

Measurement of the centrality dependence of J/ψ yields and observation of Z production in lead-lead collisions with the ATLAS detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration),

Abstract

Using the ATLAS detector, a centrality-dependent suppression has been observed in the yield of J/ψ mesons produced in the collisions of lead ions at the Large Hadron Collider. In a sample of minimum-bias lead-lead collisions at a nucleon-nucleon centre of mass energy $\sqrt{s_{NN}} = 2.76$ TeV, corresponding to an integrated luminosity of about $6.7 \mu\text{b}^{-1}$, J/ψ mesons are reconstructed via their decays to $\mu^+\mu^-$ pairs. The measured J/ψ yield, normalized to the number of binary nucleon-nucleon collisions, is found to significantly decrease from peripheral to central collisions. The centrality dependence is found to be qualitatively similar to the trends observed at previous, lower energy experiments. The same sample is used to reconstruct Z bosons in the $\mu^+\mu^-$ final state, and a total of 38 candidates are selected in the mass window of 66 to 116 GeV. The relative Z yields as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions, because of limited statistics. This analysis provides the first results on J/ψ and Z production in lead-lead collisions at the LHC.

Keywords: ATLAS, LHC, Heavy Ions, J/psi, Z Boson, Centrality dependence

1. Introduction

The measurement of quarkonia production in ultra-relativistic heavy ion collisions provides a potentially powerful tool for studying the properties of hot and dense matter created in these collisions. If deconfined matter is indeed formed, then colour screening is expected to prevent the formation of quarkonium states when the screening length becomes shorter than the

quarkonium size [1]. Since this length is directly related to the temperature, a measurement of a suppressed quarkonium yield may provide direct experimental sensitivity to the temperature of the medium created in high energy nuclear collisions [2].

The interpretation of J/ψ suppression in terms of colour screening is generally complicated by the quantitative agreement between the overall levels of J/ψ suppression measured by the NA50 experiment at the CERN SPS [3] ($\sqrt{s_{NN}} = 17.3$ GeV) and the PHENIX experiment at RHIC [4] ($\sqrt{s_{NN}} = 200$ GeV). Data from proton-nucleus and deuteron-gold collisions also show decreased rates of J/ψ production [5], indicating that other mechanisms may come into play. Finally, there exist proposals for J/ψ *enhancement* at high energies from charm quark recombination [6]. Measurements at higher energies, with concomitantly higher temperatures and heavy quark production rates, are clearly needed to address these debates with new experimental input. The production of Z bosons, only available in heavy ion collisions at LHC energies, can serve as a reference process for J/ψ production, since Z 's are not expected to be affected by the hot, dense medium, although modifications to the nuclear parton distribution functions must be considered [7].

The LHC heavy ion program, which commenced in November 2010, offers an opportunity to measure J/ψ and Z production in nuclear collisions at the highest energies ever achieved. The ATLAS detector provides excellent muon detection capabilities down to momenta of about 3 GeV, and J/ψ mesons and Z bosons can be readily detected via their decays to $\mu^+\mu^-$ final states. This Letter presents the first measurements of the relative yields of J/ψ meson and Z boson decays in lead-lead collisions at a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. The yields are measured in four bins of collision centrality, and the variation of the yields with centrality is compared to the dependence expected if hard scattering processes scale according to expectations from nuclear geometry. No attempts are made to account for “normal nuclear suppression” [3], nor for feed-down of J/ψ from higher mass charmonium states or B hadron decay.

2. Di-muon event selection

Muons are measured by combining independent measurements of the muon trajectories from the Inner Detector (ID) and the Muon Spectrometer (MS). A detailed description of these detectors and their performance in proton-proton collisions can be found in Refs. [8, 9]. The ID volume is within

the 2 T field of a superconducting solenoid, and measures the trajectories of charged particles in the pseudorapidity region $|\eta| < 2.5$ ¹. A charged particle typically traverses three layers of silicon pixel detectors, eight silicon strip sensors (SCT detector) arranged in four layers of double-sided modules, and a transition radiation tracker composed of straw tubes. The MS surrounds the calorimeters and provides tracking for muons with $|\eta| < 2.7$ and triggering in the range $|\eta| < 2.4$. The muon momentum determination is based on three stations of precision drift chambers that measure the trajectory of each muon in a toroidal magnetic field produced by three air-core toroids. In order to reach the MS, muons have to cross the electromagnetic and hadronic calorimeters, losing typically 3 to 5 GeV of energy, depending on the muon pseudorapidity. The calorimeters efficiently absorb the copious charged and neutral hadrons produced in lead-lead collisions.

The trigger system has three stages, the first of which (Level-1) is hardware based. The Level-1 minimum-bias trigger uses either the two sets of Minimum-Bias Trigger Scintillator (MBTS) counters, covering $2.1 < |\eta| < 3.9$ on each side of the experiment, or the two Zero-Degree Calorimeters (ZDC), each positioned at 140 m from the collision point, detecting neutrons and photons with $|\eta| > 8.3$. No muon-specific triggers were used to select the data presented here. The MBTS trigger was configured to require at least one hit above threshold from each side of the detector. A Level-2 timing requirement on a coincidence of signals from the MBTS was then imposed to remove beam backgrounds. The trigger efficiency was studied using an independent trigger probing random filled bunch crossings at Level-1. For these triggers, empty events were removed by testing for a minimal level of activity in the silicon detectors. The combined trigger and event selection efficiency is discussed in section 3.2.

In the offline analysis, minimum-bias triggered events are required to have a reconstructed primary vertex, at least one hit in each set of MBTS counters, and a time difference between the sides of less than 3 ns to reject beam-halo and other beam-related background events. Measurements of the

¹ In the right-handed ATLAS coordinate system, the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where the polar angle θ is measured with respect to the LHC beamline. The azimuthal angle ϕ is measured with respect to the x-axis, which points towards the centre of the LHC ring. The z-axis is parallel to the anti-clockwise beam viewed from above. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

muon trajectories from both the ID and MS are combined, resulting in a relative momentum resolution ranging from about 2% at low momentum up to about 3% at $p_T \sim 50$ GeV. For this analysis, oppositely charged muons are selected with a minimum p_T of 3 GeV each and within the region $|\eta| < 2.5$.

The data sample consists of approximately $6.7 \mu\text{b}^{-1}$ from the 2010 LHC heavy ion run. In order to determine the $J/\psi \rightarrow \mu^+\mu^-$ reconstruction efficiency, Monte Carlo (MC) samples have been produced superimposing J/ψ and Z events from PYTHIA [10] into simulated lead-lead events generated with the HIJING [11] event generator. HIJING was run in a mode with effects from jet quenching turned off, since they have not been adjusted to agree with existing experimental data. Elliptic flow was imposed on the events subsequent to generation, with a magnitude and p_T dependence derived from RHIC data. The detector response to the complete PYTHIA+HIJING event is simulated [12] using GEANT4 [13].

Lead-lead collision centrality percentiles are defined from the total transverse energy, ΣE_T^{FCal} , measured in the forward calorimeter (FCal), which covers $3.2 < |\eta| < 4.9$. The same conventions and bins for centrality are used as in our previous publication [14]. The centrality dependence of the muon detection efficiency is parameterized as a function of the total number of hits per unit of pseudorapidity detected in the first pixel layer. This is strongly correlated to ΣE_T^{FCal} , but gives a more direct measure of the ID occupancy. The full data sample is divided into four bins of collision centrality, 40-80%, 20-40%, 10-20%, and 0-10%. The most peripheral 20% of collisions are excluded from this analysis due to larger systematic uncertainties in estimating the number of binary nucleon-nucleon collisions in these events.

The $J/\psi \rightarrow \mu^+\mu^-$ reconstruction efficiency is obtained from the MC samples as a function of the event centrality. The inefficiency gradually increases from peripheral to central collisions, due primarily to an occupancy-induced inefficiency in the ID tracking, as shown in Table 1. The $Z \rightarrow \mu^+\mu^-$ reconstruction efficiency is obtained in a similar way.

An example of the very good agreement between data and MC in different centrality bins is presented in Figure 1, which shows the numbers of Pixel and SCT hits associated to tracks selected with a looser $p_T > 0.5$ GeV cut than that for the J/ψ . The figure shows results for data and MC at two different centralities (0-10% and 40-80%). The distributions of the number of hits averaged over η and the average number of hits as a function of η are shown. The slight decrease of the number of SCT hits on track as a function of centrality is well reproduced by the simulation, demonstrating that the

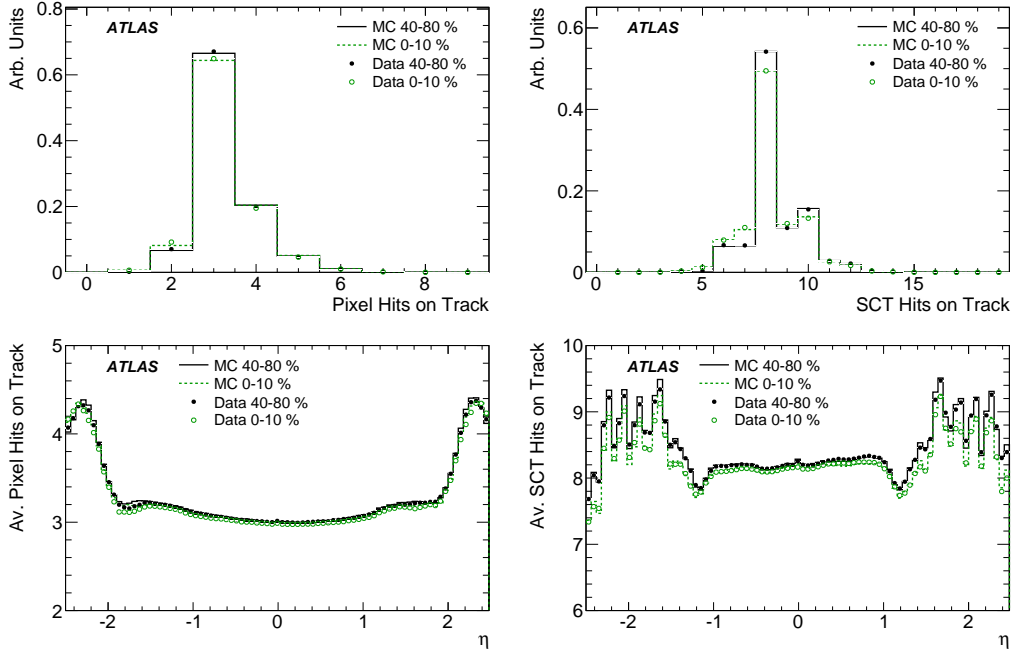


Figure 1: (top row) The number of Pixel (left) and SCT (right) hits on tracks for data (points with errors) and MC (histogram) for two different centrality bins: 0-10% (open/dotted) and 40-80% (closed/solid). (bottom row) The average number of Pixel (left) and SCT (right) hits as a function of η for MC and data in the same two centrality bins.

dense environment of the most central collisions is reasonably well modelled.

3. J/ψ production as a function of centrality

The oppositely-charged di-muon invariant mass spectra in the J/ψ region after the selection are shown in Figure 2. The number of $J/\psi \rightarrow \mu^+\mu^-$ decays is then found by a simple counting technique. The signal mass window is defined by the range 2.95–3.25 GeV. The background is derived from two mass sidebands, 2.4–2.8 GeV and 3.4–3.8 GeV, with a linear extrapolation. To determine the uncertainties related to the signal extraction, an alternative method based on a maximum likelihood fit with the mass resolution left as a free parameter is used as a cross check, as explained in section 3.1.

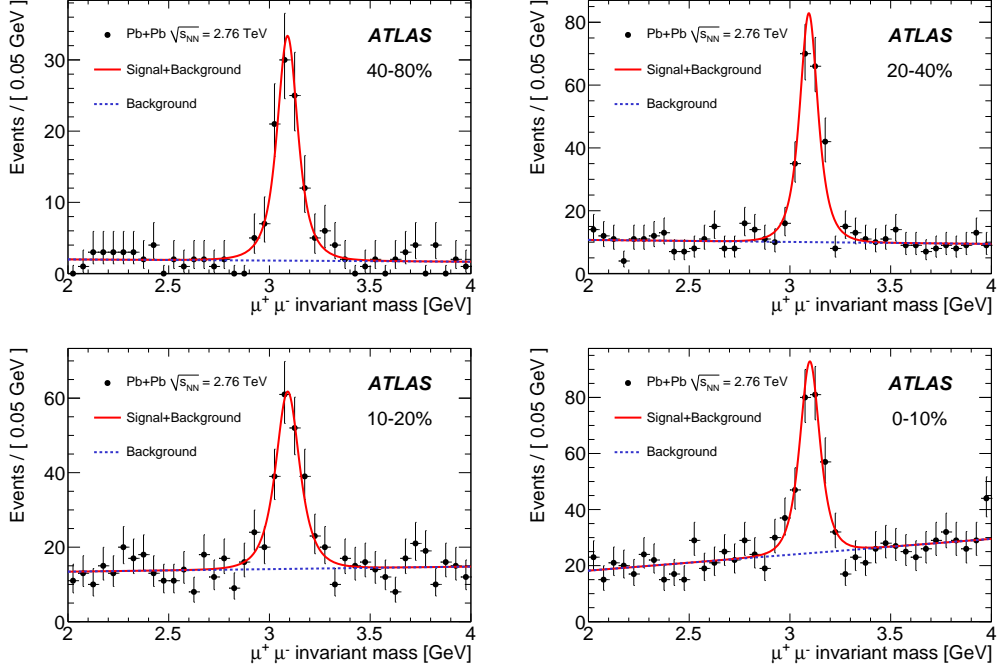


Figure 2: Oppositely-charged di-muon invariant mass spectra in the four considered centrality bins from most peripheral (40-80%) to most central (0-10%). The J/ψ yields in each centrality bin are obtained using a sideband technique. The fits shown here are used as a cross check.

