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## Medium-Induced Modification of Z-Tagged Charged Particle Yields in Pb + Pb Collisions at 5.02 TeV with the ATLAS Detector

G. Aad *et al.*\*  
(ATLAS Collaboration)

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The yield of charged particles opposite to a Z boson with large transverse momentum ( $p_T$ ) is measured in  $260 \text{ pb}^{-1}$  of  $pp$  and  $1.7 \text{ nb}^{-1}$  of Pb + Pb collision data at 5.02 TeV per nucleon pair recorded with the ATLAS detector at the Large Hadron Collider. The Z boson tag is used to select hard-scattered partons with specific kinematics, and to observe how their showers are modified as they propagate through the quark-gluon plasma created in Pb + Pb collisions. Compared with  $pp$  collisions, charged-particle yields in Pb + Pb collisions show significant modifications as a function of charged-particle  $p_T$  in a way that depends on event centrality and Z boson  $p_T$ . The data are compared with a variety of theoretical calculations and provide new information about the medium-induced energy loss of partons in a  $p_T$  regime difficult to measure through other channels.

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Collisions of heavy nuclei at ultrarelativistic energies at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) are understood to produce an extended region of hot and dense matter where partons exist in a deconfined state known as the quark-gluon plasma (QGP). The high density of unscreened color charges in the QGP causes the showers of hard-scattered partons with large transverse momentum ( $p_T$ ) to be modified as they traverse the medium [1]. These modifications are observed in measurements of dijet and photon-jet momentum imbalance [2–5], and in jet fragmentation functions [6,7].

The large integrated luminosity of Pb + Pb collisions delivered during LHC Run 2 has enabled measurements of jets produced in association with a high- $p_T$  Z boson. At leading order, the Z boson and the jet are produced back to back in the azimuthal plane, with equal  $p_T$ . Since Z bosons and their decay leptons, or similarly, photons, do not participate in the strong interaction and are not modified by the QGP [8,9], they provide an estimate of the  $p_T$  and azimuthal direction of the partner hard-scattered parton before the developing shower is modified through interactions with the QGP [10,11]. Measurements of photon-tagged fragmentation functions at the LHC [12,13] and photon-hadron correlations at RHIC [14,15] used this feature to perform detailed studies of jet

quenching. At fixed  $p_T$ , jets balancing Z bosons and photons arise from processes with different  $Q^2$ , and can test the sensitivity of the energy loss process to parton virtuality. Additionally, the use of isolated photons at low photon  $p_T$  ( $\lesssim 60 \text{ GeV}$ ) is difficult due to the large hadron-decay background, motivating the use of Z bosons. A measurement of Z + jet production with  $p_T^Z > 60 \text{ GeV}$  by CMS demonstrates that the total  $p_T$  carried inside the jet cone is decreased in Pb + Pb events compared with that in  $pp$  events [16]. However, the modification of the jet's constituent particle  $p_T$  distributions, or any lower  $p_T^Z$  selections, have not yet been studied.

This Letter presents a measurement of the yield of charged particles produced opposite in azimuth to a Z boson with  $p_T^Z > 15 \text{ GeV}$  in Pb + Pb and  $pp$  collisions at a nucleon-nucleon center-of-mass energy  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  with the ATLAS detector at the LHC. The Pb + Pb and  $pp$  data were recorded in 2018 and 2017, respectively, and correspond to integrated luminosities of up to  $1.7 \text{ nb}^{-1}$  and  $260 \text{ pb}^{-1}$ . The charged particles are required to have  $p_T^{\text{ch}} > 1 \text{ GeV}$  and be approximately back to back with the Z boson in the transverse plane, with azimuthal separation  $\Delta\phi$  larger than  $3\pi/4$  [17]. In simulations of  $pp$  collisions, particles meeting these criteria reside primarily in the leading jet azimuthally opposite to the Z boson. The per-Z yields of charged particles,  $N_{\text{ch}}$ , are reported as a function of  $p_T^{\text{ch}}$ ,  $(1/N_Z)(d^2N_{\text{ch}}/dp_T^{\text{ch}}d\Delta\phi)$ , in  $pp$  and Pb + Pb collisions. To quantify the modification resulting from the partons' propagation through the QGP, the ratio of particle yields between Pb + Pb and  $pp$  collisions,  $I_{AA}$ , is reported and compared with the expectations from theoretical calculations. This measurement explores phenomena similar to those in measurements of the photon-tagged jet fragmentation function [12]. However, requiring a

\*Full author list given at the end of the article.

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reconstructed jet may result in a bias towards events with less energy loss than average [18–20]. Since there is no such requirement in this measurement, it provides additional insight into energy loss in an unbiased way, at low  $p_T^{Z/\gamma}$  values which have not yet been measured at the LHC and where theoretical models have not been tested.

The ATLAS experiment [21] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle. It consists of an inner tracking detector surrounded by a superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors [22,23]. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). Liquid-argon calorimeters with separate EM and hadronic compartments instrument the end cap (up to  $|\eta| = 3.2$ ) and forward (FCal, up to  $|\eta| = 4.9$ ) regions. The muon spectrometer surrounds the calorimeters and includes three air-core toroidal superconducting magnets with field integrals ranging between 2.0 and 6.0 T m, a system of precision tracking chambers, and fast detectors for triggering. During Pb + Pb data taking, the muon system was operational for only  $1.4 \text{ nb}^{-1}$  of the total integrated luminosity. Thus the dimuon channel is analyzed only in this subset of data.

Events with a high- $p_T$  electron or muon are initially selected for analysis by the single-lepton triggers described in Refs. [24,25]. The centrality of Pb + Pb events is defined using the total transverse energy measured in the FCal [4,26],  $\Sigma E_T^{\text{Pb}}$ . Pb + Pb events are divided into three categories which correspond to the 0%–10%, 10%–30%, and 30%–80% centrality intervals in minimum-bias (MB) events, the smaller values indicating larger nuclear overlap regions and thus larger, hotter QGP regions. The orientation of the underlying event (UE) elliptic flow is determined from the azimuthal distribution of the FCal energy [27,28]. In  $pp$  events, the average number of interactions per bunch crossing ranged from 2 to 4, and thus all charged-particle tracks are required to originate from the primary reconstructed vertex [29].

Monte Carlo simulations of  $\sqrt{s} = 5.02 \text{ TeV}$   $pp$  collisions with  $Z$  bosons decaying in the dielectron and dimuon channels, as well as data-driven studies, are used to correct the data for bin migration and reconstruction inefficiencies. Generated events were passed through a GEANT4 simulation [30,31] of the ATLAS detector under the same conditions present during data taking and were digitized and reconstructed in the same way as the data. The  $Z$  boson events were generated at next-to-leading order (NLO) with the POWHEG-BOX v2 program [32–35] interfaced to the

PYTHIA 8.186 parton shower model [36]. The NLO CT10 parton distribution function (PDF) set [37] was used in the matrix element, while the CTEQ6L1 PDF set [38] and the AZNLO tuned set of parameters [39] were used to model the parton shower.

Four million events were generated to serve as the simulation sample for  $pp$  collisions. To model Pb + Pb events, fifteen million simulated  $pp$  events were overlaid at the detector-hit level with MB Pb + Pb events in data. This data-overlay sample was reweighted on an event-by-event basis to match the  $\Sigma E_T^{\text{Pb}}$  distribution for Pb + Pb events containing  $Z$  bosons.

The  $Z$  bosons in  $pp$  and Pb + Pb events are reconstructed in opposite-sign dielectron and dimuon decay channels using procedures similar to those described in Refs. [9,40]. Reconstructed electrons are required to have a transverse momentum  $p_T^e > 20 \text{ GeV}$ , to lie within the fiducial acceptance of the EM barrel ( $|\eta^e| < 1.37$ ) or end cap ( $1.52 < |\eta^e| < 2.47$ ) detectors, and to satisfy “loose” likelihood-based identification criteria, which have been optimized separately for  $pp$  and Pb + Pb events [41]. Reconstructed muons are required to have a transverse momentum  $p_T^\mu > 20 \text{ GeV}$ , to lie within the fiducial acceptance of the muon spectrometer ( $|\eta^\mu| < 2.5$ ), and to pass the “medium” selection requirements described in Ref. [42]. The  $Z \rightarrow \ell\ell$  candidates are required to be within the mass range  $76 < m_{\ell\ell} < 106 \text{ GeV}$  and have  $p_T^Z > 15 \text{ GeV}$ . This selection ensures that the contribution from multijet and other backgrounds is smaller than 1.5% (0.1%) for the dielectron (dimuon) channel, and is considered negligible. In total, these criteria select approximately 21 000 (28 000)  $Z \rightarrow ee$  ( $Z \rightarrow \mu\mu$ ) events in  $pp$  data, and 3400 (4100) events in Pb + Pb data.

