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# Measurement of Suppression of Large-Radius Jets and Its Dependence on Substructure in Pb + Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS Detector

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

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This letter presents a measurement of the nuclear modification factor of large-radius jets in  $\sqrt{s_{NN}} = 5.02$  TeV Pb + Pb collisions by the ATLAS experiment. The measurement is performed using  $1.72 \text{ nb}^{-1}$  and  $257 \text{ pb}^{-1}$  of Pb + Pb and  $pp$  data, respectively. The large-radius jets are reconstructed with the anti- $k_r$  algorithm using a radius parameter of  $R = 1.0$ , by reclustering anti- $k_r$   $R = 0.2$  jets, and are measured over the transverse momentum ( $p_T$ ) kinematic range of  $158 < p_T < 1000$  GeV and absolute pseudorapidity  $|y| < 2.0$ . The large-radius jet constituents are further reclustering using the  $k_r$  algorithm in order to obtain the splitting parameters,  $\sqrt{d_{12}}$  and  $\Delta R_{12}$ , which characterize the transverse momentum scale and angular separation for the hardest splitting in the jet, respectively. The nuclear modification factor,  $R_{AA}$ , obtained by comparing the Pb + Pb jet yields to those in  $pp$  collisions, is measured as a function of jet transverse momentum ( $p_T$ ) and  $\sqrt{d_{12}}$  or  $\Delta R_{12}$ . A significant difference in the quenching of large-radius jets having single subjet and those with more complex substructure is observed. Systematic comparison of jet suppression in terms of  $R_{AA}$  for different jet definitions is also provided. Presented results support the hypothesis that jets with hard internal splittings lose more energy through quenching and provide a new perspective for understanding the role of jet structure in jet suppression.

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Heavy-ion collisions at high energies lead to the creation of matter composed of unconfined quarks and gluons known as quark-gluon plasma (QGP). Studies of the collective expansion of the QGP [1] have demonstrated that the plasma is strongly coupled. A major goal of the experimental high-energy nuclear physics programs at the Relativistic Heavy Ion Collider and Large Hadron Collider (LHC) is to understand how the strong coupling of the QGP arises from a theory that is asymptotically free [2,3]. Jets, collimated sprays of hadrons originating in hard scattering processes, represent a key tool for studying the microscopic interactions between color charges within the QGP that ultimately determine its properties. Those interactions can alter the energy and angular distributions of constituents within the jets—a phenomenon referred to as “jet quenching” [4,5]. As a result, the jet yields are suppressed and jet properties are significantly modified in heavy-ion collisions relative to those measured in elementary proton-proton ( $pp$ ) collisions.

At the LHC, jet quenching was studied using many observables [6]. Jet substructure observables [7],

constructed from measured jet constituents, are versatile tools to measure the changes in jet properties due to jet quenching. These observables, calculated separately for each jet using a variety of algorithms, were originally motivated by studies of highly Lorentz-boosted massive resonances in elementary collisions [8]. Jet grooming algorithms that remove soft and wide-angle radiation can help mitigate the impact of backgrounds from multiple collisions within one bunch crossing (pileup) or the underlying event (UE) on these observables. They also can be used to separate hard components of a parton shower, for example, subjets, in a jet with multiprong structure [9,10]. In the context of jet quenching, these methods enable distinguishing subjets resulting from hard splittings in the parton shower from soft medium-induced radiation [11], soft particles resulting from jet-induced medium excitations [12], and the UE. Furthermore, the dependence of the jet quenching on such splittings, and more generally, the complexity of the parton shower [13] can be studied using substructure techniques.

One specific phenomenon connected with the parton shower complexity is color (de)coherence [14–16]. In the vacuum, the quantum interference in the parton cascade suppresses wide-angle gluon emissions [17–19]. This phenomenon in the medium-induced parton cascade is believed to largely dictate the magnitude of the energy loss [20,21]. In-medium jet evolution is then characterized by a vacuumlike parton cascade whose constituents are either resolved by the medium due to color decoherence

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

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leading to a radiation of individual color charges [22–24] or remain unresolved and radiate coherently as a single color charge. This induces a dependence of the observed jet suppression on the structure of splittings, which may be experimentally accessed and tested by substructure techniques [13].

Jet substructure was measured in lead-lead (Pb + Pb) collisions at the LHC using several observables: the momentum ratio of two leading subjets,  $z_g$  [25–27]; the groomed jet radius,  $\theta_g$  [27]; the groomed jet mass [28]; the number of branches obtained in the iterative declustering of the jet [26]; the  $N$  subjetiness [29] and momentum fraction of subjets [30]. Typically the per-jet normalized distributions of substructure observables are measured in Pb + Pb collisions and compared with the same quantity measured in  $pp$  collisions or to that obtained from Monte Carlo (MC) simulations. A recent measurement of  $z_g$ , fully corrected for detector effects and with a robust grooming method to reduce the impact of fluctuating backgrounds on the subjet selection, reported no significant change of the  $z_g$  distribution in Pb + Pb collisions [27]. A narrowing of the  $\theta_g$  distribution was observed in Pb + Pb collisions [27], which may be due to the color coherence effects or due to the difference in the relative suppression of quark- and gluon-initiated jets [31]. No change of the groomed mass distribution for the core of the jet was observed, and only a hint of an increase for jets with large jet mass was seen [28]. Furthermore, no significant change in the per-jet yields of the two-pronged structure was observed in Pb + Pb collisions relative to the MC-based reference in the measurement of  $N$  subjetiness [29].

One important conceptual issue associated with jet substructure measurements is that the QGP may not directly modify the hard splittings of a jet since their formation time may be much shorter than the formation time of the QGP [21]. Thus, modifications of substructure distributions due to quenching may depend on the structure of the part of the parton shower that is dictated by the vacuum. Rather than measuring the per-jet normalized distributions of a substructure variable, which result from an admixture of vacuum-driven and medium-driven substructure, it may be advantageous to, instead, quantify the suppression of jets having different substructure using the jet nuclear modification factor  $R_{AA}$  [32–35].

This Letter provides the first observation and quantification of the dependence of the large-radius jet suppression on the jet substructure. The large-radius ( $R = 1.0$ ) jets are reconstructed using a new method of reclustering from small-radius ( $R = 0.2$ ) jets. The measurement is done with the ATLAS detector differentially in jet transverse momentum ( $p_T$ ) and also in two specific substructure observables. The jet suppression is quantified in terms of jet  $R_{AA}$ . The two substructure observables are the splitting parameter,  $\sqrt{d_{12}}$ , and the angular separation,  $\Delta R_{12}$ , which characterize the transverse momentum scale and the angular separation,

respectively, for the hardest splitting in the jet. The differential jet suppression measurement allows direct quantification of the difference between the energy loss of jets with single subjet and the energy loss of jets with more complex structure involving early hard splittings. This quantification was not directly accessible in previous measurements. The use of large-radius jets then delimits the measured kinematics of the internal splitting. The results also provide a direct quantification of cone-size dependence of energy loss. Detailed quantification of jet suppression as a function of angular separation at small opening angles using tracks associated with calorimeter small-radius jets follows in a separate study by ATLAS [36].

The principal components of the ATLAS detector [37] used in this measurement are the inner tracking detector, the electromagnetic and hadronic calorimeters, and the online trigger system. The inner tracking detector is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and it covers the pseudorapidity range  $|\eta| < 2.5$  [38]. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead and liquid-argon sampling calorimeters provide electromagnetic energy measurements with high granularity. A steel and scintillator-tile hadron calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). Liquid-argon calorimeters with separate electromagnetic and hadronic compartments instrument the end cap (up to  $|\eta| = 3.2$ ) and forward calorimeter (FCal) (up to  $|\eta| = 4.9$ ) regions. Both the inner detector and calorimeter systems have a  $2\pi$  coverage in azimuth. Two zero-degree calorimeters are composed of four longitudinal layers of tungsten absorbers and quartz rods. They are situated in the far forward region  $|\eta| > 8.3$  and primarily measure the spectator neutrons from the struck Pb nuclei. An extensive software suite [39] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The analysis uses  $1.72 \text{ nb}^{-1}$  of Pb + Pb data at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  recorded in 2018 and  $257 \text{ pb}^{-1}$  of  $pp$  data collected in 2017 at the same center-of-mass energy. Events were selected using a combination of calorimeter-based jet triggers [40,41]. Both the  $pp$  and Pb + Pb events are required to contain at least one primary vertex. All jets in the analysis are in a kinematic range where the jet trigger was fully efficient. The Pb + Pb data contain only a small fraction of events ( $< 0.5\%$ ) with multiple collisions per bunch crossing, which are further suppressed using the anticorrelation of signal from the zero degree calorimeter and FCal. The  $pp$  data were collected with typically 1.4–4.4 inelastic interactions per bunch crossing. No pileup rejection is applied in the analysis of  $pp$  data.

The centrality of Pb + Pb events is defined using the total transverse energy measured in the FCal,  $\Sigma E_T^{\text{FCal}}$  [42,43]. Events in Pb + Pb data are classified into four centrality intervals, ordered from the most central to the most

peripheral: 0%–10%, 10%–30%, 30%–50%, and 50%–80%. The values of the mean nuclear thickness function with their uncertainties,  $\langle T_{AA} \rangle$  (used as an input to  $R_{AA}$ ), are evaluated in each centrality interval by a Glauber model analysis of the  $\Sigma E_T^{\text{FCal}}$  distribution [44,45].

Several MC simulation samples are used to evaluate the performance of the analysis procedure and to correct the measured distributions for detector effects. The  $pp$  MC sample uses  $4 \times 10^7$  PYTHIA8 [46] jet events at  $\sqrt{s} = 5.02$  TeV with the A14 ATLAS tune [47] and the NNPDF23LO parton distribution functions (PDF) [48]. Pileup from additional  $pp$  collisions is generated by PYTHIA8, with parameter values set to the A2 tune [49] and using the MSTW2008 [50] PDF set, with a distribution of the number of extra collisions matching that of data.

The Pb + Pb MC sample uses  $4 \times 10^7$   $pp$  PYTHIA8 events with the same tune and PDFs as in  $pp$  MC samples that are overlaid on top of events from a dedicated sample of Pb + Pb data events. This sample was recorded with a combination of minimum-bias and total energy triggers requiring 1.5 TeV or 6.5 TeV to enhance the number of central collisions. This “MC overlay” sample was reweighted on an event-by-event basis such that it has the same centrality distribution as the jet-triggered data sample. The detector response in all MC samples was simulated using GEANT4 [51,52].

First, jets with radius parameter  $R = 0.2$  are reconstructed using the anti- $k_t$  algorithm [53,54] from calorimeter energy deposits as described in Ref. [55]. The jet kinematics are corrected event-by-event for the contribution from the UE particles, and are calibrated using simulations of the calorimeter response and *in situ* measurement of the absolute energy scale [56].

The large-radius jets are defined by clustering the small-radius,  $R = 0.2$ , jets with  $p_T > 35$  GeV and  $|\eta| < 3.0$  using anti- $k_t$  algorithm with radius parameter  $R = 1.0$  [57]. These requirements and procedure limits the impact of UE on the measurement but prohibits recovering the quenched jet energy [11] transferred outside of the  $R = 0.2$  subjects. This procedure allows to perform the measurement in a wide kinematic range and reduces systematics uncertainties. The  $k_t$  jet-finding algorithm [54,58] is used to recluster constituents of  $R = 1.0$  jet (i.e.,  $R = 0.2$  jets) to obtain two observables of interest,  $\Delta R_{12}$  and  $\sqrt{d_{12}}$ . These are defined as the angular separation and the splitting parameter of the  $k_t$  algorithm calculated for two jets before the final clustering step of  $R = 1.0$  jet

$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2},$$

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \times \Delta R_{12}.$$

The large-radius jet yields in Pb + Pb collisions and jet cross section in  $pp$  collisions measured in the kinematic range of  $158 < p_T < 1000$  GeV and  $|y| < 2.0$  are

evaluated inclusively and differentially in each of the two substructure observables. The  $k_t$  clustering of large-radius jet constituents with only a single subjet defaults to  $\sqrt{d_{12}} = 0$  and  $\Delta R_{12} = 0$ . These jets, which consist of a single  $R = 0.2$  jet, centered on the  $R = 1.0$  jet axis with no other clustered activity in the large-radius cone, populate only the first interval in  $\sqrt{d_{12}}$  and  $\Delta R_{12}$ . The fraction of reconstructed large-radius jets with a single subjet in  $pp$  collisions is 75% in the  $p_T$  interval of 158–200 GeV and 62% in the  $p_T$  interval of 316–500 GeV. More details of the subjet multiplicity can be found in the Appendix. The jet performance of large-radius reclustered jets was analyzed using MC samples. The jet energy scale (JES) was found to be within a 3% range from 1.

The measured inclusive and differential distributions are corrected for detector effects by the iterative Bayesian unfolding method [59,60] in one dimension and two dimensions, respectively, to return the distributions to the particle level. The unfolding accounts for the effects of bin migrations due to the jet energy resolution (JER) and JES. It also corrects the combinatoric subjet contribution originating from fluctuations of the UE and from jets from different hard partonic interactions in the same Pb + Pb collision resulting in migration in the substructure observable. To better represent the data, the simulated distributions are reweighted along the generator-level jet  $p_T$ ,  $\sqrt{d_{12}}$ , and  $\Delta R_{12}$  axes by the reconstruction-level data-to-simulation ratio before the unfolding. The number of iterations in the unfolding was chosen such that the result is stable when changing the number of iterations while minimizing the amplification of statistical uncertainties. Four iterations were used for inclusive  $R = 0.2$  and  $R = 1.0$  jet yields and cross sections, while six and eight iterations were used in the unfolding of  $\sqrt{d_{12}}$  and  $\Delta R_{12}$  distributions, respectively. Generator-level jets that do not match to a reconstructed jet passing the selection criteria are incorporated as an inefficiency correction after the unfolding.

A dominant source of systematic uncertainty is the uncertainty in the JES. For more central collisions, the uncertainty in JER is equally important. The systematic uncertainty on the JES contains components from calorimeter response uncertainties derived from *in situ* studies [56], a component connected with the JES in the Pb + Pb environment [61], components accounting for inaccuracies in the description of the relative abundances of jets initiated by quarks and gluons and their calorimetric response, and a component connected with the jet radius. The magnitude of the uncertainty in the  $R_{AA}$  from the JES uncertainty varies from 5% to 20% as a function of  $p_T$ ,  $\sqrt{d_{12}}$ ,  $\Delta R_{12}$ , and centrality. The primary component of the JER uncertainty is derived using an *in situ* technique involving studies of dijet energy balance [62,63]. The resulting uncertainty in  $R_{AA}$  reaches  $\sim 20\%$  in 0–10% central collisions at low  $\sqrt{d_{12}}$  and  $\Delta R_{12}$ , but it is typically

below 5%. The systematic uncertainty of the unfolding procedure is estimated by repeating the analysis with response matrices without the re-weighting to match the shapes of measured distributions in data and it is typically below 5%. Other systematic uncertainties consist of the deviation between the unfolded result and the underlying generator-level distribution in simulation, the uncertainty in the determination of  $\langle T_{AA} \rangle$  values [55], and the uncertainty in the determination of the  $pp$  luminosity [64].

The nuclear modification factor for large-radius jets evaluated in the  $p_T$  interval of 200–251 GeV as a function of the  $\sqrt{d_{12}}$  is shown in the left panel of Fig. 1. The  $R_{AA}$  values for large-radius jets with a single subjet are significantly larger compared with the  $R_{AA}$  for large-radius jets with a more complex substructure having a nonzero  $\sqrt{d_{12}}$ . This observation is qualitatively consistent with the scenario in which the medium cannot resolve partonic fragments below a certain transverse scale [65]. This result is also consistent with the previous measurement of correlated production of pairs of nearby jets in Pb + Pb collisions [66] where a larger suppression of neighboring jets compared with inclusive jets was observed. For  $\sqrt{d_{12}} > 0$ , the  $R_{AA}$  values are constant as a function of  $\sqrt{d_{12}}$  within uncertainties for all the centrality intervals.

The right panel of Fig. 1 shows  $R_{AA}$  of large-radius jets evaluated as a function of  $\Delta R_{12}$  for  $p_T = 200$ –251 GeV. The trends seen for  $R_{AA}(\Delta R_{12})$  are the same as those seen for  $R_{AA}(\sqrt{d_{12}})$ : suppression is significantly smaller for the single subjet case, and then constant within uncertainties for nonzero  $\Delta R_{12}$  values. The other  $p_T$  intervals spanning the range of  $158 < p_T < 500$  GeV show the same trends. These observations are in contrast with nonmonotonic  $p_T$  and radial dependence of production of charged particles associated with jets measured using

fragmentation functions or jet shapes [67–69]. The measurement of the  $k_t$  splitting scale by  $\sqrt{d_{12}}$  and radial dependence of subjet suppression by  $\Delta R_{12}$  thus provide new information relative to previously measured transverse and radial structure of  $R = 0.4$  jets using charged particles. The measurement also provides new information relative to the recent substructure measurement of  $\theta_g$  distributions of  $R = 0.4$  jets [27]. In that measurement, a difference in the slope of per-jet normalized  $\theta_g$  distribution was seen in Pb + Pb with respect to  $pp$  collisions, while here we report a difference in the suppression connected with particular subjet topology.

A systematic comparison of jet suppression in terms of jet  $R_{AA}(p_T)$  for different jet definitions is provided in Fig. 2. The jet  $R_{AA}$  is measured for:  $R = 1.0$  reclustered jets with single subjet,  $R = 1.0$  reclustered jets with multiple subjets,  $R = 1.0$  reclustered inclusive jets,  $R = 0.2$  jets, and  $R = 0.4$  jets [55].

