



Search for the Dimuon Decay of the Higgs Boson in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud *et al.**

(ATLAS Collaboration)

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A search for the dimuon decay of the Higgs boson was performed using data corresponding to an integrated luminosity of 36.1 fb^{-1} collected with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider. No significant excess is observed above the expected background. The observed (expected) upper limit on the cross section times branching ratio is 3.0 (3.1) times the Standard Model prediction at the 95% confidence level for a Higgs boson mass of 125 GeV. When combined with the pp collision data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, the observed (expected) upper limit is 2.8 (2.9) times the Standard Model prediction.

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In July 2012, the ATLAS and CMS Collaborations discovered a new particle with a mass of approximately 125 GeV [1–3] at the CERN Large Hadron Collider (LHC). Subsequent measurements have indicated that this particle is consistent with the Standard Model (SM) Higgs boson [4–10], denoted by H . The $H \rightarrow \mu\mu$ decay is a sensitive channel in which the Higgs coupling to second-generation fermions can be measured with a clean final-state signature at the LHC. The SM branching ratio for the Higgs boson to dimuon decay is 2.18×10^{-4} [11] for $m_H = 125$ GeV. Several scenarios beyond the SM [12–14] predict a higher branching ratio. Any deviation from the SM prediction could be a sign of new physics. The ATLAS experiment carried out a search for the $H \rightarrow \mu\mu$ process using data collected in 2011 and 2012 (LHC Run 1), corresponding to integrated luminosities of 4.5 fb^{-1} at a center-of-mass energy $\sqrt{s} = 7$ TeV and 20 fb^{-1} at $\sqrt{s} = 8$ TeV [15]. For a Higgs boson with a mass of 125 GeV, an observed (expected) upper limit of 7.1 (7.2) was set at the 95% confidence level (C.L.) on the signal strength, defined as the production rate of the $H \rightarrow \mu\mu$ process normalized to the SM prediction. The CMS experiment also performed searches for the $H \rightarrow \mu\mu$ process with data collected in LHC Run 1 [16]. The observed (expected) upper limit from CMS on the signal strength was 7.4 (6.5) at the 95% C.L. for a Higgs boson with $m_H = 125$ GeV.

In this Letter, a search for the dimuon decay of the Higgs boson is presented. The Higgs boson mass is assumed to be $m_H = 125$ GeV for all the results presented in this Letter. The search is performed using pp collision data recorded

with the ATLAS detector in 2015 and 2016 at $\sqrt{s} = 13$ TeV. The data set corresponds to an integrated luminosity of 36.1 fb^{-1} . This analysis selects events with exactly two opposite-charge muons and classifies them into eight orthogonal categories. Two categories are defined using a multivariable discriminant and provide good sensitivity to the vector-boson fusion (VBF) process. Signal events produced in the VBF process tend to have two high- p_T forward jets in opposite detector hemispheres and little hadronic activity between them. The other six categories are sensitive to signal events produced in the gluon-gluon fusion (ggF) process and are defined with different requirements on muon pseudorapidity (η) and the transverse momentum of the dimuon system ($p_T^{\mu\mu}$). The dominant irreducible background is the $Z/\gamma^* \rightarrow \mu\mu$ (Drell-Yan) process. A simultaneous fit to distributions of the dimuon invariant mass $m_{\mu\mu}$ in all the categories is performed in the range 110 to 160 GeV to extract the overall $H \rightarrow \mu\mu$ signal strength and determine the background normalizations and shapes. The fitting range is chosen to avoid the Z boson mass peak and have enough data events to constrain the background.

The ATLAS detector [17] at the LHC covers nearly the entire solid angle around the collision point [18]. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroidal magnets. Events used in this analysis were recorded using a combination of single-muon triggers, with the transverse momentum (p_T) threshold being 26 GeV for isolated muons or 50 GeV for muons without any isolation requirement imposed. The trigger efficiency is about 95% for the signal processes.

Monte Carlo (MC) simulated samples are used to optimize the event selection, to model the signal processes, and to develop an analytic function to model the $m_{\mu\mu}$ distributions for the total background. Signal events from

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

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the ggF and VBF processes were generated with POWHEG-BOX v2 [19] at next-to-leading order (NLO) in quantum chromodynamics (QCD) using the CT10 [20] parton distribution function (PDF) set and PYTHIA8 [21] for parton showering and hadronization. PYTHIA8 was also used to model $H \rightarrow \mu\mu$ events produced in association with a W or Z boson (VH). The hadronization and underlying-event parameters were set according to the AZNLO tune based on the Z boson p_T distribution measurement in 7 TeV pp collisions [22]. The simulated Higgs boson p_T spectrum for the ggF process is tuned to match the HRES prediction [23,24].

The signal samples are normalized to the predicted cross sections times branching ratio. The production cross sections of the Higgs boson at $\sqrt{s} = 13$ TeV are reported in Refs. [11,25,26]. The cross section for the ggF process is calculated at next-to-next-to-next-to-leading-order QCD [27] and NLO electroweak accuracies [28,29]. Both the VBF and VH cross sections are computed with next-to-next-to-leading-order QCD [30] and NLO electroweak precision [31–33]. The branching ratio for the $H \rightarrow \mu\mu$ decay is calculated using HDECAY [34] at NLO in QCD.

Drell-Yan background events were generated with MADGRAPH5 [35] with the NNPDF23LO [36] PDF set interfaced to PYTHIA8. The $t\bar{t}$ and single-top quark samples were generated with POWHEG-BOX v2 using the CT10 PDF set interfaced to PYTHIA6 [37] for parton showering and hadronization. The diboson processes (WW , WZ , and ZZ) were generated with SHERPA v2.1 [38] with the CT10 PDF set.

All simulated samples were processed through the full ATLAS detector simulation [39] based on GEANT4 [40]. The effects arising from multiple pp collisions in the same or neighboring bunch crossings (pileup) were included in the MC simulation. Events are reweighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. Simulated events are corrected to reflect the muon momentum scale and resolution and the muon trigger and identification efficiencies measured in data.

