



Search for Scalar Diphoton Resonances in the Mass Range 65 – 600 GeV with the ATLAS Detector in pp Collision Data at $\sqrt{s} = 8\text{ TeV}$

G. Aad, L. Alio, M. Barbero, J. C. Clémens, Y. Coadou, Sara Diglio, F. Djama, L. Feligioni, G. Hallewell, D. Hoffmann, et al.

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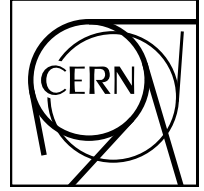
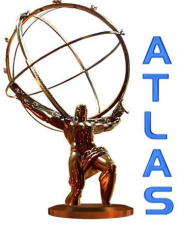
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The ATLAS Collaboration

Abstract

A search for scalar particles decaying via narrow resonances into two photons in the mass range 65–600 GeV is performed using 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data collected with the ATLAS detector at the Large Hadron Collider. The recently discovered Higgs boson is treated as a background. No significant evidence for an additional signal is observed. The results are presented as limits at the 95% confidence level on the production cross-section of a scalar boson times branching ratio into two photons, in a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The upper limits set extend over a considerably wider mass range than previous searches.

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In July 2012, the ATLAS and CMS collaborations reported the discovery of a new particle [1, 2] whose measured couplings and properties are compatible with the Standard Model Higgs boson (H) [3–6]. However, several extensions to the Standard Model, in particular models featuring an extended Higgs sector [7–13], predict new scalar resonances below or above the H mass which may be narrow when their branching ratio to two photons is non-negligible.

This Letter presents a search for a scalar particle X of mass m_X decaying via narrow resonances into two photons. It extends the method developed for the measurement of the H couplings in the $H \rightarrow \gamma\gamma$ channel [3] to the range $65 < m_X < 600$ GeV. Analytical descriptions of the signal and background distributions are fitted to the measured diphoton invariant mass spectrum $m_{\gamma\gamma}$ to determine the signal and background yields. The result is presented as a limit on the production cross-section times the branching ratio $BR(X \rightarrow \gamma\gamma)$, restricted to a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The resonance with mass m_X is considered narrow when its intrinsic width is smaller than $0.09 \text{ GeV} + 0.01 \cdot m_X$. This upper limit is defined such that the bias in the number of fitted signal events is kept below 10%, and ensures that the diphoton invariant mass width is dominated by the experimental resolution in the ATLAS detector. Model-dependent interference effects between the resonance and the continuum diphoton background are not considered.

The ATLAS detector [14] at the LHC [15] covers the pseudorapidity [16] range $|\eta| < 4.9$ and the full azimuthal angle ϕ . It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$, surrounded by electromagnetic and hadronic calorimeters and an external muon spectrometer.

The search is carried out using the $\sqrt{s} = 8$ TeV pp collision dataset collected in 2012, with stable beam conditions and all ATLAS subsystems operational, which corresponds to an integrated luminosity of $\mathcal{L} = 20.3 \pm 0.6 \text{ fb}^{-1}$ [17]. The data were recorded using a

diphoton trigger that required two electromagnetic clusters with transverse energies E_T above 20 GeV, both fulfilling identification criteria based on shower shapes in the electromagnetic calorimeter. The efficiency of the diphoton trigger [18] is $(98.7 \pm 0.5)\%$ for signal events passing the analysis selection.

The event selection requires at least one reconstructed primary vertex with two or more tracks with transverse momenta $p_T > 0.4$ GeV, and at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$, excluding the barrel/endcap transition region of the calorimeter, $1.37 < |\eta| < 1.56$.

Photon reconstruction is seeded by clusters of electromagnetic calorimeter cells. Clusters without matching tracks are classified as unconverted photons. Clusters with matched tracks are considered as electron candidates, but are classified as converted photons if they are associated with two tracks consistent with a $\gamma \rightarrow e^+e^-$ conversion process, or a single track leaving no hit in the innermost layer of the inner tracking detector. The photon energy calibration procedure is the same as in Ref. [3].

Photon candidates are required to fulfill identification criteria based on shower shapes in the electromagnetic calorimeter, and on energy leakage into the hadronic calorimeter [19]. Identification efficiencies, averaged over η , range from 70% to above 99% for the E_T range under consideration. To further reduce the background from jets, the calorimeter isolation transverse energy E_T^{iso} is required to be smaller than 6 GeV, where E_T^{iso} is defined as the sum of transverse energies of the positive-energy topological clusters [20] within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the photon candidate. The core of the photon shower is excluded, and E_T^{iso} is corrected for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pile-up are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the track isolation, defined as the scalar sum of the p_T of the primary vertex tracks with

$p_T > 1$ GeV in a $\Delta R = 0.2$ cone around the photon candidate, excluding the conversion tracks, is required to be smaller than 2.6 GeV.

The $m_{\gamma\gamma}$ invariant mass is evaluated using the leading photon (γ_1) and subleading photon (γ_2) energies measured in the calorimeter, the azimuthal angle $\Delta\phi$ and the pseudorapidity $\Delta\eta$ separations between the photons determined from their positions in the calorimeter and the position of the reconstructed diphoton vertex [3].

After selection, the data sample consists of a continuum background with dominantly $\gamma\gamma$, γ -jet, jet-jet events and Drell-Yan (DY) production of electron pairs where both electrons are misidentified as photons. Two peaking backgrounds arise from the Z boson component of the DY and from $H \rightarrow \gamma\gamma$.

To increase the sensitivity, the search is split into two analyses: a categorized low-mass analysis covering the range $65 < m_X < 110$ GeV, and an inclusive high-mass analysis covering $110 < m_X < 600$ GeV. To provide sidebands on both sides of the tested mass point m_X , the $m_{\gamma\gamma}$ ranges are wider than the m_X ranges probed and overlap at the transition between the two analyses.

The low-mass analysis requires a precise modeling of the DY background, dominated by the Z boson resonance, where both electrons are misidentified as photons, mostly classified as converted photons. The loss of signal sensitivity is mitigated by separating the events into three categories with different signal-to-background ratios, according to the conversion status of the photon pair: two unconverted (UU), one converted and one unconverted (CU) or two converted photons (CC). Table I shows the fractions of signal and DY events expected in each category.

TABLE I. Number of diphoton events in data (N_{data}), number of expected Drell-Yan events (N_{DY}), fractions of expected signal (f_X) and Drell-Yan (f_{DY}) in each conversion category for the low-mass analysis. The signal fraction is given for $m_X = 90$ GeV but the mass-dependence is negligible.

$\gamma\gamma$ category	UU	CU	CC
N_{data}	272184	253804	63224
N_{DY}	1080 ± 260	3400 ± 600	2700 ± 250
f_{DY}	15.0%	47.3%	37.7%
f_X	48.7%	42.5%	8.8%

In each category, the Z resonance shape is described by a double-sided Crystal Ball function [23]. Due to the limited size of the fully simulated $Z \rightarrow ee$ sample [24, 25] where both electrons are misidentified as photons, the shape parameters are determined by a fit to a dielectron data sample, where both electrons are required to fulfill shower shape identification criteria and the same E_T thresholds as the photons.

Since most of the electrons misidentified as photons underwent large bremsstrahlung, the invariant mass distribution of the Z boson reconstructed as a photon pair

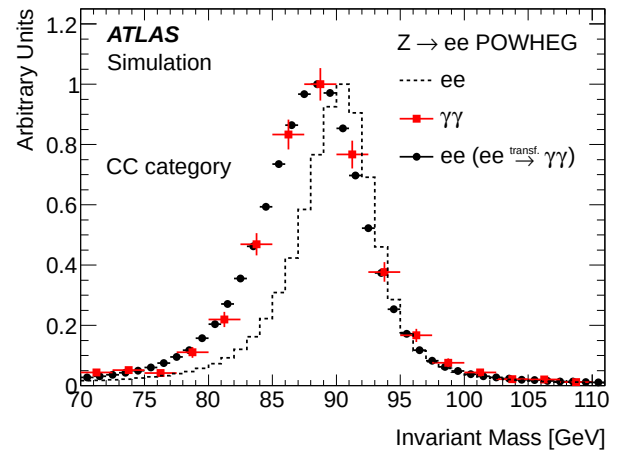


FIG. 1. Invariant mass distributions in the CC category for fully simulated $Z \rightarrow ee$ events reconstructed as ee (dotted-lines), reconstructed as $\gamma\gamma$ (squares), and reconstructed as ee after transforming the electrons to match the kinematics of the electrons misidentified as converted photons (circles).

is wider and shifted to lower masses by up to 2 GeV with respect to the Z boson mass reconstructed as an electron pair. The $Z \rightarrow ee$ invariant mass distributions extracted from data in each category are transformed by applying E_T -dependent shifts and smearing factors to the electron E_T and ϕ , to match the kinematics of the electrons misidentified as photons. Two sets of transformations are derived for γ_1 and γ_2 depending on their conversion status, using a $Z \rightarrow ee$ sample generated with POWHEG [26, 27] interfaced with PYTHIA8 [28] for showering and hadronization. Figure 1 illustrates the effect of the electrons' transformations on the invariant mass shapes in the fully simulated $Z \rightarrow ee$ sample. Systematic uncertainties on the template shapes and the Z peak position are evaluated by varying the parameters of the electrons' transformations by $\pm 1\sigma$.

The DY normalization is computed from the $e \rightarrow \gamma$ fake rates, defined as the ratios of $e\gamma$ to ee pairs measured in $Z \rightarrow ee$ data, separately for γ_1 and γ_2 and each conversion status. A correction factor obtained from fully simulated $Z \rightarrow ee$ events is applied to account for additional effects, mainly the differences in isolation efficiencies and vertex reconstruction efficiency between $\gamma\gamma$ and ee events. The associated uncertainties (9 to 25%) are dominated by the subtraction of the continuum background and the detector material description.

The determination of the analytical form of the continuum background and the corresponding uncertainties follow the method detailed in Ref. [1]. The sum of a Landau distribution and an exponential distribution is used over the full $m_{\gamma\gamma}$ range. The bias on the signal yield induced by the analytical shape function is required to be lower than 20% of the statistical uncertainty on the fitted sig-

nal yield for the background-only spectrum. This bias is measured from a large sample generated from a parameterized detector response, and is accounted for by a mass-dependent uncertainty. Figure 2 shows background-only fits to the data in the low-mass analysis for the three conversion categories.

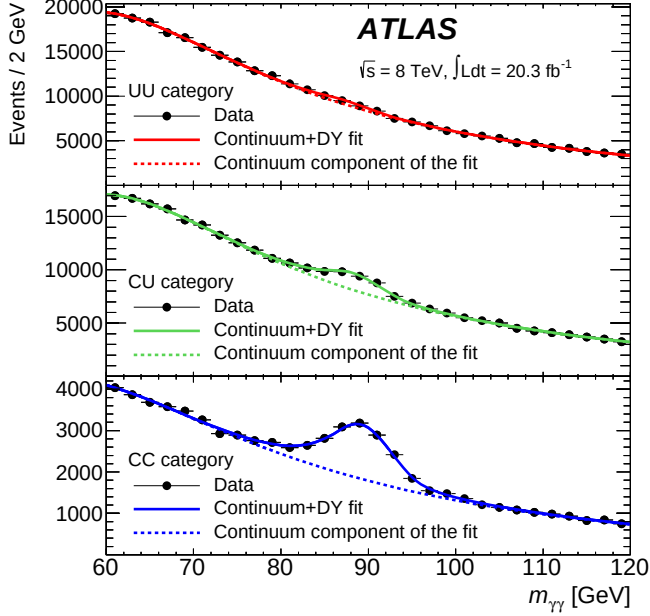


FIG. 2. Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the three conversion categories in the low-mass range. The solid lines show the sum of the Drell–Yan and the continuum background components. The dashed lines show the continuum background component only.

In the high-mass analysis, relative cuts $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$ and $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$ are added to the selection requirements to reduce the continuum backgrounds and thereby increase the signal sensitivity. In total, 108654 events with $100 < m_{\gamma\gamma} < 800$ GeV are selected.