Centrality-dependent efficiency corrections, derived from Monte Carlo events, are applied to the resulting signal yields. The number of J/ψ decays after background subtraction, but before any other correction, are listed in Table 1. With the chosen transverse momentum cuts on the decay muons, 80% of the reconstructed J/ψ have $p_T > 6.5$ GeV.

The measured J/ψ yields at different centralities are corrected by the reconstruction efficiency ϵ_c for $J/\psi \rightarrow \mu^+\mu^-$, derived from MC and parameterized in each centrality bin, and the width of the centrality bin, W_c , which represents a well-defined fraction of the minimum bias events. The corrected yield of J/ψ mesons is given by:

$$N_c^{\text{corr}}(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_c^{\text{meas}}(J/\psi \rightarrow \mu^+\mu^-)_c}{\epsilon(J/\psi)_c \cdot W_c}. \quad (1)$$

The “relative yield” is defined by normalizing to the yield found in the most

Centrality	$N^{\text{meas}}(J/\psi)$	$\epsilon(J/\psi)_c / \epsilon(J/\psi)_{40-80}$	Systematic Uncertainty		
			Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

Table 1: The measured numbers of J/ψ signal events per centrality bin before any correction, with their statistical errors, are listed in the second column. The relative efficiency corrections derived from the simulation are also shown, with the MC statistical error. The last columns give the experimental systematic uncertainties on the reconstruction efficiency and signal extraction, as well as the total uncertainty.

peripheral 40-80% centrality bin: $R_c = N_c^{\text{corr}} / N_{40-80\%}^{\text{corr}}$. Note that the uncertainties in the 40-80% bin are not propagated into this ratio for the more central bins. Finally, the “normalized yield” is defined by scaling the relative yield by the ratio R_{coll} of the mean number of binary collisions $N_{\text{coll},c}$, detailed in section 3.2, in each centrality bin to that for the most peripheral (40-80%) bin: $R_{cp} = R_c / R_{\text{coll}}$.

3.1. Experimental systematic uncertainties

Several experimental systematic effects are considered. These are grouped into those affecting the J/ψ reconstruction efficiency, and those from the extraction of the number of signal events from the di-muon mass spectra. Since this measurement only determines the relative yields as a function of centrality, only the centrality dependence of these effects is relevant. Any uncertainty on the absolute value cancels out in the ratio. The variation of the J/ψ reconstruction efficiency with centrality observed in simulation is mainly due to the larger occupancy in the ID. Because of the low occupancy in the MS by the primarily-soft tracks produced in heavy ion collisions, the fraction of muons from J/ψ decays with a reconstructed track in the MS is independent of centrality within the MC statistical uncertainty. On the other hand, to improve the reliability of the ID track reconstruction in the dense environment, rather stringent track quality requirements are made, relative to those defined for proton-proton collisions [15]. In particular, there must be at least nine silicon hits on each track, with no missing pixel hits and not more than one missing SCT hit, in both cases where such hits are expected. In order to evaluate systematic uncertainties, comparisons have

been made between the distributions of hits associated with tracks and missing hits between data and MC as a function of centrality. The differences between the fraction of tracks with associated or missing hits close to the track selection cuts have been used to derive the systematic uncertainties on the ID track reconstruction that range between 1 and 3% as a function of the centrality. These uncertainties are fully correlated for both muons from the J/ψ decay, resulting in a systematic uncertainty up to about 7% on the J/ψ reconstruction efficiency. As an additional cross-check, the ID reconstruction was run with looser cuts on the number of missing pixel and SCT hits, in order to study directly the number of tracks lost because of the cuts on these quantities. The resulting track losses, as a function of centrality in data and simulation, were compatible with the systematic uncertainties derived with the hit comparison method described above. Further cross-checks have been made by studying the matching between the MS and ID momentum measurements, and by examining variables such as the track multiplicity distribution in a cone of $\Delta R < 0.1$ (where $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$) around muon candidates, and by evaluating the relative momentum difference between the two independent measurements of the same muon candidate. The fraction of muons measured in the MS but not matched to any ID track has also been compared in data and MC as a function of centrality. All of these studies show that the MC reproduces well the behaviour of the data as a function of centrality. The relative statistical uncertainty on the MC efficiency corrections ranges between 1.6 and 3.2% and this is combined in quadrature with the other uncertainties.

To address the uncertainties associated with the J/ψ signal extraction, an independent method based on an unbinned maximum likelihood fit is used to evaluate the number of signal events from the di-muon mass spectra. An overall scale factor on the event-by-event mass resolution is a free parameter of the fit, allowing for possible variations of resolution with centrality. Two different background parameterizations are used, with either a first or second order polynomial. The maximum deviation of the fitted yield compared to the sideband subtraction method is taken as the systematic uncertainty on the signal extraction.

The systematic uncertainties from the different sources are listed in Table 1.

3.2. Definition of N_{coll}

The mean number of binary nucleon-nucleon collisions, N_{coll} , corresponding to each centrality bin was calculated using a Glauber Monte Carlo package that has been applied extensively at RHIC energies [16, 17]. The impact parameter is selected randomly event by event, and both the number of participating nucleons which undergo at least one inelastic collision (N_{part}) and the number of binary collisions (i.e. the total number of nucleon-nucleon collisions, N_{coll}) are calculated for each event. The primary experimental inputs to the Glauber calculation are the radius (R) and skin depth (a) parameters of the Wood-Saxon parameterization of the nuclear density ($\rho(r) = \rho_0/[1 + \exp((r - R)/a)]$), $R = 6.62 \pm 0.06$ fm and $a = 0.546 \pm 0.010$ fm, respectively [18], and the nucleon-nucleon inelastic cross-section, assumed to be $\sigma_{\text{inel}} = 64 \pm 6$ mb from an extrapolation of lower energy data. Using these parameters, the Glauber calculations give a total inelastic cross section of 7.6 barns, which is defined as the “geometric” cross section below.

Systematic uncertainties on the resulting R_{coll} values are estimated by separately varying R , a and σ_{inel} by one standard deviation. The variations of R and a are found to give results of the same magnitude but opposite sign, indicating that the uncertainties on the two parameters are correlated. However, they are conservatively treated as uncorrelated for the error analysis used in these studies.

Any possible variation in the fraction of the geometric cross section selected by the combination of trigger and event selection criteria, ε_{mb} , as a function of centrality must also be considered in evaluating systematic uncertainties on the lead-lead collision geometry, so that the centrality percentiles correspond to the correct fractions of the efficiency-corrected geometric cross section. The uncertainty is estimated by examining the distribution of $\Sigma E_{\text{T}}^{\text{FCal}}$ in the independent data sample selected by a random trigger and filtered by requiring a minimal amount of Inner Detector activity. The event selection criteria described above are also applied, with an additional requirement that both ZDCs see energies consistent with the presence of at least one neutron. This combination of vertex, MBTS and ZDC selections efficiently rejects photonuclear interactions [19]. The total selected fraction of the geometric cross section is estimated using a fit to the resulting $\Sigma E_{\text{T}}^{\text{FCal}}$ distribution, assuming the transverse energy in each event results from a superposition of participating nucleons and binary collisions (a similar as-

sumption to that used in Ref. [20]):

$$\Sigma E_T^{\text{FCal}} = E_T^{pp} \left\{ (1-x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}} \right\}. \quad (2)$$

In this formula, E_T^{pp} is the value of ΣE_T^{FCal} when $N_{\text{part}} = 2$ and $N_{\text{coll}} = 1$ (the values for a single proton-proton collision) and x controls the relative contribution of participants and binary collisions in lead-lead events. An additional constant noise term is also included to account for the low energy part of the distribution. Distributions of ΣE_T^{FCal} are generated for 500k MC events and fitted to the data for a range of values of x (from 0.09 to 0.15), and also varying E_T^{pp} and the noise term. For all cases, the integral of the observed distribution in data accounts for around 98% of the best fit to the simulated distribution, with a variation of around 1%. This provides an estimate of the total event selection efficiency ε_{mb} relative to the geometric cross section. An absolute systematic error of $\pm 2\%$ is assigned to ε_{mb} with the positive range also accounting for the possible leakage of photonuclear events into the event sample used to obtain the ΣE_T^{FCal} distribution.

Centrality	R_{coll}	Uncertainty
0-10%	19.5	5.3 %
10-20%	11.9	4.7 %
20-40%	5.7	3.2 %
40-80%	1.0	–

Table 2: The correction factors R_{coll} , together with the relative systematic uncertainty, stated as a 1σ value.

The total systematic uncertainties on the ratios R_{coll} are evaluated by combining the variations with R , a , σ_{inel} and ε_{mb} , in quadrature. The values of R_{coll} and their systematic uncertainties are reported in Table 2. It should be noted that the estimate of ε_{mb} leads to correlations between the extracted values of N_{coll} , and thus the uncertainties on R_{coll} are also correlated bin-to-bin.

3.3. J/ψ yields

The relative J/ψ yields after normalization and efficiency corrections as in equation 1, R_c , are compared to the expected R_{coll} values in the left panel of Figure 3. The yield errors are computed by adding the statistical and

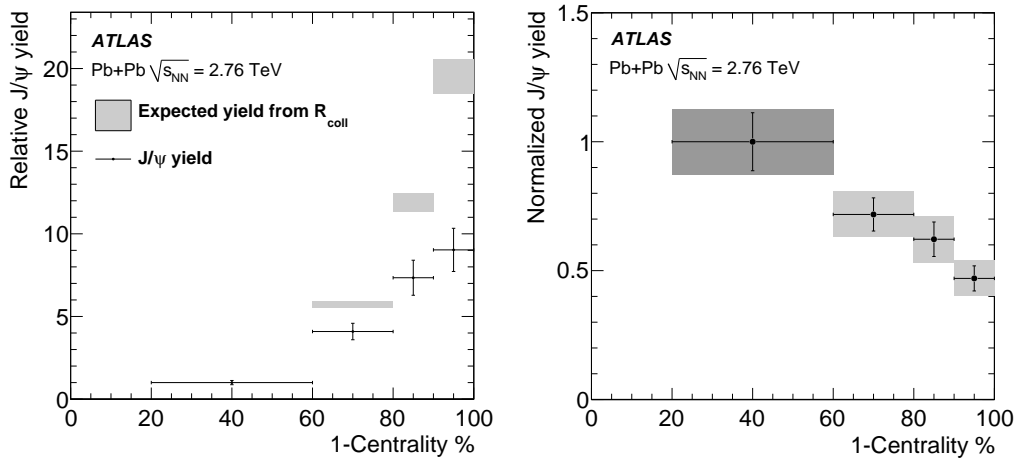


Figure 3: (left) Relative J/ψ yield as a function of centrality normalized to the most peripheral bin (black dots with errors). The expected relative yields from the (normalized) number of binary collisions (R_{coll}) are also shown (boxes, reflecting 1σ systematic uncertainties). (right) Value of R_{cp} , as described in the text, as a function of centrality. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40-80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

systematic uncertainties in quadrature. A clear difference is observed as a function of centrality between the measured relative J/ψ yield and the prediction based on R_{coll} , indicating a deviation from the simplest expectation based on QCD factorization. The ratio of these two values, R_{cp} , is shown as a function of centrality in the right panel of Figure 3. The data points are not consistent with their average, giving a $P(\chi^2, N_{DOF})$ value of 0.11% with three degrees of freedom, computed conservatively ignoring any correlations among the systematic uncertainties. Instead, a significant decrease of R_{cp} as a function of centrality is observed.

4. Z production as a function of centrality

Z candidates are selected by requiring a pair of oppositely charged muons with $p_T > 20$ GeV and $|\eta| < 2.5$ [21]. An additional cosmic ray rejection cut on the sum of the pseudorapidities of the two muons, $|\eta_1 + \eta_2| > 0.01$, is also applied. The invariant mass distribution of the selected pairs is shown in the

Centrality	N(Z)	$\epsilon(Z)_c/\epsilon(Z)_{40-80}$
0-10%	19	0.99 ± 0.01
10-20%	5	0.97 ± 0.01
20-40%	10	0.98 ± 0.01
40-80%	4	1

Table 3: The number of Z events per centrality bin and the relative efficiency corrections derived from the simulation.

left panel of Figure 4. With this selection, 38 Z candidates are retained in the signal mass window of 66 to 116 GeV. The background after this selection is expected to be below 2%, and is not corrected for in the result. The number of Z events in each centrality bin is given in Table 3.

The R_{cp} variable for the Z candidates is computed in the same way as for the J/ψ sample. The relative efficiency corrections determined from dedicated MC samples are given in Table 3. For high transverse momentum tracks, the reconstruction is expected to perform as well as or better than in the low p_T regime characteristic of the J/ψ study. For this reason, the same systematic uncertainties as for the J/ψ results have been applied to the Z relative yield measurements. Several cross-checks have been performed to support this assumption. In addition to the tracks reconstructed with the combined ID and MS information, tracks reconstructed by the MS alone have been checked, and only one additional candidate was found. This candidate has been inspected and an ID track was in fact found but with too few hits to pass the stringent reconstruction requirements. The Z selection was also applied to same charge muon pairs, and no candidates were selected within the 66–116 GeV mass window. To control the residual background from cosmic rays, the distribution of the difference of the transverse impact parameters of the two muons from Z candidates was examined and found to be compatible with that expected for collision muons.

The measured Z yields are displayed in the right panel of Figure 4, normalized to the yield in the most peripheral bin and to the number of binary collisions (R_{cp}). Although, within the large statistical uncertainty, they appear to be compatible with a linear scaling with the number of binary collisions, the low statistics preclude drawing any conclusion.