Events are required to contain at least one reconstructed pp collision vertex candidate with at least two associated ID tracks, each with $p_T > 0.4$ GeV. The vertex with the largest sum of p_T^2 of tracks is considered to be the primary vertex. Dimuon events are selected by requiring two opposite-charge muons. Muons are reconstructed by combining tracks in the ID with tracks in the MS. Candidate muons are required to satisfy the “medium” criteria defined in Ref. [41] and required to have $p_T > 15$ GeV and $|\eta| < 2.5$. Muons are matched to the primary vertex by requiring the longitudinal impact parameter z_0 to satisfy $|z_0 \sin(\theta)| < 0.5$ mm, where θ is the polar angle of the track. The significance of the transverse impact parameter d_0 calculated with respect to the measured beam line position is required to satisfy $|d_0|/\sigma(d_0) < 3$, where $\sigma(d_0)$ is the uncertainty in d_0 . Furthermore, the “loose”

isolation criteria described in Ref. [41] are applied to suppress muons from b -hadron decays. Jets are reconstructed using the anti- k_r algorithm [42] with a radius parameter of $R = 0.4$. Candidate jets must have $|\eta| < 4.5$, and the jet p_T must be larger than 25 (30) GeV for $|\eta| < 2.5$ ($2.5 < |\eta| < 4.5$). To suppress pileup contributions, an additional requirement using the track and vertex information inside a jet [43] is imposed on jets with $|\eta| < 2.4$ and $p_T < 60$ GeV. Top quark production is the second largest background with neutrinos and b hadrons in the final states. Jets containing b hadrons with $|\eta| < 2.5$ are identified as b -tagged jets using a multivariate b -tagging algorithm that provides a 60% efficiency and a rejection factor of more than 1000 for light-flavor jets [44]. Neutrinos escape from the detector and lead to missing transverse momentum E_T^{miss} . The E_T^{miss} is defined as the magnitude of the negative vectorial sum of the transverse momenta of the selected and calibrated physics objects (including muons and jets) and the ID tracks not associated with any physics object (soft term) [45]. To reduce the top quark contribution, events are required to have $E_T^{\text{miss}} < 80$ GeV and no b -tagged jets.

To ensure a high trigger efficiency, the leading muon must have $p_T > 27$ GeV. These criteria form the preselection, and events passing the preselection with $110 \text{ GeV} < m_{\mu\mu} < 160$ GeV constitute the inclusive signal region. The signal efficiency is 57% (59%) for the ggF (VBF) process. The $m_{\mu\mu}$ distributions for data and MC events in the inclusive signal region are shown in Fig. 1.

The VBF categories are only considered for events containing at least two jets. To optimize the selections, several kinematic variables that are sensitive to the

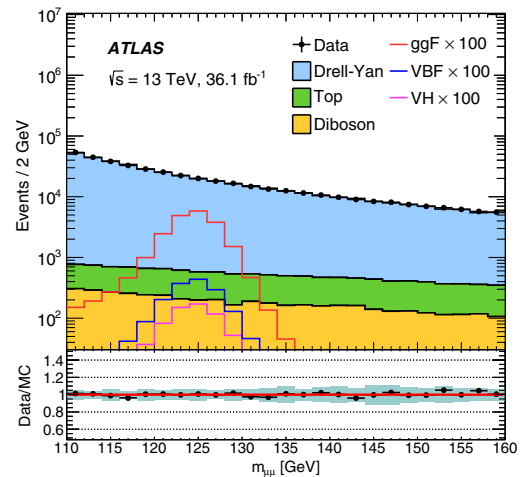


FIG. 1. Observed and simulated $m_{\mu\mu}$ distributions in the inclusive signal region. The expected signals are scaled by a factor of 100. The total background prediction is normalized to the observed data yield, while the relative fractions between the different processes are fixed to the SM predictions. The error band only reflects the statistical and experimental uncertainties in the MC background prediction, while the theoretical uncertainties are not included.

TABLE I. Event yields for the expected signal (S) and background (B) processes, and numbers of the observed data events in different categories. The full widths at half maximum (FWHM) of the signal $m_{\mu\mu}$ distributions are also shown. In each category, the event yields are counted within an $m_{\mu\mu}$ interval, which is centered at the simulated signal peak and contains 90% of the expected signal events. The expected signal event yields are normalized to 36.1 fb^{-1} . The background in each category is normalized to the observed data yield, while the relative fractions between the different processes are fixed to the SM predictions.

	S	B	S/\sqrt{B}	FWHM (GeV)	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6	7885
Noncentral low $p_T^{\mu\mu}$	32	38 000	0.16	7.0	38 777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7	6585
Noncentral medium $p_T^{\mu\mu}$	66	31 000	0.37	7.1	31 291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3	3160
Noncentral high $p_T^{\mu\mu}$	40	13 000	0.35	7.7	12 829
VBF loose	3.4	260	0.21	7.6	274
VBF tight	3.4	78	0.38	7.5	79

characteristics of the VBF production are used. For jet-related variables, only the two jets with highest p_T are considered, with the leading (subleading) jet denoted by $j_1(j_2)$. Among those variables, the most sensitive ones are dijet invariant mass (m_{jj}), $p_T^{\mu\mu}$, difference in pseudorapidity $\Delta\eta_{jj}$, and angular distance ΔR_{jj} between the two jets. Other variables with less discriminating power include transverse momentum of the dijet system (p_T^{jj}), E_T^{miss} , scalar p_T sum of muons and jets (S_T), p_T of the system containing two muons and one or two jets ($p_T^{\mu j_1}$, $p_T^{\mu j_2}$, and $p_T^{\mu j_1 j_2}$), rapidity difference between the dimuon system and the jets ($\Delta y_{\mu\mu, j_1}$, $\Delta y_{\mu\mu, j_2}$, and $\Delta y_{\mu\mu, jj}$), and “centrality”, defined as the difference between the dimuon rapidity and the averaged jet rapidity divided by the absolute rapidity difference between j_1 and j_2 . The MC modeling of these variables for the Drell-Yan process is compared with data in the region with $76 \text{ GeV} < m_{\mu\mu} < 106 \text{ GeV}$, and no significant mis-modeling is found. All these variables are combined into a multivariate discriminant, which is then trained using MC events with a boosted-decision-tree (BDT) method [46–48] to maximize the separation between the VBF signal and the total background. Events with a larger BDT score are more signallike, while background events tend to populate the low BDT score region. Finally, events with BDT score ≥ 0.9 constitute one of the VBF categories (“VBF tight”), and the other one (“VBF loose”) is defined with $0.7 < \text{BDT score} < 0.9$.