Production of  $R = 1.0$  reclustered inclusive jets is suppressed more than the production of  $R = 0.2$  or  $R = 0.4$  jets. Various theoretical calculations of the jet quenching where the jet energy is distributed to soft particles predict less suppression when expanding the jet radius by recovering more lost energy, see, e.g., Ref. [24]. This energy recovery may however not happen in the case of reclustered large-radius jets where energy radiated outside of  $R = 0.2$  subjets is removed. A singular situation when the reclustered large-radius jet is completely removed due to all subjets being suppressed below the 35 GeV cut is very unlikely given the minimum  $p_T$  threshold of 158 GeV on the  $R = 1.0$  jet and relatively small multiplicity of subjets. Thus, in general, variations in the jet definition used in this study allow including different fractions of the lost energy and energy from the medium response to the showering

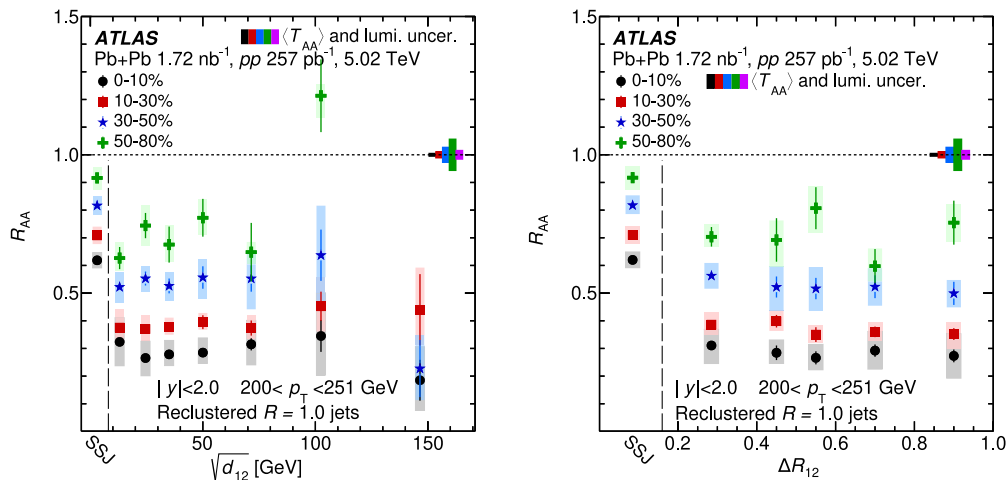


FIG. 1. The values of  $R_{AA}$  for  $R = 1.0$  reclustered jets as function of  $\sqrt{d_{12}}$  (left) and  $\Delta R_{12}$  (right) in four centrality intervals. The label “SSJ” on the  $x$ -axis identifies the single sub-jet configuration. The vertical bars on the data points indicate statistical uncertainties, the shaded boxes indicate systematic uncertainties. The fully correlated fractional uncertainties due to the luminosity and  $\langle T_{AA} \rangle$  are represented by boxes at  $R_{AA} = 1$ . One data point with a relative statistical uncertainty above 50% is not displayed.

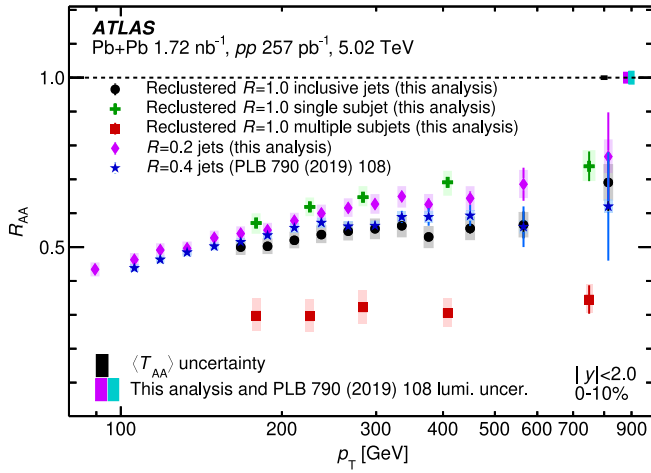


FIG. 2. Comparison of  $R_{AA}$  distributions evaluated in 0%–10% central collisions as a function of  $p_T$  for several jet definitions:  $R = 1.0$  reclustered inclusive jets (circles),  $R = 1.0$  reclustered jets with a single subjet (crosses),  $R = 1.0$  reclustered jets with multiple subjets (squares),  $R = 0.2$  jets (diamonds),  $R = 0.4$  jets (stars) [55]. The vertical bars on the data points indicate statistical uncertainties, the shaded boxes indicate systematic uncertainties. The colored boxes at  $R_{AA} = 1$  represent fractional uncertainty in  $\langle T_{AA} \rangle$  and  $pp$  luminosity in this measurement and  $pp$  luminosity in previous analysis [55], which both affect the overall normalization.

process. Comparing new results with theoretical calculations may therefore help to understand possible biases in the quantification of energy loss using traditional, small-radius jets. The presented quantification of cone-size dependence of  $R_{AA}$  may also be used to constrain theoretical uncertainties in the recently analytically calculated cone-size dependent energy loss [70].

The  $R = 1.0$  reclustered jets with multiple subjets show the largest suppression while the  $R = 1.0$  reclustered jets with a single subjet show the smallest suppression out of all jet definitions. The sizable difference between the  $R_{AA}$  for multiple subjet and single subjet configurations provides an important input for understanding the role of color decoherence in the jet quenching. This sizable difference is not due to missing a contribution from the energy radiated out of the  $R = 0.2$  cone since this radiated energy is not measured in all configurations of  $R = 1.0$  jets with subjets. The lack of jet  $p_T$  dependence in the  $R_{AA}$  of  $R = 1.0$  reclustered jets with multiple subjets might be understood to be the consequence of increasing subjet multiplicity with increasing jet  $p_T$  (see subjet multiplicity distributions in Appendix). More subjets may imply more sources of radiation which may lead to flattening of  $R_{AA}$  at high  $p_T$ . Presented results can be also used to obtain ratios of per-jet normalized substructure distributions for  $R = 1.0$  jets by dividing distributions in Fig. 1 by the inclusive  $R = 1.0$  jet  $R_{AA}$  in Fig. 2. Finally, it should be noted that any direct comparisons of  $R_{AA}$  between different jet

definitions should be treated with care as the same particles reconstructed with a different procedure might appear in different jet  $p_T$  intervals.

In conclusion, this Letter provides a measurement of the jet nuclear modification factor for large-radius jets that is differential in  $p_T$  and in transverse and radial substructure observables. Presented observations are qualitatively consistent with the hypothesis that jets with hard internal splittings lose more energy, and provide a new perspective for understanding the role of jet structure in jet suppression in the QGP.

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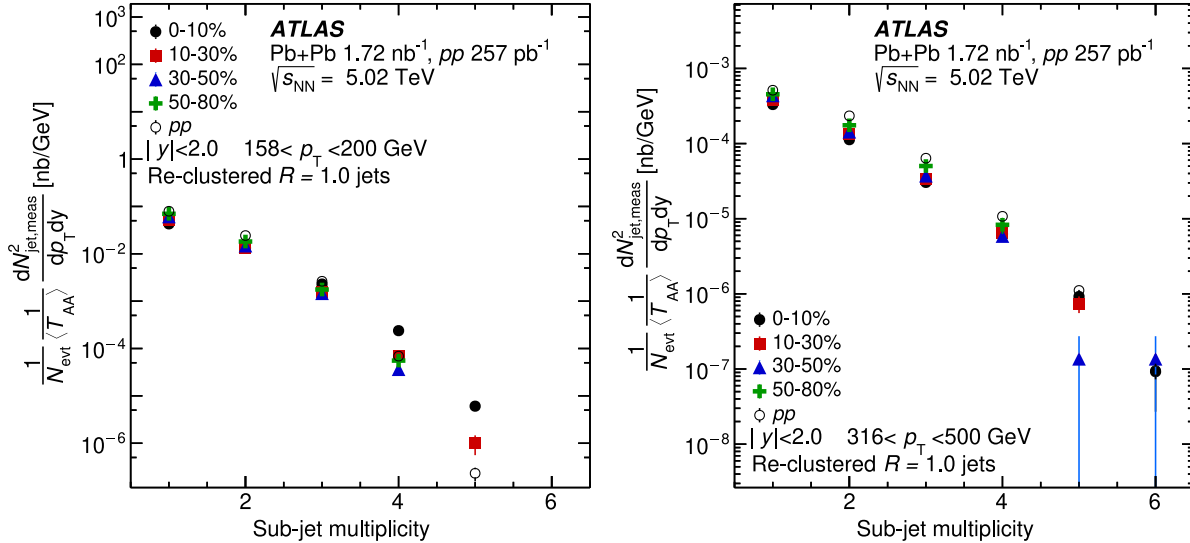


FIG. 3. Measured uncorrected distributions of the number of subjets of the large-radius jets in  $pp$  collisions and four centrality intervals of Pb + Pb collisions for jet  $p_T$  in the range 158–200 GeV (left) and 316–500 GeV (right).

*Appendix.*—The measured uncorrected distribution of the yield of jets evaluated as a function of a number of subjets with  $p_T$  above 35 GeV is shown in Fig. 3. The yield is shown for large-radius jets measured in  $pp$  collisions and in four centrality intervals of Pb + Pb collisions. The fraction of reconstructed large-radius jets with a single subjet in  $pp$  collisions is 75% in the  $p_T$  interval of 158–200 GeV and 62% in the  $p_T$  interval of 316–500 GeV. In 0%–10% central Pb + Pb collisions, the fractions are 73% and 68% in the  $p_T$  interval of 158–200 GeV and 316–500 GeV, respectively. In 50%–80% peripheral collisions, the fractions are 77% and 65%, in the  $p_T$  interval of 158–200 GeV and 316–500 GeV, respectively. The measured distributions in Pb + Pb collisions include a contribution from jets that originate from different hard partonic interactions in the same Pb + Pb collision and from the spurious fluctuations of UE. These two contributions increase with the increasing centrality of the collision. In general, the observed increase of yield of large-radius jets with multiple subjets with increasing jet  $p_T$  is expected both in  $pp$  and Pb + Pb collisions, since it was previously measured that the yield of neighboring jets that accompany a given higher- $p_T$  jet increases with increasing jet  $p_T$  [66,71].

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Bertram<sup>91</sup>, S. Bethke<sup>110</sup>, A. Betti<sup>75a,75b</sup>, A. J. Bevan<sup>94</sup>, M. Bhamjee<sup>33c</sup>, S. Bhatta<sup>145</sup>, D. S. Bhattacharya<sup>166</sup>, P. Bhattarai<sup>26</sup>, V. S. Bhopatkar<sup>121</sup>, R. Bi<sup>29,i</sup>, R. M. Bianchi<sup>129</sup>, O. Biebel<sup>109</sup>, R. Bielski<sup>123</sup>, M. Biglietti<sup>77a</sup>, T. R. V. Billoud<sup>132</sup>, M. Bindi<sup>55</sup>, A. Bingul<sup>21b</sup>, C. Bini<sup>75a,75b</sup>, A. Biondini<sup>92</sup>, C. J. Birch-sykes<sup>101</sup>, G. A. Bird<sup>20,134</sup>, M. Birman<sup>169</sup>, M. Biros<sup>133</sup>, T. Bisanz<sup>36</sup>, E. Bisceglie<sup>43b,43a</sup>, D. Biswas<sup>170</sup>, A. Bitadze<sup>101</sup>, K. Bjørke<sup>125</sup>, I. Bloch<sup>48</sup>, C. Blocker<sup>26</sup>, A. Blue<sup>59</sup>, U. Blumenschein<sup>94</sup>, J. Blumenthal<sup>100</sup>, G. J. Bobbink<sup>114</sup>, V. S. Bobrovnikov<sup>37</sup>, M. Boehler<sup>54</sup>, D. Bogavac<sup>36</sup>, A. G. Bogdanchikov<sup>37</sup>, C. Bohm<sup>47a</sup>, V. Boisvert<sup>95</sup>, P. Bokan<sup>48</sup>, T. Bold<sup>85a</sup>, M. Bomben<sup>5</sup>, M. Bona<sup>94</sup>, M. Boonekamp<sup>135</sup>, C. D. Booth<sup>95</sup>, A. G. Borbély<sup>59</sup>, H. M. Borecka-Bielska<sup>108</sup>, L. S. Borgna<sup>96</sup>, G. Borissov<sup>91</sup>, D. Bortoletto<sup>126</sup>, D. Boscherini<sup>23b</sup>, M. Bosman<sup>13</sup>, J. D. Bossio Sola<sup>36</sup>, K. Bouaouda<sup>35a</sup>, N. Bouchhar<sup>163</sup>, J. Boudreau<sup>129</sup>, E. V. Bouhova-Thacker<sup>91</sup>, D. Boumediene<sup>40</sup>, R. Bouquet<sup>5</sup>, A. Boveia<sup>119</sup>, J. Boyd<sup>36</sup>, D. Boye<sup>29</sup>, I. R. Boyko<sup>38</sup>, J. Bracik<sup>20</sup>, N. Brahimi<sup>62d</sup>, G. Brandt<sup>171</sup>, O. Brandt<sup>32</sup>, F. Braren<sup>48</sup>, B. Brau<sup>103</sup>, J. E. Brau<sup>123</sup>, K. Brendlinger<sup>48</sup>, R. Brenner<sup>169</sup>, L. Brenner<sup>114</sup>, R. Brenner<sup>161</sup>, S. Bressler<sup>169</sup>, D. Britton<sup>59</sup>, D. Britzger<sup>110</sup>, I. Brock<sup>24</sup>, G. Brooijmans<sup>41</sup>, W. K. Brooks<sup>137f</sup>, E. Brost<sup>29</sup>, L. M. Brown<sup>165</sup>, T. L. Bruckler<sup>126</sup>, P. A. Bruckman de Renstrom<sup>86</sup>, B. Brüers<sup>48</sup>, D. Bruncko<sup>28b,a</sup>, A. Bruni<sup>23b</sup>, G. Bruni<sup>23b</sup>, M. Bruschi<sup>23b</sup>, N. Bruscinò<sup>75a,75b</sup>, T. Buanes<sup>16</sup>, Q. Buat<sup>138</sup>, A. G. Buckley<sup>59</sup>, I. A. Budagov<sup>38,a</sup>, M. K. Bugge<sup>125</sup>, O. Bulekov<sup>37</sup>, B. A. Bullard<sup>143</sup>, S. Burdin<sup>92</sup>, C. D. Burgard<sup>49</sup>, A. M. Burger<sup>40</sup>, B. Burghgrave<sup>8</sup>, O. Burlayenko<sup>54</sup>, J. T. P. Burr<sup>32</sup>, C. D. Burton<sup>11</sup>, J. C. Burzynski<sup>142</sup>, E. L. Busch<sup>41</sup>, V. Büscher<sup>100</sup>, P. J. Bussey<sup>59</sup>, J. M. Butler<sup>25</sup>, C. M. Buttar<sup>59</sup>, J. M. Butterworth<sup>96</sup>, W. Buttinger<sup>134</sup>, C. J. Buxo Vazquez<sup>107</sup>, A. R. Buzykaev<sup>37</sup>, G. Cabras<sup>23b</sup>, S. Cabrera Urbán<sup>163</sup>, D. Caforio<sup>58</sup>, H. Cai<sup>129</sup>, Y. Cai<sup>14a,14d</sup>, V. M. M. Cairo<sup>36</sup>, O. Cakir<sup>3a</sup>, N. Calace<sup>36</sup>, P. Calafiura<sup>17a</sup>, G. Calderini<sup>127</sup>, P. Calfayan<sup>68</sup>, G. Callea<sup>59</sup>, L. P. Caloba<sup>82b</sup>, D. Calvet<sup>40</sup>, S. Calvet<sup>40</sup>, T. P. Calvet<sup>102</sup>, M. Calvetti<sup>74a,74b</sup>, R. Camacho Toro<sup>127</sup>, S. Camarda<sup>36</sup>, D. Camarero Munoz<sup>26</sup>, P. Camarri<sup>76a,76b</sup>, M. T. Camerlingo<sup>72a,72b</sup>, D. Cameron<sup>125</sup>, C. Camincher<sup>165</sup>, M. Campanelli<sup>96</sup>, A. Camplani<sup>42</sup>, V. Canale<sup>72a,72b</sup>, A. Canesse<sup>104</sup>, M. Cano Bret<sup>80</sup>, J. Cantero<sup>163</sup>, Y. Cao<sup>162</sup>, F. Capocasa<sup>26</sup>, M. Capua<sup>43b,43a</sup>, A. Carbone<sup>71a,71b</sup>, R. Cardarelli<sup>76a</sup>, J. C. J. Cardenas<sup>8</sup>, F. Cardillo<sup>163</sup>, T. Carli<sup>36</sup>, G. Carlino<sup>72a</sup>, J. I. Carlotto<sup>13</sup>, B. T. Carlson<sup>129,j</sup>, E. M. Carlson<sup>165,156a</sup>, L. Carminati<sup>71a,71b</sup>, M. Carnesale<sup>75a,75b</sup>, S. Caron<sup>113</sup>, E. Carquin<sup>137f</sup>, S. Carrá<sup>71a,71b</sup>, G. Carratta<sup>23b,23a</sup>, F. Carrio Argos<sup>33g</sup>, J. W. S. Carter<sup>155</sup>, T. M. Carter<sup>52</sup>, M. P. Casado<sup>13,k</sup>, A. F. Casha<sup>155</sup>, M. Caspar<sup>48</sup>, E. G. Castiglia<sup>172</sup>, F. L. Castillo<sup>63a</sup>, L. Castillo Garcia<sup>13</sup>, V. Castillo Gimenez<sup>163</sup>, N. F. Castro<sup>130a,130e</sup>