To determine the continuum background shape over this large mass range, an exponential of a second-order polynomial is fitted inside a sliding $m_{\gamma\gamma}$ window of width $80 \cdot (m_X - 110 \text{ GeV})/110 + 20 \text{ GeV}$, centered on the mass point m_X . The analytical shape and the fit window width are chosen to fulfill the signal yield bias criterion, as defined for the low-mass analysis, to minimize the statistical uncertainty on the background.

The H background shape is modeled by a double-sided Crystal Ball function, and normalized for $m_H = 125.9 \text{ GeV}$ [29][30] using the most up-to-date Standard Model cross-section calculations and corrections [31] of the five main production modes: gluon fusion (ggF), vector-boson fusion (VBF), Higgs-strahlung (WH, ZH), and associated production with a top quark pair ($t\bar{t}H$). The ggF and VBF samples [3] are simulated with the POWHEG generator interfaced with PYTHIA8. The WH ,

ZH and $t\bar{t}H$ samples [3] are simulated with PYTHIA8. Figure 3 shows background-only fits to the data in the high-mass analysis.

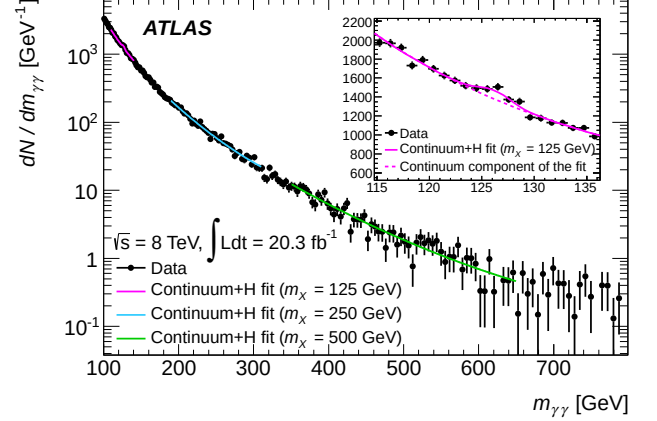


FIG. 3. Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the inclusive high-mass analysis. The solid line shows the sum of the Higgs boson and the continuum background components. The dashed line shows the continuum background component only.

The expected invariant mass distribution of the narrow resonance signal X is also modeled with a double-sided Crystal Ball function in the mass range $65 \leq m_X \leq 600 \text{ GeV}$, using fully simulated $\text{ggF}(X)$ samples generated as for H , where H is replaced by a scalar boson with a constant width of 4 MeV. Polynomial parameterizations of the signal shape parameters as a function of m_X are obtained from a simultaneous fit to all the generated mass points m_X , separately for the high-mass analysis and the three low-mass analysis categories. The signal shape parameters extracted from $\text{ggF}(X)$ are compared to the other production modes $\text{VBF}(X)$, WX , ZX and $t\bar{t}X$; the bias on the signal yield due to the choice of $\text{ggF}(X)$ shape is negligible. The systematic uncertainty on the signal shape due to the photon energy resolution uncertainty ranges from 10% to 40% as a function of m_X [3]. The systematic uncertainty on the X peak position due to the photon energy scale uncertainty is 0.6% [3].

The fiducial cross-section $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ includes an efficiency correction factor C_X through

$$\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma) = \frac{N_{\text{data}}}{C_X \cdot \mathcal{L}} \quad \text{with} \quad C_X = \frac{N_{\text{MC}}^{\text{reco}}}{N_{\text{MC}}^{\text{fid}}},$$

where N_{data} is the number of fitted signal events in data, $N_{\text{MC}}^{\text{reco}}$ the number of simulated signal events passing the selection criteria and $N_{\text{MC}}^{\text{fid}}$ the number of simulated signal events generated within the fiducial volume. The fiducial volume, defined from geometrical and kinematical constraints at the generated particle level, is optimized to reduce the model-dependence of C_X using fully simulated samples of the five X production modes to cover

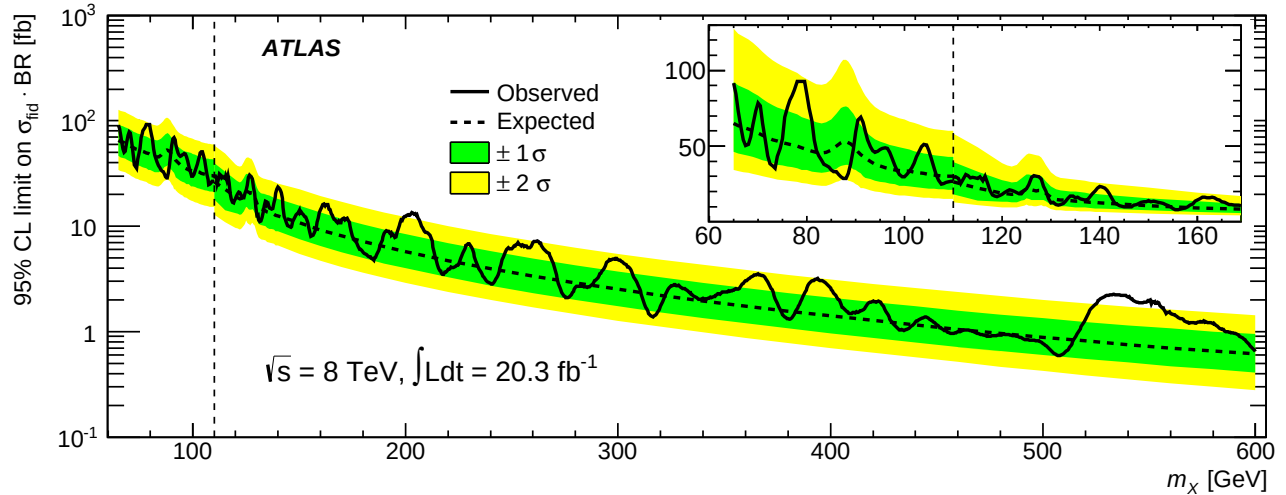


FIG. 4. Observed and expected 95% CL limit on the fiducial cross-section times branching ratio $BR(X \rightarrow \gamma\gamma)$ as a function of m_X in the range $65 < m_X < 600$ GeV. The discontinuity in the limit at $m_X = 110$ GeV (vertical dashed line) is due to the transition between the low-mass and high-mass analyses. The green and yellow bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit. The inset shows a zoom around the transition point.

a large variety of topologies. The photon selection at generation level is similar to the selection applied to the data: two photons with $E_T > 22$ GeV and $|\eta| < 2.37$ are required; for m_X greater than 110 GeV, the relative cuts $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$ and $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$ are imposed. The particle isolation, defined as the scalar sum of p_T of all the stable particles (except neutrinos) found within a $\Delta R = 0.4$ cone around the photon direction, is required to be less than 12 GeV. The C_X factor is parameterized from the $ggF(X)$ samples, and ranges from 0.56 to 0.71 as a function of m_X . Systematic uncertainties include the maximum difference between the C_X of the five production modes, the effect of the underlying event (U.E.) and pile-up.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and H shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with 2.1σ and 2.2σ local significances above the background are observed over the full mass range 65–600 GeV, for $m_X=201$ GeV and $m_X=530$ GeV respectively. This corresponds to a deviation of less than 0.5σ from the background-only hypothesis. Consequently, a 95% limit on $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of C_X . In the high-mass analysis, the largest uncertainties arise from the energy resolution and the theoretical uncertainty on the production rate of the Standard Model Higgs boson around 126 GeV.

TABLE II. Summary of the systematic uncertainties

Signal and Higgs boson yield		<i>Z</i> component of Drell-Yan	
Luminosity	2.8%	Normalization ^b	9–25%
Trigger	0.5%	Peak position ^b	1.5–3.5%
γ identification ^a	1.6–2.7%	Template shape ^b	1.5–3%
γ isolation ^a	1–6%	<i>Higgs boson background</i>	
Energy resolution ^{a,b}	10–40%	Cross-section ^c	9.6%
<i>Signal and Higgs boson peak position</i>		Branching ratio	4.8%
Energy scale	0.6%	<i>C_X factor</i>	
Continuum $\gamma\gamma$, γj , jj , DY		Topology ^a	3–15%
Signal bias ^a	1–67 events	Pile-up & U. E. ^a	1.4–3.2%

^a mass-dependent.

^b category-dependent.

^c factorization scale + PDF uncertainties [31].

The observed and expected limits, shown in Fig. 4, are in good agreement, consistent with the absence of a signal. The limits on $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ for an additional scalar resonance range from 90 fb for $m_X=65$ GeV to 1 fb for $m_X=600$ GeV. These results extend over a considerably wider mass range than the previous searches by the ATLAS and CMS collaborations [1, 35], are complementary to spin-2 particles searches [36, 37], and are the first such limits independent of the event topology.