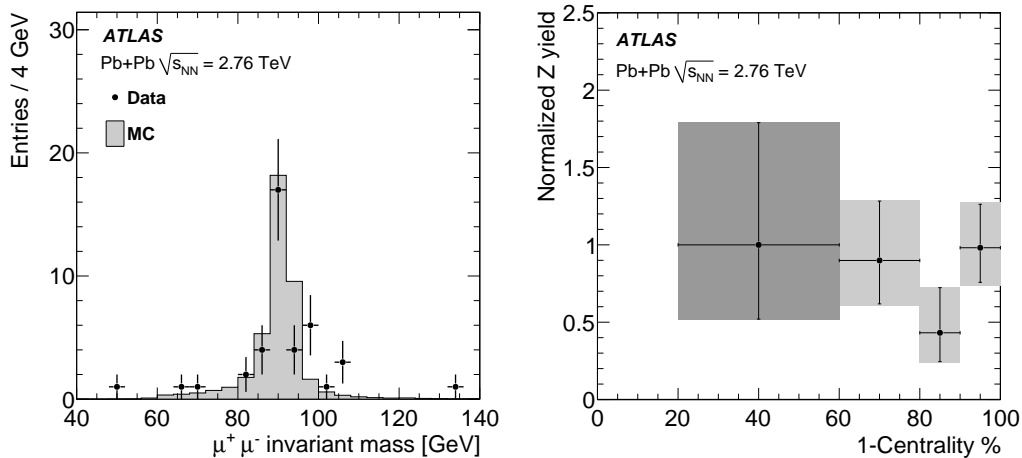


Figure 4: The di-muon invariant mass (left) after the selection described in the text. The value of R_{cp} (right) computed with the 38 selected Z candidates. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40-80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

5. Conclusion

The first results on J/ψ and $Z \rightarrow \mu^+\mu^-$ relative yields measured in lead-lead collisions obtained with the ATLAS detector at the LHC, have been presented. In a sample of events with oppositely charged muon pairs with a transverse momentum above 3 GeV and with $|\eta| < 2.5$, a centrality dependent suppression is observed in the normalized J/ψ yield. The relative yields of the 38 observed Z candidates as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions.

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The ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, A.A. Abdelalim⁴⁹, A. Abdesselam¹¹⁸, O. Abidinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, H. Abramowicz¹⁵³, H. Abreu¹¹⁵, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, M. Ackers²⁰, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁵, M. Aderholz⁹⁹, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, M.S. Alam¹, M.A. Alam⁷⁶, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁵, M. Aleppo^{89a,89b}, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob²⁰, M. Aliev¹⁵, G. Alimonti^{89a}, J. Alison¹²⁰, M. Aliyev¹⁰, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷¹, A. Alonso⁷⁹, J. Alonso¹⁴, M.G. Alviggi^{102a,102b}, K. Amako⁶⁶, P. Amaral²⁹, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,b}, G. Amorós¹⁶⁷, N. Amram¹⁵³, C. Anastopoulos¹³⁹, T. Andeen³⁴, C.F. Anders²⁰, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, S. Antonelli^{19a,19b}, J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³, L. Aperio Bella⁴, R. Apolle¹¹⁸, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁶, A.T.H. Arce⁴⁴, J.P. Archambault²⁸, S. Arfaoui^{29,c}, J-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, K.E. Arms¹⁰⁹, S.R. Armstrong²⁴, O. Arnaez⁸¹, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷², S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵, K. Assamagan²⁴, A. Astbury¹⁶⁹, A. Astvatsatourov⁵², G. Atoian¹⁷⁵, B. Aubert⁴, B. Auerbach¹⁷⁵, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aurousseau⁴, N. Austin⁷³, R. Avramidou⁹, D. Axen¹⁶⁸, C. Ay⁵⁴, G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, G. Bachy²⁹, M. Backes⁴⁹, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁵, M.D. Baker²⁴, S. Baker⁷⁷, F. Baltasar Dos Santos Pedrosa²⁹, E. Banas³⁸, P. Banerjee⁹³, Sw. Banerjee¹⁶⁹, D. Banfi^{89a,89b}, A. Bangert¹³⁷, V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷¹, S.P. Baranov⁹⁴, A. Barashkou⁶⁵, A. Barbaro Galtieri¹⁴, T. Barber²⁷, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁵, T. Barillari⁹⁹, M. Barisonzi¹⁷⁴, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, A.J. Barr¹¹⁸,

F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵,
 R. Bartoldus¹⁴³, A.E. Barton⁷¹, D. Bartsch²⁰, R.L. Bates⁵³, L. Batkova^{144a},
 J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, G. Battistoni^{89a}, F. Bauer¹³⁶,
 H.S. Bawa¹⁴³, B. Beare¹⁵⁸, T. Beau⁷⁸, P.H. Beauchemin¹¹⁸, R. Beccherle^{50a},
 P. Bechtle⁴¹, H.P. Beck¹⁶, M. Beckingham⁴⁸, K.H. Becks¹⁷⁴, A.J. Beddall^{18c},
 A. Beddall^{18c}, V.A. Bednyakov⁶⁵, C. Bee⁸³, M. Begel²⁴, S. Behar Harpaz¹⁵²,
 P.K. Behera⁶³, M. Beimforde⁹⁹, C. Belanger-Champagne¹⁶⁶, P.J. Bell⁴⁹,
 W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹, G. Bellomo^{89a,89b},
 M. Bellomo^{119a}, A. Belloni⁵⁷, K. Belotskiy⁹⁶, O. Beltramello²⁹,
 S. Ben Ami¹⁵², O. Benary¹⁵³, D. Benchekroun^{135a}, C. Benchouk⁸³,
 M. Bendel⁸¹, B.H. Benedict¹⁶³, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³,
 D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensingher²², K. Benslama¹³⁰,
 S. Bentvelsen¹⁰⁵, D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴,
 F. Berghaus¹⁶⁹, E. Berglund⁴⁹, J. Beringer¹⁴, K. Bernardet⁸³, P. Bernat¹¹⁵,
 R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶, A. Bertin^{19a,19b}, F. Bertinelli²⁹,
 F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹,
 W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{72a,72b}, O. Biebel⁹⁸, J. Biesiada¹⁴,
 M. Biglietti^{132a,132b}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, A. Bingul^{18c},
 C. Bini^{132a,132b}, C. Biscarat¹⁷⁷, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵,
 J.-B. Blanchard¹¹⁵, G. Blanchot²⁹, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹,
 W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷,
 A. Bocci⁴⁴, R. Bock²⁹, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁴,
 N. Boelaert³⁵, S. Böser⁷⁷, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷,
 A. Bogouch^{90,*}, C. Bohm^{146a}, V. Boisvert⁷⁶, T. Bold^{163,e}, V. Boldea^{25a},
 M. Bona⁷⁵, M. Boonekamp¹³⁶, G. Boorman⁷⁶, C.N. Booth¹³⁹, P. Booth¹³⁹,
 J.R.A. Booth¹⁷, S. Bordoni⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borisso⁷¹,
 I. Borjanovic^{12a}, S. Borroni^{132a,132b}, K. Bos¹⁰⁵, D. Boscherini^{19a},
 M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³,
 J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, C. Boulahouache¹²³,
 C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁵,
 N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, J. Bracini¹⁷, A. Braem²⁹,
 E. Brambilla^{72a,72b}, P. Branchini^{134a}, G.W. Brandenburg⁵⁷, A. Brandt⁷,
 G. Brandt⁴¹, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴,
 H.M. Braun¹⁷⁴, B. Brelier¹⁵⁸, J. Bremer²⁹, R. Brenner¹⁶⁶, S. Bressler¹⁵²,
 D. Breton¹¹⁵, N.D. Brett¹¹⁸, P.G. Bright-Thomas¹⁷, D. Britton⁵³,
 F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, T.J. Brodbeck⁷¹, E. Brodet¹⁵³,
 F. Broggi^{89a}, C. Bromberg⁸⁸, G. Brooijmans³⁴, W.K. Brooks^{31b},
 G. Brown⁸², E. Brubaker³⁰, P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b},

R. Bruneliere⁴⁸, S. Brunet⁶¹, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a},
 T. Buanes¹³, F. Bucci⁴⁹, J. Buchanan¹¹⁸, N.J. Buchanan², P. Buchholz¹⁴¹,
 R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁵,
 B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, D. Buira-Clark¹¹⁸, E.J. Buis¹⁰⁵,
 O. Bulekov⁹⁶, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³,
 T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶,
 F. Butin²⁹, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷,
 W. Buttinger²⁷, T. Byatt⁷⁷, S. Cabrera Urbán¹⁶⁷, M. Caccia^{89a,89b},
 D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸,
 R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, S. Calvet³³,
 R. Camacho Toro³³, A. Camard⁷⁸, P. Camarri^{133a,133b},
 M. Cambiaghi^{119a,119b}, D. Cameron¹¹⁷, J. Cammin²⁰, S. Campana²⁹,
 M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³⁰, A. Canepa^{159a},
 J. Cantero⁸⁰, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido²⁹, I. Caprini^{25a},
 M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo¹⁴⁸,
 C. Caramarcu^{25a}, R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a},
 L. Carminati^{89a,89b}, B. Caron^{159a}, S. Caron⁴⁸, C. Carpentieri⁴⁸,
 G.D. Carrillo Montoya¹⁷², S. Carron Montero¹⁵⁸, A.A. Carter⁷⁵,
 J.R. Carter²⁷, J. Carvalho^{124a,f}, D. Casadei¹⁰⁸, M.P. Casado¹¹,
 M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷²,
 E. Castaneda-Miranda¹⁷², V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124b,a},
 G. Cataldi^{72a}, F. Cataneo²⁹, A. Catinaccio²⁹, J.R. Catmore⁷¹, A. Cattai²⁹,
 G. Cattani^{133a,133b}, S. Caughron⁸⁸, A. Cavallari^{132a,132b}, P. Cavalleri⁷⁸,
 D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b}, A. Cazzato^{72a,72b},
 F. Ceradini^{134a,134b}, C. Cerna⁸³, A.S. Cerqueira^{23a}, A. Cerri²⁹, L. Cerrito⁷⁵,
 F. Cerutti⁴⁷, S.A. Cetin^{18b}, F. Cevenini^{102a,102b}, A. Chafaq^{135a},
 D. Chakraborty¹⁰⁶, K. Chan², B. Chapleau⁸⁵, J.D. Chapman²⁷,
 J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸²,
 S. Cheatham⁷¹, S. Chekanov⁵, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁵,
 H. Chen²⁴, L. Chen², S. Chen^{32c}, T. Chen^{32c}, X. Chen¹⁷², S. Cheng^{32a},
 A. Cheplakov⁶⁵, V.F. Chepurinov⁶⁵, R. Cherkaoui El Moursli^{135d},
 V. Chernyatin²⁴, E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶,
 F. Chevallier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani⁵¹, J.T. Childers^{58a},
 A. Chilingarov⁷¹, G. Chiodini^{72a}, M.V. Chizhov⁶⁵, G. Choudalakis³⁰,
 S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart²⁹,
 M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a},
 D. Cinca³³, V. Cindro⁷⁴, M.D. Ciobotaru¹⁶³, C. Ciocca^{19a,19b}, A. Ciocio¹⁴,
 M. Cirilli⁸⁷, M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³,

J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, R.W. Clift¹²⁹,
 Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro^{50a,50b}, J. Cochran⁶⁴, P. Coe¹¹⁸,
 J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁷, C.D. Cojocar²⁸, J. Colas⁴,
 A.P. Colijn¹⁰⁵, C. Collard¹¹⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵,
 G. Colon⁸⁴, R. Coluccia^{72a,72b}, G. Comune⁸⁸, P. Conde Muiño^{124a},
 E. Coniavitis¹¹⁸, M.C. Conidi¹¹, M. Consonni¹⁰⁴, S. Constantinescu^{25a},
 C. Conta^{119a,119b}, F. Conventi^{102a,g}, J. Cook²⁹, M. Cooke¹⁴, B.D. Cooper⁷⁵,
 A.M. Cooper-Sarkar¹¹⁸, N.J. Cooper-Smith⁷⁶, K. Copic³⁴,
 T. Cornelissen^{50a,50b}, M. Corradi^{19a}, S. Correard⁸³, F. Corriveau^{85,h},
 A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷,
 D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹, R. Coura Torres^{23a},
 L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸,
 M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b}, S. Crépe-Renaudin⁵⁵,
 C. Cuenca Almenar¹⁷⁵, T. Cuhadar Donszelmann¹³⁹, S. Cuneo^{50a,50b},
 M. Curatolo⁴⁷, C.J. Curtis¹⁷, P. Cwetanski⁶¹, H. Czirr¹⁴¹, Z. Czyczula¹¹⁷,
 S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{132a,132b},
 A. Da Rocha Gesualdi Mello^{23a}, P.V.M. Da Silva^{23a}, C. Da Via⁸²,
 W. Dabrowski³⁷, A. Dahlhoff⁴⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴,
 S.J. Dallison^{129,*}, M. Dam³⁵, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷,
 H.O. Danielsson²⁹, R. Dankers¹⁰⁵, D. Dannheim⁹⁹, V. Dao⁴⁹, G. Darbo^{50a},
 G.L. Darlea^{25b}, C. Daum¹⁰⁵, J.P. Dauvergne²⁹, W. Davey⁸⁶, T. Davidek¹²⁶,
 N. Davidson⁸⁶, R. Davidson⁷¹, M. Davies⁹³, A.R. Davison⁷⁷, E. Dawe¹⁴²,
 I. Dawson¹³⁹, J.W. Dawson^{5,*}, R.K. Daya³⁹, K. De⁷, R. de Asmundis^{102a},
 S. De Castro^{19a,19b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴,
 P. de Jong¹⁰⁵, E. De La Cruz-Burelo⁸⁷, C. De La Taille¹¹⁵,
 B. De Lotto^{164a,164c}, L. De Mora⁷¹, L. De Nooij¹⁰⁵, M. De Oliveira Branco²⁹,
 D. De Pedis^{132a}, P. de Saintignon⁵⁵, A. De Salvo^{132a}, U. De Sanctis^{164a,164c},
 A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, S. Dean⁷⁷, G. Dedes⁹⁹,
 D.V. Dedovich⁶⁵, J. Degenhardt¹²⁰, M. Dehchar¹¹⁸, M. Deile⁹⁸,
 C. Del Papa^{164a,164c}, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, A. Dell'Acqua²⁹,
 L. Dell'Asta^{89a,89b}, M. Della Pietra^{102a,g}, D. della Volpe^{102a,102b},
 M. Delmastro²⁹, P. Delpierre⁸³, N. Delruelle²⁹, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸,
 S. Demers¹⁷⁵, M. Demichev⁶⁵, B. Demirkoz¹¹, J. Deng¹⁶³, S.P. Denisov¹²⁸,
 C. Dennis¹¹⁸, D. Derendarz³⁸, J.E. Derkaoui^{135c}, F. Derue⁷⁸, P. Dervan⁷³,
 K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁵⁸, A. Dewhurst¹²⁹,
 B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,i}, A. Di Ciaccio^{133a,133b},
 L. Di Ciaccio⁴, A. Di Girolamo²⁹, B. Di Girolamo²⁹, S. Di Luise^{134a,134b},
 A. Di Mattia⁸⁸, B. Di Micco^{134a,134b}, R. Di Nardo^{133a,133b},