A. Catinaccio<sup>36</sup> J. R. Catmore<sup>125</sup> V. Cavaliere<sup>29</sup> N. Cavalli<sup>23b,23a</sup> V. Cavasinni<sup>74a,74b</sup> E. Celebi<sup>21a</sup> F. Celli<sup>126</sup>  
 M. S. Centonze<sup>70a,70b</sup> K. Cerny<sup>122</sup> A. S. Cerqueira<sup>82a</sup> A. Cerri<sup>146</sup> L. Cerrito<sup>76a,76b</sup> F. Cerutti<sup>17a</sup> A. Cervelli<sup>23b</sup>  
 G. Cesarini<sup>53</sup> S. A. Cetin<sup>21d</sup> Z. Chadi<sup>35a</sup> D. Chakraborty<sup>115</sup> M. Chala<sup>130f</sup> J. Chan<sup>170</sup> W. Y. Chan<sup>153</sup>  
 J. D. Chapman<sup>32</sup> B. Chargeishvili<sup>149b</sup> D. G. Charlton<sup>20</sup> T. P. Charman<sup>94</sup> M. Chatterjee<sup>19</sup> C. Chauhan<sup>133</sup>  
 S. Chekanov<sup>6</sup> S. V. Chekulaev<sup>156a</sup> G. A. Chelkov<sup>38,1</sup> A. Chen<sup>106</sup> B. Chen<sup>151</sup> B. Chen<sup>165</sup> H. Chen<sup>14c</sup>  
 H. Chen<sup>29</sup> J. Chen<sup>62c</sup> J. Chen<sup>142</sup> S. Chen<sup>153</sup> S. J. Chen<sup>14c</sup> X. Chen<sup>62c</sup> X. Chen<sup>14b,m</sup> Y. Chen<sup>62a</sup>  
 C. L. Cheng<sup>170</sup> H. C. Cheng<sup>64a</sup> S. Cheong<sup>143</sup> A. Cheplakov<sup>38</sup> E. Cheremushkina<sup>48</sup> E. Cherepanova<sup>114</sup>  
 R. Cherkaoui El Moursli<sup>35e</sup> E. Cheu<sup>7</sup> K. Cheung<sup>65</sup> L. Chevalier<sup>135</sup> V. Chiarella<sup>53</sup> G. Chiarelli<sup>74a</sup>  
 N. Chiedde<sup>102</sup> G. Chiodini<sup>70a</sup> A. S. Chisholm<sup>20</sup> A. Chitan<sup>27b</sup> M. Chitishvili<sup>163</sup> M. V. Chizhov<sup>38</sup> K. Choi<sup>11</sup>  
 A. R. Chomont<sup>75a,75b</sup> Y. Chou<sup>103</sup> E. Y. S. Chow<sup>114</sup> T. Chowdhury<sup>33g</sup> L. D. Christopher<sup>33g</sup> K. L. Chu<sup>64a</sup>  
 M. C. Chu<sup>64a</sup> X. Chu<sup>14a,14d</sup> J. Chudoba<sup>131</sup> J. J. Chwastowski<sup>86</sup> D. Cieri<sup>110</sup> K. M. Ciesla<sup>85a</sup> V. Cindro<sup>93</sup>  
 A. Ciocio<sup>17a</sup> F. Ciroto<sup>72a,72b</sup> Z. H. Citron<sup>169,n</sup> M. Citterio<sup>71a</sup> D. A. Ciubotaru<sup>27b</sup> B. M. Ciungu<sup>155</sup> A. Clark<sup>56</sup>  
 P. J. Clark<sup>52</sup> J. M. Clavijo Columbie<sup>48</sup> S. E. Clawson<sup>101</sup> C. Clement<sup>47a,47b</sup> J. Clercx<sup>48</sup> L. Clissa<sup>23b,23a</sup>  
 Y. Coadou<sup>102</sup> M. Cobal<sup>69a,69c</sup> A. Coccaro<sup>57b</sup> R. F. Coelho Barrue<sup>130a</sup> R. Coelho Lopes De Sa<sup>103</sup> S. Coelli<sup>71a</sup>  
 H. Cohen<sup>151</sup> A. E. C. Coimbra<sup>71a,71b</sup> B. Cole<sup>41</sup> J. Collot<sup>60</sup> P. Conde Muiño<sup>130a,130g</sup> M. P. Connell<sup>33c</sup>  
 S. H. Connell<sup>33c</sup> I. A. Connelly<sup>59</sup> E. I. Conroy<sup>126</sup> F. Conventi<sup>72a,o</sup> H. G. Cooke<sup>20</sup> A. M. Cooper-Sarkar<sup>126</sup>  
 F. Cormier<sup>164</sup> L. D. Corpe<sup>36</sup> M. Corradi<sup>75a,75b</sup> F. Corriveau<sup>104,p</sup> A. Cortes-Gonzalez<sup>18</sup> M. J. Costa<sup>163</sup>  
 F. Costanza<sup>4</sup> D. Costanzo<sup>139</sup> B. M. Cote<sup>119</sup> G. Cowan<sup>95</sup> K. Cranmer<sup>117</sup> S. Crépe-Renaudin<sup>60</sup> F. Crescioli<sup>127</sup>  
 M. Cristinziani<sup>141</sup> M. Cristoforetti<sup>78a,78b,q</sup> V. Croft<sup>114</sup> G. Crosetti<sup>43b,43a</sup> A. Cueto<sup>36</sup> T. Cuhadar Donszelmann<sup>160</sup>  
 H. Cui<sup>14a,14d</sup> Z. Cui<sup>7</sup> W. R. Cunningham<sup>59</sup> F. Curcio<sup>43b,43a</sup> P. Czodrowski<sup>36</sup> M. M. Czurylo<sup>63b</sup>  
 M. J. Da Cunha Sargedas De Sousa<sup>62a</sup> J. V. Da Fonseca Pinto<sup>82b</sup> C. Da Via<sup>101</sup> W. Dabrowski<sup>85a</sup> T. Dado<sup>49</sup>  
 S. Dahbi<sup>33g</sup> T. Dai<sup>106</sup> C. Dallapiccola<sup>103</sup> M. Dam<sup>42</sup> G. D'amen<sup>29</sup> V. D'Amico<sup>109</sup> J. Damp<sup>100</sup>  
 J. R. Dandoy<sup>128</sup> M. F. Daneri<sup>30</sup> M. Danninger<sup>142</sup> V. Dao<sup>36</sup> G. Darbo<sup>57b</sup> S. Darmora<sup>6</sup> S. J. Das<sup>29,i</sup>  
 S. D'Auria<sup>71a,71b</sup> C. David<sup>156b</sup> T. Davidek<sup>133</sup> B. Davis-Purcell<sup>34</sup> I. Dawson<sup>94</sup> K. De<sup>8</sup> R. De Asmundis<sup>72a</sup>  
 N. De Biase<sup>48</sup> S. De Castro<sup>23b,23a</sup> N. De Groot<sup>113</sup> P. de Jong<sup>114</sup> H. De la Torre<sup>107</sup> A. De Maria<sup>14c</sup>  
 A. De Salvo<sup>75a</sup> U. De Sanctis<sup>76a,76b</sup> A. De Santo<sup>146</sup> J. B. De Vivie De Regie<sup>60</sup> D. V. Dedovich<sup>38</sup> J. Degens<sup>114</sup>  
 A. M. Deiana<sup>44</sup> F. Del Corso<sup>23b,23a</sup> J. Del Peso<sup>99</sup> F. Del Rio<sup>63a</sup> F. Deliot<sup>135</sup> C. M. Delitzsch<sup>49</sup>  
 M. Della Pietra<sup>72a,72b</sup> D. Della Volpe<sup>56</sup> A. Dell'Acqua<sup>36</sup> L. Dell'Asta<sup>71a,71b</sup> M. Delmastro<sup>4</sup> P. A. Delsart<sup>60</sup>  
 S. Demers<sup>172</sup> M. Demichev<sup>38</sup> S. P. Denisov<sup>37</sup> L. D'Eramo<sup>115</sup> D. Derendarz<sup>86</sup> F. Derue<sup>127</sup> P. Dervan<sup>92</sup>  
 K. Desch<sup>24</sup> K. Dette<sup>155</sup> C. Deutsch<sup>24</sup> F. A. Di Bello<sup>57b,57a</sup> A. Di Ciaccio<sup>76a,76b</sup> L. Di Ciaccio<sup>4</sup>  
 A. Di Domenico<sup>75a,75b</sup> C. Di Donato<sup>72a,72b</sup> A. Di Girolamo<sup>36</sup> G. Di Gregorio<sup>5</sup> A. Di Luca<sup>78a,78b</sup>  
 B. Di Micco<sup>77a,77b</sup> R. Di Nardo<sup>77a,77b</sup> C. Diaconu<sup>102</sup> F. A. Dias<sup>114</sup> T. Dias Do Vale<sup>142</sup> M. A. Diaz<sup>137a,137b</sup>  
 F. G. Diaz Capriles<sup>24</sup> M. Didenko<sup>163</sup> E. B. Diehl<sup>106</sup> L. Diehl<sup>54</sup> S. Díez Cornell<sup>48</sup> C. Díez Pardos<sup>141</sup>  
 C. Dimitriadi<sup>24,161</sup> A. Dimitrievska<sup>17a</sup> J. Dingfelder<sup>24</sup> I-M. Dinu<sup>27b</sup> S. J. Dittmeier<sup>63b</sup> F. Dittus<sup>36</sup> F. Djama<sup>102</sup>  
 T. Djobava<sup>149b</sup> J. I. Djuvsland<sup>16</sup> C. Doglioni<sup>101,98</sup> J. Dolejsi<sup>133</sup> Z. Dolezal<sup>133</sup> M. Donadelli<sup>82c</sup> B. Dong<sup>107</sup>  
 J. Donini<sup>40</sup> A. D'Onofrio<sup>77a,77b</sup> M. D'Onofrio<sup>92</sup> J. Dopke<sup>134</sup> A. Doria<sup>72a</sup> M. T. Dova<sup>90</sup> A. T. Doyle<sup>59</sup>  
 M. A. Draguet<sup>126</sup> E. Drechsler<sup>142</sup> E. Dreyer<sup>169</sup> I. Drivas-koulouris<sup>10</sup> A. S. Drobac<sup>158</sup> M. Drozdova<sup>56</sup>  
 D. Du<sup>62a</sup> T. A. du Pree<sup>114</sup> F. Dubinin<sup>37</sup> M. Dubovsky<sup>28a</sup> E. Duchovni<sup>169</sup> G. Duckeck<sup>109</sup> O. A. Ducu<sup>27b</sup>  
 D. Duda<sup>110</sup> A. Dudarev<sup>36</sup> E. R. Duden<sup>26</sup> M. D'uffizi<sup>101</sup> L. Duflot<sup>66</sup> M. Dührssen<sup>36</sup> C. Dülsen<sup>171</sup>  
 A. E. Dumitriu<sup>27b</sup> M. Dunford<sup>63a</sup> S. Dungs<sup>49</sup> K. Dunne<sup>47a,47b</sup> A. Duperrin<sup>102</sup> H. Duran Yildiz<sup>3a</sup> M. Düren<sup>58</sup>  
 A. Durglishvili<sup>149b</sup> B. L. Dwyer<sup>115</sup> G. I. Dyckes<sup>17a</sup> M. Dyndal<sup>85a</sup> S. Dysch<sup>101</sup> B. S. Dziedzic<sup>86</sup>  
 Z. O. Earnshaw<sup>146</sup> B. Eckerova<sup>28a</sup> S. Eggebrecht<sup>55</sup> M. G. Eggleston<sup>51</sup> E. Egidio Purcino De Souza<sup>127</sup>  
 L. F. Ehrke<sup>56</sup> G. Eigen<sup>16</sup> K. Einsweiler<sup>17a</sup> T. Ekelof<sup>161</sup> P. A. Ekman<sup>98</sup> Y. El Ghazali<sup>35b</sup> H. El Jarrari<sup>35e,148</sup>  
 A. El Moussaouy<sup>35a</sup> V. Ellajosyula<sup>161</sup> M. Ellert<sup>161</sup> F. Ellinghaus<sup>171</sup> A. A. Elliot<sup>94</sup> N. Ellis<sup>36</sup> J. Elmsheuser<sup>29</sup>  
 M. Elsing<sup>36</sup> D. Emelianov<sup>134</sup> Y. Enari<sup>153</sup> I. Ene<sup>17a</sup> S. Epari<sup>13</sup> J. Erdmann<sup>49</sup> P. A. Erland<sup>86</sup> M. Errenst<sup>171</sup>  
 M. Escalier<sup>66</sup> C. Escobar<sup>163</sup> E. Etzion<sup>151</sup> G. Evans<sup>130a</sup> H. Evans<sup>68</sup> M. O. Evans<sup>146</sup> A. Ezhilov<sup>37</sup>  
 S. Ezzarqtouni<sup>35a</sup> F. Fabbri<sup>59</sup> L. Fabbri<sup>23b,23a</sup> G. Facini<sup>96</sup> V. Fadeyev<sup>136</sup> R. M. Fakhrutdinov<sup>37</sup> S. Falciano<sup>75a</sup>  
 L. F. Falda Ulhoa Coelho<sup>36</sup> P. J. Falke<sup>24</sup> S. Falke<sup>36</sup> J. Faltova<sup>133</sup> Y. Fan<sup>14a</sup> Y. Fang<sup>14a,14d</sup> M. Fanti<sup>71a,71b</sup>  
 M. Faraj<sup>69a,69b</sup> Z. Farazpay<sup>97</sup> A. Farbin<sup>8</sup> A. Farilla<sup>77a</sup> T. Farrowque<sup>107</sup> S. M. Farrington<sup>52</sup> F. Fassi<sup>35e</sup>

D. Fassouliotis<sup>9</sup>, M. Faucci Giannelli<sup>76a,76b</sup>, W. J. Fawcett<sup>32</sup>, L. Fayard<sup>66</sup>, P. Federic<sup>133</sup>, P. Federicova<sup>131</sup>, O. L. Fedin<sup>37,1</sup>, G. Fedotov<sup>37</sup>, M. Feickert<sup>170</sup>, L. Feligioni<sup>102</sup>, A. Fell<sup>139</sup>, D. E. Fellers<sup>123</sup>, C. Feng<sup>62b</sup>, M. Feng<sup>14b</sup>, Z. Feng<sup>114</sup>, M. J. Fenton<sup>160</sup>, A. B. Fenyuk<sup>37</sup>, L. Ferencz<sup>48</sup>, R. A. M. Ferguson<sup>91</sup>, S. I. Fernandez Luengo<sup>137f</sup>, J. Ferrando<sup>48</sup>, A. Ferrari<sup>161</sup>, P. Ferrari<sup>114,113</sup>, R. Ferrari<sup>73a</sup>, D. Ferrere<sup>56</sup>, C. Ferretti<sup>106</sup>, F. Fiedler<sup>100</sup>, A. Filipčić<sup>93</sup>, E. K. Filmer<sup>1</sup>, F. Filthaut<sup>113</sup>, M. C. N. Fiolhais<sup>130a,130c,r</sup>, L. Fiorini<sup>163</sup>, W. C. Fisher<sup>107</sup>, T. Fitschen<sup>101</sup>, I. Fleck<sup>141</sup>, P. Fleischmann<sup>106</sup>, T. Flick<sup>171</sup>, L. Flores<sup>128</sup>, M. Flores<sup>33d,s</sup>, L. R. Flores Castillo<sup>64a</sup>, F. M. Follega<sup>78a,78b</sup>, N. Fomin<sup>16</sup>, J. H. Foo<sup>155</sup>, B. C. Forland<sup>68</sup>, A. Formica<sup>135</sup>, A. C. Forti<sup>101</sup>, E. Fortin<sup>36</sup>, A. W. Fortman<sup>61</sup>, M. G. Foti<sup>17a</sup>, L. Fountas<sup>9,t</sup>, D. Fournier<sup>66</sup>, H. Fox<sup>91</sup>, P. Francavilla<sup>74a,74b</sup>, S. Francescato<sup>61</sup>, S. Franchellucci<sup>56</sup>, M. Franchini<sup>23b,23a</sup>, S. Franchino<sup>63a</sup>, D. Francis<sup>36</sup>, L. Franco<sup>113</sup>, L. Franconi<sup>19</sup>, M. Franklin<sup>61</sup>, G. Frattari<sup>26</sup>, A. C. Freegard<sup>94</sup>, W. S. Freund<sup>82b</sup>, Y. Y. Frid<sup>151</sup>, N. Fritzsche<sup>50</sup>, A. Froch<sup>54</sup>, D. Froidevaux<sup>36</sup>, J. A. Frost<sup>126</sup>, Y. Fu<sup>62a</sup>, M. Fujimoto<sup>118</sup>, E. Fullana Torregrosa<sup>163,a</sup>, E. Furtado De Simas Filho<sup>82b</sup>, J. Fuster<sup>163</sup>, A. Gabrielli<sup>23b,23a</sup>, A. Gabrielli<sup>155</sup>, P. Gadow<sup>48</sup>, G. Gagliardi<sup>57b,57a</sup>, L. G. Gagnon<sup>17a</sup>, E. J. Gallas<sup>126</sup>, B. J. Gallop<sup>134</sup>, K. K. Gan<sup>119</sup>, S. Ganguly<sup>153</sup>, J. Gao<sup>62a</sup>, Y. Gao<sup>52</sup>, F. M. Garay Walls<sup>137a,137b</sup>, B. Garcia<sup>29,i</sup>, C. García<sup>163</sup>, J. E. García Navarro<sup>163</sup>, M. Garcia-Sciveres<sup>17a</sup>, R. W. Gardner<sup>39</sup>, D. Garg<sup>80</sup>, R. B. Garg<sup>143,u</sup>, C. A. Garner<sup>155</sup>, S. J. Gasiorowski<sup>138</sup>, P. Gaspar<sup>82b</sup>, G. Gaudio<sup>73a</sup>, V. Gautam<sup>13</sup>, P. Gauzzi<sup>75a,75b</sup>, I. L. Gavrilenko<sup>37</sup>, A. Gavriyuk<sup>37</sup>, C. Gay<sup>164</sup>, G. Gaycken<sup>48</sup>, E. N. Gazis<sup>10</sup>, A. A. Geanta<sup>27b,27e</sup>, C. M. Gee<sup>136</sup>, C. Gemme<sup>57b</sup>, M. H. Genest<sup>60</sup>, S. Gentile<sup>75a,75b</sup>, S. George<sup>95</sup>, W. F. George<sup>20</sup>, T. Geralis<sup>46</sup>, L. O. Gerlach<sup>55</sup>, P. Gessinger-Befurt<sup>36</sup>, M. E. Geyik<sup>171</sup>, M. Ghneimat<sup>141</sup>, K. Ghorbanian<sup>94</sup>, A. Ghosal<sup>141</sup>, A. Ghosh<sup>160</sup>, A. Ghosh<sup>7</sup>, B. Giacobbe<sup>23b</sup>, S. Giagu<sup>75a,75b</sup>, P. Giannetti<sup>74a</sup>, A. Giannini<sup>62a</sup>, S. M. Gibson<sup>95</sup>, M. Gignac<sup>136</sup>, D. T. Gil<sup>85b</sup>, A. K. Gilbert<sup>85a</sup>, B. J. Gilbert<sup>41</sup>, D. Gillberg<sup>34</sup>, G. Gilles<sup>114</sup>, N. E. K. Gillwald<sup>48</sup>, L. Ginabat<sup>127</sup>, D. M. Gingrich<sup>2,e</sup>, M. P. Giordani<sup>69a,69c</sup>, P. F. Giraud<sup>135</sup>, G. Giugliarelli<sup>69a,69c</sup>, D. Giugni<sup>71a</sup>, F. Giuli<sup>36</sup>, I. Gkialas<sup>9,t</sup>, L. K. Gladilin<sup>37</sup>, C. Glasman<sup>99</sup>, G. R. Gledhill<sup>123</sup>, M. Glisic<sup>123</sup>, I. Gnesi<sup>43b,v</sup>, Y. Go<sup>29,i</sup>, M. Goblirsch-Kolb<sup>36</sup>, B. Gocke<sup>49</sup>, D. Godin<sup>108</sup>, B. Gokturk<sup>21a</sup>, S. Goldfarb<sup>105</sup>, T. Golling<sup>56</sup>, M. G. D. Gololo<sup>33g</sup>, D. Golubkov<sup>37</sup>, J. P. Gombas<sup>107</sup>, A. Gomes<sup>130a,130b</sup>, G. Gomes Da Silva<sup>141</sup>, A. J. Gomez Delegido<sup>163</sup>, R. Gonçalo<sup>130a,130c</sup>, G. Gonella<sup>123</sup>, L. Gonella<sup>20</sup>, A. Gongadze<sup>38</sup>, F. Gonnella<sup>20</sup>, J. L. Gonski<sup>41</sup>, R. Y. González Andana<sup>52</sup>, S. González de la Hoz<sup>163</sup>, S. Gonzalez Fernandez<sup>13</sup>, R. Gonzalez Lopez<sup>92</sup>, C. Gonzalez Renteria<sup>17a</sup>, R. Gonzalez Suarez<sup>161</sup>, S. Gonzalez-Sevilla<sup>56</sup>, G. R. Gonzalvo Rodriguez<sup>163</sup>, L. Goossens<sup>36</sup>, P. A. Gorbounov<sup>37</sup>, B. Gorini<sup>36</sup>, E. Gorini<sup>70a,70b</sup>, A. Gorišek<sup>93</sup>, T. C. Gosart<sup>128</sup>, A. T. Goshaw<sup>51</sup>, M. I. Gostkin<sup>38</sup>, S. Goswami<sup>121</sup>, C. A. Gottardo<sup>36</sup>, M. Goughri<sup>35b</sup>, V. Goumarre<sup>48</sup>, A. G. Goussiou<sup>138</sup>, N. Govender<sup>33c</sup>, I. Grabowska-Bold<sup>85a</sup>, K. Graham<sup>34</sup>, E. Gramstad<sup>125</sup>, S. Grancagnolo<sup>70a,70b</sup>, M. Grandi<sup>146</sup>, V. Gratchev<sup>37,a</sup>, P. M. Gravila<sup>27f</sup>, F. G. Gravili<sup>70a,70b</sup>, H. M. Gray<sup>17a</sup>, M. Greco<sup>70a,70b</sup>, C. Greife<sup>24</sup>, I. M. Gregor<sup>48</sup>, P. Grenier<sup>143</sup>, C. Grieco<sup>13</sup>, A. A. Grillo<sup>136</sup>, K. Grimm<sup>31,w</sup>, S. Grinstein<sup>13,x</sup>, J.-F. Grivaz<sup>66</sup>, E. Gross<sup>169</sup>, J. Grosse-Knetter<sup>55</sup>, C. Grud<sup>106</sup>, J. C. Grundy<sup>126</sup>, L. Guan<sup>106</sup>, W. Guan<sup>29</sup>, C. Gubbels<sup>164</sup>, J. G. R. Guerrero Rojas<sup>163</sup>, G. Guerrieri<sup>69a,69b</sup>, F. Guescini<sup>110</sup>, R. Gugel<sup>100</sup>, J. A. M. Guhit<sup>106</sup>, A. Guida<sup>48</sup>, T. Guillemin<sup>4</sup>, E. Guilloton<sup>167,134</sup>, S. Guindon<sup>36</sup>, F. Guo<sup>14a,14d</sup>, J. Guo<sup>62c</sup>, L. Guo<sup>66</sup>, Y. Guo<sup>106</sup>, R. Gupta<sup>48</sup>, S. Gurbuz<sup>24</sup>, S. S. Gurdasani<sup>54</sup>, G. Gustavino<sup>36</sup>, M. Guth<sup>56</sup>, P. Gutierrez<sup>120</sup>, L. F. Gutierrez Zagazeta<sup>128</sup>, C. Gutschow<sup>96</sup>, C. Gwenlan<sup>126</sup>, C. B. Gwilliam<sup>92</sup>, E. S. Haaland<sup>125</sup>, A. Haas<sup>117</sup>, M. Habedank<sup>48</sup>, C. Haber<sup>17a</sup>, H. K. Hadavand<sup>8</sup>, A. Hadeef<sup>100</sup>, S. Hadzic<sup>110</sup>, E. H. Haines<sup>96</sup>, M. Haleem<sup>166</sup>, J. Haley<sup>121</sup>, J. J. Hall<sup>139</sup>, G. D. Hallewell<sup>102</sup>, L. Halser<sup>19</sup>, K. Hamano<sup>165</sup>, H. Hamdaoui<sup>35e</sup>, M. Hamer<sup>24</sup>, G. N. Hamity<sup>52</sup>, E. J. Hampshire<sup>95</sup>, J. Han<sup>62b</sup>, K. Han<sup>62a</sup>, L. Han<sup>14c</sup>, L. Han<sup>62a</sup>, S. Han<sup>17a</sup>, Y. F. Han<sup>155</sup>, K. Hanagaki<sup>83</sup>, M. Hance<sup>136</sup>, D. A. Hangal<sup>41,d</sup>, H. Hanif<sup>142</sup>, M. D. Hank<sup>128</sup>, R. Hankache<sup>101</sup>, J. B. Hansen<sup>42</sup>, J. D. Hansen<sup>42</sup>, P. H. Hansen<sup>42</sup>, K. Hara<sup>157</sup>, D. Harada<sup>56</sup>, T. Harenberg<sup>171</sup>, S. Harkusha<sup>37</sup>, Y. T. Harris<sup>126</sup>, N. M. Harrison<sup>119</sup>, P. F. Harrison<sup>167</sup>, N. M. Hartman<sup>143</sup>, N. M. Hartmann<sup>109</sup>, Y. Hasegawa<sup>140</sup>, A. Hasib<sup>52</sup>, S. Haug<sup>19</sup>, R. Hauser<sup>107</sup>, M. Havranek<sup>132</sup>, C. M. Hawkes<sup>20</sup>, R. J. Hawkins<sup>36</sup>, S. Hayashida<sup>111</sup>, D. Hayden<sup>107</sup>, C. Hayes<sup>106</sup>, R. L. Hayes<sup>114</sup>, C. P. Hays<sup>126</sup>, J. M. Hays<sup>94</sup>, H. S. Hayward<sup>92</sup>, F. He<sup>62a</sup>, Y. He<sup>154</sup>, Y. He<sup>127</sup>, N. B. Heatley<sup>94</sup>, V. Hedberg<sup>98</sup>, A. L. Heggelund<sup>125</sup>, N. D. Hehir<sup>94</sup>, C. Heidegger<sup>54</sup>, K. K. Heidegger<sup>54</sup>, W. D. Heidorn<sup>81</sup>, J. Heilmann<sup>34</sup>, S. Heim<sup>48</sup>, T. Heim<sup>17a</sup>, J. G. Heinlein<sup>128</sup>, J. J. Heinrich<sup>123</sup>, L. Heinrich<sup>110,y</sup>, J. Hejbal<sup>131</sup>, L. Helary<sup>48</sup>, A. Held<sup>170</sup>, S. Hellesund<sup>16</sup>, C. M. Helling<sup>164</sup>, S. Hellman<sup>47a,47b</sup>, C. Helsen<sup>36</sup>, R. C. W. Henderson<sup>91</sup>, L. Henkelmann<sup>32</sup>, A. M. Henriques Correia<sup>36</sup>, H. Herde<sup>98</sup>, Y. Hernández Jiménez<sup>145</sup>