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The ATLAS Collaboration

G. Aad⁸⁴, B. Abbott¹¹², J. Abdallah¹⁵⁰, S. Abdel Khalek¹¹⁶, O. Abidinov¹¹, R. Aben¹⁰⁶, B. Abi¹¹³, O.S. AbouZeid¹⁵⁷, H. Abramowicz¹⁵², H. Abreu¹⁵¹, R. Abreu³⁰, Y. Abulaiti^{145a,145b}, B.S. Acharya^{163a,163b,a}, L. Adamczyk^{38a}, D.L. Adams²⁵, J. Adelman¹⁷⁵, S. Adomeit⁹⁹, T. Adye¹³⁰, T. Agatonovic-Jovin^{13a}, J.A. Aguilar-Saavedra^{125a,125f}, M. Agustoni¹⁷, S.P. Ahlen²², F. Ahmadov^{64,b}, G. Aielli^{132a,132b}, H. Akerstedt^{145a,145b}, T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁴, A.V. Akimov⁹⁵, G.L. Alberghi^{20a,20b}, J. Albert¹⁶⁸, S. Albrand⁵⁵, M.J. Alconada Verzini⁷⁰, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, C. Alexa^{26a}, G. Alexander¹⁵², G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob¹¹², G. Alimonti^{90a}, L. Alio⁸⁴, J. Alison³¹, B.M.M. Allbrooke¹⁸, L.J. Allison⁷¹, P.P. Allport⁷³, A. Aloisio^{103a,103b}, A. Alonso³⁶, F. Alonso⁷⁰, C. Alpigiani⁷⁵, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁹, M.G. Alviggi^{103a,103b}, Y. Amaral Coutinho^{24a}, C. Amelung²³, D. Amidei⁸⁸, S.P. Amor Dos Santos^{125a,125c}, S. Amoroso⁴⁸, N. Amram¹⁵², G. Amundsen²³, C. Anastopoulos¹³⁸, L.S. Ancu⁴⁹, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{57b}, G. Anders³⁰, K.J. Anderson³¹, A. Andreazza^{90a,90b}, V. Andrei^{57a}, X.S. Anduaga⁷⁰, S. Angelidakis⁹, I. Angelozzi¹⁰⁶, P. Anger⁴⁴, A. Angerami³⁵, A.V. Anisenkov^{108,c}, N. Anjos¹², A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁷, J. Antos^{143b}, F. Anulli^{131a}, M. Aoki⁶⁵, L. Aperio Bella¹⁸, R. Apolle^{119,d}, G. Arabidze⁸⁹, I. Aracena¹⁴², Y. Arai⁶⁵, J.P. Araque^{125a}, A.T.H. Arce⁴⁵, F.A. Arduh⁷⁰, J-F. Arguin⁹⁴, S. Argyropoulos⁴², M. Arik^{19a}, A.J. Armbruster³⁰, O. Arnaez³⁰, V. Arnal⁸¹, H. Arnold⁴⁸, M. Arratia²⁸, O. Arslan²¹, A. Artamonov⁹⁶, G. Artoni²³, S. Asai¹⁵⁴, N. Asbah⁴², A. Ashkenazi¹⁵², B. Åsman^{145a,145b}, L. Asquith⁶, K. Assamagan²⁵, R. Astalos^{143a}, M. Atkinson¹⁶⁴, N.B. Atlay¹⁴⁰, B. Auerbach⁶, K. Augsten¹²⁷, M. Auresseu^{144b}, G. Avolio³⁰, G. Azuelos^{94,e}, Y. Azuma¹⁵⁴, M.A. Baak³⁰, A.E. Baas^{57a}, H. Bachacou¹³⁵, K. Bachas¹⁵³, M. Backes³⁰, M. Backhaus³⁰, J. Backus Mayes¹⁴², E. Badescu^{26a}, P. Bagiacchi^{131a,131b}, P. Bagnaia^{131a,131b}, Y. Bai^{33a}, T. Bain³⁵, J.T. Baines¹³⁰, O.K. Baker¹⁷⁵, P. Balek¹²⁸, F. Balli¹³⁵, E. Banas³⁹, Sw. Banerjee¹⁷², A.A.E. Bannoura¹⁷⁴, H.S. Bansil¹⁸, L. Barak¹⁷¹, E.L. Barberio⁸⁷, D. Barberis^{50a,50b}, M. Barbero⁸⁴, T. Barillari¹⁰⁰, M. Barisonzi¹⁷⁴, T. Barklow¹⁴², N. Barlow²⁸, S.L. Barnes⁸³, B.M. Barnett¹³⁰, R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{133a}, G. Barone⁴⁹, A.J. Barr¹¹⁹, F. Barreiro⁸¹, J. Barreiro Guimarães da Costa⁵⁶, R. Bartoldus¹⁴², A.E. Barton⁷¹, P. Bartos^{143a}, V. Bartsch¹⁴⁸, A. Bassalat¹¹⁶, A. Basye¹⁶⁴, R.L. Bates⁵³, J.R. Batley²⁸, M. Battaglia¹³⁶, M. Battistin³⁰, F. Bauer¹³⁵, H.S. Bawa^{142,f}, M.D. Beattie⁷¹, T. Beau⁷⁹, P.H. Beauchemin¹⁶⁰, P. Bechtel²¹, H.P. Beck¹⁷, K. Becker¹⁷⁴, S. Becker⁹⁹, M. Beckingham¹⁶⁹, C. Becot¹¹⁶, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁵, V.A. Bednyakov⁶⁴, C.P. Bee¹⁴⁷, L.J. Beemster¹⁰⁶, T.A. Beermann¹⁷⁴, M. Begel²⁵, K. Behr¹¹⁹, C. Belanger-Champagne⁸⁶, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵², L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo⁸⁵, K. Belotskiy⁹⁷, O. Beltramello³⁰, O. Benary¹⁵², D. Benchekroun^{134a}, K. Bendtz^{145a,145b}, N. Benekos¹⁶⁴, Y. Benhammou¹⁵², E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{158b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³, S. Bentvelsen¹⁰⁶, D. Berge¹⁰⁶, E. Bergeaas Kuutmann¹⁶, N. Berger⁵, F. Berghaus¹⁶⁸, J. Beringer¹⁵, C. Bernard²², P. Bernat⁷⁷, C. Bernius⁷⁸, F.U. Bernlochner¹⁶⁸, T. Berry⁷⁶, P. Berta¹²⁸, C. Bertella⁸², G. Bertoli^{145a,145b}, F. Bertolucci^{123a,123b}, C. Bertsche¹¹², D. Bertsche¹¹², M.I. Besana^{90a}, G.J. Besjes¹⁰⁵, O. Bessidskaia^{145a,145b}, M. Bessner⁴², N. Besson¹³⁵, C. Betancourt⁴⁸, S. Bethke¹⁰⁰, W. Bhimji⁴⁶, R.M. Bianchi¹²⁴, L. Bianchini²³, M. Bianco³⁰, O. Biebel⁹⁹, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{133a}, J. Bilbao De Mendizabal⁴⁹, H. Bilokon⁴⁷, M. Bindi⁵⁴, S. Binet¹¹⁶, A. Bingul^{19c}, C. Bini^{131a,131b}, C.W. Black¹⁴⁹, J.E. Black¹⁴², K.M. Black²², D. Blackburn¹³⁷, R.E. Blair⁶, J.-B. Blanchard¹³⁵, T. Blazek^{143a}, I. Bloch⁴², C. Blocker²³, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁶, V.S. Bobrovnikov^{108,c}, S.S. Bocchetta⁸⁰, A. Bocci⁴⁵, C. Bock⁹⁹, C.R. Boddy¹¹⁹, M. Boehler⁴⁸, T.T. Boek¹⁷⁴, A.G. Bogdanchikov¹⁰⁸, C. Bohm^{145a}, V. Boisvert⁷⁶, T. Bold^{38a}, A.S. Boldyrev⁹⁸, M. Bomben⁷⁹, M. Bona⁷⁵, M. Boonekamp¹³⁵, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴², J. Bortfeldt⁹⁹, V. Bortolotto^{59a}, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Boudreau¹²⁴, J. Bouffard², E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson¹¹³, S. Boutouil^{134d}, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozic^{13a}, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt¹⁵, O. Brandt^{57a}, U. Bratzler¹⁵⁵, B. Brau⁸⁵, J.E. Brau¹¹⁵, S.F. Brazzale^{163a,163c}, B. Brelief¹⁵⁷, K. Brendlinger¹²¹, A.J. Brennan⁸⁷, R. Brenner¹⁶⁵, S. Bressler¹⁷¹, K. Bristow^{144c}, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁸⁹, J. Bronner¹⁰⁰, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b}, J. Brosamer¹⁵, E. Brost¹¹⁵, J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{143b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴, Q. Buat¹⁴¹, F. Bucci⁴⁹, P. Buchholz¹⁴⁰, A.G. Buckley⁵³, S.I. Buda^{26a}, I.A. Budagov⁶⁴, F. Buehrer⁴⁸, L. Bugge¹¹⁸, M.K. Bugge¹¹⁸, O. Bulekov⁹⁷, A.C. Bundock⁷³, S. Burdin⁷³, B. Burghgrave¹⁰⁷, S. Burke¹³⁰, I. Burmeister⁴³, E. Busato³⁴, D. Büscher⁴⁸, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁵, B. Butler⁵⁶, J.M. Butler²², A.I. Butt³, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, P. Butti¹⁰⁶, W. Buttinger²⁸, A. Buzatu⁵³, M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁶, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, A. Calandri¹³⁵, G. Calderini⁷⁹, P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, S. Camarda⁴², D. Cameron¹¹⁸,