Each  $Z$  data event is assigned a series of weights, derived from simulation and data, to account for the trigger, reconstruction and selection efficiencies of its decay leptons. Individual lepton trigger efficiencies are determined directly in  $pp$  and Pb + Pb data using tag-and-probe techniques [24,25], and are 0.70–0.80 for each muon and 0.75–0.95 for each electron. Reconstruction and selection efficiencies are determined using simulation and are 0.65–0.80 for muons and 0.65–0.95 for electrons. Although the efficiencies may vary substantially with the individual lepton  $p_T$ ,  $\eta$ , and  $\phi$ , the resulting dependence on  $p_T^Z$  is weak due to the large  $Z$  mass and weak correlation between bosons and their decay leptons.

Charged-particle tracks are reconstructed from hits in the inner detector using an algorithm [43] which, in Pb + Pb collisions, is optimized for the high-occupancy conditions [44]. They are required to meet several criteria intended to select primary charged particles [6]. All reconstructed tracks with  $p_T > 1 \text{ GeV}$ ,  $|\eta| < 2.5$  and  $\Delta\phi > 3\pi/4$  are considered. The charged-particle yield is corrected for reconstruction and selection inefficiency on a per-track basis using a simulation-derived efficiency which varies

from 0.6 to 0.8 depending on both detector occupancy and track kinematics. A small correction, typically 1%–2%, accounts for the contribution of reconstructed tracks not associated with primary particles. The  $p_T^{\text{ch}}$  resolution is found to have a negligible effect ( $\lesssim 0.3\%$ ) on the results and is not corrected for.

The contribution to the yield from UE particles in Pb + Pb collisions is estimated using MB events and is statistically subtracted from the measured yields. For each  $Z$  event in data, 40–160 unique MB events are used for this estimation. These MB events are centrality matched to within 1% in peripheral events, decreasing to within 0.1% in central events. Furthermore, to match the azimuthal modulation of the UE, the elliptic flow angles [28] in the  $Z$  data event and in the matching MB event must match within  $\pi/16$ . The signal-to-background ratio varies strongly with  $p_T^{\text{ch}}$ ,  $p_T^Z$ , and Pb + Pb centrality, with a minimum of  $5 \times 10^{-3}$  at the lowest  $p_T^{\text{ch}}$  and  $p_T^Z$  values in the most central events. In  $pp$  events, the UE is known to have larger activity in a  $Z$  event than in an ordinary MB  $pp$  collision [45,46], necessitating a different procedure. Here, the UE is determined in events with  $1 < p_T^Z < 12$  GeV in the azimuthal region perpendicular to the  $Z$  boson to avoid the contribution from jet particles.

The data are further corrected for bin migration resulting from the finite resolution in the  $p_T^Z$  measurement. This is evaluated by comparing the per- $Z$  charged-particle yields, where the  $Z$  selection is made at the generator level, with those after reconstruction, and is typically a 2%–3% correction.

The primary sources of systematic uncertainty in the yield measurement are those affecting the  $Z$  boson reconstruction, those affecting the charged-particle selection, and those affecting the UE background estimation and subtraction. The uncertainties associated with the electron and muon energy scales are evaluated using a common set of uncertainties [42,47], and are typically negligible ( $\lesssim 1\%$ ) except at high  $p_T^{\text{ch}}$ . Those associated with lepton trigger and selection efficiency determination are smaller than the ones related to the energy scale. Several sources of tracking-related uncertainty are considered, which are described in previous measurements of charged-particle fragmentation functions, and of which the largest is the sensitivity to the track selection criteria, which is 2%–3% [6,48].

The uncertainty in the determination of the UE background yield is evaluated by propagating the statistical uncertainty of the UE estimation in MB events. The sensitivity of the UE estimation to the matching criteria for the elliptic flow [27] angles between signal and MB events, or the additional requirement to match the triangular flow angles, are investigated. However, since these variations give statistically compatible results, they are not included. As a check of the background subtraction procedure, the full analysis is performed on simulated  $Z$  events overlaid with HIJING [49] Pb + Pb background, and

compared with the generator-level distributions. An absolute uncertainty in the background estimation of 0.3% is derived using this study.

Finally, an internal consistency check is performed by comparing the per- $Z$  yields between the electron and muon decay channels. A difference was observed in the  $15 < p_T^Z < 30$  GeV selections and was included as an uncertainty of at most 4% in  $pp$  and 14% in central Pb + Pb events.

For the yields at low  $p_T^{\text{ch}}$  and in central events, the uncertainty from the UE determination is dominant and can be as large as 30%. For yields at high  $p_T^{\text{ch}}$  and in lower-multiplicity events, the uncertainties associated with the track selection and the lepton energy scale are typically dominant, and as large as 5%. Uncertainty sources common to Pb + Pb and  $pp$  are canceled in the  $I_{AA}$  ratio when possible, such that the resulting measurement is dominated by uncertainties specific to Pb + Pb events. In all cases, the statistical uncertainty in the  $I_{AA}$  is larger than the total systematic uncertainty.

Figure 1 presents the charged-particle yield per  $Z$  boson, in Pb + Pb and  $pp$  events, as a function of  $p_T^{\text{ch}}$ , for the selection  $\Delta\phi > 3\pi/4$ . The yields in Pb + Pb collisions are observed to be modified relative to those in  $pp$  collisions.

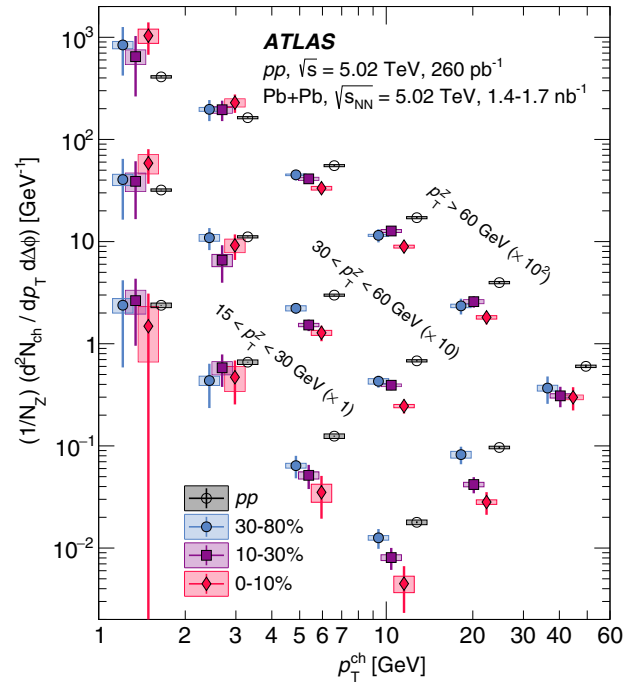


FIG. 1. Charged-particle yield per  $Z$  boson as a function of  $p_T^{\text{ch}}$ , for the selection  $\Delta\phi > 3\pi/4$ , reported for  $15 < p_T^Z < 30$  GeV,  $30 < p_T^Z < 60$  GeV, and  $p_T^Z > 60$  GeV. Results are shown for  $pp$  events and the three centralities of Pb + Pb events. These are offset horizontally around the bin centers, which are located between the 0%–10% and 10%–30% points, for visibility. The vertical bars and boxes correspond to the statistical and systematic uncertainties of the data.