L. M. Herrmann<sup>24</sup> T. Herrmann<sup>50</sup> G. Herten<sup>54</sup> R. Hertenberger<sup>109</sup> L. Hervas<sup>36</sup> N. P. Hessey<sup>156a</sup> H. Hibi<sup>84</sup>  
 S. J. Hillier<sup>20</sup> F. Hinterkeuser<sup>24</sup> M. Hirose<sup>124</sup> S. Hirose<sup>157</sup> D. Hirschbuehl<sup>171</sup> T. G. Hitchings<sup>101</sup> B. Hiti<sup>93</sup>  
 J. Hobbs<sup>145</sup> R. Hobincu<sup>27e</sup> N. Hod<sup>169</sup> M. C. Hodgkinson<sup>139</sup> B. H. Hodgkinson<sup>32</sup> A. Hoecker<sup>36</sup> J. Hofer<sup>48</sup>  
 T. Holm<sup>24</sup> M. Holzbock<sup>110</sup> L. B. A. H. Hommels<sup>32</sup> B. P. Honan<sup>101</sup> J. Hong<sup>62c</sup> T. M. Hong<sup>129</sup> J. C. Honig<sup>54</sup>  
 B. H. Hooberman<sup>162</sup> W. H. Hopkins<sup>6</sup> Y. Horii<sup>111</sup> S. Hou<sup>148</sup> A. S. Howard<sup>93</sup> J. Howarth<sup>59</sup> J. Hoya<sup>6</sup>  
 M. Hrabovsky<sup>122</sup> A. Hrynevich<sup>48</sup> T. Hryn'ova<sup>4</sup> P. J. Hsu<sup>65</sup> S.-C. Hsu<sup>138</sup> Q. Hu<sup>41</sup> Y. F. Hu<sup>14a,14d</sup>  
 D. P. Huang<sup>96</sup> S. Huang<sup>64b</sup> X. Huang<sup>14c</sup> Y. Huang<sup>62a</sup> Y. Huang<sup>14a</sup> Z. Huang<sup>101</sup> Z. Hubacek<sup>132</sup>  
 M. Huebner<sup>24</sup> F. Huegging<sup>24</sup> T. B. Huffman<sup>126</sup> M. Huhtinen<sup>36</sup> S. K. Huiberts<sup>16</sup> R. Hulsken<sup>104</sup>  
 N. Huseynov<sup>121</sup> J. Huston<sup>107</sup> J. Huth<sup>61</sup> R. Hyneman<sup>143</sup> G. Iacobucci<sup>56</sup> G. Iakovidis<sup>29</sup> I. Ibragimov<sup>141</sup>  
 L. Iconomidou-Fayard<sup>66</sup> P. Iengo<sup>72a,72b</sup> R. Iguchi<sup>153</sup> T. Iizawa<sup>56</sup> Y. Ikegami<sup>83</sup> A. Ilg<sup>19</sup> N. Ilic<sup>155</sup>  
 H. Imam<sup>35a</sup> T. Ingebretsen Carlson<sup>47a,47b</sup> G. Introzzi<sup>73a,73b</sup> M. Iodice<sup>77a</sup> V. Ippolito<sup>75a,75b</sup> M. Ishino<sup>153</sup>  
 W. Islam<sup>170</sup> C. Issever<sup>18,48</sup> S. Istin<sup>21a,z</sup> H. Ito<sup>168</sup> J. M. Iturbe Ponce<sup>64a</sup> R. Iuppa<sup>78a,78b</sup> A. Ivina<sup>169</sup>  
 J. M. Izen<sup>45</sup> V. Izzo<sup>72a</sup> P. Jacka<sup>131,132</sup> P. Jackson<sup>1</sup> R. M. Jacobs<sup>48</sup> B. P. Jaeger<sup>142</sup> C. S. Jagfeld<sup>109</sup> P. Jain<sup>54</sup>  
 G. Jäkel<sup>171</sup> K. Jakobs<sup>54</sup> T. Jakoubek<sup>169</sup> J. Jamieson<sup>59</sup> K. W. Janas<sup>85a</sup> A. E. Jaspan<sup>92</sup> M. Javurkova<sup>103</sup>  
 F. Jeanneau<sup>135</sup> L. Jeanty<sup>123</sup> J. Jejelava<sup>149a,aa</sup> P. Jenni<sup>54,bb</sup> C. E. Jessiman<sup>34</sup> S. Jézéquel<sup>4</sup> C. Jia<sup>62b</sup> J. Jia<sup>145</sup>  
 X. Jia<sup>61</sup> X. Jia<sup>14a,14d</sup> Z. Jia<sup>14c</sup> Y. Jiang<sup>62a</sup> S. Jiggins<sup>48</sup> J. Jimenez Pena<sup>110</sup> S. Jin<sup>14c</sup> A. Jinaru<sup>27b</sup>  
 O. Jinnouchi<sup>154</sup> P. Johansson<sup>139</sup> K. A. Johns<sup>7</sup> J. W. Johnson<sup>136</sup> D. M. Jones<sup>32</sup> E. Jones<sup>167</sup> P. Jones<sup>32</sup>  
 R. W. L. Jones<sup>91</sup> T. J. Jones<sup>92</sup> R. Joshi<sup>119</sup> J. Jovicevic<sup>15</sup> X. Ju<sup>17a</sup> J. J. Junggeburth<sup>36</sup> T. Junkermann<sup>63a</sup>  
 A. Juste Rozas<sup>13,x</sup> S. Kabana<sup>137e</sup> A. Kaczmarska<sup>86</sup> M. Kado<sup>110</sup> H. Kagan<sup>119</sup> M. Kagan<sup>143</sup> A. Kahn<sup>41</sup>  
 A. Kahn<sup>128</sup> C. Kahra<sup>100</sup> T. Kaji<sup>168</sup> E. Kajomovitz<sup>150</sup> N. Kakati<sup>169</sup> C. W. Kalderon<sup>29</sup> A. Kamenshchikov<sup>155</sup>  
 S. Kanayama<sup>154</sup> N. J. Kang<sup>136</sup> D. Kar<sup>33g</sup> K. Karava<sup>126</sup> M. J. Kareem<sup>156b</sup> E. Karentzos<sup>54</sup> I. Karkanias<sup>152,cc</sup>  
 S. N. Karpov<sup>38</sup> Z. M. Karpova<sup>38</sup> V. Kartvelishvili<sup>91</sup> A. N. Karyukhin<sup>37</sup> E. Kasimi<sup>152,cc</sup> J. Katzy<sup>48</sup> S. Kaur<sup>34</sup>  
 K. Kawade<sup>140</sup> T. Kawamoto<sup>135</sup> G. Kawamura<sup>55</sup> E. F. Kay<sup>165</sup> F. I. Kaya<sup>158</sup> S. Kazakos<sup>13</sup> V. F. Kazanin<sup>37</sup>  
 Y. Ke<sup>145</sup> J. M. Keaveney<sup>33a</sup> R. Keeler<sup>165</sup> G. V. Kehris<sup>61</sup> J. S. Keller<sup>34</sup> A. S. Kelly<sup>96</sup> D. Kelsey<sup>146</sup>  
 J. J. Kempster<sup>146</sup> K. E. Kennedy<sup>41</sup> P. D. Kennedy<sup>100</sup> O. Kepka<sup>131</sup> B. P. Kerridge<sup>167</sup> S. Kersten<sup>171</sup>  
 B. P. Kerševan<sup>93</sup> S. Keshri<sup>66</sup> L. Keszeghova<sup>28a</sup> S. Ketabchi Haghight<sup>155</sup> M. Khandoga<sup>127</sup> A. Khanov<sup>121</sup>  
 A. G. Kharlamov<sup>37</sup> T. Kharlamova<sup>37</sup> E. E. Khoda<sup>138</sup> T. J. Khoo<sup>18</sup> G. Khorauli<sup>166</sup> J. Khubua<sup>149b</sup>  
 Y. A. R. Khwaira<sup>66</sup> M. Kiehn<sup>36</sup> A. Kilgallon<sup>123</sup> D. W. Kim<sup>47a,47b</sup> Y. K. Kim<sup>39</sup> N. Kimura<sup>96</sup> A. Kirchhoff<sup>55</sup>  
 C. Kirfel<sup>24</sup> J. Kirk<sup>134</sup> A. E. Kiryunin<sup>110</sup> T. Kishimoto<sup>153</sup> D. P. Kisliuk<sup>155</sup> C. Kitsaki<sup>10</sup> O. Kivernyk<sup>24</sup>  
 M. Klassen<sup>63a</sup> C. Klein<sup>34</sup> L. Klein<sup>166</sup> M. H. Klein<sup>106</sup> M. Klein<sup>92</sup> S. B. Klein<sup>56</sup> U. Klein<sup>92</sup> P. Klimek<sup>36</sup>  
 A. Klimentov<sup>29</sup> T. Klioutchnikova<sup>36</sup> P. Kluit<sup>114</sup> S. Kluth<sup>110</sup> E. Kneringer<sup>79</sup> T. M. Knight<sup>155</sup> A. Knue<sup>54</sup>  
 R. Kobayashi<sup>87</sup> M. Kocian<sup>143</sup> P. Kodyš<sup>133</sup> D. M. Koeck<sup>123</sup> P. T. Koenig<sup>24</sup> T. Koffas<sup>34</sup> M. Kolb<sup>135</sup>  
 I. Koletsou<sup>4</sup> T. Komarek<sup>122</sup> K. Köneke<sup>54</sup> A. X. Y. Kong<sup>1</sup> T. Kono<sup>118</sup> N. Konstantinidis<sup>96</sup> B. Konya<sup>98</sup>  
 R. Kopeliantsky<sup>68</sup> S. Koperny<sup>85a</sup> K. Korcyl<sup>86</sup> K. Kordas<sup>152,cc</sup> G. Koren<sup>151</sup> A. Korn<sup>96</sup> S. Korn<sup>55</sup>  
 I. Korolkov<sup>13</sup> N. Korotkova<sup>37</sup> B. Kortman<sup>114</sup> O. Kortner<sup>110</sup> S. Kortner<sup>110</sup> W. H. Kostecka<sup>115</sup>  
 V. V. Kostyukhin<sup>141</sup> A. Kotsokechagia<sup>135</sup> A. Kotwal<sup>51</sup> A. Koulouris<sup>36</sup> A. Kourkoumeli-Charalampidi<sup>73a,73b</sup>  
 C. Kourkoumelis<sup>9</sup> E. Kourlitis<sup>6</sup> O. Kovanda<sup>146</sup> R. Kowalewski<sup>165</sup> W. Kozanecki<sup>135</sup> A. S. Kozhin<sup>37</sup>  
 V. A. Kramarenko<sup>37</sup> G. Kramberger<sup>93</sup> P. Kramer<sup>100</sup> M. W. Krasny<sup>127</sup> A. Krasznahorkay<sup>36</sup> J. A. Kremer<sup>100</sup>  
 T. Kresse<sup>50</sup> J. Kretzschmar<sup>92</sup> K. Kreul<sup>18</sup> P. Krieger<sup>155</sup> S. Krishnamurthy<sup>103</sup> M. Krivos<sup>133</sup> K. Krizka<sup>20</sup>  
 K. Kroeninger<sup>49</sup> H. Kroha<sup>110</sup> J. Kroll<sup>131</sup> J. Kroll<sup>128</sup> K. S. Krowpman<sup>107</sup> U. Kruchonak<sup>38</sup> H. Krüger<sup>24</sup>  
 N. Krumnack<sup>81</sup> M. C. Kruse<sup>51</sup> J. A. Krzysiak<sup>86</sup> O. Kuchinskaia<sup>37</sup> S. Kuday<sup>3a</sup> S. Kuehn<sup>36</sup> R. Kuesters<sup>54</sup>  
 T. Kuhl<sup>48</sup> V. Kukhtin<sup>38</sup> Y. Kulchitsky<sup>37,1</sup> S. Kuleshov<sup>137d,137b</sup> M. Kumar<sup>33g</sup> N. Kumari<sup>102</sup> A. Kupco<sup>131</sup>  
 T. Kupfer<sup>49</sup> A. Kupich<sup>37</sup> O. Kuprash<sup>54</sup> H. Kurashige<sup>84</sup> L. L. Kurchaninov<sup>156a</sup> O. Kurdyshev<sup>66</sup>  
 Y. A. Kurochkin<sup>37</sup> A. Kurova<sup>37</sup> M. Kuze<sup>154</sup> A. K. Kvam<sup>103</sup> J. Kvita<sup>122</sup> T. Kwan<sup>104</sup> N. G. Kyriacou<sup>106</sup>  
 L. A. O. Laatu<sup>102</sup> C. Lacasta<sup>163</sup> F. Lacava<sup>75a,75b</sup> H. Lacker<sup>18</sup> D. Lacour<sup>127</sup> N. N. Lad<sup>96</sup> E. Ladygin<sup>38</sup>  
 B. Laforge<sup>127</sup> T. Lagouri<sup>137e</sup> S. Lai<sup>55</sup> I. K. Lakomicc<sup>85a</sup> N. Lalloue<sup>60</sup> J. E. Lambert<sup>120</sup> S. Lammers<sup>68</sup>  
 W. Lampl<sup>7</sup> C. Lampoudis<sup>152,cc</sup> A. N. Lancaster<sup>115</sup> E. Lançon<sup>29</sup> U. Landgraf<sup>54</sup> M. P. J. Landon<sup>94</sup>  
 V. S. Lang<sup>54</sup> R. J. Langenberg<sup>103</sup> A. J. Lankford<sup>160</sup> F. Lanni<sup>36</sup> K. Lantzsch<sup>24</sup> A. Lanza<sup>73a</sup> A. Lapertosa<sup>57b,57a</sup>  
 J. F. Laporte<sup>135</sup> T. Lari<sup>71a</sup> F. Lasagni Manghi<sup>23b</sup> M. Lassnig<sup>36</sup> V. Latonova<sup>131</sup> A. Laudrain<sup>100</sup> A. Laurier<sup>150</sup>