The remaining events that are not selected for the VBF categories all enter into the ggF categories. Signal events from the ggF process tend to have a harder $p_T^{\mu\mu}$ spectrum than Drell-Yan events due to the higher initial-state QCD radiation. To take advantage of this feature, events are separated into three $p_T^{\mu\mu}$ categories: “low $p_T^{\mu\mu}$ ” ($p_T^{\mu\mu} \leq 15 \text{ GeV}$), “medium $p_T^{\mu\mu}$ ” ($15 \text{ GeV} < p_T^{\mu\mu} < 50 \text{ GeV}$), and “high $p_T^{\mu\mu}$ ” ($p_T^{\mu\mu} \geq 50 \text{ GeV}$). Since the muon momentum resolution in the barrel region ($|\eta| \leq 1.05$) is better than that in the end cap regions ($1.05 < |\eta| < 2.7$), events in each p_T category are further divided according to the pseudorapidities of the muons. Requiring both muons to

have $|\eta| \leq 1$ forms the “central” category, while the remaining events constitute the “noncentral” category.

Table I shows the expected signal and background event yields as well as the observed number of data events within an $m_{\mu\mu}$ interval in each category. Each chosen interval is centered at the simulated signal peak and contains 90% of the expected signal events. These numbers are provided to demonstrate the expected detection sensitivity, while in the final results, the signal and background yields are determined by fitting the observed $m_{\mu\mu}$ distributions.

Analytical models are used to describe the $m_{\mu\mu}$ distributions for both the signal and background processes. To describe the Higgs boson peak with a lower-mass tail due to final-state photon radiation, the signal model is chosen as the sum of a Crystal Ball function (CB) [49] and a Gaussian function (GS):

$$P_S(m_{\mu\mu}) = f_{\text{CB}} \times \text{CB}(m_{\mu\mu}, m_{\text{CB}}, \sigma_{\text{CB}}, \alpha, n) + (1 - f_{\text{CB}}) \times \text{GS}(m_{\mu\mu}, m_{\text{GS}}, \sigma_{\text{GS}}^S),$$

where f_{CB} is the fraction of the CB contribution when each component (CB or GS) is normalized to unity. The parameters α and n define the power-law tail of the CB distribution. The parameters m_{CB} , m_{GS} , σ_{CB} , and σ_{GS}^S denote the CB mean value, GS mean value, CB width, and GS width, respectively. These parameters are determined for each signal category by fitting the signal model to the simulated $m_{\mu\mu}$ spectrum. In each category, the ggF , VBF, and VH signal shapes are obtained separately and then combined into the total signal shape according to their SM predictions.

The background model should be able to describe the steeply falling $m_{\mu\mu}$ distributions from the dominant Drell-Yan process. At the same time, it should have sufficient flexibility to absorb potential differences between data and MC simulation, and allow variations in the $m_{\mu\mu}$ spectra due to different selections and additional contributions from minor background processes. The adopted model is the sum of a Breit-Wigner function (BW)

convolved with a GS, and an exponential function divided by a cubic function,

$$P_B(m_{\mu\mu}) = f \times [\text{BW}(m_{\text{BW}}, \Gamma_{\text{BW}}) \otimes \text{GS}(\sigma_{\text{GS}}^{\text{B}})](m_{\mu\mu}) + (1 - f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^3,$$

where f is the fraction of the BW component when each component is normalized to unity. The $\sigma_{\text{GS}}^{\text{B}}$ parameter in each category is fixed to the corresponding average $m_{\mu\mu}$ resolution as determined from MC Drell-Yan events. For all the categories, the BW parameters are fixed to $m_{\text{BW}} = 91.2$ GeV and $\Gamma_{\text{BW}} = 2.49$ GeV [50]. The parameters f and A are unconstrained and uncorrelated between different categories.

A binned maximum-likelihood fit to the observed $m_{\mu\mu}$ distributions in the range 110–160 GeV is performed using the sum of the signal and background models (“S + B model”). The fit is done simultaneously in all the categories. In addition to the background model parameters (f and A) described earlier, the background normalization in each category is a free parameter in the fit. The product of the $H \rightarrow \mu\mu$ signal strength μ_S and the expected signal yield gives the signal normalization in each category.

The expected signal yields used in the fit are subject to experimental and theoretical uncertainties. The systematic uncertainties in the expected signal are correlated between all the categories.

The uncertainty in the combined 2015 and 2016 integrated luminosity is 3.2%, derived, following a methodology similar to that detailed in Ref. [51], from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016. Other sources of experimental uncertainty include the muon reconstruction and identification efficiencies, the efficiencies due to the trigger, isolation, and impact parameter requirements, the muon momentum scale and resolution, the determination of the E_T^{miss} soft term, the b -tagging efficiency, the pileup modeling, as well as the jet energy scale and resolution. The total experimental uncertainty in the predicted signal yield in each ggF category is between 4% and 6%, dominated by the luminosity, muon, jet, and pileup contributions. The experimental uncertainty increases to 15% in the VBF categories, due to larger contributions from the jet energy scale and resolution uncertainties. The effects of the experimental uncertainties in the predicted signal $m_{\mu\mu}$ shapes are found to be minor and are therefore neglected in this search.

The theoretical uncertainties in the production cross section of the Higgs boson and the $H \rightarrow \mu\mu$ decay branching ratio are set according to Refs. [25,26]. The uncertainty in the signal acceptance in the ggF categories, due to the modeling of the Higgs boson p_T spectrum, is estimated by varying the QCD scales used in the HRES program. The acceptance uncertainties of ggF signal events

in the VBF categories are estimated using the method described in Ref. [15]. The uncertainties associated with the modeling of multiparton interactions are estimated by turning them off in the event generation, according to the recommendations in Ref. [11]. The uncertainty in the ggF signal prediction ranges from 15% to 25%, dominated by the uncertainties due to omitted high-order effects. The total theoretical uncertainty in the VBF signal yield in each category is typically around 5%.