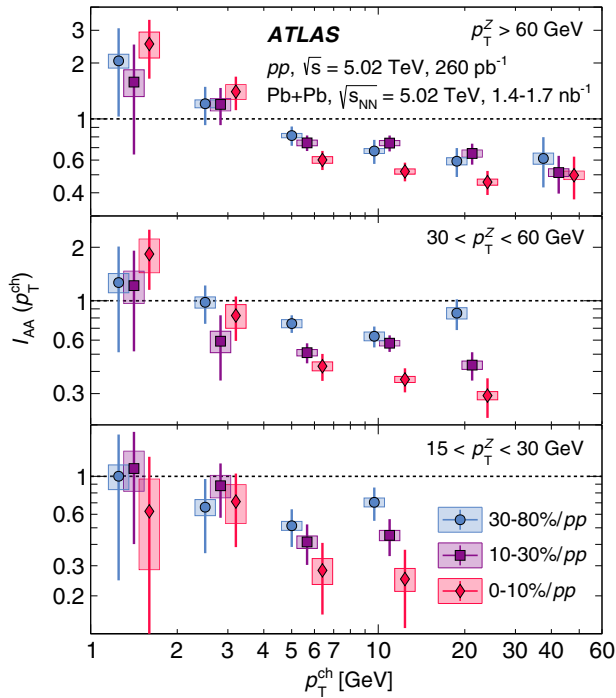


FIG. 2. Ratio of the charged-particle yield in Pb + Pb collisions to that in  $pp$  collisions,  $I_{AA}$ , as a function of charged-particle  $p_T^{\text{ch}}$ , for the selection  $\Delta\phi > 3\pi/4$ . The vertical bars and boxes correspond to the statistical and systematic uncertainties of the data. The 0%–10% and 30%–80% data are offset horizontally for visibility.

To better reveal the modification, Fig. 2 presents  $I_{AA}$  values, the ratios of yields in Pb + Pb events to those in  $pp$  events. The  $I_{AA}$  values are suppressed below unity at large  $p_T^{\text{ch}}$ , with a systematically larger suppression in more central events and for lower  $p_T^Z$  selections. For  $p_T^Z > 60$  GeV, the  $I_{AA}$  values at low  $p_T^{\text{ch}}$ , less than 2–3 GeV, are significantly different than those at high  $p_T^{\text{ch}}$ ,

and typically greater than unity. Lower  $p_T^Z$  selections are compatible with a similar increase at low  $p_T^{\text{ch}}$ , although the uncertainties limit the significance of this enhancement. The suppression over a wide range of  $p_T^{\text{ch}}$  values, and the general enhancement of the  $I_{AA}$  above unity at lower  $p_T^{\text{ch}}$ , are qualitatively similar to those observed in the ratios of jet fragmentation functions in photon-tagged events [12].

Figure 3 compares the  $I_{AA}$  in 0%–10% Pb + Pb events with the following theoretical calculations, where available, which use the same kinematic selections as the data: (1) a perturbative calculation within the framework of soft-collinear effective field theory with Glauber gluons (SCET<sub>G</sub>) in the soft-gluon-emission (energy-loss) limit, with jet-medium coupling  $g = 2.0 \pm 0.2$  [50,51]; (2) the Hybrid Strong/Weak Coupling model [52], which combines initial production using PYTHIA 8 with a parameterization of energy loss derived from holographic methods, including backreaction effects; (3) JEWEL, an MC event generator which simulates QCD jet evolution in heavy-ion collisions, including radiative and elastic energy loss processes, and configured to include medium recoils [53]; and (4) a coupled linearized Boltzmann transport (COLBT) and hydrodynamics model [54,55], which includes jet-induced medium excitations. All models qualitatively reproduce the degree of suppression at large  $p_T^{\text{ch}}$ , greater than 10 GeV. The Hybrid model, JEWEL and COLBT qualitatively capture the increase at low  $p_T^{\text{ch}}$ . For these three models, removing the backreaction, medium recoils, and jet-induced medium excitations, respectively, results in a significant underprediction of the data in this region. Several of these models also capture the relative difference in the  $I_{AA}$  between the three  $p_T^Z$  selections. A full evaluation of theoretical uncertainties is needed to further discriminate between the mechanisms of energy loss and medium response in the data.

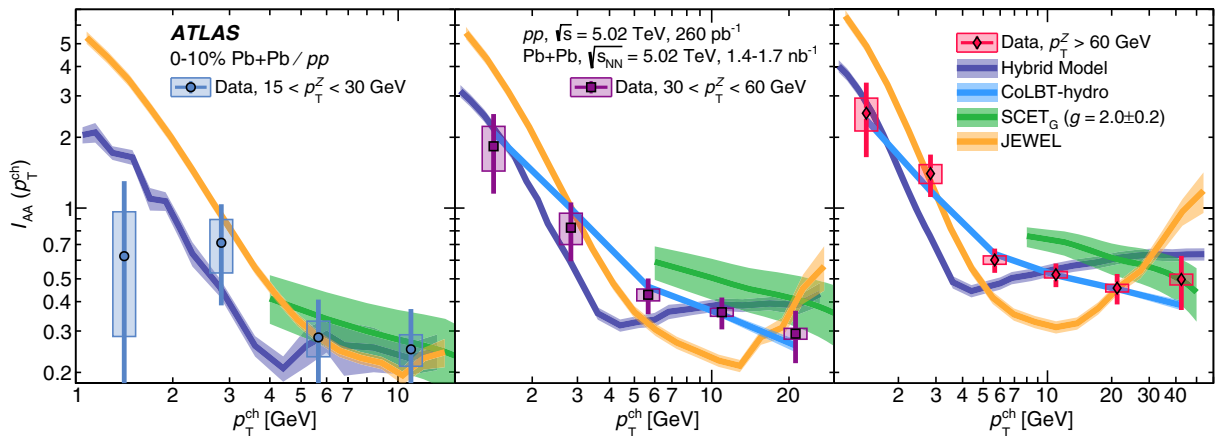


FIG. 3. The  $I_{AA}$  ratio as a function of  $p_T^{\text{ch}}$  in data compared with theoretical calculations (see text), for the selection  $\Delta\phi > 3\pi/4$ . The vertical bars and boxes correspond to the statistical and systematic uncertainties, while the shaded bands represent the theoretical uncertainty (statistical for JEWEL, Hybrid, and COLBT-hydro, parametric for SCET<sub>G</sub>). The  $I_{AA}$  is shown for 0%–10% Pb + Pb events for  $p_T^Z = 15$ –30 GeV (left), 30–60 GeV (center), and  $> 60$  GeV (right).



In conclusion, this Letter presents a measurement of charged-particle yields produced in the azimuthal direction opposite to a  $Z$  boson with  $p_T > 15$  GeV. The measurement is performed using  $260 \text{ pb}^{-1}$  of  $pp$  and up to  $1.7 \text{ nb}^{-1}$  of Pb + Pb collision data at 5.02 TeV with the ATLAS detector at the Large Hadron Collider. The per- $Z$  yields are systematically modified in Pb + Pb collisions compared with  $pp$  collisions due to the interactions between the parton shower and the hot and dense QGP medium. The charged-particle  $p_T$  distribution in Pb + Pb collisions is softer than that in  $pp$  collisions, with a suppression at high  $p_T^{\text{ch}}$  and an enhancement at low  $p_T^{\text{ch}}$ . The degree of modification varies with Pb + Pb event centrality, consistent with a larger and hotter QGP being created in more central events. At high  $p_T^Z$ , the modification pattern is qualitatively similar to that observed in measurements of photon-tagged jet fragmentation functions. In addition to the particular theoretical comparisons presented here, the data will allow systematic tests of models across centrality and  $p_T^Z$  selections. The data can also test energy loss models for low- $p_T$  partons that are otherwise difficult to access experimentally at the LHC, but which are valuable for direct comparison to future measurements at RHIC.