S. D. Lawlor<sup>95</sup> Z. Lawrence<sup>101</sup> M. Lazzaroni<sup>71a,71b</sup> B. Le,<sup>101</sup> E. M. Le Boulicaut<sup>51</sup> B. Leban<sup>93</sup> A. Lebedev<sup>81</sup>  
M. LeBlanc<sup>36</sup> F. Ledroit-Guillon<sup>60</sup> A. C. A. Lee,<sup>96</sup> G. R. Lee<sup>16</sup> S. C. Lee<sup>148</sup> S. Lee<sup>47a,47b</sup> T. F. Lee<sup>92</sup>  
L. L. Leeuw<sup>33c</sup> H. P. Lefebvre<sup>95</sup> M. Lefebvre<sup>165</sup> C. Leggett<sup>17a</sup> K. Lehmann<sup>142</sup> G. Lehmann Miotto<sup>36</sup>  
M. Leigh<sup>56</sup> W. A. Leight<sup>103</sup> A. Leisos<sup>152,dd</sup> M. A. L. Leite<sup>82c</sup> C. E. Leitgeb<sup>48</sup> R. Leitner<sup>133</sup> K. J. C. Leney<sup>44</sup>  
T. Lenz<sup>24</sup> S. Leone<sup>74a</sup> C. Leonidopoulos<sup>52</sup> A. Leopold<sup>144</sup> C. Leroy<sup>108</sup> R. Les<sup>107</sup> C. G. Lester<sup>32</sup>  
M. Levchenko<sup>37</sup> J. Levêque<sup>4</sup> D. Levin<sup>106</sup> L. J. Levinson<sup>169</sup> M. P. Lewicki<sup>86</sup> D. J. Lewis<sup>4</sup> A. Li<sup>5</sup> B. Li<sup>62b</sup>  
C. Li,<sup>62a</sup> C-Q. Li<sup>62c</sup> H. Li<sup>62a</sup> H. Li<sup>62b</sup> H. Li<sup>14c</sup> H. Li<sup>62b</sup> J. Li<sup>62c</sup> K. Li<sup>138</sup> L. Li<sup>62c</sup> M. Li<sup>14a,14d</sup> Q. Y. Li<sup>62a</sup>  
S. Li<sup>14a,14d</sup> S. Li<sup>62d,62c,ee</sup> T. Li<sup>62b</sup> X. Li<sup>104</sup> Z. Li<sup>62b</sup> Z. Li<sup>126</sup> Z. Li<sup>104</sup> Z. Li<sup>92</sup> Z. Li<sup>14a,14d</sup> Z. Liang<sup>14a</sup>  
M. Liberatore<sup>48</sup> B. Liberti<sup>76a</sup> K. Lie<sup>64c</sup> J. Lieber Marin<sup>82b</sup> H. Lien<sup>68</sup> K. Lin<sup>107</sup> R. A. Linck<sup>68</sup>  
R. E. Lindley<sup>7</sup> J. H. Lindon<sup>2</sup> A. Linss<sup>48</sup> E. Lipeles<sup>128</sup> A. Lipniacka<sup>16</sup> A. Lister<sup>164</sup> J. D. Little<sup>4</sup> B. Liu<sup>14a</sup>  
B. X. Liu<sup>142</sup> D. Liu<sup>62d,62c</sup> J. B. Liu<sup>62a</sup> J. K. K. Liu<sup>32</sup> K. Liu<sup>62d,62c</sup> M. Liu<sup>62a</sup> M. Y. Liu<sup>62a</sup> P. Liu<sup>14a</sup>  
Q. Liu<sup>62d,138,62c</sup> X. Liu<sup>62a</sup> Y. Liu<sup>14c,14d</sup> Y. L. Liu<sup>106</sup> Y. W. Liu<sup>62a</sup> J. Llorente Merino<sup>142</sup> S. L. Lloyd<sup>94</sup>  
E. M. Lobodzinska<sup>48</sup> P. Loch<sup>7</sup> S. Loffredo<sup>76a,76b</sup> T. Lohse<sup>18</sup> K. Lohwasser<sup>139</sup> E. Loiacono<sup>48</sup>  
M. Lokajicek<sup>131,a</sup> J. D. Long<sup>162</sup> I. Longarini<sup>160</sup> L. Longo<sup>70a,70b</sup> R. Longo<sup>162</sup> I. Lopez Paz<sup>67</sup> A. Lopez Solis<sup>48</sup>  
J. Lorenz<sup>109</sup> N. Lorenzo Martinez<sup>4</sup> A. M. Lory<sup>109</sup> X. Lou<sup>47a,47b</sup> X. Lou<sup>14a,14d</sup> A. Lounis<sup>66</sup> J. Love<sup>6</sup>  
P. A. Love<sup>91</sup> G. Lu<sup>14a,14d</sup> M. Lu<sup>80</sup> S. Lu<sup>128</sup> Y. J. Lu<sup>65</sup> H. J. Lubatti<sup>138</sup> C. Luci<sup>75a,75b</sup> F. L. Lucio Alves<sup>14c</sup>  
A. Lucotte<sup>60</sup> F. Luehring<sup>68</sup> I. Luise<sup>145</sup> O. Lukianchuk<sup>66</sup> O. Lundberg<sup>144</sup> B. Lund-Jensen<sup>144</sup> N. A. Luongo<sup>123</sup>  
M. S. Lutz<sup>151</sup> D. Lynn<sup>29</sup> H. Lyons<sup>92</sup> R. Lysak<sup>131</sup> E. Lytken<sup>98</sup> V. Lyubushkin<sup>38</sup> T. Lyubushkina<sup>38</sup>  
M. M. Lyukova<sup>145</sup> H. Ma<sup>29</sup> L. L. Ma<sup>62b</sup> Y. Ma<sup>96</sup> D. M. Mac Donnell<sup>165</sup> G. Maccarrone<sup>53</sup> J. C. MacDonald<sup>139</sup>  
R. Madar<sup>40</sup> W. F. Mader<sup>50</sup> J. Maeda<sup>84</sup> T. Maeno<sup>29</sup> M. Maerker<sup>50</sup> H. Maguire<sup>139</sup> A. Maio<sup>130a,130b,130d</sup>  
K. Maj<sup>85a</sup> O. Majersky<sup>48</sup> S. Majewski<sup>123</sup> N. Makovec<sup>66</sup> V. Maksimovic<sup>15</sup> B. Malaescu<sup>127</sup> Pa. Malecki<sup>86</sup>  
V. P. Maleev<sup>37</sup> F. Malek<sup>60</sup> D. Malito<sup>43b,43a</sup> U. Mallik<sup>80</sup> C. Malone<sup>32</sup> S. Maltezos<sup>10</sup> S. Malyukov<sup>38</sup>  
J. Mamuzic<sup>13</sup> G. Mancini<sup>53</sup> G. Manco<sup>73a,73b</sup> J. P. Mandalia<sup>94</sup> I. Mandić<sup>93</sup> L. Manhaes de Andrade Filho<sup>82a</sup>  
I. M. Maniatis<sup>169</sup> J. Manjarres Ramos<sup>102,ff</sup> D. C. Mankad<sup>169</sup> A. Mann<sup>109</sup> B. Mansoulié<sup>135</sup> S. Manzoni<sup>36</sup>  
A. Marantis<sup>152,dd</sup> G. Marchiori<sup>5</sup> M. Marcisovsky<sup>131</sup> C. Marcon<sup>71a,71b</sup> M. Marinescu<sup>20</sup> M. Marjanovic<sup>120</sup>  
E. J. Marshall<sup>91</sup> Z. Marshall<sup>17a</sup> S. Marti-Garcia<sup>163</sup> T. A. Martin<sup>167</sup> V. J. Martin<sup>52</sup> B. Martin dit Latour<sup>16</sup>  
L. Martinelli<sup>75a,75b</sup> M. Martinez<sup>13,x</sup> P. Martinez Agullo<sup>163</sup> V. I. Martinez Outschoorn<sup>103</sup> P. Martinez Suarez<sup>13</sup>  
S. Martin-Haugh<sup>134</sup> V. S. Martoiu<sup>27b</sup> A. C. Martyniuk<sup>96</sup> A. Marzin<sup>36</sup> S. R. Maschek<sup>110</sup> D. Mascione<sup>78a,78b</sup>  
L. Masetti<sup>100</sup> T. Mashimo<sup>153</sup> J. Masik<sup>101</sup> A. L. Maslennikov<sup>37</sup> L. Massa<sup>23b</sup> P. Massarotti<sup>72a,72b</sup>  
P. Mastrandrea<sup>74a,74b</sup> A. Mastroberardino<sup>43b,43a</sup> T. Masubuchi<sup>153</sup> T. Mathisen<sup>161</sup> N. Matsuzawa<sup>153</sup> J. Maurer<sup>27b</sup>  
B. Maček<sup>93</sup> D. A. Maximov<sup>37</sup> R. Mazini<sup>148</sup> I. Maznas<sup>152,cc</sup> M. Mazza<sup>107</sup> S. M. Mazza<sup>136</sup> C. Mc Ginn<sup>29</sup>  
J. P. Mc Gowan<sup>104</sup> S. P. Mc Kee<sup>106</sup> E. F. McDonald<sup>105</sup> A. E. McDougall<sup>114</sup> J. A. Mcfayden<sup>146</sup>  
R. P. McGovern<sup>128</sup> G. Mchedlidze<sup>149b</sup> R. P. McKenzie<sup>33g</sup> T. C. McLachlan<sup>48</sup> D. J. McLaughlin<sup>96</sup>  
K. D. McLean<sup>165</sup> S. J. McMahon<sup>134</sup> P. C. McNamara<sup>105</sup> C. M. Mcpartland<sup>92</sup> R. A. McPherson<sup>165,p</sup> T. Megy<sup>40</sup>  
S. Mehlhase<sup>109</sup> A. Mehta<sup>92</sup> D. Melini<sup>150</sup> B. R. Mellado Garcia<sup>33g</sup> A. H. Melo<sup>55</sup> F. Meloni<sup>48</sup>  
A. M. Mendes Jacques Da Costa<sup>101</sup> H. Y. Meng<sup>155</sup> L. Meng<sup>91</sup> S. Menke<sup>110</sup> M. Mentink<sup>36</sup> E. Meoni<sup>43b,43a</sup>  
C. Merlassino<sup>126</sup> L. Merola<sup>72a,72b</sup> C. Meroni<sup>71a,71b</sup> G. Merz<sup>106</sup> O. Meshkov<sup>37</sup> J. Metcalfe<sup>6</sup> A. S. Mete<sup>6</sup>  
C. Meyer<sup>68</sup> J-P. Meyer<sup>135</sup> R. P. Middleton<sup>134</sup> L. Mijović<sup>52</sup> G. Mikenberg<sup>169</sup> M. Mikesstikova<sup>131</sup> M. Mikuž<sup>93</sup>  
H. Mildner<sup>139</sup> A. Milic<sup>36</sup> C. D. Milke<sup>44</sup> D. W. Miller<sup>39</sup> L. S. Miller<sup>34</sup> A. Milov<sup>169</sup> D. A. Milstead<sup>47a,47b</sup>  
T. Min<sup>14c</sup> A. A. Minaenko<sup>37</sup> I. A. Minashvili<sup>149b</sup> L. Mince<sup>59</sup> A. I. Mincer<sup>117</sup> B. Mindur<sup>85a</sup> M. Mineev<sup>38</sup>  
Y. Mino<sup>87</sup> L. M. Mir<sup>13</sup> M. Miralles Lopez<sup>163</sup> M. Mironova<sup>17a</sup> M. C. Missio<sup>113</sup> T. Mitani<sup>168</sup> A. Mitra<sup>167</sup>  
V. A. Mitsou<sup>163</sup> O. Miu<sup>155</sup> P. S. Miyagawa<sup>94</sup> Y. Miyazaki<sup>89</sup> A. Mizukami<sup>83</sup> T. Mkrtychyan<sup>63a</sup> M. Mlinarevic<sup>96</sup>  
T. Mlinarevic<sup>96</sup> M. Mlynarikova<sup>36</sup> S. Mobius<sup>55</sup> K. Mochizuki<sup>108</sup> P. Moder<sup>48</sup> P. Mogg<sup>109</sup>  
A. F. Mohammed<sup>14a,14d</sup> S. Mohapatra<sup>41</sup> G. Mokgatitswane<sup>33g</sup> B. Mondal<sup>141</sup> S. Mondal<sup>132</sup> K. Mönig<sup>48</sup>  
E. Monnier<sup>102</sup> L. Monsonis Romero<sup>163</sup> J. Montejo Berlingen<sup>83</sup> M. Montella<sup>119</sup> F. Monticelli<sup>90</sup> N. Morange<sup>66</sup>  
A. L. Moreira De Carvalho<sup>130a</sup> M. Moreno Llácer<sup>163</sup> C. Moreno Martinez<sup>56</sup> P. Morettini<sup>57b</sup> S. Morgenstern<sup>36</sup>  
M. Morii<sup>61</sup> M. Morinaga<sup>153</sup> A. K. Morley<sup>36</sup> F. Morodei<sup>75a,75b</sup> L. Morvaj<sup>36</sup> P. Moschovakos<sup>36</sup> B. Moser<sup>36</sup>  
M. Mosidze<sup>149b</sup> T. Moskalets<sup>54</sup> P. Moskvitina<sup>113</sup> J. Moss<sup>31,gg</sup> E. J. W. Moyses<sup>103</sup> O. Mtintsilana<sup>33g</sup>  
S. Muanza<sup>102</sup> J. Mueller<sup>129</sup> D. Muenstermann<sup>91</sup> R. Müller<sup>19</sup> G. A. Mullier<sup>161</sup> J. J. Mullin<sup>128</sup> D. P. Mungo<sup>155</sup>