Any systematic bias in the background model when describing the underlying $m_{\mu\mu}$ spectrum might result in spurious signal events in the measurement. In each category, the number of spurious signal events (N_{spur}) is estimated by fitting the parameterized S + B model to the simulated background $m_{\mu\mu}$ distribution in the range 110–160 GeV. The $m_{\mu\mu}$ spectra are obtained from large Drell-Yan MC samples, which were produced with POWHEG-BOX v2[19] and MADGRAPH5 [35] for the ggF and VBF categories, respectively, and correspond to an equivalent integrated luminosity of about 5 ab^{-1} . Values of N_{spur} are derived for three nearby Higgs boson masses (120, 125, and 130 GeV), and from these the largest value between the yields and their statistical uncertainties is taken as the N_{spur} value for a certain category. A detailed discussion about how N_{spur} is used in the fitting procedure is given in Ref. [52]. The background modeling uncertainty is treated as uncorrelated among all the categories. This uncertainty varies from 8% to 50% of the statistical uncertainties of the background, depending on the selection category. The impact of the background mismodeling on the expected upper limit on the signal strength is about 2%.

The observed $m_{\mu\mu}$ spectrum is compared to the background-only fit in Fig. 2 for the VBF tight category. The S + B model is fitted to the observed $m_{\mu\mu}$ spectra in eight signal categories simultaneously, and the measured overall

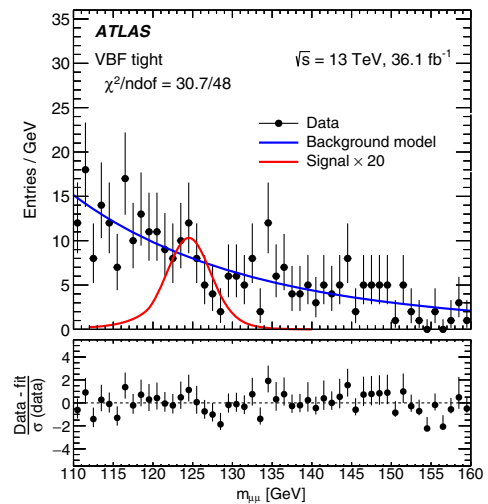


FIG. 2. Background-only fit to the observed $m_{\mu\mu}$ distribution in the VBF tight category. Only the statistical uncertainties are shown for the data points. The expected signal is scaled by a factor of 20.

signal strength is $\mu_S = -0.1 \pm 1.5$. An upper limit on μ_S is computed using a modified frequentist CL_s method [53,54] with the profile-likelihood-ratio test statistic [53]. The observed (expected) upper limit on μ_S at the 95% C.L. is found to be 3.0 (3.1). This limit is driven by the data statistical uncertainty, while the impact of the systematic uncertainties is found to be 2.2%. When combined with the ATLAS Run 1 data, the observed (expected) upper limit is 2.8 (2.9) at the 95% C.L. The corresponding measured signal strength is $\mu_S = -0.1 \pm 1.4$. The theoretical and experimental uncertainties in the expected signal and the background modeling uncertainty are correlated in the combination.

To conclude, a search for the dimuon decay of the Higgs boson is performed using 36.1 fb^{-1} of data collected with the ATLAS detector in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ at the LHC. No significant excess is observed in data, and an upper limit is set on the signal strength.