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 V. Cavasinni,<sup>72a,72b</sup> E. Celebi,<sup>12b</sup> F. Celli,<sup>134</sup> K. Cerny,<sup>130</sup> A. S. Cerqueira,<sup>81a</sup> A. Cerri,<sup>156</sup> L. Cerrito,<sup>74a,74b</sup> F. Cerutti,<sup>18</sup>  
 A. Cervelli,<sup>23b,23a</sup> S. A. Cetin,<sup>12b</sup> Z. Chadi,<sup>35a</sup> D. Chakraborty,<sup>121</sup> J. Chan,<sup>181</sup> W. S. Chan,<sup>120</sup> W. Y. Chan,<sup>91</sup> J. D. Chapman,<sup>32</sup>  
 B. Chargeishvili,<sup>159b</sup> D. G. Charlton,<sup>21</sup> T. P. Charman,<sup>93</sup> M. Chatterjee,<sup>20</sup> C. C. Chau,<sup>34</sup> S. Che,<sup>127</sup> S. Chekanov,<sup>6</sup>  
 S. V. Chekulaev,<sup>168a</sup> G. A. Chelkov,<sup>80,i</sup> B. Chen,<sup>79</sup> C. Chen,<sup>60a</sup> C. H. Chen,<sup>79</sup> H. Chen,<sup>15c</sup> H. Chen,<sup>26b</sup> J. Chen,<sup>60a</sup> J. Chen,<sup>39</sup>  
 J. Chen,<sup>27</sup> S. Chen,<sup>136</sup> S. J. Chen,<sup>15c</sup> X. Chen,<sup>15b</sup> Y. Chen,<sup>60a</sup> Y-H. Chen,<sup>46</sup> H. C. Cheng,<sup>63a</sup> H. J. Cheng,<sup>15a</sup> A. Cheplakov,<sup>80</sup>  
 E. Cheremushkina,<sup>123</sup> R. Cherkaoui El Moursli,<sup>35e</sup> E. Cheu,<sup>7</sup> K. Cheung,<sup>64</sup> T. J. A. Chevaléras,<sup>144</sup> L. Chevalier,<sup>144</sup>  
 V. Chiarella,<sup>51</sup> G. Chiarelli,<sup>72a</sup> G. Chiodini,<sup>68a</sup> A. S. Chisholm,<sup>21</sup> A. Chitan,<sup>28b</sup> I. Chiu,<sup>163</sup> Y. H. Chiu,<sup>176</sup> M. V. Chizhov,<sup>80</sup>  
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 Z. H. Citron,<sup>180,j</sup> M. Citterio,<sup>69a</sup> D. A. Ciubotaru,<sup>28b</sup> B. M. Ciungu,<sup>167</sup> A. Clark,<sup>54</sup> P. J. Clark,<sup>50</sup> S. E. Clawson,<sup>101</sup>  
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 S. Constantinescu,<sup>28b</sup> F. Conventi,<sup>70a,k</sup> A. M. Cooper-Sarkar,<sup>134</sup> F. Cormier,<sup>175</sup> K. J. R. Cormier,<sup>167</sup> L. D. Corpe,<sup>95</sup>  
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 J. V. Da Fonseca Pinto,<sup>81b</sup> C. Da Via,<sup>101</sup> W. Dabrowski,<sup>84a</sup> F. Dachs,<sup>36</sup> T. Dado,<sup>47</sup> S. Dahbi,<sup>33e</sup> T. Dai,<sup>106</sup> C. Dallapiccola,<sup>103</sup>  
 M. Dam,<sup>40</sup> G. D'amen,<sup>26b</sup> V. D'Amico,<sup>75a,75b</sup> J. Damp,<sup>100</sup> J. R. Dandoy,<sup>136</sup> M. F. Daneri,<sup>30</sup> M. Danninger,<sup>152</sup> V. Dao,<sup>36</sup>  
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 C. Delporte,<sup>65</sup> P. A. Delsart,<sup>58</sup> S. Demers,<sup>183</sup> M. Demichev,<sup>80</sup> G. Demontigny,<sup>110</sup> S. P. Denisov,<sup>123</sup> L. D'Eramo,<sup>121</sup>  
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 P. O. Deviveiros,<sup>36</sup> F. A. Di Bello,<sup>73a,73b</sup> A. Di Ciaccio,<sup>74a,74b</sup> L. Di Ciaccio,<sup>5</sup> W. K. Di Clemente,<sup>136</sup> C. Di Donato,<sup>70a,70b</sup>  
 A. Di Girolamo,<sup>36</sup> G. Di Gregorio,<sup>72a,72b</sup> A. Di Luca,<sup>76a,76b</sup> B. Di Micco,<sup>75a,75b</sup> R. Di Nardo,<sup>75a,75b</sup> K. F. Di Petrillo,<sup>59</sup>  
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 M. Didenko,<sup>166</sup> E. B. Diehl,<sup>106</sup> J. Dietrich,<sup>19</sup> S. Díez Cornell,<sup>46</sup> C. Diez Pardos,<sup>151</sup> A. Dimitrievska,<sup>18</sup> W. Ding,<sup>15b</sup>  
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 L. Dufлот,<sup>65</sup> M. Dührssen,<sup>36</sup> C. Dülsen,<sup>182</sup> M. Dumancic,<sup>180</sup> A. E. Dumitriu,<sup>28b</sup> M. Dunford,<sup>61a</sup> S. Dungs,<sup>47</sup> A. Duperrin,<sup>102</sup>  
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 Y. Fang,<sup>15a</sup> Y. Fang,<sup>15a</sup> G. Fanourakis,<sup>44</sup> M. Fanti,<sup>69a,69b</sup> M. Faraj,<sup>67a,67c</sup> A. Farbin,<sup>8</sup> A. Farilla,<sup>75a</sup> E. M. Farina,<sup>71a,71b</sup>  
 T. Farooque,<sup>107</sup> S. M. Farrington,<sup>50</sup> P. Farthouat,<sup>36</sup> F. Fassi,<sup>35e</sup> P. Fassnacht,<sup>36</sup> D. Fassouliotis,<sup>9</sup> M. Fauci Giannelli,<sup>50</sup>  
 W. J. Fawcett,<sup>32</sup> L. Fayard,<sup>65</sup> O. L. Fedin,<sup>137,m</sup> W. Fedorko,<sup>175</sup> A. Fehr,<sup>20</sup> M. Feickert,<sup>173</sup> L. Feligioni,<sup>102</sup> A. Fell,<sup>149</sup>  
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 R. Ferrari,<sup>71a</sup> D. E. Ferreira de Lima,<sup>61b</sup> A. Ferrer,<sup>174</sup> D. Ferrere,<sup>54</sup> C. Ferretti,<sup>106</sup> F. Fiedler,<sup>100</sup> A. Filipčić,<sup>92</sup> F. Filthaut,<sup>119</sup>  
 K. D. Finelli,<sup>25</sup> M. C. N. Fiolhais,<sup>139a,139c,n</sup> L. Fiorini,<sup>174</sup> F. Fischer,<sup>114</sup> J. Fischer,<sup>100</sup> W. C. Fisher,<sup>107</sup> T. Fitschen,<sup>21</sup> I. Fleck,<sup>151</sup>  
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 L. Franco,<sup>5</sup> L. Franconi,<sup>20</sup> M. Franklin,<sup>59</sup> G. Frattari,<sup>73a,73b</sup> A. N. Fray,<sup>93</sup> P. M. Freeman,<sup>21</sup> B. Freund,<sup>110</sup> W. S. Freund,<sup>81b</sup>  
 E. M. Freundlich,<sup>47</sup> D. C. Frizzell,<sup>128</sup> D. Froidevaux,<sup>36</sup> J. A. Frost,<sup>134</sup> M. Fujimoto,<sup>126</sup> C. Fukunaga,<sup>164</sup>  
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 G. Giannini,<sup>14</sup> S. M. Gibson,<sup>94</sup> M. Gignac,<sup>145</sup> D. T. Gil,<sup>84b</sup> B. J. Gilbert,<sup>39</sup> D. Gillberg,<sup>34</sup> G. Gilles,<sup>182</sup> N. E. K. Gillwald,<sup>46</sup>  
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 F. Gonnella,<sup>21</sup> J. L. Gonski,<sup>39</sup> S. González de la Hoz,<sup>174</sup> S. Gonzalez Fernandez,<sup>14</sup> R. Gonzalez Lopez,<sup>91</sup>  
 C. Gonzalez Renteria,<sup>18</sup> R. Gonzalez Suarez,<sup>172</sup> S. Gonzalez-Sevilla,<sup>54</sup> G. R. Gonzalvo Rodriguez,<sup>174</sup> L. Goossens,<sup>36</sup>  
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 J. Grosse-Knetter,<sup>53</sup> Z. J. Grout,<sup>95</sup> C. Grud,<sup>106</sup> A. Grummer,<sup>118</sup> J. C. Grundy,<sup>134</sup> L. Guan,<sup>106</sup> W. Guan,<sup>181</sup> C. Gubbels,<sup>175</sup>  
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 T. Guillemin,<sup>5</sup> S. Guindon,<sup>36</sup> J. Guo,<sup>60c</sup> W. Guo,<sup>106</sup> Y. Guo,<sup>60a</sup> Z. Guo,<sup>102</sup> R. Gupta,<sup>46</sup> S. Gurbuz,<sup>12c</sup> G. Gustavino,<sup>128</sup>  
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 K. Hanagaki,<sup>82,t</sup> M. Hance,<sup>145</sup> D. M. Handl,<sup>114</sup> M. D. Hank,<sup>37</sup> R. Hankache,<sup>135</sup> E. Hansen,<sup>97</sup> J. B. Hansen,<sup>40</sup> J. D. Hansen,<sup>40</sup>  
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 H. S. Hayward,<sup>91</sup> S. J. Haywood,<sup>143</sup> F. He,<sup>60a</sup> Y. He,<sup>165</sup> M. P. Heath,<sup>50</sup> V. Hedberg,<sup>97</sup> A. L. Heggelund,<sup>133</sup> C. Heidegger,<sup>52</sup>  
 K. K. Heidegger,<sup>52</sup> W. D. Heidorn,<sup>79</sup> J. Heilman,<sup>34</sup> S. Heim,<sup>46</sup> T. Heim,<sup>18</sup> B. Heinemann,<sup>46,u</sup> J. G. Heinlein,<sup>136</sup>  
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 C. Helsen,<sup>36</sup> R. C. W. Henderson,<sup>90</sup> L. Henkelmann,<sup>32</sup> A. M. Henriques Correia,<sup>36</sup> H. Herde,<sup>27</sup> Y. Hernández Jiménez,<sup>33e</sup>  