J. L. Munoz Martinez<sup>13</sup>, D. Munoz Perez<sup>163</sup>, F. J. Munoz Sanchez<sup>101</sup>, M. Murin<sup>101</sup>, W. J. Murray<sup>167,134</sup>, A. Murrone<sup>71a,71b</sup>, J. M. Muse<sup>120</sup>, M. Muškinja<sup>17a</sup>, C. Mwewa<sup>29</sup>, A. G. Myagkov<sup>37,1</sup>, A. J. Myers<sup>8</sup>, A. A. Myers<sup>129</sup>, G. Myers<sup>68</sup>, M. Myska<sup>132</sup>, B. P. Nachman<sup>17a</sup>, O. Nackenhorst<sup>49</sup>, A. Nag<sup>50</sup>, K. Nagai<sup>126</sup>, K. Nagano<sup>83</sup>, J. L. Nagle<sup>29,i</sup>, E. Nagy<sup>102</sup>, A. M. Nairz<sup>36</sup>, Y. Nakahama<sup>83</sup>, K. Nakamura<sup>83</sup>, H. Nanjo<sup>124</sup>, R. Narayan<sup>44</sup>, E. A. Narayanan<sup>112</sup>, I. Naryshkin<sup>37</sup>, M. Naseri<sup>34</sup>, C. Nass<sup>24</sup>, G. Navarro<sup>22a</sup>, J. Navarro-Gonzalez<sup>163</sup>, R. Nayak<sup>151</sup>, A. Nayaz<sup>18</sup>, P. Y. Nechaeva<sup>37</sup>, F. Nechansky<sup>48</sup>, L. Nedic<sup>126</sup>, T. J. Neep<sup>20</sup>, A. Negri<sup>73a,73b</sup>, M. Negrini<sup>23b</sup>, C. Nellist<sup>114</sup>, C. Nelson<sup>104</sup>, K. Nelson<sup>106</sup>, S. Nemecek<sup>131</sup>, M. Nessi<sup>36,hh</sup>, M. S. Neubauer<sup>162</sup>, F. Neuhaus<sup>100</sup>, J. Neundorff<sup>48</sup>, R. Newhouse<sup>164</sup>, P. R. Newman<sup>20</sup>, C. W. Ng<sup>129</sup>, Y. W. Y. Ng<sup>48</sup>, B. Ngair<sup>35e</sup>, H. D. N. Nguyen<sup>108</sup>, R. B. Nickerson<sup>126</sup>, R. Nicolaidou<sup>135</sup>, J. Nielsen<sup>136</sup>, M. Niemeyer<sup>55</sup>, N. Nikiforou<sup>36</sup>, V. Nikolaenko<sup>37,1</sup>, I. Nikolic-Audit<sup>127</sup>, K. Nikolopoulos<sup>20</sup>, P. Nilsson<sup>29</sup>, I. Ninca<sup>48</sup>, H. R. Nindhito<sup>56</sup>, G. Ninio<sup>151</sup>, A. Nisati<sup>75a</sup>, N. Nishu<sup>2</sup>, R. Nisius<sup>110</sup>, J-E. Nitschke<sup>50</sup>, E. K. Nkadameng<sup>33g</sup>, S. J. Noacco Rosende<sup>90</sup>, T. Nobe<sup>153</sup>, D. L. Noel<sup>32</sup>, T. Nommensen<sup>147</sup>, M. A. Nomura<sup>29</sup>, M. B. Norfolk<sup>139</sup>, R. R. B. Norisam<sup>96</sup>, B. J. Norman<sup>34</sup>, J. Novak<sup>93</sup>, T. Novak<sup>48</sup>, L. Novotny<sup>132</sup>, R. Novotny<sup>112</sup>, L. Nozka<sup>122</sup>, K. Ntekas<sup>160</sup>, N. M. J. Nunes De Moura Junior<sup>82b</sup>, E. Nurse<sup>96</sup>, J. Ocariz<sup>127</sup>, A. Ochi<sup>84</sup>, I. Ochoa<sup>130a</sup>, S. Oerdek<sup>161</sup>, J. T. Offermann<sup>39</sup>, A. Ogrodnik<sup>85a</sup>, A. Oh<sup>101</sup>, C. C. Ohm<sup>144</sup>, H. Oide<sup>83</sup>, R. Oishi<sup>153</sup>, M. L. Ojeda<sup>48</sup>, Y. Okazaki<sup>87</sup>, M. W. O'Keefe<sup>92</sup>, Y. Okumura<sup>153</sup>, L. F. Oleiro Seabra<sup>130a</sup>, S. A. Olivares Pino<sup>137d</sup>, D. Oliveira Damazio<sup>29</sup>, D. Oliveira Goncalves<sup>82a</sup>, J. L. Oliver<sup>160</sup>, M. J. R. Olsson<sup>160</sup>, A. Olszewski<sup>86</sup>, J. Olszowska<sup>86,a</sup>, Ö. Ö. Öncel<sup>54</sup>, D. C. O'Neil<sup>142</sup>, A. P. O'Neill<sup>19</sup>, A. Onofre<sup>130a,130e</sup>, P. U. E. Onyisi<sup>11</sup>, M. J. Oreglia<sup>39</sup>, G. E. Orellana<sup>90</sup>, D. Orestano<sup>77a,77b</sup>, N. Orlando<sup>13</sup>, R. S. Orr<sup>155</sup>, V. O'Shea<sup>59</sup>, R. Ospanov<sup>62a</sup>, G. Otero y Garzon<sup>30</sup>, H. Otono<sup>89</sup>, P. S. Ott<sup>63a</sup>, G. J. Ottino<sup>17a</sup>, M. Ouchrif<sup>35d</sup>, J. Ouellette<sup>29</sup>, F. Ould-Saada<sup>125</sup>, M. Owen<sup>59</sup>, R. E. Owen<sup>134</sup>, K. Y. Oyulmaz<sup>21a</sup>, V. E. Ozcan<sup>21a</sup>, N. Ozturk<sup>8</sup>, S. Ozturk<sup>21d</sup>, H. A. Pacey<sup>32</sup>, A. Pacheco Pages<sup>13</sup>, C. Padilla Aranda<sup>13</sup>, G. Padovano<sup>75a,75b</sup>, S. Pagan Griso<sup>17a</sup>, G. Palacino<sup>68</sup>, A. Palazzo<sup>70a,70b</sup>, S. Palestini<sup>36</sup>, J. Pan<sup>172</sup>, T. Pan<sup>64a</sup>, D. K. Panchal<sup>11</sup>, C. E. Pandini<sup>114</sup>, J. G. Panduro Vazquez<sup>95</sup>, H. Pang<sup>14b</sup>, P. Pani<sup>48</sup>, G. Panizzo<sup>69a,69c</sup>, L. Paolozzi<sup>56</sup>, C. Papadatos<sup>108</sup>, S. Parajuli<sup>44</sup>, A. Paramonov<sup>6</sup>, C. Paraskevopoulos<sup>10</sup>, D. Paredes Hernandez<sup>64b</sup>, T. H. Park<sup>155</sup>, M. A. Parker<sup>32</sup>, F. Parodi<sup>57b,57a</sup>, E. W. Parrish<sup>115</sup>, V. A. Parrish<sup>52</sup>, J. A. Parsons<sup>41</sup>, U. Parzefall<sup>54</sup>, B. Pascual Dias<sup>108</sup>, L. Pascual Dominguez<sup>151</sup>, F. Pasquali<sup>114</sup>, E. Pasqualucci<sup>75a</sup>, S. Passaggio<sup>57b</sup>, F. Pastore<sup>95</sup>, P. Pasuwan<sup>47a,47b</sup>, P. Patel<sup>86</sup>, U. M. Patel<sup>51</sup>, J. R. Pater<sup>101</sup>, T. Pauly<sup>36</sup>, J. Parkes<sup>143</sup>, M. Pedersen<sup>125</sup>, R. Pedro<sup>130a</sup>, S. V. Peleganchuk<sup>37</sup>, O. Penc<sup>36</sup>, E. A. Pender<sup>52</sup>, H. Peng<sup>62a</sup>, K. E. Pensi<sup>109</sup>, M. Penzin<sup>37</sup>, B. S. Peralva<sup>82d</sup>, A. P. Pereira Peixoto<sup>60</sup>, L. Pereira Sanchez<sup>47a,47b</sup>, D. V. Perepelitsa<sup>29,i</sup>, E. Perez Codina<sup>156a</sup>, M. Perganti<sup>10</sup>, L. Perini<sup>71a,71b,a</sup>, H. Pernegger<sup>36</sup>, S. Perrella<sup>36</sup>, A. Perrevoort<sup>113</sup>, O. Perrin<sup>40</sup>, K. Peters<sup>48</sup>, R. F. Y. Peters<sup>101</sup>, B. A. Petersen<sup>36</sup>, T. C. Petersen<sup>42</sup>, E. Petit<sup>102</sup>, V. Petousis<sup>132</sup>, C. Petridou<sup>152,cc</sup>, A. Petrukhin<sup>141</sup>, M. Pettee<sup>17a</sup>, N. E. Pettersson<sup>36</sup>, A. Petukhov<sup>37</sup>, K. Petukhova<sup>133</sup>, A. Peyaud<sup>135</sup>, R. Pezoa<sup>137f</sup>, L. Pezzotti<sup>36</sup>, G. Pezzullo<sup>172</sup>, T. M. Pham<sup>170</sup>, T. Pham<sup>105</sup>, P. W. Phillips<sup>134</sup>, M. W. Phipps<sup>162</sup>, G. Piacquadio<sup>145</sup>, E. Pianori<sup>17a</sup>, F. Piazza<sup>71a,71b</sup>, R. Piegai<sup>30</sup>, D. Pietreanu<sup>27b</sup>, A. D. Pilkington<sup>101</sup>, M. Pinamonti<sup>69a,69c</sup>, J. L. Pinfold<sup>2</sup>, B. C. Pinheiro Pereira<sup>130a</sup>, C. Pitman Donaldson<sup>96</sup>, D. A. Pizzi<sup>34</sup>, L. Pizzimento<sup>76a,76b</sup>, A. Pizzini<sup>114</sup>, M.-A. Pleier<sup>29</sup>, V. Plesanovs<sup>54</sup>, V. Pleskot<sup>133</sup>, E. Plotnikova<sup>38</sup>, G. Poddar<sup>4</sup>, R. Poettgen<sup>98</sup>, L. Poggioli<sup>127</sup>, D. Pohl<sup>24</sup>, I. Pokharel<sup>55</sup>, S. Polacek<sup>133</sup>, G. Polesello<sup>73a</sup>, A. Poley<sup>142,156a</sup>, R. Polifka<sup>132</sup>, A. Polini<sup>23b</sup>, C. S. Pollard<sup>167</sup>, Z. B. Pollock<sup>119</sup>, V. Polychronakos<sup>29</sup>, E. Pompa Pacchi<sup>75a,75b</sup>, D. Ponomarenko<sup>113</sup>, L. Pontecorvo<sup>36</sup>, S. Popa<sup>27a</sup>, G. A. Popeneciu<sup>27d</sup>, D. M. Portillo Quintero<sup>156a</sup>, S. Pospisil<sup>132</sup>, P. Postolache<sup>27c</sup>, K. Potamianos<sup>126</sup>, P. A. Potepa<sup>85a</sup>, I. N. Potrap<sup>38</sup>, C. J. Potter<sup>32</sup>, H. Potti<sup>1</sup>, T. Poulsen<sup>48</sup>, J. Poveda<sup>163</sup>, M. E. Pozo Astigarraga<sup>36</sup>, A. Prades Ibanez<sup>163</sup>, M. M. Prapa<sup>46</sup>, J. Pretel<sup>54</sup>, D. Price<sup>101</sup>, M. Primavera<sup>70a</sup>, M. A. Principe Martin<sup>99</sup>, R. Privara<sup>122</sup>, M. L. Proffitt<sup>138</sup>, N. Proklova<sup>128</sup>, K. Prokofiev<sup>64c</sup>, G. Proto<sup>76a,76b</sup>, S. Protopopescu<sup>29</sup>, J. Proudfoot<sup>6</sup>, M. Przybycien<sup>85a</sup>, W. W. Przygoda<sup>85b</sup>, J. E. Puddefoot<sup>139</sup>, D. Pudzha<sup>37</sup>, D. Pyatiizbyantseva<sup>37</sup>, J. Qian<sup>106</sup>, D. Qichen<sup>101</sup>, Y. Qin<sup>101</sup>, T. Qiu<sup>52</sup>, A. Quadt<sup>55</sup>, M. Queitsch-Maitland<sup>101</sup>, G. Quetant<sup>56</sup>, G. Rabanal Bolanos<sup>61</sup>, D. Rafanoharana<sup>54</sup>, F. Ragusa<sup>71a,71b</sup>, J. L. Rainbolt<sup>39</sup>, J. A. Raine<sup>56</sup>, S. Rajagopalan<sup>29</sup>, E. Ramakoti<sup>37</sup>, K. Ran<sup>48,14d</sup>, N. P. Rapheeha<sup>33g</sup>, V. Raskina<sup>127</sup>, D. F. Rassloff<sup>63a</sup>, S. Rave<sup>100</sup>, B. Ravina<sup>55</sup>, I. Ravinovich<sup>169</sup>, M. Raymond<sup>36</sup>, A. L. Read<sup>125</sup>, N. P. Readioff<sup>139</sup>, D. M. Rebuzzi<sup>73a,73b</sup>, G. Redlinger<sup>29</sup>, K. Reeves<sup>26</sup>, J. A. Reidelsturz<sup>171</sup>, D. Reikher<sup>151</sup>, A. Rej<sup>141</sup>, C. Rembser<sup>36</sup>, A. Renardi<sup>48</sup>, M. Renda<sup>27b</sup>, M. B. Rendel<sup>110</sup>, F. Renner<sup>48</sup>

A. G. Rennie<sup>59</sup> S. Resconi<sup>71a</sup> M. Ressegotti<sup>57b,57a</sup> E. D. Resseguie<sup>17a</sup> S. Rettie<sup>36</sup> J. G. Reyes Rivera<sup>107</sup>  
 B. Reynolds<sup>119</sup> E. Reynolds<sup>17a</sup> M. Rezaei Estabragh<sup>171</sup> O. L. Rezanova<sup>37</sup> P. Reznicek<sup>133</sup> N. Ribaric<sup>91</sup>  
 E. Ricci<sup>78a,78b</sup> R. Richter<sup>110</sup> S. Richter<sup>47a,47b</sup> E. Richter-Was<sup>85b</sup> M. Ridel<sup>127</sup> S. Ridouani<sup>35d</sup> P. Rieck<sup>117</sup>  
 P. Riedler<sup>36</sup> M. Rijssenbeek<sup>145</sup> A. Rimoldi<sup>73a,73b</sup> M. Rimoldi<sup>48</sup> L. Rinaldi<sup>23b,23a</sup> T. T. Rinn<sup>29</sup>  
 M. P. Rinnagel<sup>109</sup> G. Ripellino<sup>161</sup> I. Riu<sup>13</sup> P. Rivadeneira<sup>48</sup> J. C. Rivera Vergara<sup>165</sup> F. Rizatdinova<sup>121</sup>  
 E. Rizvi<sup>94</sup> C. Rizzi<sup>56</sup> B. A. Roberts<sup>167</sup> B. R. Roberts<sup>17a</sup> S. H. Robertson<sup>104,p</sup> M. Robin<sup>48</sup> D. Robinson<sup>32</sup>  
 C. M. Robles Gajardo<sup>137f</sup> M. Robles Manzano<sup>100</sup> A. Robson<sup>59</sup> A. Rocchi<sup>76a,76b</sup> C. Roda<sup>74a,74b</sup>  
 S. Rodriguez Bosca<sup>63a</sup> Y. Rodriguez Garcia<sup>22a</sup> A. Rodriguez Rodriguez<sup>54</sup> A. M. Rodríguez Vera<sup>156b</sup> S. Roe<sup>36</sup>  
 J. T. Roemer<sup>160</sup> A. R. Roepe-Gier<sup>136</sup> J. Roggel<sup>171</sup> O. Røhne<sup>125</sup> R. A. Rojas<sup>103</sup> C. P. A. Roland<sup>68</sup> J. Roloff<sup>29</sup>  
 A. Romaniouk<sup>37</sup> E. Romano<sup>73a,73b</sup> M. Romano<sup>23b</sup> A. C. Romero Hernandez<sup>162</sup> N. Rompotis<sup>92</sup> L. Roos<sup>127</sup>  
 S. Rosati<sup>75a</sup> B. J. Rosser<sup>39</sup> E. Rossi<sup>4</sup> E. Rossi<sup>72a,72b</sup> L. P. Rossi<sup>57b</sup> L. Rossini<sup>48</sup> R. Rosten<sup>119</sup> M. Rotaru<sup>27b</sup>  
 B. Rottler<sup>54</sup> C. Rougier<sup>102,ff</sup> D. Rousseau<sup>66</sup> D. Rousso<sup>32</sup> A. Roy<sup>162</sup> S. Roy-Garand<sup>155</sup> A. Rozanov<sup>102</sup>  
 Y. Rozen<sup>150</sup> X. Ruan<sup>33g</sup> A. Rubio Jimenez<sup>163</sup> A. J. Ruby<sup>92</sup> V. H. Ruelas Rivera<sup>18</sup> T. A. Ruggeri<sup>1</sup>  
 A. Ruiz-Martinez<sup>163</sup> A. Rummeler<sup>36</sup> Z. Rurikova<sup>54</sup> N. A. Rusakovich<sup>38</sup> H. L. Russell<sup>165</sup> J. P. Rutherford<sup>7</sup>  
 K. Rybacki<sup>91</sup> M. Rybar<sup>133</sup> E. B. Rye<sup>125</sup> A. Ryzhov<sup>37</sup> J. A. Sabater Iglesias<sup>56</sup> P. Sabatini<sup>163</sup> L. Sabetta<sup>75a,75b</sup>  
 H. F.-W. Sadrozinski<sup>136</sup> F. Safai Tehrani<sup>75a</sup> B. Safarzadeh Samani<sup>146</sup> M. Safdari<sup>143</sup> S. Saha<sup>104</sup> M. Sahinsoy<sup>110</sup>  
 M. Saimpert<sup>135</sup> M. Saito<sup>153</sup> T. Saito<sup>153</sup> D. Salamani<sup>36</sup> A. Salmikov<sup>143</sup> J. Salt<sup>163</sup> A. Salvador Salas<sup>13</sup>  
 D. Salvatore<sup>43b,43a</sup> F. Salvatore<sup>146</sup> A. Salzburger<sup>36</sup> D. Sammel<sup>54</sup> D. Sampsonidis<sup>152,cc</sup> D. Sampsonidou<sup>123,62c</sup>  
 J. Sánchez<sup>163</sup> A. Sanchez Pineda<sup>4</sup> V. Sanchez Sebastian<sup>163</sup> H. Sandaker<sup>125</sup> C. O. Sander<sup>48</sup> J. A. Sandesara<sup>103</sup>  
 M. Sandhoff<sup>171</sup> C. Sandoval<sup>22b</sup> D. P. C. Sankey<sup>134</sup> T. Sano<sup>87</sup> A. Sansoni<sup>53</sup> L. Santi<sup>75a,75b</sup> C. Santoni<sup>40</sup>  
 S. N. Santpur<sup>17a</sup> A. Santra<sup>169</sup> K. A. Saoucha<sup>139</sup> J. G. Saraiva<sup>130a,130d</sup> J. Sardain<sup>7</sup> O. Sasaki<sup>83</sup> K. Sato<sup>157</sup>  
 C. Sauer<sup>63b</sup> F. Sauerburger<sup>54</sup> E. Sauvan<sup>4</sup> P. Savard<sup>155,e</sup> R. Sawada<sup>153</sup> C. Sawyer<sup>134</sup> L. Sawyer<sup>97</sup>  
 I. Sayago Galvan<sup>163</sup> C. Sbarra<sup>23b</sup> A. Sbrizzi<sup>23b,23a</sup> T. Scanlon<sup>96</sup> J. Schaarschmidt<sup>138</sup> P. Schacht<sup>110</sup>  
 D. Schaefer<sup>39</sup> U. Schäfer<sup>100</sup> A. C. Schaffer<sup>66,44</sup> D. Schaile<sup>109</sup> R. D. Schamberger<sup>145</sup> E. Schanet<sup>109</sup>  
 C. Scharf<sup>18</sup> M. M. Schefer<sup>19</sup> V. A. Schegelsky<sup>37</sup> D. Scheirich<sup>133</sup> F. Schenck<sup>18</sup> M. Schernau<sup>160</sup> C. Scheulen<sup>55</sup>  
 C. Schiavi<sup>57b,57a</sup> E. J. Schioppa<sup>70a,70b</sup> M. Schioppa<sup>43b,43a</sup> B. Schlag<sup>143,u</sup> K. E. Schleicher<sup>54</sup> S. Schlenker<sup>36</sup>  
 J. Schmeing<sup>171</sup> M. A. Schmidt<sup>171</sup> K. Schmieden<sup>100</sup> C. Schmitt<sup>100</sup> S. Schmitt<sup>48</sup> L. Schoeffel<sup>135</sup>  
 A. Schoening<sup>63b</sup> P. G. Scholer<sup>54</sup> E. Schopf<sup>126</sup> M. Schott<sup>100</sup> J. Schovancova<sup>36</sup> S. Schramm<sup>56</sup> F. Schroeder<sup>171</sup>  
 H.-C. Schultz-Coulon<sup>63a</sup> M. Schumacher<sup>54</sup> B. A. Schumm<sup>136</sup> Ph. Schune<sup>135</sup> H. R. Schwartz<sup>136</sup>  
 A. Schwartzman<sup>143</sup> T. A. Schwarz<sup>106</sup> Ph. Schwemling<sup>135</sup> R. Schwienhorst<sup>107</sup> A. Sciandra<sup>136</sup> G. Sciolla<sup>26</sup>  
 F. Scuri<sup>74a</sup> F. Scutti<sup>105</sup> C. D. Sebastiani<sup>92</sup> K. Sedlaczek<sup>49</sup> P. Seema<sup>18</sup> S. C. Seidel<sup>112</sup> A. Seiden<sup>136</sup>  
 B. D. Seidlitz<sup>41</sup> C. Seitz<sup>48</sup> J. M. Seixas<sup>82b</sup> G. Sekhniaidze<sup>72a</sup> S. J. Sekula<sup>44</sup> L. Selem<sup>4</sup>  
 N. Semprini-Cesari<sup>23b,23a</sup> S. Sen<sup>51</sup> D. Sengupta<sup>56</sup> V. Senthilkumar<sup>163</sup> L. Serin<sup>66</sup> L. Serkin<sup>69a,69b</sup>  
 M. Sessa<sup>77a,77b</sup> H. Severini<sup>120</sup> F. Sforza<sup>57b,57a</sup> A. Sfyrla<sup>56</sup> E. Shabalina<sup>55</sup> R. Shaheen<sup>144</sup> J. D. Shahinian<sup>128</sup>  
 D. Shaked Renous<sup>169</sup> L. Y. Shan<sup>14a</sup> M. Shapiro<sup>17a</sup> A. Sharma<sup>36</sup> A. S. Sharma<sup>164</sup> P. Sharma<sup>80</sup> S. Sharma<sup>48</sup>  
 P. B. Shatalov<sup>37</sup> K. Shaw<sup>146</sup> S. M. Shaw<sup>101</sup> Q. Shen<sup>62c,5</sup> P. Sherwood<sup>96</sup> L. Shi<sup>96</sup> C. O. Shimmin<sup>172</sup>  
 Y. Shimogama<sup>168</sup> J. D. Shinner<sup>95</sup> I. P. J. Shipsey<sup>126</sup> S. Shirabe<sup>60</sup> M. Shiyakova<sup>38,ii</sup> J. Shlomi<sup>169</sup>  
 M. J. Shochet<sup>39</sup> J. Shojaii<sup>105</sup> D. R. Shope<sup>125</sup> S. Shrestha<sup>119,jj</sup> E. M. Shrif<sup>33g</sup> M. J. Shroff<sup>165</sup> P. Sicho<sup>131</sup>  
 A. M. Sickles<sup>162</sup> E. Sideras Haddad<sup>33g</sup> A. Sidoti<sup>23b</sup> F. Siegert<sup>50</sup> Dj. Sijacki<sup>15</sup> R. Sikora<sup>85a</sup> F. Sili<sup>90</sup>  
 J. M. Silva<sup>20</sup> M. V. Silva Oliveira<sup>36</sup> S. B. Silverstein<sup>47a</sup> S. Simion<sup>66</sup> R. Simoniello<sup>36</sup> E. L. Simpson<sup>59</sup>  
 H. Simpson<sup>146</sup> L. R. Simpson<sup>106</sup> N. D. Simpson<sup>98</sup> S. Simsek<sup>21d</sup> S. Sindhu<sup>55</sup> P. Sinervo<sup>155</sup> S. Singh<sup>142</sup>  
 S. Singh<sup>155</sup> S. Sinha<sup>48</sup> S. Sinha<sup>33g</sup> M. Sioli<sup>23b,23a</sup> I. Siral<sup>36</sup> S. Yu. Sivoklovov<sup>37,a</sup> J. Sjölin<sup>47a,47b</sup> A. Skaf<sup>55</sup>  
 E. Skorda<sup>98</sup> P. Skubic<sup>120</sup> M. Slawinska<sup>86</sup> V. Smakhtin<sup>169</sup> B. H. Smart<sup>134</sup> J. Smiesko<sup>36</sup> S. Yu. Smirnov<sup>37</sup>  
 Y. Smirnov<sup>37</sup> L. N. Smirnova<sup>37,1</sup> O. Smirnova<sup>98</sup> A. C. Smith<sup>41</sup> E. A. Smith<sup>39</sup> H. A. Smith<sup>126</sup> J. L. Smith<sup>92</sup>  
 R. Smith<sup>143</sup> M. Smizanska<sup>91</sup> K. Smolek<sup>132</sup> A. A. Snesarev<sup>37</sup> H. L. Snoek<sup>114</sup> S. Snyder<sup>29</sup> R. Sobie<sup>165,p</sup>  
 A. Soffer<sup>151</sup> C. A. Solans Sanchez<sup>36</sup> E. Yu. Soldatov<sup>37</sup> U. Soldevila<sup>163</sup> A. A. Solodkov<sup>37</sup> S. Solomon<sup>54</sup>  
 A. Soloshenko<sup>38</sup> K. Solovieva<sup>54</sup> O. V. Solovyanov<sup>40</sup> V. Solovyev<sup>37</sup> P. Sommer<sup>36</sup> A. Sonay<sup>13</sup> W. Y. Song<sup>156b</sup>  
 J. M. Sonneveld<sup>114</sup> A. Sopczak<sup>132</sup> A. L. Sopic<sup>96</sup> F. Sopkova<sup>28b</sup> V. Sothilingam<sup>63a</sup> S. Sottocornola<sup>68</sup>  
 R. Soualah<sup>116b</sup> Z. Soumami<sup>35e</sup> D. South<sup>48</sup> S. Spagnolo<sup>70a,70b</sup> M. Spalla<sup>110</sup> D. Sperlich<sup>54</sup> G. Spigo<sup>36</sup>