A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c},
 E.B. Diehl⁸⁷, H. Dietl⁹⁹, J. Dietrich⁴⁸, T.A. Dietzsch^{58a}, S. Diglio¹¹⁵,
 K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a},
 F. Dittus²⁹, F. Djama⁸³, R. Djilkibaev¹⁰⁸, T. Djobava⁵¹, M.A.B. do Vale^{23a},
 A. Do Valle Wemans^{124a}, T.K.O. Doan⁴, M. Dobbs⁸⁵, R. Dobinson^{29,*},
 D. Dobos⁴², E. Dobson²⁹, M. Dobson¹⁶³, J. Dodd³⁴, O.B. Dogan^{18a,*},
 C. Doglioni¹¹⁸, T. Doherty⁵³, Y. Doi^{66,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴,
 Z. Dolezal¹²⁶, B.A. Dolgoshein⁹⁶, T. Dohmae¹⁵⁵, M. Donadelli^{23b},
 M. Donega¹²⁰, J. Donini⁵⁵, J. Dopke¹⁷⁴, A. Doria^{102a}, A. Dos Anjos¹⁷²,
 M. Dosil¹¹, A. Dotti^{122a,122b}, M.T. Dova⁷⁰, J.D. Dowell¹⁷, A.D. Doxiadis¹⁰⁵,
 A.T. Doyle⁵³, Z. Drasal¹²⁶, J. Drees¹⁷⁴, N. Dressnandt¹²⁰, H. Drevermann²⁹,
 C. Driouichi³⁵, M. Dris⁹, J.G. Drohan⁷⁷, J. Dubbert⁹⁹, T. Dubbs¹³⁷,
 S. Dube¹⁴, E. Duchovni¹⁷¹, G. Duckeck⁹⁸, A. Dudarev²⁹, F. Dudziak¹¹⁵,
 M. Dührssen²⁹, I.P. Duerdoth⁸², L. Duflot¹¹⁵, M-A. Dufour⁸⁵,
 M. Dunford²⁹, H. Duran Yildiz^{3b}, R. Duxfield¹³⁹, M. Dwuznik³⁷,
 F. Dydak²⁹, D. Dzahini⁵⁵, M. Düren⁵², J. Ebke⁹⁸, S. Eckert⁴⁸,
 S. Eckweiler⁸¹, K. Edmonds⁸¹, C.A. Edwards⁷⁶, I. Efthymiopoulos⁴⁹,
 W. Ehrenfeld⁴¹, T. Ehrich⁹⁹, T. Eifert²⁹, G. Eigen¹³, K. Einsweiler¹⁴,
 E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi⁴, M. Ellert¹⁶⁶, S. Elles⁴,
 F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹,
 R. Ely¹⁴, D. Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶²,
 A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, D. Eriksson^{146a}, J. Ernst¹,
 M. Ernst²⁴, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹,
 M. Escalier¹¹⁵, C. Escobar¹⁶⁷, X. Espinal Curull¹¹, B. Esposito⁴⁷,
 F. Etienne⁸³, A.I. Etienvre¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶¹,
 L. Fabbri^{19a,19b}, C. Fabre²⁹, K. Facius³⁵, R.M. Fakhrutdinov¹²⁸,
 S. Falciano^{132a}, A.C. Falou¹¹⁵, Y. Fang¹⁷², M. Fanti^{89a,89b}, A. Farbin⁷,
 A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S.M. Farrington¹¹⁸,
 P. Farthouat²⁹, D. Fasching¹⁷², P. Fassnacht²⁹, D. Fassouliotis⁸,
 B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, S. Fazio^{36a,36b},
 R. Febbraro³³, P. Federic^{144a}, O.L. Fedin¹²¹, I. Fedorko²⁹, W. Fedorko⁸⁸,
 M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, D. Fellmann⁵, C.U. Felzmann⁸⁶,
 C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, D. Ferguson¹⁷²,
 J. Ferland⁹³, B. Fernandes^{124a,j}, W. Fernando¹⁰⁹, S. Ferrag⁵³, J. Ferrando¹¹⁸,
 V. Ferrara⁴¹, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, A. Ferrer¹⁶⁷,
 M.L. Ferrer⁴⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b},
 M. Fiascaris³⁰, F. Fiedler⁸¹, A. Filipčič⁷⁴, A. Filippas⁹, F. Filthaut¹⁰⁴,
 M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,f}, L. Fiorini¹¹, A. Firan³⁹,

G. Fischer⁴¹, P. Fischer²⁰, M.J. Fisher¹⁰⁹, S.M. Fisher¹²⁹, J. Flammer²⁹,
 M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷³, S. Fleischmann²⁰,
 T. Flick¹⁷⁴, L.R. Flores Castillo¹⁷², M.J. Flowerdew⁹⁹, F. Föhlisch^{58a},
 M. Fokitis⁹, T. Fonseca Martin¹⁶, D.A. Forbush¹³⁸, A. Formica¹³⁶,
 A. Forti⁸², D. Fortin^{159a}, J.M. Foster⁸², D. Fournier¹¹⁵, A. Foussat²⁹,
 A.J. Fowler⁴⁴, K. Fowler¹³⁷, H. Fox⁷¹, P. Francavilla^{122a,122b},
 S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷¹, M. Franklin⁵⁷, S. Franz²⁹,
 M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁷, R. Froeschl²⁹,
 D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa²⁹,
 J. Fuster¹⁶⁷, C. Gabaldon²⁹, O. Gabizon¹⁷¹, T. Gadfort²⁴, S. Gadomski⁴⁹,
 G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea⁹⁸, E.J. Gallas¹¹⁸, M.V. Gallas²⁹,
 V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, E. Galyaev⁴⁰, K.K. Gan¹⁰⁹,
 Y.S. Gao^{143,k}, V.A. Gapienko¹²⁸, A. Gaponenko¹⁴, F. Garberson¹⁷⁵,
 M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro⁴⁹, R.W. Gardner³⁰,
 N. Garelli²⁹, H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷,
 G. Gaudio^{119a}, O. Gaumer⁴⁹, B. Gaur¹⁴¹, L. Gauthier¹³⁶, I.L. Gavrilenko⁹⁴,
 C. Gay¹⁶⁸, G. Gaycken²⁰, J-C. Gayde²⁹, E.N. Gazis⁹, P. Ge^{32d},
 C.N.P. Gee¹²⁹, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a},
 A. Gemmell⁵³, M.H. Genest⁹⁸, S. Gentile^{132a,132b}, F. Georgatos⁹,
 S. George⁷⁶, P. Gerlach¹⁷⁴, A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135d},
 P. Ghez⁴, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b},
 V. Giakoumopoulou⁸, V. Giangiobbe^{122a,122b}, F. Gianotti²⁹, B. Gibbard²⁴,
 A. Gibson¹⁵⁸, S.M. Gibson²⁹, G.F. Gieraltowski⁵, L.M. Gilbert¹¹⁸,
 M. Gilchriese¹⁴, O. Gildemeister²⁹, V. Gilewsky⁹¹, D. Gillberg²⁸,
 A.R. Gillman¹²⁹, D.M. Gingrich^{2,d}, J. Ginzburg¹⁵³, N. Giokaris⁸,
 R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶,
 D. Giugni^{89a}, P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰,
 J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁴, G.L. Glonti⁶⁵, J. Godfrey¹⁴²,
 J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴²,
 T. Göttfert⁹⁹, S. Goldfarb⁸⁷, D. Goldin³⁹, T. Golling¹⁷⁵, N.P. Gollub²⁹,
 S.N. Golovnia¹²⁸, A. Gomes^{124a,l}, L.S. Gomez Fajardo⁴¹, R. Gonçalo⁷⁶,
 L. Gonella²⁰, A. Gonidec²⁹, S. Gonzalez¹⁷², S. González de la Hoz¹⁶⁷,
 M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸,
 L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³,
 G. Gorfine¹⁷⁴, B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸,
 S.A. Gorokhov¹²⁸, B.T. Gorski²⁹, V.N. Goryachev¹²⁸, B. Godzik⁴¹,
 M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁵, M. Gouanère⁴, I. Gough Eschrich¹⁶³,
 M. Gouighri^{135a}, D. Goujdami^{135a}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸,

C. Goy⁴, I. Grabowska-Bold^{163,e}, V. Grabski¹⁷⁶, P. Grafström²⁹, C. Grah¹⁷⁴,
 K.-J. Grah¹⁴⁷, F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸,
 V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray^{34,m}, J.A. Gray¹⁴⁸, E. Graziani^{134a},
 O.G. Grebenyuk¹²¹, D. Greenfield¹²⁹, T. Greenshaw⁷³, Z.D. Greenwood^{24,i},
 I.M. Gregor⁴¹, P. Grenier¹⁴³, E. Griesmayer⁴⁶, J. Griffiths¹³⁸,
 N. Grigalashvili⁶⁵, A.A. Grillo¹³⁷, K. Grimm¹⁴⁸, S. Grinstein¹¹,
 P.L.Y. Gris³³, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, J. Grognez²⁹, M. Groh⁹⁹,
 E. Gross¹⁷¹, J. Grosse-Knetter⁵⁴, J. Groth-Jensen⁷⁹, M. Gruwe²⁹,
 K. Grybel¹⁴¹, V.J. Guarino⁵, C. Guicheney³³, A. Guida^{72a,72b},
 T. Guillemin⁴, S. Guindon⁵⁴, H. Guler^{85,n}, J. Gunther¹²⁵, B. Guo¹⁵⁸,
 J. Guo³⁴, A. Gupta³⁰, Y. Gusakov⁶⁵, V.N. Gushchin¹²⁸, A. Gutierrez⁹³,
 P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷², C. Guyot¹³⁶,
 C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴,
 R. Hackenburg²⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner⁹⁹,
 F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁶, J. Haller⁵⁴,
 K. Hamacher¹⁷⁴, A. Hamilton⁴⁹, S. Hamilton¹⁶¹, H. Han^{32a}, L. Han^{32b},
 K. Hanagaki¹¹⁶, M. Hance¹²⁰, C. Handel⁸¹, P. Hanke^{58a}, C.J. Hansen¹⁶⁶,
 J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵, P. Hansson¹⁴³,
 K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁴, D. Harper⁸⁷, R.D. Harrington²¹,
 O.M. Harris¹³⁸, K. Harrison¹⁷, J.C. Hart¹²⁹, J. Hartert⁴⁸, F. Hartjes¹⁰⁵,
 T. Haruyama⁶⁶, A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰,
 S. Hassani¹³⁶, M. Hatch²⁹, D. Hauff⁹⁹, S. Haug¹⁶, M. Hauschild²⁹,
 R. Hauser⁸⁸, M. Havranek¹²⁵, B.M. Hawes¹¹⁸, C.M. Hawkes¹⁷,
 R.J. Hawkings²⁹, D. Hawkins¹⁶³, T. Hayakawa⁶⁷, D. Hayden⁷⁶,
 H.S. Hayward⁷³, S.J. Haywood¹²⁹, E. Hazen²¹, M. He^{32d}, S.J. Head¹⁷,
 V. Hedberg⁷⁹, L. Heelan²⁸, S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵,
 L. Helary⁴, M. Heldmann⁴⁸, M. Heller¹¹⁵, S. Hellman^{146a,146b}, C. Helsen¹¹,
 R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴,
 A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³,
 C. Hensel⁵⁴, T. Henß¹⁷⁴, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵,
 A.D. Hershenhorn¹⁵², G. Herten⁴⁸, R. Hertenberger⁹⁸, L. Hervas²⁹,
 N.P. Hessey¹⁰⁵, A. Hidvegi^{146a}, E. Higón-Rodríguez¹⁶⁷, D. Hill^{5,*}, J.C. Hill²⁷,
 N. Hill⁵, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰,
 M. Hirose¹¹⁶, F. Hirsch⁴², D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁵³,
 M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹, M.R. Hoefkamp¹⁰³,
 J. Hoffman³⁹, D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, A. Holmes¹¹⁸,
 S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, R.J. Homer¹⁷,
 Y. Homma⁶⁷, T. Horazdovsky¹²⁷, C. Horn¹⁴³, S. Horner⁴⁸, K. Horton¹¹⁸,