 H. Herr,<sup>100</sup> M. G. Herrmann,<sup>114</sup> T. Herrmann,<sup>48</sup> G. Herten,<sup>52</sup> R. Hertenberger,<sup>114</sup> L. Hervas,<sup>36</sup> T. C. Herwig,<sup>136</sup>  
 G. G. Hesketh,<sup>95</sup> N. P. Hesse,<sup>168a</sup> H. Hibi,<sup>83</sup> S. Higashino,<sup>82</sup> E. Higón-Rodríguez,<sup>174</sup> K. Hildebrand,<sup>37</sup> J. C. Hill,<sup>32</sup>  
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 M. Janus,<sup>53</sup> P. A. Janus,<sup>84a</sup> G. Jarlskog,<sup>97</sup> A. E. Jaspán,<sup>91</sup> N. Javadov,<sup>80,w</sup> T. Javůrek,<sup>36</sup> M. Javurkova,<sup>103</sup> F. Jeanneau,<sup>144</sup>  
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 J. Jovicevic,<sup>36</sup> X. Ju,<sup>18</sup> J. J. Junggeburth,<sup>115</sup> A. Juste Rozas,<sup>14,s</sup> A. Kaczmarska,<sup>85</sup> M. Kado,<sup>73a,73b</sup> H. Kagan,<sup>127</sup> M. Kagan,<sup>153</sup>  
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Kouskoura,<sup>26b</sup> R. Kowalewski,<sup>176</sup> W. Kozanecki,<sup>101</sup> A. S. Kozhin,<sup>123</sup> V. A. Kramarenko,<sup>113</sup> G. Kramberger,<sup>92</sup> D. Krasnopevtsev,<sup>60a</sup> M. W. Krasny,<sup>135</sup> A. Krasznahorkay,<sup>36</sup> D. Krauss,<sup>115</sup> J. A. Kremer,<sup>100</sup> J. Kretzschmar,<sup>91</sup> P. Krieger,<sup>167</sup> F. Krieter,<sup>114</sup> S. Krishnamurthy,<sup>103</sup> A. Krishnan,<sup>61b</sup> M. Krivos,<sup>142</sup> K. Krizka,<sup>18</sup> K. Kroeninger,<sup>47</sup> H. Kroha,<sup>115</sup> J. Kroll,<sup>140</sup> J. Kroll,<sup>136</sup> K. S. Krowpman,<sup>107</sup> U. Kruchonak,<sup>80</sup> H. Krüger,<sup>24</sup> N. Krumnack,<sup>79</sup> M. C. Kruse,<sup>49</sup> J. A. Krzysiak,<sup>85</sup> A. Kubota,<sup>165</sup> O. Kuchinskaia,<sup>166</sup> S. Kудay,<sup>4b</sup> D. Kuechler,<sup>46</sup> J. T. Kuechler,<sup>46</sup> S. Kuehn,<sup>36</sup> T. Kuhl,<sup>46</sup> V. Kukhtin,<sup>80</sup> Y. Kulchitsky,<sup>108,y</sup> S. Kuleshov,<sup>146b</sup> Y. P. Kulinich,<sup>173</sup> M. Kuna,<sup>58</sup> A. Kupco,<sup>140</sup> T. Kupfer,<sup>47</sup> O. Kuprash,<sup>52</sup> H. Kurashige,<sup>83</sup> L. L. Kurchaninov,<sup>168a</sup> Y. A. Kurochkin,<sup>108</sup> A. Kurova,<sup>112</sup> M. G. Kurth,<sup>15a,15d</sup> E. S. Kuwertz,<sup>36</sup> M. Kuze,<sup>165</sup> A. K. Kvam,<sup>148</sup> J. Kvita,<sup>130</sup> T. Kwan,<sup>104</sup> F. La Ruffa,<sup>41b,41a</sup> C. Lacasta,<sup>174</sup> F. Lacava,<sup>73a,73b</sup> D. P. J. Lack,<sup>101</sup> H. Lacker,<sup>19</sup> D. Lacour,<sup>135</sup> E. Ladygin,<sup>80</sup> R. Lafaye,<sup>5</sup> B. Laforge,<sup>135</sup> T. Lagouri,<sup>146c</sup> S. Lai,<sup>53</sup> I. K. Lakomicz,<sup>84a</sup> J. E. Lambert,<sup>128</sup> S. Lammers,<sup>66</sup> W. Lampl,<sup>7</sup> C. Lampoudis,<sup>162</sup> E. Lançon,<sup>26b</sup> U. Landgraf,<sup>52</sup> M. P. J. Landon,<sup>93</sup> V. S. Lang,<sup>52</sup> J. C. 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A. Traet,<sup>17</sup> C. J. Treado,<sup>125</sup> T. Trefzger,<sup>177</sup> F. Tresoldi,<sup>156</sup> A. Tricoli,<sup>26b</sup> I. M. Trigger,<sup>168a</sup> S. Trincaz-Duvoid,<sup>135</sup>  
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A. Trzupek,<sup>85</sup> F. Tsai,<sup>46</sup> J. C-L. Tseng,<sup>134</sup> P. V. Tsiarshka,<sup>108,y</sup> A. Tsirigotis,<sup>162,z</sup> V. Tsiskaridze,<sup>155</sup> E. G. Tskhadadze,<sup>159a</sup>  
M. Tsopoulou,<sup>162</sup> I. I. Tsukerman,<sup>124</sup> V. Tsulaia,<sup>18</sup> S. Tsuno,<sup>82</sup> D. Tsybychev,<sup>155</sup> Y. Tu,<sup>63b</sup> A. Tudorache,<sup>28b</sup> V. Tudorache,<sup>28b</sup>  
T. T. Tulbure,<sup>28a</sup> A. N. Tuna,<sup>59</sup> S. Turchikhin,<sup>80</sup> D. Turgeman,<sup>180</sup> I. Turk Cakir,<sup>4b,kk</sup> R. J. Turner,<sup>21</sup> R. Turra,<sup>69a</sup> P. M. Tuts,<sup>39</sup>  
S. Tzamarias,<sup>162</sup> E. Tzovara,<sup>100</sup> K. Uchida,<sup>163</sup> F. Ukegawa,<sup>169</sup> G. Unal,<sup>36</sup> M. Unal,<sup>11</sup> A. Undrus,<sup>26b</sup> G. Unel,<sup>171</sup>  
F. C. Ungaro,<sup>105</sup> Y. Unno,<sup>82</sup> K. Uno,<sup>163</sup> J. Urban,<sup>29b</sup> P. Urquijo,<sup>105</sup> G. Usai,<sup>8</sup> Z. Uysal,<sup>12d</sup> V. Vacek,<sup>141</sup> B. Vachon,<sup>104</sup>  
K. O. H. Vadla,<sup>133</sup> T. Vafeiadis,<sup>36</sup> A. Vaidya,<sup>95</sup> C. Valderanis,<sup>114</sup> E. Valdes Santurio,<sup>45a,45b</sup> M. Valente,<sup>168a</sup>  
S. Valentinetti,<sup>23b,23a</sup> A. Valero,<sup>174</sup> L. Valéry,<sup>46</sup> R. A. Vallance,<sup>21</sup> A. Vallier,<sup>36</sup> J. A. Valls Ferrer,<sup>174</sup> T. R. Van Daalen,<sup>14</sup>  
P. Van Gemmeren,<sup>6</sup> S. Van Stroud,<sup>95</sup> I. Van Vulpen,<sup>120</sup> M. Vanadia,<sup>74a,74b</sup> W. Vandelli,<sup>36</sup> M. Vandenbroucke,<sup>144</sup>  
E. R. Vandewall,<sup>129</sup> A. Vaniachine,<sup>166</sup> D. Vannicola,<sup>73a,73b</sup> R. Vari,<sup>73a</sup> E. W. Varnes,<sup>7</sup> C. Varni,<sup>55b,55a</sup> T. Varol,<sup>158</sup>  
D. Varouchas,<sup>65</sup> K. E. Varvell,<sup>157</sup> M. E. Vasile,<sup>28b</sup> G. A. Vasquez,<sup>176</sup> F. Vazeille,<sup>38</sup> D. Vazquez Furelos,<sup>14</sup>  
T. Vazquez Schroeder,<sup>36</sup> J. Veatch,<sup>53</sup> V. Vecchio,<sup>101</sup> M. J. Veen,<sup>120</sup> L. M. Veloce,<sup>167</sup> F. Veloso,<sup>139a,139c</sup> S. Veneziano,<sup>73a</sup>  
A. Ventura,<sup>68a,68b</sup> A. Verbytskyi,<sup>115</sup> V. Vercesi,<sup>71a</sup> M. Verducci,<sup>72a,72b</sup> C. M. Vergel Infante,<sup>79</sup> C. Vergis,<sup>24</sup> W. Verkerke,<sup>120</sup>  
A. T. Vermeulen,<sup>120</sup> J. C. Vermeulen,<sup>120</sup> C. Vernieri,<sup>153</sup> P. J. Verschuuren,<sup>94</sup> M. C. Vetterli,<sup>152,d</sup> N. Viaux Maira,<sup>146d</sup>  
T. Vickey,<sup>149</sup> O. E. Vickey Boeriu,<sup>149</sup> G. H. A. Viehhauser,<sup>134</sup> L. Vignani,<sup>61b</sup> M. Villa,<sup>23b,23a</sup> M. Villaplana Perez,<sup>3</sup>  
E. M. Villhauer,<sup>50</sup> E. Vilucchi,<sup>51</sup> M. G. Vincter,<sup>34</sup> G. S. Virdee,<sup>21</sup> A. Vishwakarma,<sup>50</sup> C. Vittori,<sup>23b,23a</sup> I. Vivarelli,<sup>156</sup>  
M. Vogel,<sup>182</sup> P. Vokac,<sup>141</sup> J. Von Ahnen,<sup>46</sup> S. E. von Buddenbrock,<sup>33e</sup> E. Von Toerne,<sup>24</sup> V. Vorobel,<sup>142</sup> K. Vorobev,<sup>112</sup>  
M. Vos,<sup>174</sup> J. H. Vosseveld,<sup>91</sup> M. Vozak,<sup>101</sup> N. Vranjes,<sup>16</sup> M. Vranjes Milosavljevic,<sup>16</sup> V. Vrba,<sup>141</sup> M. Vreeswijk,<sup>120</sup>  
N. K. Vu,<sup>102</sup> R. Vuillermet,<sup>36</sup> I. Vukotic,<sup>37</sup> S. Wada,<sup>169</sup> P. Wagner,<sup>24</sup> W. Wagner,<sup>182</sup> J. Wagner-Kuhr,<sup>114</sup> S. Wahdan,<sup>182</sup>  
H. Wahlberg,<sup>89</sup> R. Wakasa,<sup>169</sup> V. M. Walbrecht,<sup>115</sup> J. Walder,<sup>143</sup> R. Walker,<sup>114</sup> S. D. Walker,<sup>94</sup> W. Walkowiak,<sup>151</sup>  
V. Wallangen,<sup>45a,45b</sup> A. M. Wang,<sup>59</sup> A. Z. Wang,<sup>181</sup> C. Wang,<sup>60a</sup> C. Wang,<sup>60c</sup> H. Wang,<sup>18</sup> H. Wang,<sup>3</sup> J. Wang,<sup>63a</sup> P. Wang,<sup>42</sup>  
Q. Wang,<sup>128</sup> R.-J. Wang,<sup>100</sup> R. Wang,<sup>60a</sup> R. Wang,<sup>6</sup> S. M. Wang,<sup>158</sup> W. T. Wang,<sup>60a</sup> W. Wang,<sup>15c</sup> W. X. Wang,<sup>60a</sup> Y. Wang,<sup>60a</sup>