M. Spina<sup>146</sup> S. Spinali<sup>91</sup> D. P. Spiteri<sup>59</sup> M. Spousta<sup>133</sup> E. J. Staats<sup>34</sup> A. Stabile<sup>71a,71b</sup> R. Stamen<sup>63a</sup>  
 M. Stamenkovic<sup>114</sup> A. Stampekis<sup>20</sup> M. Standke<sup>24</sup> E. Stanecka<sup>86</sup> M. V. Stange<sup>50</sup> B. Stanislaus<sup>17a</sup>  
 M. M. Stanitzki<sup>48</sup> M. Stankaityte<sup>126</sup> B. Stapf<sup>48</sup> E. A. Starchenko<sup>37</sup> G. H. Stark<sup>136</sup> J. Stark<sup>102,ff</sup>  
 D. M. Starko<sup>156b</sup> P. Staroba<sup>131</sup> P. Starovoitov<sup>63a</sup> S. Stärz<sup>104</sup> R. Staszewski<sup>86</sup> G. Stavropoulos<sup>46</sup> J. Steentoft<sup>161</sup>  
 P. Steinberg<sup>29</sup> B. Stelzer<sup>142,156a</sup> H. J. Stelzer<sup>129</sup> O. Stelzer-Chilton<sup>156a</sup> H. Stenzel<sup>58</sup> T. J. Stevenson<sup>146</sup>  
 G. A. Stewart<sup>36</sup> J. R. Stewart<sup>121</sup> M. C. Stockton<sup>36</sup> G. Stoicea<sup>27b</sup> M. Stolarski<sup>130a</sup> S. Stonjek<sup>110</sup>  
 A. Straessner<sup>50</sup> J. Strandberg<sup>144</sup> S. Strandberg<sup>47a,47b</sup> M. Strauss<sup>120</sup> T. Strebler<sup>102</sup> P. Strizenec<sup>28b</sup>  
 R. Ströhmer<sup>166</sup> D. M. Strom<sup>123</sup> L. R. Strom<sup>48</sup> R. Stroynowski<sup>44</sup> A. Strubig<sup>47a,47b</sup> S. A. Stucci<sup>29</sup> B. Stugu<sup>16</sup>  
 J. Stupak<sup>120</sup> N. A. Styles<sup>48</sup> D. Su<sup>143</sup> S. Su<sup>62a</sup> W. Su<sup>62d,138,62c</sup> X. Su<sup>62a,66</sup> K. Sugizaki<sup>153</sup> V. V. Sulim<sup>37</sup>  
 M. J. Sullivan<sup>92</sup> D. M. S. Sultan<sup>78a,78b</sup> L. Sultanaliev<sup>37</sup> S. Sultansoy<sup>3b</sup> T. Sumida<sup>87</sup> S. Sun<sup>106</sup> S. Sun<sup>170</sup>  
 O. Sunneborn Gudnadottir<sup>161</sup> M. R. Sutton<sup>146</sup> M. Svatos<sup>131</sup> M. Swiatlowski<sup>156a</sup> T. Swirski<sup>166</sup> I. Sykora<sup>28a</sup>  
 M. Sykora<sup>133</sup> T. Sykora<sup>133</sup> D. Ta<sup>100</sup> K. Tackmann<sup>48,kk</sup> A. Taffard<sup>160</sup> R. Tafirout<sup>156a</sup> J. S. Tafoya Vargas<sup>66</sup>  
 R. H. M. Taibah<sup>127</sup> R. Takashima<sup>88</sup> E. P. Takeva<sup>52</sup> Y. Takubo<sup>83</sup> M. Talby<sup>102</sup> A. A. Talyshev<sup>37</sup> K. C. Tam<sup>64b</sup>  
 N. M. Tamir<sup>151</sup> A. Tanaka<sup>153</sup> J. Tanaka<sup>153</sup> R. Tanaka<sup>66</sup> M. Tanasini<sup>57b,57a</sup> J. Tang<sup>62c</sup> Z. Tao<sup>164</sup>  
 S. Tapia Araya<sup>137f</sup> S. Tapprogge<sup>100</sup> A. Tarek Abouelfadl Mohamed<sup>107</sup> S. Tarem<sup>150</sup> K. Tariq<sup>62b</sup> G. Tarna<sup>102,27b</sup>  
 G. F. Tartarelli<sup>71a</sup> P. Tas<sup>133</sup> M. Tasevsky<sup>131</sup> E. Tassi<sup>43b,43a</sup> A. C. Tate<sup>162</sup> G. Tateno<sup>153</sup> Y. Tayalati<sup>35e,ll</sup>  
 G. N. Taylor<sup>105</sup> W. Taylor<sup>156b</sup> H. Teagle<sup>92</sup> A. S. Tee<sup>170</sup> R. Teixeira De Lima<sup>143</sup> P. Teixeira-Dias<sup>95</sup> J. J. Teoh<sup>155</sup>  
 K. Terashi<sup>153</sup> J. Terron<sup>99</sup> S. Terzo<sup>13</sup> M. Testa<sup>53</sup> R. J. Teuscher<sup>155,p</sup> A. Thaler<sup>79</sup> O. Theiner<sup>56</sup>  
 N. Themistokleous<sup>52</sup> T. Thevenaux-Pelzer<sup>102</sup> O. Thielmann<sup>171</sup> D. W. Thomas<sup>95</sup> J. P. Thomas<sup>20</sup>  
 E. A. Thompson<sup>17a</sup> P. D. Thompson<sup>20</sup> E. Thomson<sup>128</sup> Y. Tian<sup>55</sup> V. Tikhomirov<sup>37,1</sup> Yu. A. Tikhonov<sup>37</sup>  
 S. Timoshenko<sup>37</sup> E. X. L. Ting<sup>1</sup> P. Tipton<sup>172</sup> S. H. Tlou<sup>33g</sup> A. Tmourji<sup>40</sup> K. Todome<sup>23b,23a</sup>  
 S. Todorova-Nova<sup>133</sup> S. Todt<sup>50</sup> M. Togawa<sup>83</sup> J. Tojo<sup>89</sup> S. Tokár<sup>28a</sup> K. Tokushuku<sup>83</sup> O. Toldaiev<sup>68</sup>  
 R. Tombs<sup>32</sup> M. Tomoto<sup>83,111</sup> L. Tompkins<sup>143,u</sup> K. W. Topolnicki<sup>85b</sup> E. Torrence<sup>123</sup> H. Torres<sup>102,ff</sup>  
 E. Torró Pastor<sup>163</sup> M. Toscani<sup>30</sup> C. Toscirri<sup>39</sup> M. Tost<sup>11</sup> D. R. Tovey<sup>139</sup> A. Traeet<sup>16</sup> I. S. Trandafir<sup>27b</sup>  
 T. Trefzger<sup>166</sup> A. Tricoli<sup>29</sup> I. M. Trigger<sup>156a</sup> S. Trincaz-Duvoid<sup>127</sup> D. A. Trischuk<sup>26</sup> B. Trocmé<sup>60</sup>  
 C. Troncon<sup>71a</sup> L. Truong<sup>33c</sup> M. Trzebinski<sup>86</sup> A. Trzuppek<sup>86</sup> F. Tsai<sup>145</sup> M. Tsai<sup>106</sup> A. Tsiamis<sup>152,cc</sup>  
 P. V. Tsiarshka<sup>37</sup> S. Tsigaridas<sup>156a</sup> A. Tsirigotis<sup>152,dd</sup> V. Tsiskaridze<sup>145</sup> E. G. Tskhadadze<sup>149a</sup>  
 M. Tsooulou<sup>152,cc</sup> Y. Tsujikawa<sup>87</sup> I. I. Tsukerman<sup>37</sup> V. Tsulaia<sup>17a</sup> S. Tsuno<sup>83</sup> O. Tsur<sup>150</sup> D. Tsybychev<sup>145</sup>  
 Y. Tu<sup>64b</sup> A. Tudorache<sup>27b</sup> V. Tudorache<sup>27b</sup> A. N. Tuna<sup>36</sup> S. Turchikhin<sup>38</sup> I. Turk Cakir<sup>3a</sup> R. Turra<sup>71a</sup>  
 T. Turtuvshin<sup>38,mm</sup> P. M. Tuts<sup>41</sup> S. Tzamarias<sup>152,cc</sup> P. Tzani<sup>10</sup> E. Tzovara<sup>100</sup> K. Uchida<sup>153</sup> F. Ukegawa<sup>157</sup>  
 P. A. Ulloa Poblete<sup>137c</sup> E. N. Umaka<sup>29</sup> G. Unal<sup>36</sup> M. Unal<sup>11</sup> A. Undrus<sup>29</sup> G. Unel<sup>160</sup> J. Urban<sup>28b</sup>  
 P. Urquijo<sup>105</sup> G. Usai<sup>8</sup> R. Ushioda<sup>154</sup> M. Usman<sup>108</sup> Z. Uysal<sup>21b</sup> L. Vacavant<sup>102</sup> V. Vacek<sup>132</sup> B. Vachon<sup>104</sup>  
 K. O. H. Vadla<sup>125</sup> T. Vafeiadis<sup>36</sup> A. Vaitkus<sup>96</sup> C. Valderanis<sup>109</sup> E. Valdes Santurio<sup>47a,47b</sup> M. Valente<sup>156a</sup>  
 S. Valentinetti<sup>23b,23a</sup> A. Valero<sup>163</sup> E. Valiente Moreno<sup>163</sup> A. Vallier<sup>102,ff</sup> J. A. Valls Ferrer<sup>163</sup>  
 D. R. Van Arneeman<sup>114</sup> T. R. Van Daalen<sup>138</sup> P. Van Gemmeren<sup>6</sup> M. Van Rijnbach<sup>125,36</sup> S. Van Stroud<sup>96</sup>  
 I. Van Vulpen<sup>114</sup> M. Vanadia<sup>76a,76b</sup> W. Vandelli<sup>36</sup> M. Vandenbroucke<sup>135</sup> E. R. Vandewall<sup>121</sup> D. Vannicola<sup>151</sup>  
 L. Vannoli<sup>57b,57a</sup> R. Vari<sup>75a</sup> E. W. Varnes<sup>7</sup> C. Varni<sup>17a</sup> T. Varol<sup>148</sup> D. Varouchas<sup>66</sup> L. Varriale<sup>163</sup>  
 K. E. Varvell<sup>147</sup> M. E. Vasile<sup>27b</sup> L. Vaslin<sup>40</sup> G. A. Vasquez<sup>165</sup> F. Vazeille<sup>40</sup> T. Vazquez Schroeder<sup>36</sup> J. Veatch<sup>31</sup>  
 V. Vecchio<sup>101</sup> M. J. Veen<sup>103</sup> I. Veliscek<sup>126</sup> L. M. Veloce<sup>155</sup> F. Veloso<sup>130a,130c</sup> S. Veneziano<sup>75a</sup>  
 A. Ventura<sup>70a,70b</sup> A. Verbytskyi<sup>110</sup> M. Verducci<sup>74a,74b</sup> C. Vergis<sup>24</sup> M. Verissimo De Araujo<sup>82b</sup> W. Verkerke<sup>114</sup>  
 J. C. Vermeulen<sup>114</sup> C. Vernieri<sup>143</sup> P. J. Verschuuren<sup>95</sup> M. Vessella<sup>103</sup> M. C. Vetterli<sup>142,e</sup> A. Vgenopoulos<sup>152,cc</sup>  
 N. Viaux Maira<sup>137f</sup> T. Vickey<sup>139</sup> O. E. Vickey Boeriu<sup>139</sup> G. H. A. Viehhauser<sup>126</sup> L. Vignani<sup>63b</sup> M. Villa<sup>23b,23a</sup>  
 M. Villaplana Perez<sup>163</sup> E. M. Villhauer<sup>52</sup> E. Vilucchi<sup>53</sup> M. G. Vincter<sup>34</sup> G. S. Virdee<sup>20</sup> A. Vishwakarma<sup>52</sup>  
 C. Vittori<sup>36</sup> I. Vivarelli<sup>146</sup> V. Vladimirov<sup>167</sup> E. Voevodina<sup>110</sup> F. Vogel<sup>109</sup> P. Vokac<sup>132</sup> J. Von Ahnen<sup>48</sup>  
 E. Von Toerne<sup>24</sup> B. Vormwald<sup>36</sup> V. Vorobel<sup>133</sup> K. Vorobev<sup>37</sup> M. Vos<sup>163</sup> K. Voss<sup>141</sup> J. H. Vosseveld<sup>92</sup>  
 M. Vozak<sup>114</sup> L. Vozdecky<sup>94</sup> N. Vranjes<sup>15</sup> M. Vranjes Milosavljevic<sup>15</sup> M. Vreeswijk<sup>114</sup> R. Vuillermet<sup>36</sup>  
 O. Vujanovic<sup>100</sup> I. Vukotic<sup>39</sup> S. Wada<sup>157</sup> C. Wagner<sup>103</sup> J. M. Wagner<sup>17a</sup> W. Wagner<sup>171</sup> S. Wahdan<sup>171</sup>  
 H. Wahlberg<sup>90</sup> R. Wakasa<sup>157</sup> M. Wakida<sup>111</sup> J. Walder<sup>134</sup> R. Walker<sup>109</sup> W. Walkowiak<sup>141</sup> A. Z. Wang<sup>170</sup>  
 C. Wang<sup>100</sup> C. Wang<sup>62c</sup> H. Wang<sup>17a</sup> J. Wang<sup>64a</sup> R.-J. Wang<sup>100</sup> R. Wang<sup>61</sup> R. Wang<sup>6</sup> S. M. Wang<sup>148</sup>