L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁷, A. Campoverde¹⁴⁷, V. Canale^{103a,103b},
 A. Canepa^{158a}, M. Cano Bret⁷⁵, J. Cantero⁸¹, R. Cantrill^{125a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a},
 M. Caprini^{26a}, M. Capua^{37a,37b}, R. Caputo⁸², R. Cardarelli^{132a}, T. Carli³⁰, G. Carlino^{103a}, L. Carminati^{90a,90b},
 S. Caron¹⁰⁵, E. Carquin^{32a}, G.D. Carrillo-Montoya^{144c}, J.R. Carter²⁸, D. Casadei⁷⁷, M.P. Casado¹², M. Casolino¹²,
 E. Castaneda-Miranda^{144b}, A. Castelli¹⁰⁶, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{125a}, P. Catastini⁵⁶, A. Catinaccio³⁰,
 J.R. Catmore¹¹⁸, A. Cattai³⁰, G. Cattani^{132a,132b}, J. Caudron⁸², V. Cavaliere¹⁶⁴, D. Cavalli^{90a}, M. Cavalli-Sforza¹²,
 V. Cavasinni^{123a,123b}, F. Ceradini^{133a,133b}, B.C. Cerio⁴⁵, K. Cerny¹²⁸, A.S. Cerqueira^{24b}, A. Cerri¹⁴⁸, L. Cerrito⁷⁵,
 F. Cerutti¹⁵, M. Cerv³⁰, A. Cervelli¹⁷, S.A. Cetin^{19b}, A. Chafaq^{134a}, D. Chakraborty¹⁰⁷, I. Chalupkova¹²⁸,
 P. Chang¹⁶⁴, B. Chapleau⁸⁶, J.D. Chapman²⁸, D. Charfeddine¹¹⁶, D.G. Charlton¹⁸, C.C. Chau¹⁵⁷,
 C.A. Chavez Barajas¹⁴⁸, S. Cheatham⁸⁶, A. Chegwiddden⁸⁹, S. Chekanov⁶, S.V. Chekulaev^{158a}, G.A. Chelkov^{64,g},
 M.A. Chelstowska⁸⁸, C. Chen⁶³, H. Chen²⁵, K. Chen¹⁴⁷, L. Chen^{33d,h}, S. Chen^{33c}, X. Chen^{33f}, Y. Chen⁶⁶,
 H.C. Cheng⁸⁸, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{134e}, E. Cheu⁷, L. Chevalier¹³⁵, V. Chiarella⁴⁷,
 G. Chiefari^{103a,103b}, J.T. Childers⁶, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷,
 A. Chitan^{26a}, M.V. Chizhov⁶⁴, S. Chouridou⁹, B.K.B. Chow⁹⁹, J. Chudoba¹²⁶, J.J. Chwastowski³⁹, L. Chytka¹¹⁴,
 A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁵³, V. Cindro⁷⁴, A. Ciocio¹⁵, Z.H. Citron¹⁷¹, M. Ciubancan^{26a}, A. Clark⁴⁹,
 P.J. Clark⁴⁶, R.N. Clarke¹⁵, J.C. Clemens⁸⁴, C. Clement^{145a,145b}, Y. Coadou⁸⁴, M. Cobal^{163a,163c}, A. Cocco¹³⁷,
 J. Cochran⁶³, L. Coffey²³, J.G. Cogan¹⁴², B. Cole³⁵, S. Cole¹⁰⁷, A.P. Colijn¹⁰⁶, J. Collot⁵⁵, T. Colombo^{57c},
 G. Compostella¹⁰⁰, P. Conde Muiño^{125a,125b}, E. Coniavitis⁴⁸, S.H. Connell^{144b}, I.A. Connolly⁷⁶,
 S.M. Consonni^{90a,90b}, V. Consorti⁴⁸, S. Constantinescu^{26a}, G. Conti⁵⁶, F. Conventi^{103a,i}, M. Cooke¹⁵,
 B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁹, N.J. Cooper-Smith⁷⁶, K. Copic¹⁵, T. Cornelissen¹⁷⁴, M. Corradi^{20a},
 F. Corriveau^{86,j}, A. Cortes-Gonzalez¹², G. Cortiana¹⁰⁰, G. Costa^{90a}, M.J. Costa¹⁶⁶, D. Costanzo¹³⁸, D. Côté⁸,
 G. Cottin²⁸, G. Cowan⁷⁶, B.E. Cox⁸³, K. Cranmer¹⁰⁹, G. Cree²⁹, S. Crépé-Renaudin⁵⁵, F. Crescioli⁷⁹,
 W.A. Cribbs^{145a,145b}, M. Crispin Ortuzar¹¹⁹, M. Cristinziani²¹, V. Croft¹⁰⁵, G. Crosetti^{37a,37b}, C.-M. Cuciuc^{26a},
 T. Cuhadar Donszelmann¹³⁸, J. Cummings¹⁷⁵, M. Curatolo⁴⁷, C. Cuthbert¹⁴⁹, H. Czirr¹⁴⁰, P. Czodrowski³,
 S. D'Auria⁵³, M. D'Onofrio⁷³, M.J. Da Cunha Sargedas De Sousa^{125a,125b}, C. Da Via⁸³, W. Dabrowski^{38a},
 A. Dafinca¹¹⁹, T. Dai⁸⁸, O. Dale¹⁴, F. Dallaire⁹⁴, C. Dallapiccola⁸⁵, M. Dam³⁶, A.C. Daniells¹⁸,
 M. Dano Hoffmann¹³⁵, V. Dao⁴⁸, G. Darbo^{50a}, S. Darmora⁸, J.A. Dassoulas⁴², A. Dattagupta⁶⁰, W. Davey²¹,
 C. David¹⁶⁸, T. Davidek¹²⁸, E. Davies^{119,d}, M. Davies¹⁵², O. Davignon⁷⁹, A.R. Davison⁷⁷, P. Davison⁷⁷,
 Y. Davygora^{57a}, E. Dawe¹⁴¹, I. Dawson¹³⁸, R.K. Daya-Ishmukhametova⁸⁵, K. De⁸, R. de Asmundis^{103a},
 S. De Castro^{20a,20b}, S. De Cecco⁷⁹, N. De Groot¹⁰⁵, P. de Jong¹⁰⁶, H. De la Torre⁸¹, F. De Lorenzi⁶³,
 L. De Nooij¹⁰⁶, D. De Pedis^{131a}, A. De Salvo^{131a}, U. De Sanctis¹⁴⁸, A. De Santo¹⁴⁸, J.B. De Vivie De Regie¹¹⁶,
 W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti¹³⁶, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, I. Deigaard¹⁰⁶, J. Del Peso⁸¹,
 F. Deliot¹³⁵, C.M. Delitzsch⁴⁹, M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Dell'Orso^{123a,123b},
 M. Della Pietra^{103a,i}, D. della Volpe⁴⁹, M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁶, S. Demers¹⁷⁵, M. Demichev⁶⁴,
 A. Demilly⁷⁹, S.P. Denisov¹²⁹, D. Derendarz³⁹, J.E. Derkaoui^{134d}, F. Derue⁷⁹, P. Dervan⁷³, K. Desch²¹,
 C. Deterre⁴², P.O. Deviveiros³⁰, A. Dewhurst¹³⁰, S. Dhaliwal¹⁰⁶, A. Di Ciaccio^{132a,132b}, L. Di Ciaccio⁵,
 A. Di Domenico^{131a,131b}, C. Di Donato^{103a,103b}, A. Di Girolamo³⁰, B. Di Girolamo³⁰, A. Di Mattia¹⁵¹,
 B. Di Micco^{133a,133b}, R. Di Nardo⁴⁷, A. Di Simone⁴⁸, R. Di Sipio^{20a,20b}, D. Di Valentino²⁹, F.A. Dias⁴⁶,
 M.A. Diaz^{32a}, E.B. Diehl⁸⁸, J. Dietrich¹⁶, T.A. Dietzsch^{57a}, S. Diglio⁸⁴, A. Dimitrievska^{13a}, J. Dingfelder²¹,
 P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸⁴, T. Djobava^{51b}, M.A.B. do Vale^{24c}, D. Dobos³⁰, C. Doglioni⁴⁹,
 T. Doherty⁵³, T. Dohmae¹⁵⁴, J. Dolejsi¹²⁸, Z. Dolezal¹²⁸, M. Donadelli^{24d}, S. Donati^{123a,123b}, P. Dondero^{120a,120b},
 J. Donini³⁴, J. Dopke¹³⁰, A. Doria^{103a}, M.T. Dova⁷⁰, A.T. Doyle⁵³, M. Dris¹⁰, J. Dubbert⁸⁸, S. Dube¹⁵,
 E. Dubreuil³⁴, E. Duchovni¹⁷¹, G. Duckeck⁹⁹, O.A. Ducu^{26a}, D. Duda¹⁷⁴, A. Dudarev³⁰, F. Dudziak⁶³, L. Duflot¹¹⁶,
 L. Duguid⁷⁶, M. Dührssen³⁰, M. Dunford^{57a}, H. Duran Yildiz^{4a}, M. Düren⁵², A. Durglishvili^{51b}, M. Dwuznik^{38a},
 M. Dyndal^{38a}, J. Ebke⁹⁹, W. Edson², N.C. Edwards⁴⁶, W. Ehrenfeld²¹, T. Eifert¹⁴², G. Eigen¹⁴, K. Einsweiler¹⁵,
 T. Ekelof¹⁶⁵, M. El Kacimi^{134c}, M. Ellert¹⁶⁵, S. Elles⁵, F. Ellinghaus⁸², N. Ellis³⁰, J. Elmsheuser⁹⁹, M. Elsing³⁰,
 D. Emelianov¹³⁰, Y. Enari¹⁵⁴, O.C. Endner⁸², M. Endo¹¹⁷, J. Erdmann¹⁷⁵, A. Ereditato¹⁷, G. Ernis¹⁷⁴, J. Ernst²,
 M. Ernst²⁵, J. Ernwein¹³⁵, D. Errede¹⁶⁴, S. Errede¹⁶⁴, E. Ertel⁸², M. Escalier¹¹⁶, H. Esch⁴³, C. Escobar¹²⁴,
 B. Esposito⁴⁷, A.I. Etiennevire¹³⁵, E. Etzion¹⁵², H. Evans⁶⁰, A. Ezhilov¹²², L. Fabbri^{20a,20b}, G. Facini³¹,
 R.M. Fakhruddinov¹²⁹, S. Falciano^{131a}, R.J. Falla⁷⁷, J. Faltova¹²⁸, Y. Fang^{33a}, M. Fanti^{90a,90b}, A. Farbin⁸,
 A. Farilla^{133a}, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁶⁹, P. Farthouat³⁰, F. Fassi^{134e}, P. Fassnacht³⁰,
 D. Fassouliotis⁹, A. Favareto^{50a,50b}, L. Fayard¹¹⁶, P. Federic^{143a}, O.L. Fedin^{122,k}, W. Fedorko¹⁶⁷, S. Feigl³⁰,
 L. Feligioni⁸⁴, C. Feng^{33d}, E.J. Feng⁶, H. Feng⁸⁸, A.B. Fenyuk¹²⁹, S. Fernandez Perez³⁰, S. Ferrag⁵³, J. Ferrando⁵³,
 A. Ferrari¹⁶⁵, P. Ferrari¹⁰⁶, R. Ferrari^{120a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁶, D. Ferrere⁴⁹, C. Ferretti⁸⁸,
 A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸², A. Filipčić⁷⁴, M. Filipuzzi⁴², F. Filthaut¹⁰⁵,
 M. Fincke-Keeler¹⁶⁸, K.D. Finelli¹⁴⁹, M.C.N. Fiolhais^{125a,125c}, L. Fiorini¹⁶⁶, A. Firan⁴⁰, A. Fischer², J. Fischer¹⁷⁴,

W.C. Fisher⁸⁹, E.A. Fitzgerald²³, M. Flechl⁴⁸, I. Fleck¹⁴⁰, P. Fleischmann⁸⁸, S. Fleischmann¹⁷⁴, G.T. Fletcher¹³⁸, G. Fletcher⁷⁵, T. Flick¹⁷⁴, A. Floderus⁸⁰, L.R. Flores Castillo^{172,l}, M.J. Flowerdew¹⁰⁰, A. Formica¹³⁵, A. Forti⁸³, D. Fortin^{158a}, D. Fournier¹¹⁶, H. Fox⁷¹, S. Fracchia¹², P. Francavilla⁷⁹, M. Franchini^{20a,20b}, S. Franchino³⁰, D. Francis³⁰, L. Franconi¹¹⁸, M. Franklin⁵⁶, M. Fraternali^{120a,120b}, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁵, E. Fullana Torregrosa⁸², B.G. Fulsom¹⁴², J. Fuster¹⁶⁶, C. Gabaldon⁵⁵, O. Gabizon¹⁷¹, A. Gabrielli^{20a,20b}, A. Gabrielli^{131a,131b}, S. Gadatsch¹⁰⁶, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea¹⁰⁵, B. Galhardo^{125a,125c}, E.J. Gallas¹¹⁹, B.J. Gallop¹³⁰, P. Gallus¹²⁷, G. Galster³⁶, K.K. Gan¹¹⁰, J. Gao^{33b,h}, Y.S. Gao^{142,f}, F.M. Garay Walls⁴⁶, F. Garbersson¹⁷⁵, C. García¹⁶⁶, J.E. García Navarro¹⁶⁶, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴², V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{120a}, B. Gaur¹⁴⁰, L. Gauthier⁹⁴, I.L. Gavrilenko⁹⁵, C. Gay¹⁶⁷, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gecse¹⁶⁷, C.N.P. Gee¹³⁰, D.A.A. Geerts¹⁰⁶, Ch. Geich-Gimbel²¹, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{131a,131b}, M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹⁶², A. Gershon¹⁵², N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{131a,131b}, V. Giangiobbe¹², P. Giannetti^{123a,123b}, F. Gianotti³⁰, S.M. Gibson⁷⁶, T.P.S. Gillam²⁸, D. Gillberg³⁰, G. Gilles³⁴, D.M. Gingrich^{3,e}, N. Giokaris⁹, M.P. Giordani^{163a,163c}, R. Giordano^{103a,103b}, F.M. Giorgi^{20a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁵, D. Giugni^{90a}, C. Giuliani⁴⁸, M. Giuliani^{57b}, B.K. Gjelsten¹¹⁸, S. Gkaitatzis¹⁵³, I. Gkialas^{153,m}, E.L. Gkougkousis¹¹⁶, L.K. Gladilin⁹⁸, C. Glasman⁸¹, J. Glatzer³⁰, P.C.F. Glaysheer⁴⁶, A. Glazov⁴², G.L. Glonti⁶¹, M. Goblirsch-Kolb¹⁰⁰, J.R. Goddard⁷⁵, J. Godlewski³⁰, C. Goeringer⁸², S. Goldfarb⁸⁸, T. Golling¹⁷⁵, D. Golubkov¹²⁹, A. Gomes^{125a,125b,125d}, L.S. Gomez Fajardo⁴², R. Gonçalo^{125a}, J. Goncalves Pinto Firmino Da Costa¹³⁵, L. Gonella²¹, S. González de la Hoz¹⁶⁶, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁶, H.A. Gordon²⁵, I. Gorelov¹⁰⁴, B. Gorini³⁰, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁴⁵, C. Gössling⁴³, M.I. Gostkin⁶⁴, M. Goughri^{134a}, D. Goujdami^{134c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁷, C. Goy⁵, H.M.X. Grabas¹³⁶, L. Graber⁵⁴, I. Grabowska-Bold^{38a}, P. Grafström^{20a,20b}, K.-J. Grahn⁴², J. Gramling⁴⁹, E. Gramstad¹¹⁸, S. Grancagnolo¹⁶, V. Grassi¹⁴⁷, V. Gratchev¹²², H.M. Gray³⁰, E. Graziani^{133a}, O.G. Grebenyuk¹²², Z.D. Greenwood^{78,n}, K. Gregersen⁷⁷, I.M. Gregor⁴², P. Grenier¹⁴², J. Griffiths⁸, A.A. Grillo¹³⁶, K. Grimm⁷¹, S. Grinstein^{12,o}, Ph. Gris³⁴, Y.V. Grishkevich⁹⁸, J.-F. Grivaz¹¹⁶, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷¹, J. Grosse-Knetter⁵⁴, G.C. Grossi^{132a,132b}, J. Groth-Jensen¹⁷¹, Z.J. Grout¹⁴⁸, L. Guan^{33b}, F. Guescini⁴⁹, D. Guest¹⁷⁵, O. Gueta¹⁵², C. Guicheney³⁴, E. Guido^{50a,50b}, T. Guillemain¹¹⁶, S. Guindon², U. Gul⁵³, C. Gumpert⁴⁴, J. Gunther¹²⁷, J. Guo³⁵, S. Gupta¹¹⁹, P. Gutierrez¹¹², N.G. Gutierrez Ortiz⁵³, C. Gutsche⁷⁷, N. Guttman¹⁵², C. Guyot¹³⁵, C. Gwenlan¹¹⁹, C.B. Gwilliam⁷³, A. Haas¹⁰⁹, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{134e}, P. Haefner²¹, S. Hageböck²¹, H. Hakobyan¹⁷⁶, M. Haleem⁴², D. Hall¹¹⁹, G. Halladjian⁸⁹, G.D. Hallewell⁸⁴, K. Hamacher¹⁷⁴, P. Hamal¹¹⁴, K. Hamano¹⁶⁸, M. Hamer⁵⁴, A. Hamilton^{144a}, S. Hamilton¹⁶⁰, G.N. Hamity^{144c}, P.G. Hamnett⁴², L. Han^{33b}, K. Hanagaki¹¹⁷, K. Hanawa¹⁵⁴, M. Hance¹⁵, P. Hanke^{57a}, R. Hanna¹³⁵, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, K. Hara¹⁵⁹, A.S. Hard¹⁷², T. Harenberg¹⁷⁴, F. Hariri¹¹⁶, S. Harkusha⁹¹, D. Harper⁸⁸, R.D. Harrington⁴⁶, O.M. Harris¹³⁷, P.F. Harrison¹⁶⁹, M. Hasegawa⁶⁶, S. Hasegawa¹⁰², Y. Hasegawa¹³⁹, A. Hasib¹¹², S. Hassani¹³⁵, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁹, M. Havranek¹²⁶, C.M. Hawkes¹⁸, R.J. Hawkins³⁰, A.D. Hawkins⁸⁰, T. Hayashi¹⁵⁹, D. Hayden⁸⁹, C.P. Hays¹¹⁹, H.S. Hayward⁷³, S.J. Haywood¹³⁰, S.J. Head¹⁸, T. Heck⁸², V. Hedberg⁸⁰, L. Heelan⁸, S. Heim¹²¹, T. Heim¹⁷⁴, B. Heinemann¹⁵, L. Heinrich¹⁰⁹, J. Hejbal¹²⁶, L. Helary²², C. Heller⁹⁹, M. Heller³⁰, S. Hellman^{145a,145b}, D. Hellmich²¹, C. Helsens³⁰, J. Henderson¹¹⁹, R.C.W. Henderson⁷¹, Y. Heng¹⁷², C. Hengler⁴², A. Henrichs¹⁷⁵, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁶, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁶, R. Herrberg-Schubert¹⁶, G. Herten⁴⁸, R. Hertenberger⁹⁹, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁶, R. Hickling⁷⁵, E. Higón-Rodríguez¹⁶⁶, E. Hill¹⁶⁸, J.C. Hill²⁸, K.H. Hiller⁴², S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²¹, M. Hirose¹⁵⁶, D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁷, N. Hod¹⁰⁶, M.C. Hodgkinson¹³⁸, P. Hodgson¹³⁸, A. Hoecker³⁰, M.R. Hoefkamp¹⁰⁴, F. Hoenig⁹⁹, D. Hoffmann⁸⁴, J.I. Hofmann^{57a}, M. Hohlfeld⁸², T.R. Holmes¹⁵, T.M. Hong¹²¹, L. Hooft van Huysduynen¹⁰⁹, W.H. Hopkins¹¹⁵, Y. Horii¹⁰², J.-Y. Hostachy⁵⁵, S. Hou¹⁵⁰, A. Hoummada^{134a}, J. Howard¹¹⁹, J. Howarth⁴², M. Hrabovsky¹¹⁴, I. Hristova¹⁶, J. Hrivnac¹¹⁶, T. Hryn'ova⁵, C. Hsu^{144c}, P.J. Hsu⁸², S.-C. Hsu¹³⁷, D. Hu³⁵, X. Hu²⁵, Y. Huang⁴², Z. Hubacek³⁰, F. Hubaut⁸⁴, F. Huegging²¹, T.B. Huffman¹¹⁹, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, T.A. Hülsing⁸², M. Hurwitz¹⁵, N. Huseynov^{64,b}, J. Huston⁸⁹, J. Huth⁵⁶, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, I. Ibragimov¹⁴⁰, L. Iconomidou-Fayard¹¹⁶, E. Ideal¹⁷⁵, Z. Idrissi^{134e}, P. Iengo^{103a}, O. Igonkina¹⁰⁶, T. Iizawa¹⁷⁰, Y. Ikegami⁶⁵, K. Ikematsu¹⁴⁰, M. Ikeno⁶⁵, Y. Ilchenko³¹, D. Iliadis¹⁵³, N. Ilic¹⁵⁷, Y. Inamaru⁶⁶, T. Ince¹⁰⁰, P. Ioannou⁹, M. Iodice^{133a}, K. Iordanidou⁹, V. Ippolito⁵⁶, A. Irles Quiles¹⁶⁶, C. Isaksson¹⁶⁵, M. Ishino⁶⁷, M. Ishitsuka¹⁵⁶, R. Ishmukhametov¹¹⁰, C. Issever¹¹⁹, S. Istin^{19a}, J.M. Iturbe Ponce⁸³, R. Iuppa^{132a,132b}, J. Ivarsson⁸⁰, W. Iwanski³⁹, H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{103a}, B. Jackson¹²¹, M. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁰, T. Jakoubek¹²⁶, J. Jakubek¹²⁷, D.O. Jamin¹⁵⁰, D.K. Jana⁷⁸, E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, M. Janus¹⁶⁹, G. Jarlskog⁸⁰, N. Javadov^{64,b}, T. Javůrek⁴⁸, L. Jeanty¹⁵,