Z. Wang,<sup>106</sup> C. Wanotayaroj,<sup>46</sup> A. Warburton,<sup>104</sup> C. P. Ward,<sup>32</sup> R. J. Ward,<sup>21</sup> N. Warrack,<sup>57</sup> A. T. Watson,<sup>21</sup> M. F. Watson,<sup>21</sup> G. Watts,<sup>148</sup> B. M. Waugh,<sup>95</sup> A. F. Webb,<sup>11</sup> C. Weber,<sup>26b</sup> M. S. Weber,<sup>20</sup> S. A. Weber,<sup>34</sup> S. M. Weber,<sup>61a</sup> A. R. Weidberg,<sup>134</sup> J. Weingarten,<sup>47</sup> M. Weirich,<sup>100</sup> C. Weiser,<sup>52</sup> P. S. Wells,<sup>36</sup> T. Wenaus,<sup>26b</sup> B. Wendland,<sup>47</sup> T. Wengler,<sup>36</sup> S. Wenig,<sup>36</sup> N. Vermes,<sup>24</sup> M. Wessels,<sup>61a</sup> T. D. Weston,<sup>20</sup> K. Whalen,<sup>131</sup> A. M. Wharton,<sup>90</sup> A. S. White,<sup>106</sup> A. White,<sup>8</sup> M. J. White,<sup>1</sup> D. Whiteson,<sup>171</sup> B. W. Whitmore,<sup>90</sup> W. Wiedenmann,<sup>181</sup> C. Wiel,<sup>48</sup> M. Wieler,<sup>143</sup> N. Wieseotte,<sup>100</sup> C. Wiglesworth,<sup>40</sup> L. A. M. Wiik-Fuchs,<sup>52</sup> H. G. Wilkens,<sup>36</sup> L. J. Wilkins,<sup>94</sup> D. M. Williams,<sup>39</sup> H. H. Williams,<sup>136</sup> S. Williams,<sup>32</sup> S. Willocq,<sup>103</sup> P. J. Windischhofer,<sup>134</sup> I. Wingerter-Seez,<sup>5</sup> E. Winkels,<sup>156</sup> F. Winklmeier,<sup>131</sup> B. T. Winter,<sup>52</sup> M. Wittgen,<sup>153</sup> M. Wobisch,<sup>96</sup> A. Wolf,<sup>100</sup> R. Wölker,<sup>134</sup> J. Wollrath,<sup>52</sup> M. W. Wolter,<sup>85</sup> H. Wolters,<sup>139a,139c</sup> V. W. S. Wong,<sup>175</sup> A. F. Wongel,<sup>46</sup> N. L. Woods,<sup>145</sup> S. D. Worm,<sup>46</sup> B. K. Wosiek,<sup>85</sup> K. W. Woźniak,<sup>85</sup> K. Wraight,<sup>57</sup> S. L. Wu,<sup>181</sup> X. Wu,<sup>54</sup> Y. Wu,<sup>60a</sup> J. Wuerzinger,<sup>134</sup> T. R. Wyatt,<sup>101</sup> B. M. Wynne,<sup>50</sup> S. Xella,<sup>40</sup> L. Xia,<sup>178</sup> J. Xiang,<sup>63c</sup> X. Xiao,<sup>106</sup> X. Xie,<sup>60a</sup> I. Xiotidis,<sup>156</sup> D. Xu,<sup>15a</sup> H. Xu,<sup>60a</sup> H. Xu,<sup>60a</sup> L. Xu,<sup>26b</sup> R. Xu,<sup>136</sup> T. Xu,<sup>144</sup> W. Xu,<sup>106</sup> Y. Xu,<sup>15b</sup> Z. Xu,<sup>60b</sup> Z. Xu,<sup>153</sup> B. Yabsley,<sup>157</sup> S. Yacoob,<sup>33a</sup> D. P. Yallup,<sup>95</sup> N. Yamaguchi,<sup>88</sup> Y. Yamaguchi,<sup>165</sup> A. Yamamoto,<sup>82</sup> M. Yamatani,<sup>163</sup> T. Yamazaki,<sup>163</sup> Y. Yamazaki,<sup>83</sup> J. Yan,<sup>60c</sup> Z. Yan,<sup>25</sup> H. J. Yang,<sup>60c,60d</sup> H. T. Yang,<sup>18</sup> S. Yang,<sup>60a</sup> T. Yang,<sup>63c</sup> X. Yang,<sup>60a</sup> X. Yang,<sup>60b,58</sup> Y. Yang,<sup>163</sup> Z. Yang,<sup>60a</sup> W-M. Yao,<sup>18</sup> Y. C. Yap,<sup>46</sup> E. Yatsenko,<sup>60c</sup> H. Ye,<sup>15c</sup> J. Ye,<sup>42</sup> S. Ye,<sup>26b</sup> I. Yeletsikh,<sup>80</sup> M. R. Yexley,<sup>90</sup> E. Yigitbasi,<sup>25</sup> P. Yin,<sup>39</sup> K. Yorita,<sup>179</sup> K. Yoshihara,<sup>79</sup> C. J. S. Young,<sup>36</sup> C. Young,<sup>153</sup> J. Yu,<sup>79</sup> R. Yuan,<sup>60b,11</sup> X. Yue,<sup>61a</sup> M. Zaazoua,<sup>35e</sup> B. Zabinski,<sup>85</sup> G. Zacharis,<sup>10</sup> E. Zaffaroni,<sup>54</sup> J. Zahreddine,<sup>135</sup> A. M. Zaitsev,<sup>123,i</sup> T. Zakareishvili,<sup>159b</sup> N. Zakharchuk,<sup>34</sup> S. Zambito,<sup>36</sup> D. Zanzi,<sup>36</sup> S. V. Zeißner,<sup>47</sup> C. Zeitnitz,<sup>182</sup> G. Zemaityte,<sup>134</sup> J. C. Zeng,<sup>173</sup> O. Zenin,<sup>123</sup> T. Ženiš,<sup>29a</sup> D. Zerwas,<sup>65</sup> M. Zgubič,<sup>134</sup> B. Zhang,<sup>15c</sup> D. F. Zhang,<sup>15b</sup> G. Zhang,<sup>15b</sup> J. Zhang,<sup>6</sup> K. Zhang,<sup>15a</sup> L. Zhang,<sup>15c</sup> L. Zhang,<sup>60a</sup> M. Zhang,<sup>173</sup> R. Zhang,<sup>181</sup> S. Zhang,<sup>106</sup> X. Zhang,<sup>60c</sup> X. Zhang,<sup>60b</sup> Y. Zhang,<sup>15a,15d</sup> Z. Zhang,<sup>63a</sup> Z. Zhang,<sup>65</sup> P. Zhao,<sup>49</sup> Y. Zhao,<sup>145</sup> Z. Zhao,<sup>60a</sup> A. Zhemchugov,<sup>80</sup> Z. Zheng,<sup>106</sup> D. Zhong,<sup>173</sup> B. Zhou,<sup>106</sup> C. Zhou,<sup>181</sup> H. Zhou,<sup>7</sup> M. S. Zhou,<sup>15a,15d</sup> M. Zhou,<sup>155</sup> N. Zhou,<sup>60c</sup> Y. Zhou,<sup>7</sup> C. G. Zhu,<sup>60b</sup> C. Zhu,<sup>15a,15d</sup> H. L. Zhu,<sup>60a</sup> H. Zhu,<sup>15a</sup> J. Zhu,<sup>106</sup> Y. Zhu,<sup>60a</sup> X. Zhuang,<sup>15a</sup> K. Zhukov,<sup>111</sup> V. Zhulanov,<sup>122b,122a</sup> D. Zieminska,<sup>66</sup> N. I. Zimine,<sup>80</sup> S. Zimmermann,<sup>52</sup> Z. Zinonos,<sup>115</sup> M. Ziolkowski,<sup>151</sup> L. Živković,<sup>16</sup> G. Zobernig,<sup>181</sup> A. Zoccoli,<sup>23b,23a</sup> K. Zoch,<sup>53</sup> T. G. Zorbas,<sup>149</sup> R. Zou,<sup>37</sup> and L. Zwalinski<sup>36</sup>