S. Wang<sup>62b</sup>, T. Wang<sup>62a</sup>, W. T. Wang<sup>80</sup>, X. Wang<sup>14c</sup>, X. Wang<sup>162</sup>, X. Wang<sup>62c</sup>, Y. Wang<sup>62d</sup>, Y. Wang<sup>14c</sup>,  
 Z. Wang<sup>106</sup>, Z. Wang<sup>62d,51,62c</sup>, Z. Wang<sup>106</sup>, A. Warburton<sup>104</sup>, R. J. Ward<sup>20</sup>, N. Warrack<sup>59</sup>, A. T. Watson<sup>20</sup>,  
 H. Watson<sup>59</sup>, M. F. Watson<sup>20</sup>, G. Watts<sup>138</sup>, B. M. Waugh<sup>96</sup>, C. Weber<sup>29</sup>, H. A. Weber<sup>18</sup>, M. S. Weber<sup>19</sup>,  
 S. M. Weber<sup>63a</sup>, C. Wei<sup>62a</sup>, Y. Wei<sup>126</sup>, A. R. Weidberg<sup>126</sup>, E. J. Weik<sup>117</sup>, J. Weingarten<sup>49</sup>, M. Weirich<sup>100</sup>,  
 C. Weiser<sup>54</sup>, C. J. Wells<sup>48</sup>, T. Wenaus<sup>29</sup>, B. Wendland<sup>49</sup>, T. Wengler<sup>36</sup>, N. S. Wenke<sup>110</sup>, N. Wermes<sup>24</sup>,  
 M. Wessels<sup>63a</sup>, K. Whalen<sup>123</sup>, A. M. Wharton<sup>91</sup>, A. S. White<sup>61</sup>, A. White<sup>8</sup>, M. J. White<sup>1</sup>, D. Whiteson<sup>160</sup>,  
 L. Wickremasinghe<sup>124</sup>, W. Wiedenmann<sup>170</sup>, C. Wiel<sup>50</sup>, M. Wielers<sup>134</sup>, C. Wiglesworth<sup>42</sup>, L. A. M. Wiik-Fuchs<sup>54</sup>,  
 D. J. Wilbern<sup>120</sup>, H. G. Wilkens<sup>36</sup>, D. M. Williams<sup>41</sup>, H. H. Williams<sup>128</sup>, S. Williams<sup>32</sup>, S. Willocq<sup>103</sup>,  
 B. J. Wilson<sup>101</sup>, P. J. Windischhofer<sup>39</sup>, F. Winklmeier<sup>123</sup>, B. T. Winter<sup>54</sup>, J. K. Winter<sup>101</sup>, M. Wittgen<sup>143</sup>,  
 M. Wobisch<sup>97</sup>, R. Wölker<sup>126</sup>, J. Wollrath<sup>160</sup>, M. W. Wolter<sup>86</sup>, H. Wolters<sup>130a,130c</sup>, V. W. S. Wong<sup>164</sup>,  
 A. F. Wongel<sup>48</sup>, S. D. Worm<sup>48</sup>, B. K. Wosiek<sup>86</sup>, K. W. Woźniak<sup>86</sup>, K. Wraight<sup>59</sup>, J. Wu<sup>14a,14d</sup>, M. Wu<sup>64a</sup>,  
 M. Wu<sup>113</sup>, S. L. Wu<sup>170</sup>, X. Wu<sup>56</sup>, Y. Wu<sup>62a</sup>, Z. Wu<sup>135,62a</sup>, J. Wuerzinger<sup>110</sup>, T. R. Wyatt<sup>101</sup>, B. M. Wynne<sup>52</sup>,  
 S. Xella<sup>42</sup>, L. Xia<sup>14c</sup>, M. Xia<sup>14b</sup>, J. Xiang<sup>64c</sup>, X. Xiao<sup>106</sup>, M. Xie<sup>62a</sup>, X. Xie<sup>62a</sup>, S. Xin<sup>14a,14d</sup>, J. Xiong<sup>17a</sup>,  
 I. Xiotidis<sup>146</sup>, D. Xu<sup>14a</sup>, H. Xu<sup>62a</sup>, H. Xu<sup>62a</sup>, L. Xu<sup>62a</sup>, R. Xu<sup>128</sup>, T. Xu<sup>106</sup>, Y. Xu<sup>14b</sup>, Z. Xu<sup>62b</sup>, Z. Xu<sup>14a</sup>,  
 B. Yabsley<sup>147</sup>, S. Yacoob<sup>33a</sup>, N. Yamaguchi<sup>89</sup>, Y. Yamaguchi<sup>154</sup>, H. Yamauchi<sup>157</sup>, T. Yamazaki<sup>17a</sup>,  
 Y. Yamazaki<sup>84</sup>, J. Yan<sup>62c</sup>, S. Yan<sup>126</sup>, Z. Yan<sup>25</sup>, H. J. Yang<sup>62c,62d</sup>, H. T. Yang<sup>62a</sup>, S. Yang<sup>62a</sup>, T. Yang<sup>64c</sup>,  
 X. Yang<sup>62a</sup>, X. Yang<sup>14a</sup>, Y. Yang<sup>44</sup>, Y. Yang<sup>62a</sup>, Z. Yang<sup>62a,106</sup>, W-M. Yao<sup>17a</sup>, Y. C. Yap<sup>48</sup>, H. Ye<sup>14c</sup>, H. Ye<sup>55</sup>,  
 J. Ye<sup>44</sup>, S. Ye<sup>29</sup>, X. Ye<sup>62a</sup>, Y. Yeh<sup>96</sup>, I. Yeletsikh<sup>38</sup>, B. K. Yeo<sup>17a</sup>, M. R. Yexley<sup>91</sup>, P. Yin<sup>41</sup>, K. Yorita<sup>168</sup>,  
 S. Younas<sup>27b</sup>, C. J. S. Young<sup>54</sup>, C. Young<sup>143</sup>, Y. Yu<sup>62a</sup>, M. Yuan<sup>106</sup>, R. Yuan<sup>62b,nn</sup>, L. Yue<sup>96</sup>, M. Zaazoua<sup>35e</sup>,  
 B. Zabinski<sup>86</sup>, E. Zaid<sup>52</sup>, T. Zakareishvili<sup>149b</sup>, N. Zakharchuk<sup>34</sup>, S. Zambito<sup>56</sup>, J. A. Zamora Saa<sup>137d,137b</sup>,  
 J. Zang<sup>153</sup>, D. Zanzi<sup>54</sup>, O. Zaplatilek<sup>132</sup>, C. Zeitnitz<sup>171</sup>, H. Zeng<sup>14a</sup>, J. C. Zeng<sup>162</sup>, D. T. Zenger Jr.<sup>26</sup>, O. Zenin<sup>37</sup>,  
 T. Ženiš<sup>28a</sup>, S. Zenz<sup>94</sup>, S. Zerradi<sup>35a</sup>, D. Zerwas<sup>66</sup>, M. Zhai<sup>14a,14d</sup>, B. Zhang<sup>14c</sup>, D. F. Zhang<sup>139</sup>, J. Zhang<sup>62b</sup>,  
 J. Zhang<sup>6</sup>, K. Zhang<sup>14a,14d</sup>, L. Zhang<sup>14c</sup>, P. Zhang<sup>14a,14d</sup>, R. Zhang<sup>170</sup>, S. Zhang<sup>106</sup>, T. Zhang<sup>153</sup>, X. Zhang<sup>62c</sup>,  
 X. Zhang<sup>62b</sup>, Y. Zhang<sup>62c,5</sup>, Z. Zhang<sup>17a</sup>, Z. Zhang<sup>66</sup>, H. Zhao<sup>138</sup>, P. Zhao<sup>51</sup>, T. Zhao<sup>62b</sup>, Y. Zhao<sup>136</sup>,  
 Z. Zhao<sup>62a</sup>, A. Zhemchugov<sup>38</sup>, X. Zheng<sup>62a</sup>, Z. Zheng<sup>143</sup>, D. Zhong<sup>162</sup>, B. Zhou<sup>106</sup>, C. Zhou<sup>170</sup>, H. Zhou<sup>7</sup>,  
 N. Zhou<sup>62c</sup>, Y. Zhou<sup>7</sup>, C. G. Zhu<sup>62b</sup>, J. Zhu<sup>106</sup>, Y. Zhu<sup>62c</sup>, Y. Zhu<sup>62a</sup>, X. Zhuang<sup>14a</sup>, K. Zhukov<sup>37</sup>,  
 V. Zhulanov<sup>37</sup>, N. I. Zimine<sup>38</sup>, J. Zinsser<sup>63b</sup>, M. Ziolkowski<sup>141</sup>, L. Živković<sup>15</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>56</sup>,  
 T. G. Zorbas<sup>139</sup>, O. Zormpa<sup>46</sup>, W. Zou<sup>41</sup> and L. Zwalinski<sup>36</sup>

(ATLAS Collaboration)

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

<sup>2</sup>Department of Physics, University of Alberta, Edmonton, Alberta, Canada

<sup>3a</sup>Department of Physics, Ankara University, Ankara, Türkiye

<sup>3b</sup>Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye

<sup>4</sup>LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>5</sup>APC, Université Paris Cité, CNRS/IN2P3, Paris, France

<sup>6</sup>High Energy Physics Division, Argonne National Laboratory, Argonne, 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>12</sup>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>13</sup>Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>14a</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

<sup>14b</sup>Physics Department, Tsinghua University, Beijing, China

<sup>14c</sup>Department of Physics, Nanjing University, Nanjing, China

<sup>14d</sup>University of Chinese Academy of Science (UCAS), Beijing, China

<sup>15</sup>Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>16</sup>Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>17a</sup>Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

- <sup>17b</sup>*University of California, Berkeley, California, USA*
- <sup>18</sup>*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- <sup>19</sup>*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- <sup>20</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- <sup>21a</sup>*Department of Physics, Bogazici University, Istanbul, Türkiye*
- <sup>21b</sup>*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
- <sup>21c</sup>*Department of Physics, Istanbul University, Istanbul, Türkiye*
- <sup>21d</sup>*Istinye University, Sariyer, Istanbul, Türkiye*
- <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*
- <sup>23a</sup>*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, 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>26</sup>*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
- <sup>27a</sup>*Transilvania University of Brasov, Brasov, Romania*
- <sup>27b</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- <sup>27c</sup>*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- <sup>27d</sup>*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
- <sup>27e</sup>*University Politehnica Bucharest, Bucharest, Romania*
- <sup>27f</sup>*West University in Timisoara, Timisoara, Romania*
- <sup>27g</sup>*Faculty of Physics, University of Bucharest, Bucharest, Romania*
- <sup>28a</sup>*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- <sup>28b</sup>*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- <sup>29</sup>*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- <sup>30</sup>*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
- <sup>31</sup>*California State University, 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>*National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines*
- <sup>33e</sup>*University of South Africa, Department of Physics, Pretoria, South Africa*
- <sup>33f</sup>*University of Zululand, KwaDlangezwa, South Africa*
- <sup>33g</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>*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
- <sup>35e</sup>*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- <sup>35f</sup>*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
- <sup>36</sup>*CERN, Geneva, Switzerland*
- <sup>37</sup>*Affiliated with an institute covered by a cooperation agreement with CERN*
- <sup>38</sup>*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
- <sup>39</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- <sup>40</sup>*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- <sup>41</sup>*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- <sup>42</sup>*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- <sup>43a</sup>*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- <sup>43b</sup>*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- <sup>44</sup>*Physics Department, Southern Methodist University, Dallas, Texas, USA*
- <sup>45</sup>*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
- <sup>46</sup>*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- <sup>47a</sup>*Department of Physics, Stockholm University, Sweden*

- <sup>47b</sup>Oskar Klein Centre, Stockholm, Sweden
- <sup>48</sup>Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- <sup>49</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- <sup>50</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>51</sup>Department of Physics, Duke University, Durham, North Carolina, USA
- <sup>52</sup>SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>53</sup>INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>54</sup>Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- <sup>55</sup>II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- <sup>56</sup>Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- <sup>57a</sup>Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>57b</sup>INFN Sezione di Genova, Italy
- <sup>58</sup>II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>59</sup>SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>60</sup>LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- <sup>61</sup>Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
- <sup>62a</sup>Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
- <sup>62b</sup>Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
- <sup>62c</sup>School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
- <sup>62d</sup>Tsung-Dao Lee Institute, Shanghai, China
- <sup>63a</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>63b</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>64a</sup>Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
- <sup>64b</sup>Department of Physics, University of Hong Kong, Hong Kong, China
- <sup>64c</sup>Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>65</sup>Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- <sup>66</sup>IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
- <sup>67</sup>Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
- <sup>68</sup>Department of Physics, Indiana University, Bloomington, Indiana, USA
- <sup>69a</sup>INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- <sup>69b</sup>ICTP, Trieste, Italy
- <sup>69c</sup>Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
- <sup>70a</sup>INFN Sezione di Lecce, Italy
- <sup>70b</sup>Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>71a</sup>INFN Sezione di Milano, Italy
- <sup>71b</sup>Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>72a</sup>INFN Sezione di Napoli, Italy
- <sup>72b</sup>Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>73a</sup>INFN Sezione di Pavia, Italy
- <sup>73b</sup>Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>74a</sup>INFN Sezione di Pisa, Italy
- <sup>74b</sup>Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>75a</sup>INFN Sezione di Roma, Italy
- <sup>75b</sup>Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>76a</sup>INFN Sezione di Roma Tor Vergata, Italy
- <sup>76b</sup>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>77a</sup>INFN Sezione di Roma Tre, Italy
- <sup>77b</sup>Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>78a</sup>INFN-TIFPA, Italy
- <sup>78b</sup>Università degli Studi di Trento, Trento, Italy
- <sup>79</sup>Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria
- <sup>80</sup>University of Iowa, Iowa City, Iowa, USA
- <sup>81</sup>Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
- <sup>82a</sup>Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
- <sup>82b</sup>Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
- <sup>82c</sup>Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

- <sup>82d</sup>Rio de Janeiro State University, Rio de Janeiro, Brazil
- <sup>83</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>84</sup>Graduate School of Science, Kobe University, Kobe, Japan
- <sup>85a</sup>AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland
- <sup>85b</sup>Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>86</sup>Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>87</sup>Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>88</sup>Kyoto University of Education, Kyoto, Japan
- <sup>89</sup>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>90</sup>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>91</sup>Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>92</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>93</sup>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- <sup>94</sup>School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>95</sup>Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- <sup>96</sup>Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>97</sup>Louisiana Tech University, Ruston, Los Angeles, USA
- <sup>98</sup>Fysiska institutionen, Lunds universitet, Lund, Sweden
- <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>Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>109</sup>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>110</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>111</sup>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>112</sup>Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
- <sup>113</sup>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
- <sup>114</sup>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>115</sup>Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
- <sup>116a</sup>New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
- <sup>116b</sup>University of Sharjah, Sharjah, United Arab Emirates
- <sup>117</sup>Department of Physics, New York University, New York, New York, USA
- <sup>118</sup>Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
- <sup>119</sup>Ohio State University, Columbus, Ohio, USA
- <sup>120</sup>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
- <sup>121</sup>Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
- <sup>122</sup>Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
- <sup>123</sup>Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
- <sup>124</sup>Graduate School of Science, Osaka University, Osaka, Japan
- <sup>125</sup>Department of Physics, University of Oslo, Oslo, Norway
- <sup>126</sup>Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>127</sup>LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
- <sup>128</sup>Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
- <sup>129</sup>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
- <sup>130a</sup>Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- <sup>130b</sup>Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
- <sup>130c</sup>Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
- <sup>130d</sup>Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
- <sup>130e</sup>Departamento de Física, Universidade do Minho, Braga, Portugal
- <sup>130f</sup>Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
- <sup>130g</sup>Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
- <sup>131</sup>Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- <sup>132</sup>Czech Technical University in Prague, Prague, Czech Republic

- <sup>133</sup>Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- <sup>134</sup>Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>135</sup>IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- <sup>136</sup>Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
- <sup>137a</sup>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- <sup>137b</sup>Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
- <sup>137c</sup>Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile
- <sup>137d</sup>Universidad Andres Bello, Department of Physics, Santiago, Chile
- <sup>137e</sup>Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
- <sup>137f</sup>Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>138</sup>Department of Physics, University of Washington, Seattle, Washington, USA
- <sup>139</sup>Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup>Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup>Department Physik, Universität Siegen, Siegen, Germany
- <sup>142</sup>Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>143</sup>SLAC National Accelerator Laboratory, Stanford, California, USA
- <sup>144</sup>Department of Physics, Royal Institute of Technology, Stockholm, Sweden
- <sup>145</sup>Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
- <sup>146</sup>Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>147</sup>School of Physics, University of Sydney, Sydney, Australia
- <sup>148</sup>Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>149a</sup>E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
- <sup>149b</sup>High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>149c</sup>University of Georgia, Tbilisi, Georgia
- <sup>150</sup>Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
- <sup>151</sup>Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>152</sup>Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>153</sup>International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
- <sup>154</sup>Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>155</sup>Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>156a</sup>TRIUMF, Vancouver BC, Canada
- <sup>156b</sup>Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>157</sup>Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- <sup>158</sup>Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
- <sup>159</sup>United Arab Emirates University, Al Ain, United Arab Emirates
- <sup>160</sup>Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
- <sup>161</sup>Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>162</sup>Department of Physics, University of Illinois, Urbana, Illinois, USA
- <sup>163</sup>Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
- <sup>164</sup>Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>165</sup>Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>166</sup>Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
- <sup>167</sup>Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>168</sup>Waseda University, Tokyo, Japan
- <sup>169</sup>Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
- <sup>170</sup>Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
- <sup>171</sup>Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>172</sup>Department of Physics, Yale University, New Haven, 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 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

<sup>d</sup>Also at Lawrence Livermore National Laboratory, Livermore, California, USA.

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

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

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

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

<sup>i</sup>Also at University of Colorado Boulder, Department of Physics, Colorado, USA.

- <sup>j</sup>Also at Department of Physics, Westmont College, Santa Barbara, California, USA.
- <sup>k</sup>Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
- <sup>l</sup>Also at Affiliated with an institute covered by a cooperation agreement with CERN.
- <sup>m</sup>Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
- <sup>n</sup>Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.
- <sup>o</sup>Also at Università di Napoli Parthenope, Napoli, Italy.
- <sup>p</sup>Also at Institute of Particle Physics (IPP), Canada.
- <sup>q</sup>Also at Bruno Kessler Foundation, Trento, Italy.
- <sup>r</sup>Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
- <sup>s</sup>Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.
- <sup>t</sup>Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- <sup>u</sup>Also at Department of Physics, Stanford University, Stanford, California, USA.
- <sup>v</sup>Also at Centro Studi e Ricerche Enrico Fermi, Italy.
- <sup>w</sup>Also at Department of Physics, California State University, East Bay, California, USA.
- <sup>x</sup>Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- <sup>y</sup>Also at Technical University of Munich, Munich, Germany.
- <sup>z</sup>Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
- <sup>aa</sup>Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- <sup>bb</sup>Also at CERN, Geneva, Switzerland.
- <sup>cc</sup>Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
- <sup>dd</sup>Also at Hellenic Open University, Patras, Greece.
- <sup>ee</sup>Also at Center for High Energy Physics, Peking University, China.
- <sup>ff</sup>Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France.
- <sup>gg</sup>Also at Department of Physics, California State University, Sacramento, California, USA.
- <sup>hh</sup>Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- <sup>ii</sup>Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- <sup>jj</sup>Also at Washington College, Maryland, USA.
- <sup>kk</sup>Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- <sup>ll</sup>Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
- <sup>mm</sup>Also at Institute of Physics and Technology, Ulaanbaatar, Mongolia.
- <sup>nn</sup>Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.