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Seventh Framework Programme

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Alvarez Gonzalez,³² D. Álvarez Piqueras,¹⁷⁰ M. G. Alviggi,^{106a,106b} B. T. Amadio,¹⁶ Y. Amaral Coutinho,^{26a} C. Amelung,²⁵ D. Amidei,⁹² S. P. Amor Dos Santos,^{128a,128c} A. Amorim,^{128a,128b} S. Amoroso,³² G. Amundsen,²⁵ C. Anastopoulos,¹⁴¹ L. S. Ancu,⁵² N. Andari,¹⁹ T. Andeen,¹¹ C. F. Anders,^{60b} J. K. Anders,⁷⁷ K. J. Anderson,³³ A. Andreazza,^{94a,94b} V. Andrei,^{60a} S. Angelidakis,⁹ I. Angelozzi,¹⁰⁹ A. Angerami,³⁸ A. V. Anisenkov,^{111,d} N. Anjos,¹³ A. Annovi,^{126a,126b} C. Antel,^{60a} M. Antonelli,⁵⁰ A. Antonov,^{100,a} D. J. Antrim,¹⁶⁶ F. Anulli,^{134a} M. Aoki,⁶⁹ L. Aperio Bella,³² G. Arabidze,⁹³ Y. Arai,⁶⁹ J. P. Araque,^{128a} V. Araujo Ferraz,^{26a} A. T. H. Arce,⁴⁸ R. E. Ardell,⁸⁰ F. A. Arduh,⁷⁴ J-F. Arguin,⁹⁷ S. Argyropoulos,⁶⁶ M. Arik,^{20a} A. J. Armbruster,³² L. J. Armitage,⁷⁹ O. Arnaez,¹⁶¹ H. Arnold,⁵¹ M. Arratia,³⁰ O. Arslan,²³ A. Artamonov,⁹⁹ G. Artoni,¹²² S. Artz,⁸⁶ S. Asai,¹⁵⁷ N. Asbah,⁴⁵ A. Ashkenazi,¹⁵⁵ L. Asquith,¹⁵¹ K. Assamagan,²⁷ R. 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E. V. Bouhova-Thacker,⁷⁵ D. Boumediene,³⁷ C. Bourdarios,¹¹⁹ S. K. Boutle,⁵⁶ A. Boveia,¹¹³ J. Boyd,³² I. R. Boyko,⁶⁸ J. Bracinik,¹⁹ A. Brandt,⁸ G. Brandt,⁵⁷ O. Brandt,^{60a} U. Bratzler,¹⁵⁸ B. Brau,⁸⁹ J. E. Brau,¹¹⁸ W. D. Breaden Madden,⁵⁶ K. Brendlinger,⁴⁵ A. J. Brennan,⁹¹ L. Brenner,¹⁰⁹ R. Brenner,¹⁶⁸ S. Bressler,¹⁷⁵ D. L. Briglin,¹⁹ T. M. Bristow,⁴⁹ D. Britton,⁵⁶ D. Britzger,⁴⁵ F. M. Brochu,³⁰ I. Brock,²³ R. Brock,⁹³ G. Brooijmans,³⁸ T. Brooks,⁸⁰ W. K. Brooks,^{34b} J. Brosamer,¹⁶ E. Brost,¹¹⁰ J. H. Broughton,¹⁹ P. A. Bruckman de Renstrom,⁴² D. Bruncko,^{146b} A. Bruni,^{22a} G. Bruni,^{22a} L. S. Bruni,¹⁰⁹ BH Brunt,³⁰ M. Bruschi,^{22a} N. Bruscolo,²³ P. Bryant,³³ L. Bryngemark,⁴⁵ T. Buanes,¹⁵ Q. Buat,¹⁴⁴ P. Buchholz,¹⁴³ A. G. Buckley,⁵⁶ I. A. Budagov,⁶⁸ F. Buehrer,⁵¹ M. K. Bugge,¹²¹ O. Bulekov,¹⁰⁰ D. Bullock,⁸ T. J. Burch,¹¹⁰ S. Burdin,⁷⁷ C. D. Burgard,⁵¹ A. M. Burger,⁵ B. Burghgrave,¹¹⁰ K. Burka,⁴² S. Burke,¹³³ I. Burmeister,⁴⁶ J. T. P. Burr,¹²² E. Busato,³⁷ D. Büscher,⁵¹ V. 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Cheung,⁶³ L. Chevalier,¹³⁸ V. Chiarella,⁵⁰ G. Chiarelli,^{126a,126b} G. Chiodini,^{76a} A. S. Chisholm,³² A. Chitan,^{28b} Y. H. Chiu,¹⁷² M. V. Chizhov,⁶⁸ K. Choi,⁶⁴ A. R. Chomont,³⁷ S. Chouridou,¹⁵⁶ V. Christodoulou,⁸¹ D. Chromek-Burckhart,³² M. C. Chu,^{62a} J. Chudoba,¹²⁹ A. J. Chuinard,⁹⁰ J. J. Chwastowski,⁴² L. Chytka,¹¹⁷ A. K. Ciftci,^{4a} D. Cinca,⁴⁶ V. Cindro,⁷⁸ I. A. Cioara,²³ C. Ciocca,^{22a,22b} A. Ciocio,¹⁶ F. Ciotto,^{106a,106b} Z. H. Citron,¹⁷⁵ M. Citterio,^{94a} M. Ciubancan,^{28b} A. Clark,⁵² B. L. Clark,⁵⁹ M. R. Clark,³⁸ P. J. Clark,⁴⁹ R. N. Clarke,¹⁶ C. Clement,^{148a,148b} Y. Coadou,⁸⁸ M. Cobal,^{167a,167c} A. Coccaro,⁵² J. Cochran,⁶⁷ L. Colasurdo,¹⁰⁸ B. Cole,³⁸ A. P. Colijn,¹⁰⁹ J. Collot,⁵⁸ T. Colombo,¹⁶⁶ P. Conde Muiño,^{128a,128b} E. Coniavitis,⁵¹ S. H. Connell,^{147b} I. A. Connelly,⁸⁷ S. Constantinescu,^{28b} G. Conti,³² F. Conventi,^{106a,o} M. Cooke,¹⁶ A. M. Cooper-Sarkar,¹²² F. Cormier,¹⁷¹ K. J. R. Cormier,¹⁶¹ M. Corradi,^{134a,134b} F. Corriveau,^{90,p} A. Cortes-Gonzalez,³² G. Cortiana,¹⁰³ G. Costa,^{94a} M. J. Costa,¹⁷⁰ D. Costanzo,¹⁴¹ G. Cottin,³⁰ G. Cowan,⁸⁰ B. E. Cox,⁸⁷ K. Cranmer,¹¹² S. J. Crawley,⁵⁶ R. A. Creager,¹²⁴ G. Cree,³¹ S. Crépe-Renaudin,⁵⁸ F. Crescioli,⁸³ W. A. Cribbs,^{148a,148b} M. Cristinziani,²³ V. Croft,¹⁰⁸ G. Crosetti,^{40a,40b} A. Cueto,⁸⁵ T. Cuhadar Donszelmann,¹⁴¹ A. R. Cukierman,¹⁴⁵ J. Cummings,¹⁷⁹ M. Curatolo,⁵⁰ J. Cúth,⁸⁶ P. Czodrowski,³² G. D'amen,^{22a,22b} S. D'Auria,⁵⁶ L. D'eraimo,⁸³ M. D'Onofrio,⁷⁷ M. J. Da Cunha Sargedas De Sousa,^{128a,128b} C. Da Via,⁸⁷ W. Dabrowski,^{41a} T. Dado,^{146a} T. Dai,⁹² O. Dale,¹⁵ F. Dallaire,⁹⁷ C. Dallapiccola,⁸⁹ M. Dam,³⁹ J. R. Dandoy,¹²⁴ M. F. Daneri,²⁹ N. P. Dang,¹⁷⁶ A. C. Daniells,¹⁹ N. S. Dann,⁸⁷ M. Danninger,¹⁷¹ M. Dano Hoffmann,¹³⁸ V. Dao,¹⁵⁰ G. Darbo,^{53a} S. Darmora,⁸ J. Dassoulas,³ A. Dattagupta,¹¹⁸ T. Daubney,⁴⁵ W. Davey,²³ C. David,⁴⁵ T. Davidek,¹³¹ D. R. Davis,⁴⁸ P. Davison,⁸¹ E. Dawe,⁹¹ I. Dawson,¹⁴¹ K. De,⁸ R. de Asmundis,^{106a} A. De Benedetti,¹¹⁵ S. De Castro,^{22a,22b} S. De Cecco,⁸³ N. De Groot,¹⁰⁸ P. de Jong,¹⁰⁹ H. De la Torre,⁹³ F. De Lorenzi,⁶⁷ A. De Maria,⁵⁷ D. De Pedis,^{134a} A. De Salvo,^{134a} U. De Sanctis,^{135a,135b} A. De Santo,¹⁵¹ K. De Vasconcelos Corga,⁸⁸ J. B. De Vivie De Regie,¹¹⁹ W. J. Dearnaley,⁷⁵ R. Debbe,²⁷ C. Debenedetti,¹³⁹ D. V. Dedovich,⁶⁸ N. Dehghanian,³ I. Deigaard,¹⁰⁹ M. Del Gaudio,^{40a,40b} J. Del Peso,⁸⁵ D. Delgove,¹¹⁹ F. Deliot,¹³⁸ C. M. Delitzsch,⁵² A. Dell'Acqua,³² L. Dell'Asta,²⁴ M. Dell'Orso,^{126a,126b} M. Della Pietra,^{106a,106b} D. della Volpe,⁵² M. Delmastro,⁵ C. Delporte,¹¹⁹ P. A. Delsart,⁵⁸ D. A. DeMarco,¹⁶¹ S. Demers,¹⁷⁹ M. Demichev,⁶⁸ A. Demilly,⁸³ S. P. Denisov,¹³² D. Denysiuk,¹³⁸ D. Derendarz,⁴² J. E. Derkaoui,^{137d} F. Derue,⁸³ P. Dervan,⁷⁷ K. Desch,²³ C. Deterre,⁴⁵ K. Dette,⁴⁶ M. R. Devesa,²⁹ P. O. Deviveiros,³² A. Dewhurst,¹³³ S. Dhaliwal,²⁵ F. A. Di Bello,⁵² A. Di Ciaccio,^{135a,135b} L. Di Ciaccio,⁵ W. K. Di Clemente,¹²⁴ C. Di Donato,^{106a,106b} A. Di Girolamo,³² B. Di Girolamo,³² B. Di Micco,^{136a,136b} R. Di Nardo,³² K. F. Di Petrillo,⁵⁹ A. Di Simone,⁵¹ R. Di Sipio,¹⁶¹ D. Di Valentino,³¹ C. Diaconu,⁸⁸