(ATLAS Collaboration)

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

<sup>2</sup>Physics Department, SUNY Albany, Albany, New York, USA

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

<sup>4a</sup>Department of Physics, Ankara University, Ankara, Turkey

<sup>4b</sup>Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey

<sup>4c</sup>Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup>LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>6</sup>High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

<sup>7</sup>Department of Physics, University of Arizona, Tucson, Arizona, USA

<sup>8</sup>Department of Physics, University of Texas at Arlington, Arlington, Texas, USA

<sup>9</sup>Physics Department, National and Kapodistrian University of Athens, Athens, Greece

<sup>10</sup>Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup>Department of Physics, University of Texas at Austin, Austin, Texas, USA

<sup>12a</sup>Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

<sup>12b</sup>Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

<sup>12c</sup>Department of Physics, Bogazici University, Istanbul, Turkey

<sup>12d</sup>Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>13</sup>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>14</sup>Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>15a</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

<sup>15b</sup>Physics Department, Tsinghua University, Beijing, China

<sup>15c</sup>Department of Physics, Nanjing University, Nanjing, China

<sup>15d</sup>University of Chinese Academy of Science (UCAS), Beijing, China

<sup>16</sup>Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>17</sup>Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>18</sup>Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA



- <sup>19</sup>*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- <sup>20</sup>*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- <sup>21</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- <sup>22a</sup>*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia*
- <sup>22b</sup>*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia*
- <sup>23a</sup>*INFN Bologna and Università di Bologna, Dipartimento di Fisica, Italy*
- <sup>23b</sup>*INFN Sezione di Bologna, Italy*
- <sup>24</sup>*Physikalisches Institut, Universität Bonn, Bonn, Germany*
- <sup>25</sup>*Department of Physics, Boston University, Boston, Massachusetts, USA*
- <sup>26a</sup>*University of Colorado Boulder, Department of Physics, Colorado, USA*
- <sup>26b</sup>*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- <sup>27</sup>*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
- <sup>28a</sup>*Transilvania University of Brasov, Brasov, Romania*
- <sup>28b</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- <sup>28c</sup>*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- <sup>28d</sup>*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
- <sup>28e</sup>*University Politehnica Bucharest, Bucharest, Romania*
- <sup>28f</sup>*West University in Timisoara, Timisoara, Romania*
- <sup>29a</sup>*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- <sup>29b</sup>*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- <sup>30</sup>*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- <sup>31</sup>*California State University, California, USA*
- <sup>32</sup>*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>33a</sup>*Department of Physics, University of Cape Town, Cape Town, South Africa*
- <sup>33b</sup>*iThemba Labs, Western Cape, South Africa*
- <sup>33c</sup>*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- <sup>33d</sup>*University of South Africa, Department of Physics, Pretoria, South Africa*
- <sup>33e</sup>*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- <sup>34</sup>*Department of Physics, Carleton University, Ottawa ON, Canada*
- <sup>35a</sup>*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- <sup>35b</sup>*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
- <sup>35c</sup>*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- <sup>35d</sup>*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
- <sup>35e</sup>*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- <sup>36</sup>*CERN, Geneva, Switzerland*
- <sup>37</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- <sup>38</sup>*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- <sup>39</sup>*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- <sup>40</sup>*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- <sup>41a</sup>*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- <sup>41b</sup>*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- <sup>42</sup>*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- <sup>43</sup>*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- <sup>44</sup>*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- <sup>45a</sup>*Department of Physics, Stockholm University, Sweden*
- <sup>45b</sup>*Oskar Klein Centre, Stockholm, Sweden*
- <sup>46</sup>*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- <sup>47</sup>*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- <sup>48</sup>*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- <sup>49</sup>*Department of Physics, Duke University, Durham, North Carolina, USA*
- <sup>50</sup>*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- <sup>51</sup>*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- <sup>52</sup>*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- <sup>53</sup>*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- <sup>54</sup>*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- <sup>55a</sup>*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- <sup>55b</sup>*INFN Sezione di Genova, Italy*
- <sup>56</sup>*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*