J. Jejelava^{51a,p}, G.-Y. Jeng¹⁴⁹, D. Jennens⁸⁷, P. Jenni^{48,q}, J. Jentzsch⁴³, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁷, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, A. Jinaru^{26a}, O. Jinnouchi¹⁵⁶, M.D. Joergensen³⁶, K.E. Johansson^{145a,145b}, P. Johansson¹³⁸, K.A. Johns⁷, K. Jon-And^{145a,145b}, G. Jones¹⁶⁹, R.W.L. Jones⁷¹, T.J. Jones⁷³, J. Jongmanns^{57a}, P.M. Jorge^{125a,125b}, K.D. Joshi⁸³, J. Jovicevic¹⁴⁶, X. Ju¹⁷², C.A. Jung⁴³, R.M. Jungst³⁰, P. Jussel⁶¹, A. Juste Rozas^{12,o}, M. Kaci¹⁶⁶, A. Kaczmarska³⁹, M. Kado¹¹⁶, H. Kagan¹¹⁰, M. Kagan¹⁴², E. Kajomovitz⁴⁵, C.W. Kalderon¹¹⁹, S. Kama⁴⁰, A. Kamenshchikov¹²⁹, N. Kanaya¹⁵⁴, M. Kaneda³⁰, S. Kaneti²⁸, V.A. Kantserov⁹⁷, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁹, A. Kapliy³¹, D. Kar⁵³, K. Karakostas¹⁰, N. Karastathis¹⁰, M.J. Kareem⁵⁴, M. Karneviskiy⁸², S.N. Karpov⁶⁴, Z.M. Karpova⁶⁴, K. Karthik¹⁰⁹, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁹, L. Kashif¹⁷², G. Kasieczka^{57b}, R.D. Kass¹¹⁰, A. Kastanas¹⁴, Y. Kataoka¹⁵⁴, A. Katre⁴⁹, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁴, G. Kawamura⁵⁴, S. Kazama¹⁵⁴, V.F. Kazanin¹⁰⁸, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁸, R. Kehoe⁴⁰, J.S. Keller⁴², J.J. Kempster⁷⁶, H. Keoshkerian⁵, O. Kepka¹²⁶, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁴, K. Kessoku¹⁵⁴, J. Keung¹⁵⁷, R.A. Keyes⁸⁶, F. Khalil-zada¹¹, H. Khandanyan^{145a,145b}, A. Khanov¹¹³, A. Khodinov⁹⁷, T.J. Khoo²⁸, G. Khorauli²¹, V. Khovanskiy⁹⁶, E. Khramov⁶⁴, J. Khubua^{51b}, H.Y. Kim⁸, H. Kim^{145a,145b}, S.H. Kim¹⁵⁹, N. Kimura¹⁷⁰, O. Kind¹⁶, B.T. King⁷³, M. King¹⁶⁶, R.S.B. King¹¹⁹, S.B. King¹⁶⁷, J. Kirk¹³⁰, A.E. Kiryunin¹⁰⁰, T. Kishimoto⁶⁶, D. Kisielevska^{38a}, F. Kiss⁴⁸, K. Kiuchi¹⁵⁹, E. Kladiva^{143b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸², P. Klimek^{145a,145b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸³, T. Klioutchnikova³⁰, E.-E. Kluge^{57a}, P. Kluit¹⁰⁶, S. Kluth¹⁰⁰, E. Kneringer⁶¹, E.B.F.G. Knoop⁸⁴, A. Knue⁵³, D. Kobayashi¹⁵⁶, T. Kobayashi¹⁵⁴, M. Kobel⁴⁴, M. Kocian¹⁴², P. Kodys¹²⁸, T. Koffas²⁹, E. Koffeman¹⁰⁶, L.A. Kogan¹¹⁹, S. Kohlmann¹⁷⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴², H. Kolanoski¹⁶, I. Koletsou⁵, J. Koll⁸⁹, Y. Komori¹⁵⁴, T. Kondo⁶⁵, N. Kondrashova⁴², K. Köneke⁴⁸, A.C. König¹⁰⁵, S. König⁸², T. Kono^{65,r}, R. Konoplich^{109,s}, N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵¹, S. Koperny^{38a}, L. Köpke⁸², A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵³, A. Korn⁷⁷, A.A. Korol^{108,c}, I. Korolkov¹², E.V. Korolkova¹³⁸, V.A. Korotkov¹²⁹, O. Kortner¹⁰⁰, S. Kortner¹⁰⁰, V.V. Kostyukhin²¹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, A. Kourkouveli-Charalampidi¹⁵³, C. Kourkouvelis⁹, V. Kouskoura¹⁵³, A. Koutsman^{158a}, R. Kowalewski¹⁶⁸, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁵, A.S. Kozhin¹²⁹, V.A. Kramarenko⁹⁸, G. Kramberger⁷⁴, D. Krasnopevtsev⁹⁷, M.W. Krasny⁷⁹, A. Krasznahorkay³⁰, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁹, M. Kretz^{57c}, J. Kretzschmar⁷³, K. Kreutzfeldt⁵², P. Krieger¹⁵⁷, K. Kroeninger⁵⁴, H. Kroha¹⁰⁰, J. Kroll¹²¹, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruse¹⁷², M.C. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁷, S. Kuday^{4c}, S. Kuehn⁴⁸, A. Kugel^{57c}, A. Kuhl¹³⁶, T. Kuhl⁴², V. Kukhtin⁶⁴, Y. Kulchitsky⁹¹, S. Kuleshov^{32b}, M. Kuna^{131a,131b}, T. Kunigo⁶⁷, A. Kupco¹²⁶, H. Kurashige⁶⁶, Y.A. Kurochkin⁹¹, R. Kurumida⁶⁶, V. Kus¹²⁶, E.S. Kuwertz¹⁴⁶, M. Kuze¹⁵⁶, J. Kvita¹¹⁴, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, C. Lacasta¹⁶⁶, F. Lacava^{131a,131b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁹, V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁹, T. Lagouri¹⁷⁵, S. Lai⁴⁸, H. Laier^{57a}, L. Lambourne⁷⁷, S. Lammers⁶⁰, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁵, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, V.S. Lang^{57a}, A.J. Lankford¹⁶², F. Lanni²⁵, K. Lantzsch³⁰, S. Laplace⁷⁹, C. Lapoire²¹, J.F. Laporte¹³⁵, T. Lari^{90a}, F. Lasagni Manghi^{20a,20b}, M. Lassnig³⁰, P. Laurelli⁴⁷, W. Lavrijsen¹⁵, A.T. Law¹³⁶, P. Laycock⁷³, O. Le Dortz⁷⁹, E. Le Guirriec⁸⁴, E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee^{144b}, H. Lee¹⁰⁶, J.S.H. Lee¹¹⁷, S.C. Lee¹⁵⁰, L. Lee¹, G. Lefebvre⁷⁹, M. Lefebvre¹⁶⁸, F. Legger⁹⁹, C. Leggett¹⁵, A. Lehan⁷³, G. Lehmann Miotto³⁰, X. Lei⁷, W.A. Leight²⁹, A. Leisos¹⁵³, A.G. Leister¹⁷⁵, M.A.L. Leite^{24d}, R. Leitner¹²⁸, D. Lellouch¹⁷¹, B. Lemmer⁵⁴, K.J.C. Leney⁷⁷, T. Lenz²¹, B. Lenzi³⁰, R. Leone⁷, S. Leone^{123a,123b}, C. Leonidopoulos⁴⁶, S. Leontsinis¹⁰, C. Leroy⁹⁴, C.G. Lester²⁸, C.M. Lester¹²¹, M. Levchenko¹²², J. Levêque⁵, D. Levin⁸⁸, L.J. Levinson¹⁷¹, M. Levy¹⁸, A. Lewis¹¹⁹, G.H. Lewis¹⁰⁹, A.M. Leyko²¹, M. Leyton⁴¹, B. Li^{33b,t}, B. Li⁸⁴, H. Li¹⁴⁷, H.L. Li³¹, L. Li⁴⁵, L. Li^{33e}, S. Li⁴⁵, Y. Li^{33c,u}, Z. Liang¹³⁶, H. Liao³⁴, B. Liberti^{132a}, K. Lie¹⁶⁴, J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani¹⁴⁹, S.C. Lin^{150,v}, T.H. Lin⁸², B.E. Lindquist¹⁴⁷, J.T. Linnemann⁸⁹, E. Lipeles¹²¹, A. Lipniacka¹⁴, M. Lisovyi⁴², T.M. Liss¹⁶⁴, A. Lister¹⁶⁷, A.M. Litke¹³⁶, B. Liu¹⁵⁰, D. Liu¹⁵⁰, J.B. Liu^{33b}, K. Liu^{33b,w}, L. Liu⁸⁸, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{120a,120b}, A. Lleres⁵⁵, J. Llorente Merino⁸¹, S.L. Lloyd⁷⁵, F. Lo Sterzo¹⁵⁰, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁶, T. Loddenkoetter²¹, F.K. Loebinger⁸³, A.E. Loevschall-Jensen³⁶, A. Loginov¹⁷⁵, T. Lohse¹⁶, K. Lohwasser⁴², M. Lokajicek¹²⁶, V.P. Lombardo⁵, B.A. Long²², J.D. Long⁸⁸, R.E. Long⁷¹, L. Lopes^{125a}, D. Lopez Mateos⁵⁶, B. Lopez Paredes¹³⁸, I. Lopez Paz¹², J. Lorenz⁹⁹, N. Lorenzo Martinez⁶⁰, M. Losada¹⁶¹, P. Loscutoff¹⁵, X. Lou⁴¹, A. Lounis¹¹⁶, J. Love⁶, P.A. Love⁷¹, F. Lu^{33a}, N. Lu⁸⁸, H.J. Lubatti¹³⁷, C. Luci^{131a,131b}, A. Lucotte⁵⁵, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{131a}, O. Lundberg^{145a,145b}, B. Lund-Jensen¹⁴⁶, M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶, E. Lytken⁸⁰, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, J. Machado Miguens^{125a,125b}, D. Macina³⁰, D. Madaffari⁸⁴, R. Madar⁴⁸, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, A. Madsen¹⁶⁵, M. Maeno⁸, T. Maeno²⁵, A. Maevskiy⁹⁸, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, C. Maiani¹³⁵, C. Maidantchik^{24a}, A.A. Maier¹⁰⁰, A. Maio^{125a,125b,125d}, S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶, P. Mal^{135,x}, B. Malaescu⁷⁹, Pa. Malecki³⁹, V.P. Maleev¹²², F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴², S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸,