J-Y. Hostachy⁵⁵, T. Hott⁹⁹, S. Hou¹⁵¹, M.A. Houlden⁷³, A. Hoummada^{135a},
 J. Howarth⁸², D.F. Howell¹¹⁸, I. Hristova⁴¹, J. Hrivnac¹¹⁵, I. Hruska¹²⁵,
 T. Hryn'ova⁴, P.J. Hsu¹⁷⁵, S.-C. Hsu¹⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷,
 F. Hubaut⁸³, F. Huegging²⁰, T.B. Huffman¹¹⁸, E.W. Hughes³⁴, G. Hughes⁷¹,
 R.E. Hughes-Jones⁸², M. Huhtinen²⁹, P. Hurst⁵⁷, M. Hurwitz¹⁴,
 U. Husemann⁴¹, N. Huseynov^{65,o}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci^{102a},
 G. Iakovidis⁹, M. Ibbotson⁸², I. Ibragimov¹⁴¹, R. Ichimiya⁶⁷,
 L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, M. Idzik³⁷, P. Iengo⁴,
 O. Igonkina¹⁰⁵, Y. Ikegami⁶⁶, M. Ikeno⁶⁶, Y. Ilchenko³⁹, D. Iliadis¹⁵⁴,
 D. Imbault⁷⁸, M. Imhaeuser¹⁷⁴, M. Imori¹⁵⁵, T. Ince²⁰, J. Inigo-Golfin²⁹,
 P. Ioannou⁸, M. Iodice^{134a}, G. Ionescu⁴, A. Irlles Quiles¹⁶⁷, K. Ishii⁶⁶,
 A. Ishikawa⁶⁷, M. Ishino⁶⁶, R. Ishmukhametov³⁹, T. Isobe¹⁵⁵, C. Issever¹¹⁸,
 S. Istin^{18a}, Y. Itoh¹⁰¹, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁶,
 J.M. Izen⁴⁰, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³,
 M.R. Jaekel²⁹, V. Jain⁶¹, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁷,
 D.K. Jana¹¹¹, E. Jankowski¹⁵⁸, E. Jansen⁷⁷, A. Jantsch⁹⁹, M. Janus²⁰,
 G. Jarlskog⁷⁹, L. Jeanty⁵⁷, K. Jelen³⁷, I. Jen-La Plante³⁰, P. Jenni²⁹,
 A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴, H. Ji¹⁷², W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b},
 M. Jimenez Belenguer²⁹, G. Jin^{32b}, S. Jin^{32a}, O. Jinnouchi¹⁵⁷,
 M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b},
 K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶,
 K. Jon-And^{146a,146b}, G. Jones⁸², R.W.L. Jones⁷¹, T.W. Jones⁷⁷,
 T.J. Jones⁷³, O. Jonsson²⁹, K.K. Joo¹⁵⁸, C. Joram²⁹, P.M. Jorge^{124a,b},
 J. Joseph¹⁴, X. Ju¹³⁰, V. Juranek¹²⁵, P. Jussel⁶², V.V. Kabachenko¹²⁸,
 S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarska³⁸, P. Kadlecik³⁵, M. Kado¹¹⁵,
 H. Kagan¹⁰⁹, M. Kagan⁵⁷, S. Kaiser⁹⁹, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁴,
 L.V. Kalinovskaya⁶⁵, S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda¹⁵⁵, T. Kanno¹⁵⁷,
 V.A. Kantserov⁹⁶, J. Kanzaki⁶⁶, B. Kaplan¹⁷⁵, A. Kapliy³⁰, J. Kaplon²⁹,
 D. Kar⁴³, M. Karagoz¹¹⁸, M. Karnevskiy⁴¹, K. Kari⁵, V. Kartvelishvili⁷¹,
 A.N. Karyukhin¹²⁸, L. Kashif⁵⁷, A. Kasmi³⁹, R.D. Kass¹⁰⁹, A. Kastanas¹³,
 M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶,
 K. Kawagoe⁶⁷, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵,
 V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁵, S.I. Kazi⁸⁶, J.R. Keates⁸², R. Keeler¹⁶⁹,
 R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁵, M. Kelly⁸², J. Kennedy⁹⁸,
 C.J. Kenney¹⁴³, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴,
 S. Kersten¹⁷⁴, K. Kessoku¹⁵⁵, C. Ketterer⁴⁸, M. Khakzad²⁸, F. Khalil-zada¹⁰,
 H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁵, A. Khodinov¹⁴⁸,
 A.G. Kholodenko¹²⁸, A. Khomich^{58a}, T.J. Khoo²⁷, G. Khoriali²⁰,

N. Khovanskiy⁶⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁵, J. Khubua⁵¹,
 G. Kilvington⁷⁶, H. Kim⁷, M.S. Kim², P.C. Kim¹⁴³, S.H. Kim¹⁶⁰,
 N. Kimura¹⁷⁰, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁷, R.S.B. King¹¹⁸,
 J. Kirk¹²⁹, G.P. Kirsch¹¹⁸, L.E. Kirsch²², A.E. Kiryunin⁹⁹, D. Kisielewska³⁷,
 T. Kittelmann¹²³, A.M. Kiver¹²⁸, H. Kiyamura⁶⁷, E. Kladiva^{144b},
 J. Klaiber-Lodewigs⁴², M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹,
 M. Klemetti⁸⁵, A. Klier¹⁷¹, A. Klimentov²⁴, R. Klingenberg⁴²,
 E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵,
 E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, E. Kneringer⁶²,
 J. Knobloch²⁹, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³,
 B. Koblitz²⁹, M. Kocian¹⁴³, A. Kocnar¹¹³, P. Kodys¹²⁶, K. Köneke²⁹,
 A.C. König¹⁰⁴, S. Koenig⁸¹, S. König⁴⁸, L. Köpke⁸¹, F. Koetsveld¹⁰⁴,
 P. Koevesarki²⁰, T. Koffas²⁹, E. Koffeman¹⁰⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷,
 T. Kohriki⁶⁶, T. Koi¹⁴³, T. Kokott²⁰, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵,
 V. Kolesnikov⁶⁵, I. Koletsou^{89a,89b}, J. Koll⁸⁸, D. Kollar²⁹, M. Kollefrath⁴⁸,
 S.D. Kolya⁸², A.A. Komar⁹⁴, J.R. Komaragiri¹⁴², T. Kondo⁶⁶, T. Kono^{41,p},
 A.I. Kononov⁴⁸, R. Konoplich^{108,q}, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁴,
 S. Koperny³⁷, S.V. Kopikov¹²⁸, K. Korcyl³⁸, K. Kordas¹⁵⁴, V. Koreshev¹²⁸,
 A. Korn¹⁴, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸,
 O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰, M.J. Kotamäki²⁹,
 S. Kotov⁹⁹, V.M. Kotov⁶⁵, C. Kourkoumelis⁸, V. Kouskoura¹⁵⁴,
 A. Koutsman¹⁰⁵, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶,
 A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴,
 O. Krasel⁴², M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, A. Kreisel¹⁵³,
 F. Krejci¹²⁷, J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴,
 H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁵,
 H. Krüger²⁰, Z.V. Krumshteyn⁶⁵, A. Kruth²⁰, T. Kubota¹⁵⁵, S. Kuehn⁴⁸,
 A. Kugel^{58c}, T. Kuhl¹⁷⁴, D. Kuhn⁶², V. Kukhtin⁶⁵, Y. Kulchitsky⁹⁰,
 S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁸³, N. Kundu¹¹⁸, J. Kunkle¹²⁰,
 A. Kupco¹²⁵, H. Kurashige⁶⁷, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵,
 W. Kuykendall¹³⁸, M. Kuze¹⁵⁷, P. Kuzhir⁹¹, O. Kvasnicka¹²⁵, R. Kwee¹⁵,
 A. La Rosa²⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, C. Lacasta¹⁶⁷,
 F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁵,
 R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna²⁹,
 C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵,
 H. Landsman¹⁵², J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴,
 K. Lantzschn²⁹, V.V. Lapin^{128,*}, S. Laplace⁴, C. Lapoire²⁰, J.F. Laporte¹³⁶,
 T. Lari^{89a}, A.V. Larionov¹²⁸, A. Larner¹¹⁸, C. Lasseur²⁹, M. Lassnig²⁹,

W. Lau¹¹⁸, P. Laurelli⁴⁷, A. Lavorato¹¹⁸, W. Lavrijsen¹⁴, P. Laycock⁷³,
 A.B. Lazarev⁶⁵, A. Lazzaro^{89a,89b}, O. Le Dortz⁷⁸, E. Le Guirriec⁸³,
 C. Le Maner¹⁵⁸, E. Le Menedeu¹³⁶, M. Leahu²⁹, A. Lebedev⁶⁴, C. Lebel⁹³,
 T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹⁵⁰, S.C. Lee¹⁵¹,
 L. Lee¹⁷⁵, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, A. Leger⁴⁹, B.C. LeGeyt¹²⁰,
 F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹,
 M. Lehto¹³⁹, X. Lei⁶, M.A.L. Leite^{23b}, R. Leitner¹²⁶, D. Lellouch¹⁷¹,
 J. Lellouch⁷⁸, M. Leltchouk³⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b},
 T. Lenz¹⁷⁴, G. Lenzen¹⁷⁴, B. Lenzi¹³⁶, K. Leonhardt⁴³, S. Leontsinis⁹,
 C. Leroy⁹³, J-R. Lessard¹⁶⁹, J. Lesser^{146a}, C.G. Lester²⁷,
 A. Leung Fook Cheong¹⁷², J. Levêque⁸³, D. Levin⁸⁷, L.J. Levinson¹⁷¹,
 M.S. Levitski¹²⁸, M. Lewandowska²¹, M. Leyton¹⁵, B. Li⁸³, H. Li¹⁷²,
 S. Li^{32b}, X. Li⁸⁷, Z. Liang³⁹, Z. Liang^{118,r}, B. Liberti^{133a}, P. Lichard²⁹,
 M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, R. Lifshitz¹⁵², J.N. Lilley¹⁷,
 A. Limosani⁸⁶, M. Limper⁶³, S.C. Lin^{151,s}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸,
 E. Lipeles¹²⁰, L. Lipinsky¹²⁵, A. Lipniacka¹³, T.M. Liss¹⁶⁵, A. Lister⁴⁹,
 A.M. Litke¹³⁷, C. Liu²⁸, D. Liu^{151,t}, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, S. Liu²,
 Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, S.L. Lloyd⁷⁵,
 E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, S. Lockwitz¹⁷⁵,
 T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁵, C.W. Loh¹⁶⁸,
 T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, J. Loken¹¹⁸,
 V.P. Lombardo^{89a,89b}, R.E. Long⁷¹, L. Lopes^{124a,b}, D. Lopez Mateos^{34,m},
 M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰,
 A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe¹⁴³,
 F. Lu^{32a}, J. Lu², L. Lu³⁹, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵,
 A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶¹,
 G. Luijckx¹⁰⁵, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷,
 B. Lundberg⁷⁹, J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹,
 A. Lupi^{122a,122b}, G. Lutz⁹⁹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴,
 L.L. Ma¹⁷², M. Maaßen⁴⁸, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷,
 A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a,b}, D. Macina⁴⁹,
 R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c},
 T. Maeno²⁴, P. Mättig¹⁷⁴, S. Mättig⁴¹, P.J. Magalhaes Martins^{124a,f},
 L. Magnoni²⁹, E. Magradze⁵¹, C.A. Magrath¹⁰⁴, Y. Mahalalel¹⁵³,
 K. Mahboubi⁴⁸, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a},
 A. Maio^{124a,l}, S. Majewski²⁴, Y. Makida⁶⁶, N. Makovec¹¹⁵, P. Mal⁶,
 Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶³,
 D. Malon⁵, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov⁶⁵, R. Mameghani⁹⁸,

J. Mamuzic^{12b}, A. Manabe⁶⁶, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵,
 J. Maneira^{124a}, P.S. Mangeard⁸⁸, I.D. Manjavidze⁶⁵, A. Mann⁵⁴,
 P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Manz⁹⁹,
 A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁹,
 F. Marchese^{133a,133b}, M. Marchesotti²⁹, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵,
 A. Marin^{21,*}, C.P. Marino⁶¹, F. Marroquin^{23a}, R. Marshall⁸²,
 Z. Marshall^{34,m}, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, A.J. Martin¹⁷⁵,
 B. Martin²⁹, B. Martin⁸⁸, F.F. Martin¹²⁰, J.P. Martin⁹³, Ph. Martin⁵⁵,
 T.A. Martin¹⁷, B. Martin dit Latour⁴⁹, M. Martinez¹¹,
 V. Martinez Outschoorn⁵⁷, A.C. Martyniuk⁸², M. Marx⁸², F. Marzano^{132a},
 A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸²,
 A.L. Maslennikov¹⁰⁷, M. Maß⁴², I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴,
 A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, M. Mathes²⁰, P. Matricon¹¹⁵,
 H. Matsumoto¹⁵⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁷, C. Mattravers^{118,u},
 J.M. Maugain²⁹, S.J. Maxfield⁷³, E.N. May⁵, A. Mayne¹³⁹, R. Mazini¹⁵¹,
 M. Mazur²⁰, M. Mazzanti^{89a}, E. Mazzoni^{122a,122b}, S.P. Mc Kee⁸⁷,
 A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹,
 K.W. McFarlane⁵⁶, J.A. Mcfayden¹³⁹, H. McGlone⁵³, G. Mchedlidze⁵¹,
 R.A. McLaren²⁹, T. McLaughlan¹⁷, S.J. McMahon¹²⁹, T.R. McMahon⁷⁶,
 T.J. McMahon¹⁷, R.A. McPherson^{169,h}, A. Meade⁸⁴, J. Mechnich¹⁰⁵,
 M. Mechtel¹⁷⁴, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶,
 R. Mehdiyev⁹³, S. Mehlhase⁴¹, A. Mehta⁷³, K. Meier^{58a}, J. Meinhardt⁴⁸,
 B. Meirose⁷⁹, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷²,
 L. Mendoza Navas¹⁶², Z. Meng^{151,t}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹,
 C. Menot²⁹, E. Meoni¹¹, D. Merkl⁹⁸, P. Mermoud¹¹⁸, L. Merola^{102a,102b},
 C. Meroni^{89a}, F.S. Merritt³⁰, A. Messina²⁹, J. Metcalfe¹⁰³, A.S. Mete⁶⁴,
 S. Meuser²⁰, C. Meyer⁸¹, J-P. Meyer¹³⁶, J. Meyer¹⁷³, J. Meyer⁵⁴,
 T.C. Meyer²⁹, W.T. Meyer⁶⁴, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a},
 R.P. Middleton¹²⁹, P. Miele²⁹, S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷¹,
 M. Mikestikova¹²⁵, B. Mikulec⁴⁹, M. Mikuš⁷⁴, D.W. Miller¹⁴³, R.J. Miller⁸⁸,
 W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, D. Milstein¹⁷¹,
 A.A. Minaenko¹²⁸, M. Miñano¹⁶⁷, I.A. Minashvili⁶⁵, A.I. Mincer¹⁰⁸,
 B. Mindur³⁷, M. Mineev⁶⁵, Y. Ming¹³⁰, L.M. Mir¹¹, G. Mirabelli^{132a},
 L. Miralles Verge¹¹, A. Misiejuk⁷⁶, A. Mitra¹¹⁸, J. Mitrevski¹³⁷,
 G.Y. Mitrofanov¹²⁸, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁶, P.S. Miyagawa⁸²,
 K. Miyazaki⁶⁷, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, P. Mockett¹³⁸,
 S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸,
 B. Mohn¹³, W. Mohr⁴⁸, S. Mohrdieck-Möck⁹⁹, A.M. Moisseev^{128,*},