- <sup>57</sup>*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- <sup>58</sup>*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- <sup>59</sup>*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- <sup>60a</sup>*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- <sup>60b</sup>*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- <sup>60c</sup>*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
- <sup>60d</sup>*Tsung-Dao Lee Institute, Shanghai, China*
- <sup>61a</sup>*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- <sup>61b</sup>*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- <sup>62</sup>*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- <sup>63a</sup>*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- <sup>63b</sup>*Department of Physics, University of Hong Kong, Hong Kong, China*
- <sup>63c</sup>*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- <sup>64</sup>*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- <sup>65</sup>*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
- <sup>66</sup>*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- <sup>67a</sup>*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- <sup>67b</sup>*ICTP, Trieste, Italy*
- <sup>67c</sup>*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- <sup>68a</sup>*INFN Sezione di Lecce, Italy*
- <sup>68b</sup>*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- <sup>69a</sup>*INFN Sezione di Milano, Italy*
- <sup>69b</sup>*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- <sup>70a</sup>*INFN Sezione di Napoli, Italy*
- <sup>70b</sup>*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- <sup>71a</sup>*INFN Sezione di Pavia, Italy*
- <sup>71b</sup>*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- <sup>72a</sup>*INFN Sezione di Pisa, Italy*
- <sup>72b</sup>*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- <sup>73a</sup>*INFN Sezione di Roma, Italy*
- <sup>73b</sup>*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- <sup>74a</sup>*INFN Sezione di Roma Tor Vergata, Italy*
- <sup>74b</sup>*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- <sup>75a</sup>*INFN Sezione di Roma Tre, Italy*
- <sup>75b</sup>*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- <sup>76a</sup>*INFN-TIFPA, Italy*
- <sup>76b</sup>*Università degli Studi di Trento, Trento, Italy*
- <sup>77</sup>*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- <sup>78</sup>*University of Iowa, Iowa City, Iowa, USA*
- <sup>79</sup>*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
- <sup>80</sup>*Joint Institute for Nuclear Research, Dubna, Russia*
- <sup>81a</sup>*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
- <sup>81b</sup>*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- <sup>81c</sup>*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- <sup>82</sup>*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- <sup>83</sup>*Graduate School of Science, Kobe University, Kobe, Japan*
- <sup>84a</sup>*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- <sup>84b</sup>*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- <sup>85</sup>*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- <sup>86</sup>*Faculty of Science, Kyoto University, Kyoto, Japan*
- <sup>87</sup>*Kyoto University of Education, Kyoto, Japan*
- <sup>88</sup>*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- <sup>89</sup>*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- <sup>90</sup>*Physics Department, Lancaster University, Lancaster, United Kingdom*
- <sup>91</sup>*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- <sup>92</sup>*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*

- <sup>93</sup>*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- <sup>94</sup>*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- <sup>95</sup>*Department of Physics and Astronomy, University College London, London, United Kingdom*
- <sup>96</sup>*Louisiana Tech University, Ruston, Louisiana, USA*
- <sup>97</sup>*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- <sup>98</sup>*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- <sup>99</sup>*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- <sup>100</sup>*Institut für Physik, Universität Mainz, Mainz, Germany*
- <sup>101</sup>*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- <sup>102</sup>*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- <sup>103</sup>*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- <sup>104</sup>*Department of Physics, McGill University, Montreal QC, Canada*
- <sup>105</sup>*School of Physics, University of Melbourne, Victoria, Australia*
- <sup>106</sup>*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
- <sup>107</sup>*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- <sup>108</sup>*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
- <sup>109</sup>*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
- <sup>110</sup>*Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- <sup>111</sup>*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- <sup>112</sup>*National Research Nuclear University MEPhI, Moscow, Russia*
- <sup>113</sup>*D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- <sup>114</sup>*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- <sup>115</sup>*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- <sup>116</sup>*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- <sup>117</sup>*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- <sup>118</sup>*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- <sup>119</sup>*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- <sup>120</sup>*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- <sup>121</sup>*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- <sup>122a</sup>*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
- <sup>122b</sup>*Novosibirsk State University Novosibirsk, Russia*
- <sup>123</sup>*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- <sup>124</sup>*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, Russia*
- <sup>125</sup>*Department of Physics, New York University, New York, New York, USA*
- <sup>126</sup>*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- <sup>127</sup>*Ohio State University, Columbus, Ohio, USA*
- <sup>128</sup>*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- <sup>129</sup>*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- <sup>130</sup>*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- <sup>131</sup>*Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA*
- <sup>132</sup>*Graduate School of Science, Osaka University, Osaka, Japan*
- <sup>133</sup>*Department of Physics, University of Oslo, Oslo, Norway*
- <sup>134</sup>*Department of Physics, Oxford University, Oxford, United Kingdom*
- <sup>135</sup>*LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France*
- <sup>136</sup>*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- <sup>137</sup>*Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia*
- <sup>138</sup>*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- <sup>139a</sup>*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- <sup>139b</sup>*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- <sup>139c</sup>*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- <sup>139d</sup>*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- <sup>139e</sup>*Departamento de Física, Universidade do Minho, Braga, Portugal*
- <sup>139f</sup>*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- <sup>139g</sup>*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- <sup>139h</sup>*Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- <sup>140</sup>*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- <sup>141</sup>*Czech Technical University in Prague, Prague, Czech Republic*
- <sup>142</sup>*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- <sup>143</sup>*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*

- <sup>144</sup>*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>145</sup>*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- <sup>146a</sup>*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- <sup>146b</sup>*Universidad Andres Bello, Department of Physics, Santiago, Chile*
- <sup>146c</sup>*Instituto de Alta Investigación, Universidad de Tarapacá, Chile*
- <sup>146d</sup>*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- <sup>147</sup>*Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil*
- <sup>148</sup>*Department of Physics, University of Washington, Seattle, Washington, USA*
- <sup>149</sup>*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- <sup>150</sup>*Department of Physics, Shinshu University, Nagano, Japan*
- <sup>151</sup>*Department Physik, Universität Siegen, Siegen, Germany*
- <sup>152</sup>*Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- <sup>153</sup>*SLAC National Accelerator Laboratory, Stanford, California, USA*
- <sup>154</sup>*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- <sup>155</sup>*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- <sup>156</sup>*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- <sup>157</sup>*School of Physics, University of Sydney, Sydney, Australia*
- <sup>158</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- <sup>159a</sup>*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- <sup>159b</sup>*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- <sup>160</sup>*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- <sup>161</sup>*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- <sup>162</sup>*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- <sup>163</sup>*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- <sup>164</sup>*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- <sup>165</sup>*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- <sup>166</sup>*Tomsk State University, Tomsk, Russia*
- <sup>167</sup>*Department of Physics, University of Toronto, Toronto ON, Canada*
- <sup>168a</sup>*TRIUMF, Vancouver BC, Canada*
- <sup>168b</sup>*Department of Physics and Astronomy, York University, Toronto ON, Canada*
- <sup>169</sup>*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- <sup>170</sup>*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- <sup>171</sup>*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- <sup>172</sup>*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- <sup>173</sup>*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- <sup>174</sup>*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
- <sup>175</sup>*Department of Physics, University of British Columbia, Vancouver BC, Canada*
- <sup>176</sup>*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
- <sup>177</sup>*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
- <sup>178</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*
- <sup>179</sup>*Waseda University, Tokyo, Japan*
- <sup>180</sup>*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
- <sup>181</sup>*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- <sup>182</sup>*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- <sup>183</sup>*Department of Physics, Yale University, New Haven, Connecticut, USA*

<sup>a</sup>Deceased.

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

<sup>c</sup>Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.

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

<sup>e</sup>Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

<sup>f</sup>Also at Physics Department, An-Najah National University, Nablus, Palestine.

<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 Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

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

<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 Borough of Manhattan Community College, City University of New York, New York, New York, USA.

<sup>o</sup>Also at Department of Physics, California State University, Fresno, USA.

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

<sup>q</sup>Also at Centro Studi e Ricerche Enrico Fermi, Italy.

<sup>r</sup>Also at Department of Physics, California State University, East Bay, USA.

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

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

<sup>u</sup>Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

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

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

<sup>x</sup>Also at CERN, Geneva, Switzerland.

<sup>y</sup>Also at Joint Institute for Nuclear Research, Dubna, Russia.

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

<sup>aa</sup>Also at The City College of New York, New York, New York, USA.

<sup>bb</sup>Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.

<sup>cc</sup>Also at Department of Physics, California State University, Sacramento, USA.

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

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

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

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

<sup>hh</sup>Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

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

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

<sup>kk</sup>Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

<sup>ll</sup>Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.