S. Malyukov³⁰, J. Mamuzic^{13b}, B. Mandelli³⁰, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a,125b}, A. Manfredini¹⁰⁰, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos^{158b}, A. Mann⁹⁹, P.M. Manning¹³⁶, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁵, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March^{144c}, J.F. Marchand²⁹, G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁶⁸, M. Marjanovic^{13a}, F. Marroquin^{24a}, S.P. Marsden⁸³, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁶, B. Martin³⁰, B. Martin⁸⁹, T.A. Martin¹⁶⁹, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, H. Martinez¹³⁵, M. Martinez^{12,o}, S. Martin-Haugh¹³⁰, A.C. Martyniuk⁷⁷, M. Marx¹³⁷, A. Marzin³⁰, L. Masetti⁸², T. Mashimo¹⁵⁴, R. Mashinistov⁹⁵, J. Masik⁸³, A.L. Maslennikov^{108,c}, I. Massa^{20a,20b}, L. Massa^{20a,20b}, N. Massol⁵, P. Mastrandrea¹⁴⁷, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁴, P. Mättig¹⁷⁴, J. Mattmann⁸², J. Maurer^{26a}, S.J. Maxfield⁷³, D.A. Maximov^{108,c}, R. Mazini¹⁵⁰, L. Mazzaferro^{132a,132b}, G. Mc Goldrick¹⁵⁷, S.P. Mc Kee⁸⁸, A. McCarn⁸⁸, R.L. McCarthy¹⁴⁷, T.G. McCarthy²⁹, J.A. Mcfayden⁷⁷, G. Mchedlidze⁵⁴, S.J. McMahon¹³⁰, R.A. McPherson^{168,j}, J. Mechnich¹⁰⁶, M. Medinnis⁴², S. Meehan³¹, S. Mehlhase⁹⁹, A. Mehta⁷³, K. Meier^{57a}, C. Meineck⁹⁹, B. Meirose⁸⁰, C. Melachrinou³¹, B.R. Mellado Garcia^{144c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰⁰, E. Meoni¹⁶⁰, K.M. Mercurio⁵⁶, S. Mergelmeyer²¹, N. Meric¹³⁵, P. Mermod⁴⁹, L. Merola^{103a,103b}, C. Meroni^{90a}, F.S. Merritt³¹, H. Merritt¹¹⁰, A. Messina^{30,y}, J. Metcalfe²⁵, A.S. Mete¹⁶², C. Meyer⁸², C. Meyer¹²¹, J-P. Meyer¹³⁵, J. Meyer³⁰, R.P. Middleton¹³⁰, S. Migas⁷³, L. Mijović²¹, G. Mikenberg¹⁷¹, M. Mikesikova¹²⁶, M. Mikuz⁷⁴, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷¹, D.A. Milstead^{145a,145b}, A.A. Minaenko¹²⁹, Y. Minami¹⁵⁴, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁹, B. Mindur^{38a}, M. Mineev⁶⁴, Y. Ming¹⁷², L.M. Mir¹², T. Mitani¹⁷⁰, J. Mitrevski⁹⁹, V.A. Mitsou¹⁶⁶, A. Miucci⁴⁹, P.S. Miyagawa¹³⁸, J.U. Mjörnmark⁸⁰, T. Moa^{145a,145b}, K. Mochizuki⁸⁴, S. Mohapatra³⁵, S. Molander^{145a,145b}, R. Moles-Valls¹⁶⁶, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁴, J. Montejó Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{131a,131b}, R.W. Moore³, N. Morange⁶², D. Moreno⁸², M. Moreno Llácer⁵⁴, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁶, V. Morisbak¹¹⁸, S. Moritz⁸², A.K. Morley¹⁴⁶, G. Mornacchi³⁰, J.D. Morris⁷⁵, A. Morton⁴², L. Morvaj¹⁰², H.G. Moser¹⁰⁰, M. Mosidze^{51b}, J. Moss¹¹⁰, K. Motohashi¹⁵⁶, R. Mount¹⁴², E. Mountricha²⁵, E.J.W. Moyse⁸⁵, S. Muanza⁸⁴, R.D. Mudd¹⁸, F. Mueller^{57a}, J. Mueller¹²⁴, K. Mueller²¹, T. Mueller²⁸, T. Mueller⁸², D. Muenstermann⁴⁹, Y. Munwes¹⁵², J.A. Murillo Quijada¹⁸, W.J. Murray^{169,130}, H. Musheghyan⁵⁴, E. Musto¹⁵¹, A.G. Myagkov^{129,z}, M. Myska¹²⁷, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai¹¹⁹, R. Nagai¹⁵⁶, Y. Nagai⁸⁴, K. Nagano⁶⁵, A. Nagarkar¹¹⁰, Y. Nagasaka⁵⁸, K. Nagata¹⁵⁹, M. Nagel¹⁰⁰, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁵, T. Nakamura¹⁵⁴, I. Nakano¹¹¹, H. Namasivayam⁴¹, G. Nanava²¹, R.F. Naranjo Garcia⁴², R. Narayan^{57b}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶¹, R. Nayyar⁷, H.A. Neal⁸⁸, P.Yu. Nechaeva⁹⁵, T.J. Neep⁸³, P.D. Nef¹⁴², A. Negri^{120a,120b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, C. Nellist¹¹⁶, A. Nelson¹⁶², T.K. Nelson¹⁴², S. Nemecek¹²⁶, P. Nemethy¹⁰⁹, A.A. Nepomuceno^{24a}, M. Nessi^{30,aa}, M.S. Neubauer¹⁶⁴, M. Neumann¹⁷⁴, R.M. Neves¹⁰⁹, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹¹⁹, R. Nicolaidou¹³⁵, J. Nielsen¹³⁶, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{129,z}, I. Nikolic-Audit⁷⁹, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁴, A. Nisati^{131a}, R. Nisius¹⁰⁰, T. Nobe¹⁵⁶, L. Nodulman⁶, M. Nomachi¹¹⁷, I. Nomidis²⁹, S. Norberg¹¹², M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰⁰, M. Nozaki⁶⁵, L. Nozka¹¹⁴, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁷, T. Nunnemann⁹⁹, E. Nurse⁷⁷, F. Nuti⁸⁷, B.J. O'Brien⁴⁶, F. O'grady⁷, D.C. O'Neil¹⁴¹, V. O'Shea⁵³, F.G. Oakham^{29,e}, H. Oberlack¹⁰⁰, T. Obermann²¹, J. Ocariz⁷⁹, A. Ochi⁶⁶, M.I. Ochoa⁷⁷, S. Oda⁶⁹, S. Odaka⁶⁵, A. Oh⁸³, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁵, H. Oide³⁰, W. Okamura¹¹⁷, H. Okawa¹⁵⁹, Y. Okumura³¹, T. Okuyama¹⁵⁴, A. Olariu^{26a}, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁶, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{125a,125e}, P.U.E. Onyisi^{31,ab}, M.J. Oreglia³¹, Y. Oren¹⁵², D. Orestano^{133a,133b}, N. Orlando^{72a,72b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁷, B. Osculati^{50a,50b}, R. Ospanov¹²¹, G. Otero y Garzon²⁷, H. Otono⁶⁹, M. Ouchrif^{134d}, E.A. Ouellette¹⁶⁸, F. Ould-Saada¹¹⁸, A. Ouraou¹³⁵, K.P. Oussoren¹⁰⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸³, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹¹⁹, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹³⁸, C. Pahl¹⁰⁰, F. Paige²⁵, P. Pais⁸⁵, K. Pajchel¹¹⁸, G. Palacino^{158b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{125a,125b}, J.D. Palmer¹⁸, Y.B. Pan¹⁷², E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁶, S. Panitkin²⁵, D. Pantea^{26a}, L. Paolozzi^{132a,132b}, Th.D. Papadopoulos¹⁰, K. Papageorgiou^{153,m}, A. Paramonov⁶, D. Paredes Hernandez³⁴, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{131a}, S. Passaggio^{50a}, Fr. Pastore⁷⁶, G. Pásztor²⁹, S. Patariaia¹⁷⁴, N.D. Patel¹⁴⁹, J.R. Pater⁸³, S. Patricelli^{103a,103b}, T. Pauly³⁰, J. Pearce¹⁶⁸, L.E. Pedersen³⁶, M. Pedersen¹¹⁸, S. Pedraza Lopez¹⁶⁶, R. Pedro^{125a,125b}, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁵, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶⁰, D.V. Perepelitsa²⁵, E. Perez Codina^{158a}, M.T. Pérez García-Estañ¹⁶⁶, L. Perini^{90a,90b}, H. Pernegger³⁰, S. Perrella^{103a,103b}, R. Peschke⁴², V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters⁸³, B.A. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁴², A. Petridis^{145a,145b}, C. Petridou¹⁵³, E. Petrolo^{131a}, F. Petrucci^{133a,133b}, N.E. Pettersson¹⁵⁶, R. Pezoa^{32b}, P.W. Phillips¹³⁰, G. Piacquadio¹⁴², E. Pianori¹⁶⁹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, R. Piegai²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, M. Pinamonti^{163a,163c,ac}, A. Pinder¹¹⁹, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{125a}, S. Pires⁷⁹, M. Pitt¹⁷¹, C. Pizio^{90a,90b}, L. Plazak^{143a}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴,