R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, L. Moneta⁴⁹, J. Monk⁷⁷, E. Monnier⁸³,
 S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore²,
 G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, A. Morais^{124a,b},
 N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹, M. Moreno
 Llácer¹⁶⁷, P. Morettini^{50a}, M. Morii⁵⁷, J. Morin⁷⁵, Y. Morita⁶⁶,
 A.K. Morley²⁹, G. Mornacchi²⁹, M-C. Morone⁴⁹, J.D. Morris⁷⁵,
 H.G. Moser⁹⁹, M. Mosidze⁵¹, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha⁹,
 S.V. Mouraviev⁹⁴, E.J.W. Moyse⁸⁴, M. Mudrinic^{12b}, F. Mueller^{58a},
 J. Mueller¹²³, K. Mueller²⁰, T.A. Müller⁹⁸, D. Muenstermann⁴², A. Muijs¹⁰⁵,
 A. Muir¹⁶⁸, Y. Munwes¹⁵³, K. Murakami⁶⁶, W.J. Murray¹²⁹, I. Mussche¹⁰⁵,
 E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰,
 K. Nagano⁶⁶, Y. Nagasaka⁶⁰, A.M. Nairz²⁹, Y. Nakahama¹¹⁵,
 K. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, M. Nash^{77,u},
 I. Nasteva⁸², N.R. Nation²¹, T. Nattermann²⁰, T. Naumann⁴¹,
 G. Navarro¹⁶², H.A. Neal⁸⁷, E. Nebot⁸⁰, P.Yu. Nechaeva⁹⁴, A. Negri^{119a,119b},
 G. Negri²⁹, S. Nektarijevic⁴⁹, A. Nelson⁶⁴, S. Nelson¹⁴³, T.K. Nelson¹⁴³,
 S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi²⁹,
 S.Y. Nesterov¹²¹, M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸,
 P. Nevski²⁴, P.R. Newman¹⁷, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶,
 L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷,
 T. Niinikoski²⁹, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, K. Nikolaev⁶⁵,
 I. Nikolic-Audit⁷⁸, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷,
 Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁷, R. Nisius⁹⁹, L. Nodulman⁵,
 M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, H. Nomoto¹⁵⁵, M. Nordberg²⁹,
 B. Nordkvist^{146a,146b}, O. Norriella Francisco¹¹, P.R. Norton¹²⁹,
 J. Novakova¹²⁶, M. Nozaki⁶⁶, M. Nožička⁴¹, I.M. Nugent^{159a},
 A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger²⁰, T. Nunnemann⁹⁸,
 E. Nurse⁷⁷, T. Nyman²⁹, B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴²,
 V. O'Shea⁵³, F.G. Oakham^{28,d}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁷,
 S. Oda¹⁵⁵, S. Odaka⁶⁶, J. Odier⁸³, G.A. Odino^{50a,50b}, H. Ogren⁶¹, A. Oh⁸²,
 S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, H. Ohshita¹⁴⁰, T.K. Ohska⁶⁶,
 T. Ohsugi⁵⁹, S. Okada⁶⁷, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵,
 M. Olcese^{50a}, A.G. Olchevski⁶⁵, M. Oliveira^{124a,f}, D. Oliveira Damazio²⁴,
 E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸,
 C. Omachi⁶⁷, A. Onofre^{124a,v}, P.U.E. Onyisi³⁰, C.J. Oram^{159a},
 G. Ordonez¹⁰⁴, M.J. Oreglia³⁰, F. Orellana⁴⁹, Y. Oren¹⁵³,
 D. Orestano^{134a,134b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸,
 E.O. Ortega¹³⁰, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹,

G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135c}, F. Ould-Saada¹¹⁷,
 A. Ouraou¹³⁶, Q. Ouyang^{32a}, M. Owen⁸², S. Owen¹³⁹, A. Oyarzun^{31b},
 O.K. Øye¹³, V.E. Ozcan⁷⁷, N. Ozturk⁷, A. Pacheco Pages¹¹,
 C. Padilla Aranda¹¹, E. Paganis¹³⁹, F. Paige²⁴, K. Pajchel¹¹⁷, S. Palestini²⁹,
 D. Pallin³³, A. Palma^{124a,b}, J.D. Palmer¹⁷, Y.B. Pan¹⁷²,
 E. Panagiotopoulou⁹, B. Panes^{31a}, N. Panikashvili⁸⁷, S. Panitkin²⁴,
 D. Pantea^{25a}, M. Panuskova¹²⁵, V. Paolone¹²³, A. Paoloni^{133a,133b},
 A. Papadelis^{146a}, Th.D. Papadopoulou⁹, A. Paramonov⁵, W. Park^{24,w},
 M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸,
 E. Pasqualucci^{132a}, A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore²⁹,
 G. Pásztor^{49,x}, S. Pataraiia¹⁷², N. Patel¹⁵⁰, J.R. Pater⁸²,
 S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsya^{144a}, M.I. Pedraza Morales¹⁷²,
 S.V. Peleganchuk¹⁰⁷, H. Peng¹⁷², R. Pengo²⁹, A. Penson³⁴, J. Penwell⁶¹,
 M. Perantoni^{23a}, K. Perez^{34,m}, T. Perez Cavalcanti⁴¹, E. Perez Codina¹¹,
 M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, I. Peric²⁰, L. Perini^{89a,89b},
 H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴, S. Persebe^{3a}, P. Perus¹¹⁵,
 V.D. Peshekhonov⁶⁵, O. Peters¹⁰⁵, B.A. Petersen²⁹, J. Petersen²⁹,
 T.C. Petersen³⁵, E. Petit⁸³, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a},
 F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, A. Phan⁸⁶,
 A.W. Phillips²⁷, P.W. Phillips¹²⁹, G. Piacquadio²⁹, E. Piccaro⁷⁵,
 M. Piccinini^{19a,19b}, A. Pickford⁵³, R. Piegaiia²⁶, J.E. Pilcher³⁰,
 A.D. Pilkington⁸², J. Pina^{124a,l}, M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸,
 J.L. Pinfeld², J. Ping^{32c}, B. Pinto^{124a,b}, O. Pirotte²⁹, C. Pizio^{89a,89b},
 R. Placakyte⁴¹, M. Plamondon¹⁶⁹, W.G. Plano⁸², M.-A. Pleier²⁴,
 A.V. Pleskach¹²⁸, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlisky³³,
 L. Poggioli¹¹⁵, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a},
 A. Policicchio¹³⁸, A. Polini^{19a}, J. Poll⁷⁵, V. Polychronakos²⁴,
 D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a},
 B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹,
 X. Portell Bueso⁴⁸, R. Porter¹⁶³, C. Posch²¹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷,
 I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter⁸⁵, G. Poulard²⁹, J. Poveda¹⁷²,
 R. Prabhu⁷⁷, P. Pralavorio⁸³, S. Prasad⁵⁷, R. Pravahan⁷, S. Prell⁶⁴,
 K. Pretzl¹⁶, L. Pribyl²⁹, D. Price⁶¹, L.E. Price⁵, M.J. Price²⁹,
 P.M. Prichard⁷³, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸,
 F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³,
 H. Przysieszniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴, J. Purdham⁸⁷,
 M. Purohit^{24,w}, P. Puzo¹¹⁵, Y. Pylypchenko¹¹⁷, J. Qian⁸⁷, Z. Qian⁸³,
 Z. Qin⁴¹, A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷², F. Quinonez^{31a},

M. Raas¹⁰⁴, V. Radescu^{58b}, B. Radics²⁰, T. Rador^{18a}, F. Ragusa^{89a,89b},
G. Rahal¹⁷⁷, A.M. Rahimi¹⁰⁹, S. Rajagopalan²⁴, S. Rajek⁴²,
M. Rammensee⁴⁸, M. Rammes¹⁴¹, M. Ramstedt^{146a,146b},
K. Randrianarivony²⁸, P.N. Ratoff⁷¹, F. Rauscher⁹⁸, E. Rauter⁹⁹,
M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b}, A. Redelbach¹⁷³,
G. Redlinger²⁴, R. Reece¹²⁰, K. Reeves⁴⁰, A. Reichold¹⁰⁵,
E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², D. Reljic^{12a},
C. Rembser²⁹, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, P. Renkel³⁹, B. Rensch³⁵,
M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸,
A. Richards⁷⁷, R. Richter⁹⁹, E. Richter-Was^{38,y}, M. Ridel⁷⁸, S. Rieke⁸¹,
M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a},
R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵,
S.H. Robertson^{85,h}, A. Robichaud-Veronneau⁴⁹, D. Robinson²⁷,
J.E.M. Robinson⁷⁷, M. Robinson¹¹⁴, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶,
C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, S. Rodier⁸⁰, D. Rodriguez¹⁶²,
Y. Rodriguez Garcia¹⁵, A. Roe⁵⁴, S. Roe²⁹, O. Røhne¹¹⁷, V. Rojo¹,
S. Rolli¹⁶¹, A. Romaniouk⁹⁶, V.M. Romanov⁶⁵, G. Romeo²⁶,
D. Romero Maltrana^{31a}, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati¹³⁸, M. Rose⁷⁶,
G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶⁴, P.L. Rosendahl¹³, L. Rosselet⁴⁹,
V. Rossetti¹¹, E. Rossi^{102a,102b}, L.P. Rossi^{50a}, L. Rossi^{89a,89b}, M. Rotaru^{25a},
I. Roth¹⁷¹, J. Rothberg¹³⁸, I. Rottländer²⁰, D. Rousseau¹¹⁵, C.R. Royon¹³⁶,
A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan¹¹⁵, I. Rubinskiy⁴¹, B. Ruckert⁹⁸,
N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, G. Rudolph⁶², F. Rühr⁶, A. Ruiz-Martinez⁶⁴,
E. Rulikowska-Zarebska³⁷, V. Rumiantsev^{91,*}, L. Rummyantsev⁶⁵,
K. Runge⁴⁸, O. Runolfsson²⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵,
D.R. Rust⁶¹, J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁵,
Y.F. Ryabov¹²¹, V. Ryadovikov¹²⁸, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵,
N.C. Ryder¹¹⁸, S. Rzaeva¹⁰, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³,
H.F-W. Sadrozinski¹³⁷, R. Sadykov⁶⁵, F. Safai Tehrani^{132a,132b},
H. Sakamoto¹⁵⁵, G. Salamanna¹⁰⁵, A. Salamon^{133a}, M. Saleem¹¹¹,
D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁵,
D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salzburger²⁹, D. Sampsonidis¹⁵⁴,
B.H. Samset¹¹⁷, H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸,
M. Sandhoff¹⁷⁴, P. Sandhu¹⁵⁸, T. Sandoval²⁷, R. Sandstroem¹⁰⁵,
S. Sandvoss¹⁷⁴, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵,
C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a,l},
T. Sarangi¹⁷², E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisoehn¹⁷⁴,
O. Sasaki⁶⁶, T. Sasaki⁶⁶, N. Sasao⁶⁸, I. Satsounkevitch⁹⁰, G. Sauvage⁴,

J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³, P. Savva⁹, L. Sawyer^{24,i},
 D.H. Saxon⁵³, L.P. Says³³, C. Sbarra^{19a,19b}, A. Sbrizzi^{19a,19b}, O. Scallon⁹³,
 D.A. Scannicchio¹⁶³, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, U. Schäfer⁸¹,
 S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸,
 A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷,
 M.I. Scherzer¹⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{36a,36b},
 S. Schlenker²⁹, J.L. Schlereth⁵, E. Schmidt⁴⁸, M.P. Schmidt^{175,*},
 K. Schmieden²⁰, C. Schmitt⁸¹, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹,
 D. Schouten¹⁴², J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹,
 N. Schroer^{58c}, S. Schuh²⁹, G. Schuler²⁹, J. Schultes¹⁷⁴,
 H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰,
 M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸²,
 A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³,
 J. Schwindling¹³⁶, W.G. Scott¹²⁹, J. Searcy¹¹⁴, E. Sedykh¹²¹, E. Segura¹¹,
 S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniadze^{102a},
 D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b},
 N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, R. Seuster⁹⁹,
 H. Severini¹¹¹, M.E. Sevier⁸⁶, A. Sfyrla²⁹, E. Shabalina⁵⁴, M. Shamim¹¹⁴,
 L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵,
 L. Shaver⁶, C. Shaw⁵³, K. Shaw^{164a,164c}, D. Sherman¹⁷⁵, P. Sherwood⁷⁷,
 A. Shibata¹⁰⁸, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, A. Shmeleva⁹⁴,
 M.J. Shochet³⁰, D. Short¹¹⁸, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti¹⁵,
 A. Siebel¹⁷⁴, F. Siegert⁴⁸, J. Siegrist¹⁴, Dj. Sijacki^{12a}, O. Silbert¹⁷¹,
 J. Silva^{124a,z}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷,
 O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, M. Simonyan³⁵,
 P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa⁸¹, A.N. Sisakyan⁶⁵,
 S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjursen¹³, L.A. Skinnari¹⁴,
 K. Skovpen¹⁰⁷, P. Skubic¹¹¹, N. Skvorodnev²², M. Slater¹⁷, T. Slavicek¹²⁷,
 K. Sliwa¹⁶¹, T.J. Sloan⁷¹, J. Sloper²⁹, V. Smakhtin¹⁷¹, S.Yu. Smirnov⁹⁶,
 L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³,
 M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹,
 J. Snuverink¹⁰⁵, S. Snyder²⁴, M. Soares^{124a}, R. Sobie^{169,h}, J. Sodomka¹²⁷,
 A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, U. Soldevila¹⁶⁷,
 E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸,
 J. Sondericker²⁴, N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sorbi^{89a,89b},
 M. Sosebee⁷, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò³⁴, R. Spighi^{19a},
 G. Spigo²⁹, F. Spila^{132a,132b}, E. Spiriti^{134a}, R. Spiwoks²⁹, M. Spousta¹²⁶,
 T. Spreitzer¹⁵⁸, B. Spurlock⁷, R.D. St. Denis⁵³, T. Stahl¹⁴¹, J. Stahlman¹²⁰,

