sup>, S. Zimmermann<sup>48</sup>, Z. Zinonos<sup>54</sup>, M. Zinser<sup>83</sup>, M. Ziolkowski<sup>140</sup>, L. Živković<sup>13</sup>, G. Zobernig<sup>172</sup>, A. Zoccoli<sup>20a,20b</sup>, M. zur Nedden<sup>16</sup>, G. Zurzolo<sup>103a,103b</sup>, L. Zwalinski<sup>30</sup>.

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c)

Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
- <sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America
- <sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
- <sup>9</sup> Physics Department, University of Athens, Athens, Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>12</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
- <sup>13</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- <sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(d)</sup> Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; <sup>(e)</sup> Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
- <sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>22</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>23</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>24</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>26</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov, Romania; <sup>(b)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(d)</sup> University Politehnica Bucharest, Bucharest; <sup>(e)</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>32</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP); <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and



CNRS/IN2P3, Clermont-Ferrand, France

<sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America

<sup>36</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

<sup>37</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy

<sup>38</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

<sup>39</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

<sup>40</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America

<sup>41</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America

<sup>42</sup> DESY, Hamburg and Zeuthen, Germany

<sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

<sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

<sup>45</sup> Department of Physics, Duke University, Durham NC, United States of America

<sup>46</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

<sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

<sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland

<sup>50</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy

<sup>51</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

<sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

<sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

<sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

<sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

<sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States of America

<sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

<sup>58</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup>

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

<sup>59</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

<sup>60</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup>

Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

<sup>61</sup> Department of Physics, Indiana University, Bloomington IN, United States of America

<sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

<sup>63</sup> University of Iowa, Iowa City IA, United States of America

<sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

<sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

<sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

<sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan

<sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan

<sup>69</sup> Kyoto University of Education, Kyoto, Japan

<sup>70</sup> Department of Physics, Kyushu University, Fukuoka, Japan

<sup>71</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

- 72 Physics Department, Lancaster University, Lancaster, United Kingdom
- 73 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 75 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 78 Department of Physics and Astronomy, University College London, London, United Kingdom
- 79 Louisiana Tech University, Ruston LA, United States of America
- 80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 81 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 82 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 83 Institut für Physik, Universität Mainz, Mainz, Germany
- 84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
- 87 Department of Physics, McGill University, Montreal QC, Canada
- 88 School of Physics, University of Melbourne, Victoria, Australia
- 89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- 90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- 91 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- 93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- 94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 95 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 97 National Research Nuclear University MEPhI, Moscow, Russia
- 98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 101 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 103 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 109 Department of Physics, New York University, New York NY, United States of America

- <sup>110</sup> Ohio State University, Columbus OH, United States of America
- <sup>111</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>112</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>113</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>114</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>115</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>116</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- <sup>117</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>118</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>119</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>120</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>121</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>122</sup> National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- <sup>123</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>124</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>125</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>126</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>127</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>128</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>129</sup> State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- <sup>130</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>131</sup> <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>132</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V, Rabat, Morocco
- <sup>135</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>136</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- <sup>137</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>138</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>139</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>140</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany

- <sup>141</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>142</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>143</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>144</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>145</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>146</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>147</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- <sup>148</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>149</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>150</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>151</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>152</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>153</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>154</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>155</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>156</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>157</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>158</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>159</sup> Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- <sup>160</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- <sup>161</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>162</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- <sup>163</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>164</sup> Department of Physics, University of Illinois, Urbana IL, United States of America
- <sup>165</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>166</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- <sup>167</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>168</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>169</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>170</sup> Waseda University, Tokyo, Japan
- <sup>171</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>172</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America
- <sup>173</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>174</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität

Wuppertal, Wuppertal, Germany

<sup>175</sup> Department of Physics, Yale University, New Haven CT, United States of America

<sup>176</sup> Yerevan Physics Institute, Yerevan, Armenia

<sup>177</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

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

<sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia

<sup>d</sup> Also at TRIUMF, Vancouver BC, Canada

<sup>e</sup> Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America

<sup>f</sup> Also at Department of Physics, California State University, Fresno CA, United States of America

<sup>g</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland

<sup>h</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

<sup>i</sup> Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal

<sup>j</sup> Also at Tomsk State University, Tomsk, Russia

<sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy

<sup>l</sup> Also at Institute of Particle Physics (IPP), Canada

<sup>m</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia

<sup>n</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

<sup>o</sup> Also at Louisiana Tech University, Ruston LA, United States of America

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

<sup>q</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan

<sup>r</sup> Also at Department of Physics, National Tsing Hua University, Taiwan

<sup>s</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

<sup>t</sup> Also at Institute of Theoretical Physics, Iliia State University, Tbilisi, Georgia

<sup>u</sup> Also at CERN, Geneva, Switzerland

<sup>v</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia

<sup>w</sup> Also at O Chadai Academic Production, Ochanomizu University, Tokyo, Japan

<sup>x</sup> Also at Manhattan College, New York NY, United States of America

<sup>y</sup> Also at Hellenic Open University, Patras, Greece

<sup>z</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>aa</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

<sup>ab</sup> Also at School of Physics, Shandong University, Shandong, China

<sup>ac</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

<sup>ad</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland

<sup>ae</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy

<sup>af</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

<sup>ag</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China

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

<sup>ai</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

<sup>aj</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia

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

<sup>al</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest,

**Hungary**

<sup>am</sup> Also at Flensburg University of Applied Sciences, Flensburg, Germany

<sup>an</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

<sup>ao</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

\* Deceased