P. Plucinski^{145a,145b}, D. Pluth⁶³, S. Poddar^{57a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioni¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁷, A. Polini^{20a}, C.S. Pollard⁴⁵, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{131a}, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, X. Portell Bueso¹², S. Pospisil¹²⁷, K. Potamianos¹⁵, I.N. Potrap⁶⁴, C.J. Potter¹⁴⁸, C.T. Potter¹¹⁵, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan⁸, S. Prell⁶³, D. Price⁸³, J. Price⁷³, M. Primavera^{72a}, M. Proissl⁴⁶, K. Prokofiev⁴⁷, F. Prokoshin^{32b}, E. Protopapadaki¹³⁵, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, H. Przysieznik⁵, E. Ptacek¹¹⁵, D. Puddu^{133a,133b}, E. Pueschel⁸⁵, D. Pulton¹⁴⁷, M. Purohit^{25,ad}, P. Puzo¹¹⁶, J. Qian⁸⁸, G. Qin⁵³, Y. Qin⁸³, A. Quadri⁵⁴, W.B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸³, D. Quilty⁵³, A. Qureshi^{158b}, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁷, P. Radloff¹¹⁵, P. Rados⁸⁷, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁷, S. Rajagopalan²⁵, M. Rammensee³⁰, C. Rangel-Smith¹⁶⁵, K. Rao¹⁶², F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁸, N.P. Readioff⁷³, D.M. Rebuzzi^{120a,120b}, A. Redelbach¹⁷³, G. Redlinger²⁵, R. Reece¹³⁶, K. Reeves⁴¹, L. Rehnisch¹⁶, H. Reisin²⁷, M. Relich¹⁶², C. Rembser³⁰, H. Ren^{33a}, A. Renaud¹¹⁶, M. Rescigno^{131a}, S. Resconi^{90a}, O.L. Rezanova^{108,c}, P. Reznicek¹²⁸, R. Rezvani⁹⁴, R. Richter¹⁰⁰, M. Ridel⁷⁹, P. Rieck¹⁶, J. Rieger⁵⁴, M. Rijssenbeek¹⁴⁷, A. Rimoldi^{120a,120b}, L. Rinaldi^{20a}, E. Ritsch⁶¹, I. Riu¹², F. Rizatdinova¹¹³, E. Rizvi⁷⁵, S.H. Robertson^{86,j}, A. Robichaud-Veronneau⁸⁶, D. Robinson²⁸, J.E.M. Robinson⁸³, A. Robson⁵³, C. Roda^{123a,123b}, L. Rodrigues³⁰, S. Roe³⁰, O. Røhne¹¹⁸, A. Romanouk⁹⁷, M. Romano^{20a,20b}, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁷, M. Ronzani⁴⁸, L. Roos⁷⁹, E. Ros¹⁶⁶, S. Rosati^{131a}, K. Rosbach⁴⁹, M. Rose⁷⁶, P. Rose¹³⁶, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴⁰, V. Rossetti^{145a,145b}, E. Rossi^{103a,103b}, L.P. Rossi^{50a}, R. Rosten¹³⁷, M. Rotaru^{26a}, I. Roth¹⁷¹, J. Rothberg¹³⁷, D. Rousseau¹¹⁶, C.R. Royon¹³⁵, A. Rozanov⁸⁴, Y. Rozen¹⁵¹, X. Ruan^{144c}, F. Rubbo¹², I. Rubinskiy⁴², V.I. Rud⁹⁸, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁷, F. Rühr⁴⁸, A. Ruiz-Martinez³⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸, Y.F. Ryabov¹²², M. Rybar¹²⁸, G. Rybkin¹¹⁶, N.C. Ryder¹¹⁹, A.F. Saavedra¹⁴⁹, G. Sabato¹⁰⁶, S. Sacerdoti²⁷, A. Saddique³, I. Sadeh¹⁵², H.F.W. Sadrozinski¹³⁶, R. Sadykov⁶⁴, F. Safai Tehrani^{131a}, H. Sakamoto¹⁵⁴, Y. Sakurai¹⁷⁰, G. Salamanna^{133a,133b}, A. Salamon^{132a}, M. Saleem¹¹², D. Salek¹⁰⁶, P.H. Sales De Bruin¹³⁷, D. Salihagic¹⁰⁰, A. Salmikov¹⁴², J. Salt¹⁶⁶, D. Salvatore^{37a,37b}, F. Salvatore¹⁴⁸, A. Salvucci¹⁰⁵, A. Salzburger³⁰, D. Sampsonidis¹⁵³, A. Sanchez^{103a,103b}, J. Sánchez¹⁶⁶, V. Sanchez Martinez¹⁶⁶, H. Sandaker¹⁴, R.L. Sandbach⁷⁵, H.G. Sander⁸², M.P. Sanders⁹⁹, M. Sandhoff¹⁷⁴, T. Sandoval²⁸, C. Sandoval¹⁶¹, R. Sandstroem¹⁰⁰, D.P.C. Sankey¹³⁰, A. Sansoni⁴⁷, C. Santoni³⁴, H. Santos^{125a}, I. Santoyo Castillo¹⁴⁸, K. Sapp¹²⁴, A. Sapronov⁶⁴, J.G. Saraiva^{125a,125d}, B. Sarrazin²¹, G. Sartisohn¹⁷⁴, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁴, E. Sauvan⁵, P. Savard^{157,e}, D.O. Savu³⁰, C. Sawyer¹¹⁹, L. Sawyer^{78,n}, J. Saxon¹²¹, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, T. Scanlon⁷⁷, D.A. Scannicchio¹⁶², M. Scarcella¹⁴⁹, V. Scarfone^{37a,37b}, J. Schaarschmidt¹⁷¹, P. Schacht¹⁰⁰, D. Schaefer³⁰, R. Schaefer⁴², S. Schaepe²¹, S. Schaetzel^{157b}, U. Schäfer⁸², A.C. Schaffer¹¹⁶, D. Schaile⁹⁹, R.D. Schamberger¹⁴⁷, V. Scharf^{57a}, V.A. Schegelsky¹²², D. Scheirich¹²⁸, M. Schernau¹⁶², M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁹, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden³⁰, C. Schmitt⁸², S. Schmitt^{57b}, B. Schneider¹⁷, Y.J. Schnellbach⁷³, U. Schnoor⁴⁴, L. Schoeffel¹³⁵, A. Schoening^{57b}, B.D. Schoenrock⁸⁹, A.L.S. Schorlemmer⁵⁴, M. Schott⁸², D. Schouten^{158a}, J. Schovancova²⁵, S. Schramm¹⁵⁷, M. Schreyer¹⁷³, C. Schroeder⁸², N. Schuh⁸², M.J. Schultens²¹, H.-C. Schultz-Coulon^{57a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁶, Ph. Schune¹³⁵, C. Schwanenberger⁸³, A. Schwartzman¹⁴², T.A. Schwarz⁸⁸, Ph. Schwegler¹⁰⁰, Ph. Schwemling¹³⁵, R. Schwienhorst⁸⁹, J. Schwindling¹³⁵, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, E. Scifo¹¹⁶, G. Sciolla²³, F. Scuri^{123a,123b}, F. Scutti²¹, J. Searcy⁸⁸, G. Sedov⁴², E. Sedykh¹²², P. Seema²¹, S.C. Seidel¹⁰⁴, A. Seiden¹³⁶, F. Seifert¹²⁷, J.M. Seixas^{24a}, G. Sekhniaidze^{103a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov^{122,*}, G. Sellers⁷³, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁶, L. Serkin⁵⁴, T. Serre⁸⁴, R. Seuster^{158a}, H. Severini¹¹², T. Sfiligoi⁷⁴, F. Sforza¹⁰⁰, A. Sfyrila³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁵, L.Y. Shan^{33a}, R. Shang¹⁶⁴, J.T. Shank²², M. Shapiro¹⁵, P.B. Shatalov⁹⁶, K. Shaw^{163a,163b}, C.Y. Shehu¹⁴⁸, P. Sherwood⁷⁷, L. Shi^{150,ae}, S. Shimizu⁶⁶, C.O. Shimmmin¹⁶², M. Shimojima¹⁰¹, M. Shiyakova⁶⁴, A. Shmeleva⁹⁵, D. Shoaleh Saadi⁹⁴, M.J. Shochet³¹, D. Short¹¹⁹, S. Shrestha⁶³, E. Shulga⁹⁷, M.A. Shupe⁷, S. Shushkevich⁴², P. Sicho¹²⁶, O. Sidiropoulou¹⁵³, D. Sidorov¹¹³, A. Sidoti^{131a}, F. Siegert⁴⁴, Dj. Sijacki^{13a}, J. Silva^{125a,125d}, Y. Silver¹⁵², D. Silverstein¹⁴², S.B. Silverstein^{145a}, V. Simak¹²⁷, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁶, E. Simioni⁸², B. Simmons⁷⁷, R. Simoniello^{90a,90b}, P. Sinervo¹⁵⁷, N.B. Sinev¹¹⁵, G. Siragusa¹⁷³, A. Sircar⁷⁸, S.Yu. Sivoklokov⁹⁸, J. Sjölin^{145a,145b}, T.B. Sjörsen¹⁴, H.P. Skottowe⁵⁶, K.Yu. Skovpen¹⁰⁸, P. Skubic¹¹², M. Slater¹⁸, T. Slavicek¹²⁷, M. Slawinska¹⁰⁶, K. Sliwa¹⁶⁰, V. Smakhtin¹⁷¹, B.H. Smart⁴⁶, L. Smestad¹⁴, S.Yu. Smirnov⁹⁷, Y. Smirnov⁹⁷, L.N. Smirnova^{98,af}, O. Smirnova⁸⁰, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁵, G. Snidero⁷⁵, S. Snyder²⁵, R. Sobie^{168,j}, F. Socher⁴⁴, A. Soffer¹⁵², D.A. Soh^{150,ae}, C.A. Solans³⁰, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁷, U. Soldevila¹⁶⁶, A.A. Solodkov¹²⁹, A. Soloshenko⁶⁴, O.V. Solovyanov¹²⁹, V. Solovyev¹²², P. Sommer⁴⁸, H.Y. Song^{33b}, N. Soni¹⁵, A. Sood¹⁵, A. Sopczak¹²⁷, B. Sopko¹²⁷, V. Sopko¹²⁷, V. Sorin¹², M. Sosebee⁸, R. Soualah^{163a,163c}, P. Soueid⁹⁴, A.M. Soukharev^{108,c}, D. South⁴², S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, W.R. Spearman⁵⁶, F. Spettel¹⁰⁰, R. Spighi^{20a}, G. Spigo³⁰, L.A. Spiller⁸⁷, M. Spousta¹²⁸, T. Spreitzer¹⁵⁷,