M. Diamond,¹⁶¹ F. A. Dias,³⁹ M. A. Diaz,^{34a} E. B. Diehl,⁹² J. Dietrich,¹⁷ S. Díez Cornell,⁴⁵ A. Dimitrievska,¹⁴ J. Dingfelder,²³ P. Dita,^{28b} S. Dita,^{28b} F. Dittus,³² F. Djama,⁸⁸ T. Djobava,^{54b} J. I. Djuvsland,^{60a} M. A. B. do Vale,^{26c} D. Dobos,³² M. Dobre,^{28b} C. Doglioni,⁸⁴ J. Dolejsi,¹³¹ Z. Dolezal,¹³¹ M. Donadelli,^{26d} S. Donati,^{126a,126b} P. Dondero,^{123a,123b} J. Donini,³⁷ J. Dopke,¹³³ A. Doria,^{106a} M. T. Dova,⁷⁴ A. T. Doyle,⁵⁶ E. Drechsler,⁵⁷ M. Dris,¹⁰ Y. Du,^{36b} J. Duarte-Camperderros,¹⁵⁵ A. Dubreuil,⁵² E. Duchovni,¹⁷⁵ G. Duckeck,¹⁰² A. Ducourthial,⁸³ O. A. Ducu,^{97,q} D. Duda,¹⁰⁹ A. Dudarev,³² A. Chr. Dudder,⁸⁶ E. M. Duffield,¹⁶ L. Duflot,¹¹⁹ M. Dührssen,³² M. Dumancic,¹⁷⁵ A. E. Dumitriu,^{28b} A. K. Duncan,⁵⁶ M. Dunford,^{60a} H. Duran Yildiz,^{4a} M. Düren,⁵⁵ A. Durglishvili,^{54b} D. Duschinger,⁴⁷ B. Dutta,⁴⁵ M. Dyndal,⁴⁵ B. S. Dziedzic,⁴² C. Eckardt,⁴⁵ K. M. Ecker,¹⁰³ R. C. Edgar,⁹² T. Eifert,³² G. Eigen,¹⁵ K. Einsweiler,¹⁶ T. Ekelof,¹⁶⁸ M. El Kacimi,^{137c} R. El Kosseifi,⁸⁸ V. Ellajosyula,⁸⁸ M. Ellert,¹⁶⁸ S. Elles,⁵ F. Ellinghaus,¹⁷⁸ A. A. Elliot,¹⁷² N. Ellis,³² J. Elmsheuser,²⁷ M. Elsing,³² D. Emelianov,¹³³ Y. Enari,¹⁵⁷ O. C. Endner,⁸⁶ J. S. Ennis,¹⁷³ J. Erdmann,⁴⁶ A. Ereditato,¹⁸ M. Ernst,²⁷ S. Errede,¹⁶⁹ M. Escalier,¹¹⁹ C. Escobar,¹⁷⁰ B. Esposito,⁵⁰ O. Estrada Pastor,¹⁷⁰ A. I. Etiennevre,¹³⁸ E. Etzion,¹⁵⁵ H. Evans,⁶⁴ A. Ezhilov,¹²⁵ M. Ezzi,^{137e} F. Fabbri,^{22a,22b} L. Fabbri,^{22a,22b} V. Fabiani,¹⁰⁸ G. Facini,⁸¹ R. M. Fakhrutdinov,¹³² S. Falciano,^{134a} R. J. Falla,⁸¹ J. Faltova,³² Y. Fang,^{35a} M. Fanti,^{94a,94b} A. Farbin,⁸ A. Farilla,^{136a} C. Farina,¹²⁷ E. M. Farina,^{123a,123b} T. Farooque,⁹³ S. Farrell,¹⁶ S. M. Farrington,¹⁷³ P. Farthouat,³² F. Fassi,^{137e} P. Fassnacht,³² D. Fassouliotis,⁹ M. Fauci Giannelli,⁸⁰ A. Favareto,^{53a,53b} W. J. Fawcett,¹²² L. Fayard,¹¹⁹ O. L. Fedin,^{125,r} W. Fedorko,¹⁷¹ S. Feigl,¹²¹ L. Feligioni,⁸⁸ C. Feng,^{36b} E. J. Feng,³² H. Feng,⁹² M. J. Fenton,⁵⁶ A. B. Fenyuk,¹³² L. Feremenga,⁸ P. Fernandez Martinez,¹⁷⁰ S. Fernandez Perez,¹³ J. Ferrando,⁴⁵ A. Ferrari,¹⁶⁸ P. Ferrari,¹⁰⁹ R. Ferrari,^{123a} D. E. Ferreira de Lima,^{60b} A. Ferrer,¹⁷⁰ D. Ferrere,⁵² C. Ferretti,⁹² F. Fiedler,⁸⁶ A. Filipčič,⁷⁸ M. Filipuzzi,⁴⁵ F. Filthaut,¹⁰⁸ M. Fincke-Keeler,¹⁷² K. D. Finelli,¹⁵² M. C. N. Fiolhais,^{128a,128c,s} L. Fiorini,¹⁷⁰ A. Fischer,² C. Fischer,¹³ J. Fischer,¹⁷⁸ W. C. Fisher,⁹³ N. Flaschel,⁴⁵ I. Fleck,¹⁴³ P. Fleischmann,⁹² R. R. M. Fletcher,¹²⁴ T. Flick,¹⁷⁸ B. M. Flierl,¹⁰² L. R. Flores Castillo,^{62a} M. J. Flowerdew,¹⁰³ G. T. Forcolin,⁸⁷ A. Formica,¹³⁸ F. A. Förster,¹³ A. Forti,⁸⁷ A. G. Foster,¹⁹ D. Fournier,¹¹⁹ H. Fox,⁷⁵ S. Fracchia,¹⁴¹ P. Francavilla,⁸³ M. Franchini,^{22a,22b} S. Franchino,^{60a} D. Francis,³² L. Franconi,¹²¹ M. Franklin,⁵⁹ M. Frate,¹⁶⁶ M. Fraternali,^{123a,123b} A. N. Fray,⁷⁹ D. Freeborn,⁸¹ S. M. Fressard-Batraneanu,³² B. Freund,⁹⁷ D. Froidevaux,³² J. A. Frost,¹²² C. Fukunaga,¹⁵⁸ T. Fusayasu,¹⁰⁴ J. Fuster,¹⁷⁰ C. Gabaldon,⁵⁸ O. Gabizon,¹⁵⁴ A. Gabrielli,^{22a,22b} A. Gabrielli,¹⁶ G. P. Gach,^{41a} S. Gadatsch,³² S. Gadowski,⁸⁰ G. Gagliardi,^{53a,53b} L. G. Gagnon,⁹⁷ C. Galea,¹⁰⁸ B. Galhardo,^{128a,128c} E. J. Gallas,¹²² B. J. Gallop,¹³³ P. Gallus,¹³⁰ G. Galster,³⁹ K. K. Gan,¹¹³ S. Ganguly,³⁷ Y. Gao,⁷⁷ Y. S. Gao,^{145,h} F. M. Garay Walls,⁴⁹ C. García,¹⁷⁰ J. E. García Navarro,¹⁷⁰ J. A. García Pascual,^{35a} M. Garcia-Sciveres,¹⁶ R. W. Gardner,³³ N. Garelli,¹⁴⁵ V. Garonne,¹²¹ A. Gascon Bravo,⁴⁵ K. Gasnikova,⁴⁵ C. Gatti,⁵⁰ A. Gaudiello,^{53a,53b} G. Gaudio,^{123a} I. L. Gavrilenko,⁹⁸ C. Gay,¹⁷¹ G. Gaycken,²³ E. N. Gazis,¹⁰ C. N. P. Gee,¹³³ J. Geisen,⁵⁷ M. Geisen,⁸⁶ M. P. Geisler,^{60a} K. Gellerstedt,^{148a,148b} C. Gemme,^{53a} M. H. Genest,⁵⁸ C. Geng,⁹² S. Gentile,^{134a,134b} C. Gentsos,¹⁵⁶ S. George,⁸⁰ D. Gerbaudo,¹³ A. Gershon,¹⁵⁵ G. Geßner,⁴⁶ S. Ghasemi,¹⁴³ M. Ghneimat,²³ B. Giacobbe,^{22a} S. Giagu,^{134a,134b} N. Giangiacomi,^{22a,22b} P. Giannetti,^{126a,126b} S. M. Gibson,⁸⁰ M. Gignac,¹⁷¹ M. Gilchriese,¹⁶ D. Gillberg,³¹ G. Gilles,¹⁷⁸ D. M. Gingrich,^{3,e} N. Giokaris,^{9a} M. P. Giordani,^{167a,167c} F. M. Giorgi,^{22a} P. F. Giraud,¹³⁸ P. Giromini,⁵⁹ D. Giugni,^{94a} F. Giuli,¹²² C. Giuliani,¹⁰³ M. Giulini,^{60b} B. K. Gjelsten,¹²¹ S. Gkaitatzis,¹⁵⁶ I. Gkialas,^{9,t} E. L. Gkoukousis,¹³⁹ P. Gkoutoumis,¹⁰ L. K. Gladilin,¹⁰¹ C. Glasman,⁸⁵ J. Glatzer,¹³ P. C. F. Glaysher,⁴⁵ A. Glazov,⁴⁵ M. Goblirsch-Kolb,²⁵ J. Godlewski,⁴² S. Goldfarb,⁹¹ T. Golling,⁵² D. Golubkov,¹³² A. Gomes,^{128a,128b,128d} R. Gonçalo,^{128a} R. Goncalves Gama,^{26a} J. Goncalves Pinto Firmino Da Costa,¹³⁸ G. Gonella,⁵¹ L. Gonella,¹⁹ A. Gongadze,⁶⁸ S. González de la Hoz,¹⁷⁰ S. Gonzalez-Sevilla,⁵² L. Goossens,³² P. A. Gorbounov,⁹⁹ H. A. Gordon,²⁷ I. Gorelov,¹⁰⁷ B. Gorini,³² E. Gorini,^{76a,76b} A. Gorišek,⁷⁸ A. T. Goshaw,⁴⁸ C. Gössling,⁴⁶ M. I. Gostkin,⁶⁸ C. A. Gottardo,²³ C. R. Goudet,¹¹⁹ D. Goujdami,^{137c} A. G. Goussiou,¹⁴⁰ N. Govender,^{147b,u} E. Gozani,¹⁵⁴ L. Graber,⁵⁷ I. Grabowska-Bold,^{41a} P. O. J. Gradin,¹⁶⁸ J. Gramling,¹⁶⁶ E. Gramstad,¹²¹ S. Grancagnolo,¹⁷ V. Gratchev,¹²⁵ P. M. Gravila,^{28f} C. Gray,⁵⁶ H. M. Gray,¹⁶ Z. D. Greenwood,^{82,v} C. Greife,²³ K. Gregersen,⁸¹ I. M. Gregor,⁴⁵ P. Grenier,¹⁴⁵ K. Grevtsov,⁵ J. Griffiths,⁸ A. A. Grillo,¹³⁹ K. Grimm,⁷⁵ S. Grinstein,^{13,w} Ph. Gris,³⁷ J.-F. Grivaz,¹¹⁹ S. Groh,⁸⁶ E. Gross,¹⁷⁵ J. Grosse-Knetter,⁵⁷ G. C. Grossi,⁸² Z. J. Grout,⁸¹ A. Grummer,¹⁰⁷ L. Guan,⁹² W. Guan,¹⁷⁶ J. Guenther,⁶⁵ F. Guescini,^{163a} D. Guest,¹⁶⁶ O. Gueta,¹⁵⁵ B. Gui,¹¹³ E. Guido,^{53a,53b} T. Guillemin,⁵ S. Guindon,² U. Gul,⁵⁶ C. Gumpert,³² J. Guo,^{36c} W. Guo,⁹² Y. Guo,^{36a} R. Gupta,⁴³ S. Gupta,¹²² G. Gustavino,^{134a,134b} P. Gutierrez,¹¹⁵ N. G. Gutierrez Ortiz,⁸¹ C. Gutsche,⁸¹ C. Guyot,¹³⁸ M. P. Guzik,^{41a} C. Gwenlan,¹²² C. B. Gwilliam,⁷⁷ A. Haas,¹¹² C. Haber,¹⁶ H. K. Hadavand,⁸ N. Haddad,^{137e} A. Hadeef,⁸⁸ S. Hageböck,²³ M. Hagihara,¹⁶⁴ H. Hakobyan,^{180,a} M. Haleem,⁴⁵ J. Haley,¹¹⁶ G. Halladjian,⁹³ G. D. Hallewell,⁸⁸ K. Hamacher,¹⁷⁸ P. Hamal,¹¹⁷ K. Hamano,¹⁷² A. Hamilton,^{147a} G. N. Hamity,¹⁴¹ P. G. Hamnett,⁴⁵ L. Han,^{36a} S. Han,^{35a} K. Hanagaki,^{69,x} K. Hanawa,¹⁵⁷