R. Stamen^{58a}, E. Stanecka²⁹, R.W. Stanek⁵, C. Stanescu^{134a}, S. Stapnes¹¹⁷,
 E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁹¹, A. Staude⁹⁸,
 P. Stavina^{144a}, G. Stavropoulos¹⁴, G. Steele⁵³, P. Steinbach⁴³,
 P. Steinberg²⁴, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁴¹,
 O. Stelzer-Chilton^{159a}, H. Stenzel⁵², K. Stevenson⁷⁵, G.A. Stewart⁵³,
 J.A. Stillings²⁰, T. Stockmanns²⁰, M.C. Stockton²⁹, K. Stoerig⁴⁸,
 G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷,
 A. Straessner⁴³, J. Strandberg⁸⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷,
 M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷³,
 D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹, J. Strube¹²⁹, B. Stugu¹³,
 I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁴, D.A. Soh^{151,r}, D. Su¹⁴³,
 S. Subramania², Y. Sugaya¹¹⁶, T. Sugimoto¹⁰¹, C. Suhr¹⁰⁶, K. Suita⁶⁷,
 M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{3d}, T. Sumida²⁹, X. Sun⁵⁵,
 J.E. Sundermann⁴⁸, K. Suruliz^{164a,164b}, S. Sushkov¹¹, G. Susinno^{36a,36b},
 M.R. Sutton¹³⁹, Y. Suzuki⁶⁶, Yu.M. Sviridov¹²⁸, S. Swedish¹⁶⁸, I. Sykora^{144a},
 T. Sykora¹²⁶, B. Szeless²⁹, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann²⁹,
 A. Taffard¹⁶³, R. Tafirout^{159a}, A. Taga¹¹⁷, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹,
 H. Takai²⁴, R. Takashima⁶⁹, H. Takeda⁶⁷, T. Takeshita¹⁴⁰, M. Talby⁸³,
 A. Talyshev¹⁰⁷, M.C. Tamsett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹,
 S. Tanaka⁶⁶, Y. Tanaka¹⁰⁰, K. Tani⁶⁷, N. Tannoury⁸³, G.P. Tappern²⁹,
 S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁴, G.F. Tartarelli^{89a},
 P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, C. Taylor⁷⁷,
 F.E. Taylor⁹², G. Taylor¹³⁷, G.N. Taylor⁸⁶, W. Taylor^{159b},
 M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸,
 H. Ten Kate²⁹, P.K. Teng¹⁵¹, Y.D. Tennenbaum-Katan¹⁵², S. Terada⁶⁶,
 K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Terwort^{41,p}, M. Testa⁴⁷, R.J. Teuscher^{158,h},
 C.M. Tevlin⁸², J. Thadome¹⁷⁴, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸,
 M. Thioye¹⁷⁵, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson⁸⁴,
 P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, E. Thomson¹²⁰,
 M. Thomson²⁷, R.P. Thun⁸⁷, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴,
 Y.A. Tikhonov¹⁰⁷, C.J.W.P. Timmermans¹⁰⁴, P. Tipton¹⁷⁵,
 F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, J. Tobias⁴⁸, B. Toczec³⁷,
 T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁶, S. Tokár^{144a},
 K. Tokunaga⁶⁷, K. Tokushuku⁶⁶, K. Tollefson⁸⁸, M. Tomoto¹⁰¹,
 L. Tompkins¹⁴, K. Toms¹⁰³, A. Tonazzo^{134a,134b}, G. Tong^{32a}, A. Tonoyan¹³,
 C. Topfel¹⁶, N.D. Topilin⁶⁵, I. Torchiani²⁹, E. Torrence¹¹⁴, E. Torró
 Pastor¹⁶⁷, J. Toth^{83,x}, F. Touchard⁸³, D.R. Tovey¹³⁹, D. Traynor⁷⁵,
 T. Trefzger¹⁷³, J. Treis²⁰, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a},

S. Trincaz-Duvoid⁷⁸, T.N. Trinh⁷⁸, M.F. Tripiana⁷⁰, N. Triplett⁶⁴,
 W. Trischuk¹⁵⁸, A. Trivedi^{24,w}, B. Trocmé⁵⁵, C. Troncon^{89a},
 M. Trottier-McDonald¹⁴², A. Trzupek³⁸, C. Tsarouchas²⁹, J.C-L. Tseng¹¹⁸,
 M. Tsiakiris¹⁰⁵, P.V. Tsiarehka⁹⁰, D. Tsionou⁴, G. Tsipolitis⁹,
 V. Tsiskaridze⁴⁸, E.G. Tskhadadze⁵¹, I.I. Tsukerman⁹⁵, V. Tsulaia¹²³,
 J.-W. Tsung²⁰, S. Tsuno⁶⁶, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, J.M. Tuggle³⁰,
 M. Turala³⁸, D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, P.M. Tuts³⁴,
 A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, D. Typaldos¹⁷,
 H. Tyrvaiven²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸,
 M. Ugland¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹,
 D.G. Underwood⁵, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁶, D. Urbaniec³⁴,
 E. Urkovsky¹⁵³, P. Urquijo⁴⁹, P. Urrejola^{31a}, G. Usai⁷, M. Uslenghi^{119a,119b},
 L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, C. Valderanis⁹⁹,
 J. Valenta¹²⁵, P. Valente^{132a}, S. Valentinetti^{19a,19b}, S. Valkar¹²⁶,
 E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷,
 H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, E. van der Poel¹⁰⁵,
 D. van der Ster²⁹, B. Van Eijk¹⁰⁵, N. van Eldik⁸⁴, P. van Gemmeren⁵,
 Z. van Kesteren¹⁰⁵, I. van Vulpen¹⁰⁵, W. Vandelli²⁹, G. Vandoni²⁹,
 A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, F. Varela Rodriguez²⁹,
 R. Vari^{132a}, E.W. Varnes⁶, D. Varouchas¹⁴, A. Vartapetian⁷,
 K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, G. Vegni^{89a,89b},
 J.J. Veillet¹¹⁵, C. Vellidis⁸, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a},
 A. Ventura^{72a,72b}, D. Ventura¹³⁸, S. Ventura⁴⁷, M. Venturi⁴⁸, N. Venturi¹⁶,
 V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵,
 A. Vest⁴³, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵, T. Vickey^{145b,aa},
 G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷,
 E. Vilucchi⁴⁷, M.G. Vincter²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁵,
 M. Virchaux^{136,*}, S. Viret³³, J. Virzi¹⁴, A. Vitale^{19a,19b}, O. Vitells¹⁷¹,
 I. Vivarelli⁴⁸, F. Vives Vaque¹¹, S. Vlachos⁹, M. Vlasak¹²⁷, N. Vlasov²⁰,
 A. Vogel²⁰, P. Vokac¹²⁷, M. Volpi¹¹, G. Volpini^{89a}, H. von der Schmitt⁹⁹,
 J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶,
 A.P. Vorobiev¹²⁸, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁴,
 J.H. Vosseveld⁷³, A.S. Vovenko¹²⁸, N. Vranjes^{12a},
 M. Vranjes Milosavljevic^{12a}, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁸¹,
 R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁴, P. Wagner¹²⁰, H. Wahlen¹⁷⁴,
 J. Wakabayashi¹⁰¹, J. Walbersloh⁴², S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸,
 W. Walkowiak¹⁴¹, R. Wall¹⁷⁵, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷²,
 J. Wang¹⁵¹, J. Wang^{32d}, J.C. Wang¹³⁸, R. Wang¹⁰³, S.M. Wang¹⁵¹,

A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸, P.M. Watkins¹⁷,
 A.T. Watson¹⁷, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰,
 B.M. Waugh⁷⁷, J. Weber⁴², M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴,
 A.R. Weidberg¹¹⁸, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²²,
 P.S. Wells²⁹, M. Wen⁴⁷, T. Wenaus²⁴, S. Wendler¹²³, Z. Weng^{151,r},
 T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹,
 M. Werth¹⁶³, M. Wessels^{58a}, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³,
 S.P. Whitaker²¹, A. White⁷, M.J. White⁸⁶, S. White²⁴, S.R. Whitehead¹¹⁸,
 D. Whiteson¹⁶³, D. Whittington⁶¹, F. Wicek¹¹⁵, D. Wicke¹⁷⁴,
 F.J. Wickens¹²⁹, W. Wiedenmann¹⁷², M. Wielers¹²⁹, P. Wienemann²⁰,
 C. Wiglesworth⁷³, L.A.M. Wiik⁴⁸, A. Wildauer¹⁶⁷, M.A. Wildt^{41,p},
 I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰,
 W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷,
 I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³,
 M.W. Wolter³⁸, H. Wolters^{124a,f}, G. Wooden¹¹⁸, B.K. Wosiek³⁸,
 J. Wotschack²⁹, M.J. Woudstra⁸⁴, K. Wraight⁵³, C. Wright⁵³, B. Wrona⁷³,
 S.L. Wu¹⁷², X. Wu⁴⁹, Y. Wu^{32b}, E. Wulf³⁴, R. Wunstorf⁴², B.M. Wynne⁴⁵,
 L. Xaplanteris⁹, S. Xella³⁵, S. Xie⁴⁸, Y. Xie^{32a}, C. Xu^{32b}, D. Xu¹³⁹,
 G. Xu^{32a}, B. Yabsley¹⁵⁰, M. Yamada⁶⁶, A. Yamamoto⁶⁶, K. Yamamoto⁶⁴,
 S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵,
 Y. Yamazaki⁶⁷, Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶¹, Y. Yang^{32a},
 Z. Yang^{146a,146b}, S. Yanush⁹¹, W-M. Yao¹⁴, Y. Yao¹⁴, Y. Yasu⁶⁶, J. Ye³⁹,
 S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷⁰, R. Yoshida⁵,
 C. Young¹⁴³, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu^{32c,ab}, L. Yuan^{32a,ac},
 A. Yurkewicz¹⁴⁸, V.G. Zaets¹²⁸, R. Zaidan⁶³, A.M. Zaitsev¹²⁸,
 Z. Zajacova²⁹, Yo.K. Zalite¹²¹, L. Zanello^{132a,132b}, P. Zarzhitsky³⁹,
 A. Zaytsev¹⁰⁷, M. Zdrzil¹⁴, C. Zeitnitz¹⁷⁴, M. Zeller¹⁷⁵, P.F. Zema²⁹,
 A. Zemla³⁸, C. Zender²⁰, A.V. Zenin¹²⁸, O. Zenin¹²⁸, T. Ženiš^{144a},
 Z. Zenonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷,
 Z. Zhan^{32d}, D. Zhang^{32b}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵,
 L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁵, S. Zheng^{32a},
 J. Zhong^{151,ad}, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹,
 Y. Zhu¹⁷², X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶¹, B. Zilka^{144a},
 R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹,
 R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷²,
 A. Zoccoli^{19a,19b}, Y. Zolnierowski⁴, A. Zsenei²⁹, M. zur Nedden¹⁵,
 V. Zutshi¹⁰⁶, L. Zwalinski²⁹.

- ¹ University at Albany, 1400 Washington Ave, Albany, NY 12222, United States of America
- ² University of Alberta, Department of Physics, Centre for Particle Physics, Edmonton, AB T6G 2G7, Canada
- ³ Ankara University^(a), Faculty of Sciences, Department of Physics, TR 061000 Tandogan, Ankara; Dumlupinar University^(b), Faculty of Arts and Sciences, Department of Physics, Kutahya; Gazi University^(c), Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara; TOBB University of Economics and Technology^(d), Faculty of Arts and Sciences, Division of Physics, 06560, Sogutozu, Ankara; Turkish Atomic Energy Authority^(e), 06530, Lodumlu, Ankara, Turkey
- ⁴ LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France
- ⁵ Argonne National Laboratory, High Energy Physics Division, 9700 S. Cass Avenue, Argonne IL 60439, United States of America
- ⁶ University of Arizona, Department of Physics, Tucson, AZ 85721, United States of America
- ⁷ The University of Texas at Arlington, Department of Physics, Box 19059, Arlington, TX 76019, United States of America
- ⁸ University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopouli, Zografou, GR 15771 Athens, Greece
- ⁹ National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780 Zografou, Greece
- ¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan
- ¹¹ Institut de Física d'Altes Energies, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES - 08193 Bellaterra (Barcelona), Spain
- ¹² University of Belgrade^(a), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences^(b) M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia, Serbia
- ¹³ University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway
- ¹⁴ Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States of America
- ¹⁵ Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany
- ¹⁶ University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern,

Switzerland

¹⁷ University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom

¹⁸ Bogazici University^(a), Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul; Dogus University^(b), Faculty of Arts and Sciences, Department of Physics, 34722, Kadikoy, Istanbul; ^(c)Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Sehitkamil, Gaziantep, Turkey; Istanbul Technical University^(d), Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, Istanbul, Turkey

¹⁹ INFN Sezione di Bologna^(a); Università di Bologna, Dipartimento di Fisica^(b), viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy

²⁰ University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany

²¹ Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States of America

²² Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States of America

²³ Universidade Federal do Rio De Janeiro, COPPE/EE/IF ^(a), Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro;

^(b)Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil

²⁴ Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States of America

²⁵ National Institute of Physics and Nuclear Engineering^(a)Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania; University Politehnica Bucharest^(b), Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University^(c) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania

²⁶ Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina

²⁷ University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom

²⁸ Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada

²⁹ CERN, CH - 1211 Geneva 23, Switzerland

³⁰ University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States of America

³¹ Pontificia Universidad Católica de Chile, Facultad de Fisica,

- Departamento de Física^(a), Avda. Vicuna Mackenna 4860, San Joaquin, Santiago; Universidad Técnica Federico Santa María, Departamento de Física^(b), Avda. España 1680, Casilla 110-V, Valparaíso, Chile
- ³² Institute of High Energy Physics, Chinese Academy of Sciences^(a), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics^(b), Hefei, CN - Anhui 230026; Nanjing University, Department of Physics^(c), Nanjing, CN - Jiangsu 210093; Shandong University, High Energy Physics Group^(d), Jinan, CN - Shandong 250100, China
- ³³ Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubiere Cedex, France
- ³⁴ Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States of America
- ³⁵ University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 Kobenhavn 0, Denmark
- ³⁶ INFN Gruppo Collegato di Cosenza^(a); Università della Calabria, Dipartimento di Fisica^(b), IT-87036 Arcavacata di Rende, Italy
- ³⁷ Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland
- ³⁹ Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States of America
- ⁴⁰ University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States of America
- ⁴¹ DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
- ⁴² TU Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany
- ⁴³ Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
- ⁴⁴ Duke University, Department of Physics, Durham, NC 27708, United States of America
- ⁴⁵ University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom

- ⁴⁶ Fachhochschule Wiener Neustadt; Johannes Gutenbergstrasse 3 AT - 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, via Enrico Fermi 40, IT-00044 Frascati, Italy
- ⁴⁸ Albert-Ludwigs-Universität, Fakultät für Mathematik und Physik, Hermann-Herder Str. 3, D - 79104 Freiburg i.Br., Germany
- ⁴⁹ Université de Genève, Section de Physique, 24 rue Ernest Ansermet, CH - 1211 Geneve 4, Switzerland
- ⁵⁰ INFN Sezione di Genova^(a); Università di Genova, Dipartimento di Fisica^(b), via Dodecaneso 33, IT - 16146 Genova, Italy
- ⁵¹ Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili St., GE - 380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE - 380086 Tbilisi, Georgia
- ⁵² Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany
- ⁵³ University of Glasgow, Department of Physics and Astronomy, Glasgow G12 8QQ, United Kingdom
- ⁵⁴ Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany
- ⁵⁵ LPSC, CNRS/IN2P3 and Univ. Joseph Fourier Grenoble, 53 avenue des Martyrs, FR-38026 Grenoble Cedex, France
- ⁵⁶ Hampton University, Department of Physics, Hampton, VA 23668, United States of America
- ⁵⁷ Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, MA 02138, United States of America
- ⁵⁸ Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik^(a), Im Neuenheimer Feld 227, D-69120 Heidelberg; Physikalisches Institut^(b), Philosophenweg 12, D-69120 Heidelberg; ZITI Ruprecht-Karls-University Heidelberg^(c), Lehrstuhl für Informatik V, B6, 23-29, DE - 68131 Mannheim, Germany
- ⁵⁹ Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP - Hiroshima 739-8526, Japan
- ⁶⁰ Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP - Hiroshima 731-5193, Japan
- ⁶¹ Indiana University, Department of Physics, Swain Hall West 117, Bloomington, IN 47405-7105, United States of America
- ⁶² Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A - 6020

Innsbruck, Austria

⁶³ University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242-1479, United States of America

⁶⁴ Iowa State University, Department of Physics and Astronomy, Ames High Energy Physics Group, Ames, IA 50011-3160, United States of America

⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, RU-141980 Moscow Region, Russia, Russia

⁶⁶ KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan

⁶⁷ Kobe University, Graduate School of Science, 1-1 Rokkodai-cho, Nada-ku, JP Kobe 657-8501, Japan

⁶⁸ Kyoto University, Faculty of Science, Oiwake-cho, Kitashirakawa, Sakyou-ku, Kyoto-shi, JP - Kyoto 606-8502, Japan

⁶⁹ Kyoto University of Education, 1 Fukakusa, Fujimori, fushimi-ku, Kyoto-shi, JP - Kyoto 612-8522, Japan

⁷⁰ Universidad Nacional de La Plata, FCE, Departamento de Física, IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina

⁷¹ Lancaster University, Physics Department, Lancaster LA1 4YB, United Kingdom

⁷² INFN Sezione di Lecce^(a); Università del Salento, Dipartimento di Fisica^(b)Via Arnesano IT - 73100 Lecce, Italy

⁷³ University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, United Kingdom

⁷⁴ Jožef Stefan Institute and University of Ljubljana, Department of Physics, SI-1000 Ljubljana, Slovenia

⁷⁵ Queen Mary University of London, Department of Physics, Mile End Road, London E1 4NS, United Kingdom

⁷⁶ Royal Holloway, University of London, Department of Physics, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom

⁷⁷ University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, United Kingdom

⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, Université Pierre et Marie Curie (Paris 6), Université Denis Diderot (Paris-7), CNRS/IN2P3, Tour 33, 4 place Jussieu, FR - 75252 Paris Cedex 05, France

⁷⁹ Fysiska institutionen, Lunds universitet, Box 118, SE - 221 00 Lund, Sweden

⁸⁰ Universidad Autonoma de Madrid, Facultad de Ciencias, Departamento de Física Teórica, ES - 28049 Madrid, Spain

- ⁸¹ Universität Mainz, Institut für Physik, Staudinger Weg 7, DE - 55099 Mainz, Germany
- ⁸² University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ⁸⁴ University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States of America
- ⁸⁵ McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada
- ⁸⁶ University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia
- ⁸⁷ The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States of America
- ⁸⁸ Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States of America
- ⁸⁹ INFN Sezione di Milano^(a); Università di Milano, Dipartimento di Fisica^(b), via Celoria 16, IT - 20133 Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
- ⁹¹ National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
- ⁹² Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States of America
- ⁹³ University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia
- ⁹⁶ Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU - 115409 Moscow, Russia
- ⁹⁷ Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia
- ⁹⁸ Ludwig-Maximilians-Universität München, Fakultät für Physik, Am

Coulombwall 1, DE - 85748 Garching, Germany

⁹⁹ Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

¹⁰⁰ Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan

¹⁰¹ Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan

¹⁰² INFN Sezione di Napoli^(a); Università di Napoli, Dipartimento di Scienze Fisiche^(b), Complesso Universitario di Monte Sant'Angelo, via Cinthia, IT - 80126 Napoli, Italy

¹⁰³ University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131 USA, United States of America

¹⁰⁴ Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands

¹⁰⁵ Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands

¹⁰⁶ Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States of America

¹⁰⁷ Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia

¹⁰⁸ New York University, Department of Physics, 4 Washington Place, New York NY 10003, USA, United States of America

¹⁰⁹ Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States of America

¹¹⁰ Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan

¹¹¹ University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States of America

¹¹² Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States of America

¹¹³ Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic

¹¹⁴ University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States of America

¹¹⁵ LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France

¹¹⁶ Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan

- ¹¹⁷ University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO - 0316 Oslo 3, Norway
- ¹¹⁸ Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
- ¹¹⁹ INFN Sezione di Pavia^(a); Università di Pavia, Dipartimento di Fisica Nucleare e Teorica^(b), Via Bassi 6, IT-27100 Pavia, Italy
- ¹²⁰ University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States of America
- ¹²¹ Petersburg Nuclear Physics Institute, RU - 188 300 Gatchina, Russia
- ¹²² INFN Sezione di Pisa^(a); Università di Pisa, Dipartimento di Fisica E. Fermi^(b), Largo B. Pontecorvo 3, IT - 56127 Pisa, Italy
- ¹²³ University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, PA 15260, United States of America
- ¹²⁴ Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP^(a), Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE^(b), E-18071 Granada, Spain
- ¹²⁵ Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ - 18221 Praha 8, Czech Republic
- ¹²⁶ Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2, CZ - 18000 Praha 8, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Zikova 4, CZ - 166 35 Praha 6, Czech Republic
- ¹²⁸ State Research Center Institute for High Energy Physics, Moscow Region, 142281, Protvino, Pobeda street, 1, Russia
- ¹²⁹ Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
- ¹³⁰ University of Regina, Physics Department, Canada
- ¹³¹ Ritsumeikan University, Noji Higashi 1 chome 1-1, JP - Kusatsu, Shiga 525-8577, Japan
- ¹³² INFN Sezione di Roma I^(a); Università La Sapienza, Dipartimento di Fisica^(b), Piazzale A. Moro 2, IT- 00185 Roma, Italy
- ¹³³ INFN Sezione di Roma Tor Vergata^(a); Università di Roma Tor Vergata, Dipartimento di Fisica^(b), via della Ricerca Scientifica, IT-00133 Roma, Italy

- ¹³⁴ INFN Sezione di Roma Tre^(a); Università Roma Tre, Dipartimento di Fisica^(b), via della Vasca Navale 84, IT-00146 Roma, Italy
- ¹³⁵ Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II, Faculté des Sciences Ain Chock^(a), B.P. 5366, MA - Casablanca; Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN)^(b), B.P. 1382 R.P. 10001 Rabat 10001; Université Mohamed Premier^(c), LPTPM, Faculté des Sciences, B.P.717. Bd. Mohamed VI, 60000, Oujda ; Université Mohammed V, Faculté des Sciences^(d) 4 Avenue Ibn Battouta, BP 1014 RP, 10000 Rabat, Morocco
- ¹³⁶ CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR - 91191 Gif-sur-Yvette, France
- ¹³⁷ University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, CA 95064, United States of America
- ¹³⁸ University of Washington, Seattle, Department of Physics, Box 351560, Seattle, WA 98195-1560, United States of America
- ¹³⁹ University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom
- ¹⁴⁰ Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP - Nagano 390-8621, Japan
- ¹⁴¹ Universität Siegen, Fachbereich Physik, D 57068 Siegen, Germany
- ¹⁴² Simon Fraser University, Department of Physics, 8888 University Drive, CA - Burnaby, BC V5A 1S6, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford, California 94309, United States of America
- ¹⁴⁴ Comenius University, Faculty of Mathematics, Physics & Informatics^(a), Mlynska dolina F2, SK - 84248 Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics^(b), Watsonova 47, SK - 04353 Kosice, Slovak Republic
- ¹⁴⁵ ^(a)University of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006; ^(b)School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa
- ¹⁴⁶ Stockholm University: Department of Physics^(a); The Oskar Klein Centre^(b), AlbaNova, SE - 106 91 Stockholm, Sweden
- ¹⁴⁷ Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden
- ¹⁴⁸ Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States of America

- ¹⁴⁹ University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
- ¹⁵⁰ University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
- ¹⁵¹ Institute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
- ¹⁵² Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
- ¹⁵³ Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv 69978, Israel
- ¹⁵⁴ Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR - 54124, Thessaloniki, Greece
- ¹⁵⁵ The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan
- ¹⁵⁶ Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
- ¹⁵⁷ Tokyo Institute of Technology, Department of Physics, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
- ¹⁵⁸ University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada
- ¹⁵⁹ TRIUMF^(a), 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; ^(b)York University, Department of Physics and Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada
- ¹⁶⁰ University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan
- ¹⁶¹ Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States of America
- ¹⁶² Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia
- ¹⁶³ University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States of America
- ¹⁶⁴ INFN Gruppo Collegato di Udine^(a); ICTP^(b), Strada Costiera 11, IT-34014, Trieste; Università di Udine, Dipartimento di Fisica^(c), via delle Scienze 208, IT - 33100 Udine, Italy
- ¹⁶⁵ University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of America
- ¹⁶⁶ University of Uppsala, Department of Physics and Astronomy, P.O. Box

516, SE -751 20 Uppsala, Sweden

¹⁶⁷ Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. of Valencia, and Inst. de Microelectrónica de Barcelona (IMB-CNM-CSIC) 08193 Bellaterra, Spain

¹⁶⁸ University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada

¹⁶⁹ University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada

¹⁷⁰ Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan

¹⁷¹ The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel

¹⁷² University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, Wisconsin, United States of America

¹⁷³ Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany

¹⁷⁴ Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany

¹⁷⁵ Yale University, Department of Physics, PO Box 208121, New Haven CT, 06520-8121, United States of America

¹⁷⁶ Yerevan Physics Institute, Alikhanian Brothers Street 2, AM - 375036 Yerevan, Armenia

¹⁷⁷ Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France

^a Also at LIP, Portugal

^b Also at Faculdade de Ciencias, Universidade de Lisboa, Lisboa, Portugal

^c Also at CPPM, Marseille, France.

^d Also at TRIUMF, Vancouver, Canada

^e Also at FPACS, AGH-UST, Cracow, Poland

^f Also at Department of Physics, University of Coimbra, Coimbra, Portugal

^g Also at Università di Napoli Parthenope, Napoli, Italy

^h Also at Institute of Particle Physics (IPP), Canada

ⁱ Also at Louisiana Tech University, Ruston, USA

^j Also at Universidade de Lisboa, Lisboa, Portugal

^k At California State University, Fresno, USA

^l Also at Faculdade de Ciencias, Universidade de Lisboa and at Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

- ^m Also at California Institute of Technology, Pasadena, USA
- ⁿ Also at University of Montreal, Montreal, Canada
- ^o Also at Baku Institute of Physics, Baku, Azerbaijan
- ^p Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^q Also at Manhattan College, New York, USA
- ^r Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- ^s Also at Taiwan Tier-1, ASGC, Academia Sinica, Taipei, Taiwan
- ^t Also at School of Physics, Shandong University, Jinan, China
- ^u Also at Rutherford Appleton Laboratory, Didcot, UK
- ^v Also at Departamento de Física, Universidade de Minho, Braga, Portugal
- ^w Also at Department of Physics and Astronomy, University of South Carolina, Columbia, USA
- ^x Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ^y Also at Institute of Physics, Jagiellonian University, Cracow, Poland
- ^z Also at Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
- ^{aa} Also at Department of Physics, Oxford University, Oxford, UK
- ^{ab} Also at CEA, Gif sur Yvette, France
- ^{ac} Also at LPNHE, Paris, France
- ^{ad} Also at Nanjing University, Nanjing Jiangsu, China
- * Deceased