R.D. St. Denis^{53,*}, S. Staerz⁴⁴, J. Stahlman¹²¹, R. Stamen^{57a}, S. Stamm¹⁶, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{133a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴², R. Staszewski³⁹, P. Steinberg²⁵, B. Stelzer¹⁴¹, H.J. Stelzer³⁰, O. Stelzer-Chilton^{158a}, H. Stenzel⁵², S. Stern¹⁰⁰, G.A. Stewart⁵³, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, G. Stoicea^{26a}, P. Stolte⁵⁴, S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁶, S. Strandberg^{145a,145b}, E. Strauss¹⁴², M. Strauss¹¹², P. Strizenec^{143b}, R. Ströhmer¹⁷³, D.M. Strom¹¹⁵, R. Stroynowski⁴⁰, A. Strubig¹⁰⁵, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴², D. Su¹⁴², J. Su¹²⁴, R. Subramaniam⁷⁸, A. Succurro¹², Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulin⁹⁵, S. Sultansoy^{4d}, T. Sumida⁶⁷, S. Sun⁵⁶, X. Sun^{33a}, J.E. Sundermann⁴⁸, K. Suruliz¹³⁸, M.R. Sutton¹⁴⁸, Y. Suzuki⁶⁵, M. Svatos¹²⁶, S. Swedish¹⁶⁷, M. Swiatlowski¹⁴², I. Sykora^{143a}, T. Sykora¹²⁸, D. Ta⁸⁹, C. Taccini^{133a,133b}, K. Tackmann⁴², J. Taenzer¹⁵⁷, A. Taffard¹⁶², R. Tafirout^{158a}, N. Taiblum¹⁵², H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹³⁹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshev^{108,c}, J.Y.C. Tam¹⁷³, K.G. Tan⁸⁷, J. Tanaka¹⁵⁴, R. Tanaka¹¹⁶, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴¹, B.B. Tannenwald¹¹⁰, N. Tannoury²¹, S. Tapprogge⁸², S. Tarem¹⁵¹, F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b}, A. Tavares Delgado^{125a,125b}, Y. Tayalati^{134d}, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{158b}, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵⁰, J.J. Teoh¹¹⁷, S. Terada⁶⁵, K. Terashi¹⁵⁴, J. Terron⁸¹, S. Terzo¹⁰⁰, M. Testa⁴⁷, R.J. Teuscher^{157,j}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁶, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁷, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, F. Tian³⁵, M.J. Tibbetts¹⁵, V.O. Tikhomirov^{95,ag}, Yu.A. Tikhonov^{108,c}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴, P. Tipton¹⁷⁵, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹²⁸, J. Tojo⁶⁹, S. Tokár^{143a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, E. Tolley⁵⁶, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹, K. Toms¹⁰⁴, E. Torrence¹¹⁵, H. Torres¹⁴¹, E. Torró Pastor¹⁶⁶, J. Toth^{84,ah}, F. Touchard⁸⁴, D.R. Tovey¹³⁸, H.L. Tran¹¹⁶, T. Trefzger¹⁷³, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{158a}, S. Trincas-Duvoid⁷⁹, M.F. Tripiana¹², W. Trischuk¹⁵⁷, B. Trocme⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁵, M. Trovatelli^{133a,133b}, P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C-L. Tseng¹¹⁹, P.V. Tsiarehsha⁹¹, D. Tsiou¹³⁵, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁷, A. Tudorache^{26a}, V. Tudorache^{26a}, A.N. Tuna¹²¹, S.A. Tupputi^{20a,20b}, S. Turchikhin^{98,af}, D. Turecek¹²⁷, R. Turra^{90a,90b}, A.J. Turvey⁴⁰, P.M. Tuts³⁵, A. Tykhonov⁴⁹, M. Tylmad^{145a,145b}, K. Uchida²¹, I. Ueda¹⁵⁴, R. Ueno²⁹, M. Ughetto⁸⁴, M. Ugland¹⁴, M. Uhlenbrock²¹, F. Ukegawa¹⁵⁹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶², F.C. Ungaro⁴⁸, Y. Unno⁶⁵, C. Unverdorben⁹⁹, J. Urban^{143b}, D. Urbaniec³⁵, P. Urquijo⁸⁷, G. Usai⁸, A. Usanova⁶¹, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, N. Valencic¹⁰⁶, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁶, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁶, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁶, W. Van Den Wollenberg¹⁰⁶, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶, H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴¹, I. van Vulpen¹⁰⁶, M.C. van Woerden³⁰, M. Vanadia^{131a,131b}, W. Vandelli³⁰, R. Vanguri¹²¹, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁹, G. Vardanyan¹⁷⁶, R. Vari^{131a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas⁷⁹, A. Vartapetian⁸, K.E. Varvell¹⁴⁹, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{125a,125c}, S. Veneziano^{131a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi¹⁶⁸, N. Venturi¹⁵⁷, A. Venturini²³, V. Vercesi^{120a}, M. Verducci^{131a,131b}, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{141,e}, O. Viazlo⁸⁰, I. Vichou¹⁶⁴, T. Vickey^{144c,ai}, O.E. Vickey Boeriu^{144c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁷, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez^{90a,90b}, E. Vilucchi⁴⁷, M.G. Vincker²⁹, V.B. Vinogradov⁶⁴, J. Virzi¹⁵, I. Vivarelli¹⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹, M. Vlasak¹²⁷, A. Vogel²¹, M. Vogel^{32a}, P. Vokac¹²⁷, G. Volpi^{123a,123b}, M. Volpi⁸⁷, H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, K. Vorobev⁹⁷, M. Vos¹⁶⁶, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁵, M. Vranjes Milosavljevic^{13a}, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, P. Wagner²¹, W. Wagner¹⁷⁴, H. Wahlberg⁷⁰, S. Wahrenmund⁴⁴, J. Wakabayashi¹⁰², J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴⁰, R. Wall¹⁷⁵, P. Waller⁷³, B. Walsh¹⁷⁵, C. Wang^{150,aj}, C. Wang⁴⁵, F. Wang¹⁷², H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵⁰, T. Wang²¹, X. Wang¹⁷⁵, C. Wanotayaroj¹¹⁵, A. Warburton⁸⁶, C.P. Ward²⁸, D.R. Wardrope⁷⁷, A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁴⁹, M.F. Watson¹⁸, G. Watts¹³⁷, S. Watts⁸³, B.M. Waugh⁷⁷, S. Webb⁸³, M.S. Weber¹⁷, S.W. Weber¹⁷³, J.S. Webster³¹, A.R. Weidberg¹¹⁹, B. Weinert⁶⁰, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁶, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{150,ae}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{57a}, J. Wetter¹⁶⁰, K. Whalen²⁹, A. White⁸, M.J. White¹, R. White^{32b}, D. Whiteson¹⁶², F.J. Wickens¹³⁰, W. Wiedenmann¹⁷², M. WIELERS¹³⁰, P. Wienemann²¹, C. Wiglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42,ak}, H.G. Wilkens³⁰, H.H. Williams¹²¹, S. Williams²⁸, C. Willis⁸⁹, S. Willocq⁸⁵, A. Wilson⁸⁸, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁵, B.T. Winter²¹, M. Wittgen¹⁴², T. Wittig⁴³, J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹,

H. Wolters^{125a,125c}, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, M. Wright⁵³, M. Wu⁵⁵, S.L. Wu¹⁷², X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, T.R. Wyatt⁸³, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁵, D. Xu^{33a}, L. Xu^{33b,al}, B. Yabsley¹⁴⁹, S. Yacoob^{144b,am}, R. Yakabe⁶⁶, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁴, Y. Yamaguchi¹¹⁷, A. Yamamoto⁶⁵, S. Yamamoto¹⁵⁴, T. Yamamura¹⁵⁴, T. Yamanaka¹⁵⁴, K. Yamauchi¹⁰², Y. Yamazaki⁶⁶, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷², U.K. Yang⁸³, Y. Yang¹¹⁰, S. Yanush⁹², L. Yao^{33a}, W.-M. Yao¹⁵, Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, I. Yeletsikh⁶⁴, A.L. Yen⁵⁶, E. Yildirim⁴², M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷⁰, R. Yoshida⁶, K. Yoshihara¹⁵⁴, C. Young¹⁴², C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁸⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷, I. Yusuf^{28,an}, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129,z}, A. Zaman¹⁴⁷, S. Zambito²³, D. Zanzi⁸⁷, C. Zeitnitz¹⁷⁴, M. Zeman¹²⁷, A. Zemla^{38a}, K. Zengel²³, O. Zenin¹²⁹, T. Ženiš^{143a}, D. Zerwas¹¹⁶, G. Zevi della Porta⁵⁶, D. Zhang⁸⁸, F. Zhang¹⁷², J. Zhang⁶, L. Zhang¹⁵⁰, R. Zhang^{33b}, X. Zhang^{33d}, Z. Zhang¹¹⁶, Y. Zhao^{33d}, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, L. Zhou³⁵, N. Zhou¹⁶², C.G. Zhu^{33d}, H. Zhu^{33a}, J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁵, A. Zibell¹⁷³, D. Zieminska⁶⁰, N.I. Zimine⁶⁴, C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Ziolkowski¹⁴⁰, G. Zobernig¹⁷², A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{103a,103b}, V. Zutshi¹⁰⁷, L. Zwalinski³⁰.

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany NY, United States of America

³ Department of Physics, University of Alberta, Edmonton AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Istanbul Aydin University, Istanbul; (d) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁷ Department of Physics, University of Arizona, Tucson AZ, United States of America

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

¹³ (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

²⁰ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²¹ Physikalisches Institut, University of Bonn, Bonn, Germany

²² Department of Physics, Boston University, Boston MA, United States of America

²³ Department of Physics, Brandeis University, Waltham MA, United States of America

²⁴ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁵ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

²⁶ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁹ Department of Physics, Carleton University, Ottawa ON, Canada

- ³⁰ CERN, Geneva, Switzerland
- ³¹ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³² ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c) Department of Physics, Nanjing University, Jiangsu; ^(d) School of Physics, Shandong University, Shandong; ^(e) Physics Department, Shanghai Jiao Tong University, Shanghai; ^(f) Physics Department, Tsinghua University, Beijing 100084, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁶ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁶ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- ⁵⁷ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁸ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁵⁹ ^(a) Department of Physics, Shatin, N.T., Hong Kong; ^(b) Department of Physics, Hong Kong; ^(c) Department of Physics, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶⁰ Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City IA, United States of America
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Louisiana Tech University, Ruston LA, United States of America
- ⁷⁹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁰ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸¹ Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- ⁸² Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸³ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁴ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁵ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁶ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁷ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁸ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁸⁹ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁹⁰ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹¹ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹² National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹³ Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹⁴ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁵ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁶ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁷ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁸ D.V.Skobeltzyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ⁹⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰¹ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰² Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰³ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁴ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁵ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁶ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁷ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁸ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁹ Department of Physics, New York University, New York NY, United States of America
- ¹¹⁰ Ohio State University, Columbus OH, United States of America
- ¹¹¹ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹² Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹³ Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹⁴ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁵ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁶ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁷ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁸ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²⁰ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²¹ Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²² Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²³ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁴ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- ¹²⁵ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física

- Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁶ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁸ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹²⁹ State Research Center Institute for High Energy Physics, Protvino, Russia
- ¹³⁰ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³¹ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³² ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³³ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁴ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- ¹³⁵ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ¹³⁶ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- ¹³⁷ Department of Physics, University of Washington, Seattle WA, United States of America
- ¹³⁸ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹³⁹ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴⁰ Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴¹ Department of Physics, Simon Fraser University, Burnaby BC, Canada
- ¹⁴² SLAC National Accelerator Laboratory, Stanford CA, United States of America
- ¹⁴³ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁴ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁵ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁶ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁷ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- ¹⁴⁸ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁴⁹ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵⁰ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵¹ Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵² Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵³ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁴ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁵ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁶ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁷ Department of Physics, University of Toronto, Toronto ON, Canada
- ¹⁵⁸ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- ¹⁵⁹ Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁶⁰ Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- ¹⁶¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶² Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ¹⁶³ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁴ Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁶⁵ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁶ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

- ¹⁶⁷ Department of Physics, University of British Columbia, Vancouver BC, Canada
¹⁶⁸ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
¹⁶⁹ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁰ Waseda University, Tokyo, Japan
¹⁷¹ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷² Department of Physics, University of Wisconsin, Madison WI, United States of America
¹⁷³ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁴ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁵ Department of Physics, Yale University, New Haven CT, United States of America
¹⁷⁶ Yerevan Physics Institute, Yerevan, Armenia
¹⁷⁷ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, United Kingdom
^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
^c Also at Novosibirsk State University, Novosibirsk, Russia
^d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
^e Also at TRIUMF, Vancouver BC, Canada
^f Also at Department of Physics, California State University, Fresno CA, United States of America
^g Also at Tomsk State University, Tomsk, Russia
^h Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
ⁱ Also at Università di Napoli Parthenope, Napoli, Italy
^j Also at Institute of Particle Physics (IPP), Canada
^k Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
^l Also at Chinese University of Hong Kong, China
^m Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
ⁿ Also at Louisiana Tech University, Ruston LA, United States of America
^o Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
^p Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
^q Also at CERN, Geneva, Switzerland
^r Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
^s Also at Manhattan College, New York NY, United States of America
^t Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
^u Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
^v Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
^w Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
^x Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
^y Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
^z Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland
^{ab} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
^{ac} Also at International School for Advanced Studies (SISSA), Trieste, Italy
^{ad} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
^{ae} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
^{af} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
^{ag} Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
^{ah} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom
^{aj} Also at Department of Physics, Nanjing University, Jiangsu, China
^{ak} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
^{al} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
^{am} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- * Deceased