M. Hance,¹³⁹ B. Haney,¹²⁴ P. Hanke,^{60a} J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²³ P. H. Hansen,³⁹ K. Hara,¹⁶⁴ A. S. Hard,¹⁷⁶ T. Harenberg,¹⁷⁸ F. Hariri,¹¹⁹ S. Harkusha,⁹⁵ R. D. Harrington,⁴⁹ P. F. Harrison,¹⁷³ N. M. Hartmann,¹⁰² M. Hasegawa,⁷⁰ Y. Hasegawa,¹⁴² A. Hasib,⁴⁹ S. Hassani,¹³⁸ S. Haug,¹⁸ R. Hauser,⁹³ L. Hauswald,⁴⁷ L. B. Havener,³⁸ M. Havranek,¹³⁰ C. M. Hawkes,¹⁹ R. J. Hawkings,³² D. Hayakawa,¹⁵⁹ D. Hayden,⁹³ C. P. Hays,¹²² J. M. Hays,⁷⁹ H. S. Hayward,⁷⁷ S. J. Haywood,¹³³ S. J. Head,¹⁹ T. Heck,⁸⁶ V. Hedberg,⁸⁴ L. Heelan,⁸ S. Heer,²³ K. K. Heidegger,⁵¹ S. Heim,⁴⁵ T. Heim,¹⁶ B. Heinemann,^{45,y} J. J. Heinrich,¹⁰² L. Heinrich,¹¹² C. Heinz,⁵⁵ J. Hejbal,¹²⁹ L. Helary,³² A. Held,¹⁷¹ S. Hellman,^{148a,148b} C. Hensens,³² R. C. W. Henderson,⁷⁵ Y. Heng,¹⁷⁶ S. Henkelmann,¹⁷¹ A. M. Henriques Correia,³² S. Henrot-Versille,¹¹⁹ G. H. Herbert,¹⁷ H. Herde,²⁵ V. Herget,¹⁷⁷ Y. Hernández Jiménez,^{147c} H. Herr,⁸⁶ G. Herten,⁵¹ R. Hertenberger,¹⁰² L. Hervas,³² T. C. Herwig,¹²⁴ G. G. Hesketh,⁸¹ N. P. Hessey,^{163a} J. W. Hetherly,⁴³ S. Higashino,⁶⁹ E. Higón-Rodríguez,¹⁷⁰ K. Hildebrand,³³ E. Hill,¹⁷² J. C. Hill,³⁰ K. H. Hiller,⁴⁵ S. J. Hillier,¹⁹ M. Hils,⁴⁷ I. Hinchliffe,¹⁶ M. Hirose,⁵¹ D. Hirschbuehl,¹⁷⁸ B. Hiti,⁷⁸ O. Hladik,¹²⁹ X. Hoad,⁴⁹ J. Hobbs,¹⁵⁰ N. Hod,^{163a} M. C. Hodgkinson,¹⁴¹ P. Hodgson,¹⁴¹ A. Hoecker,³² M. R. Hoferkamp,¹⁰⁷ F. Hoenig,¹⁰² D. Hohn,²³ T. R. Holmes,³³ M. Homann,⁴⁶ S. Honda,¹⁶⁴ T. Honda,⁶⁹ T. M. Hong,¹²⁷ B. H. Hooberman,¹⁶⁹ W. H. Hopkins,¹¹⁸ Y. Horii,¹⁰⁵ A. J. Horton,¹⁴⁴ J.-Y. Hostachy,⁵⁸ S. Hou,¹⁵³ A. Hoummada,^{137a} J. Howarth,⁸⁷ J. Hoya,⁷⁴ M. Hrabovsky,¹¹⁷ J. Hrdinka,³² I. Hristova,¹⁷ J. Hrivnac,¹¹⁹ T. Hryn'ova,⁵ A. Hrynevich,⁹⁶ P. J. Hsu,⁶³ S.-C. Hsu,¹⁴⁰ Q. Hu,^{36a} S. Hu,^{36c} Y. Huang,^{35a} Z. Hubacek,¹³⁰ F. Hubaut,⁸⁸ F. Huegging,²³ T. B. Huffman,¹²² E. W. Hughes,³⁸ G. Hughes,⁷⁵ M. Huhtinen,³² P. Huo,¹⁵⁰ N. Huseynov,^{68,c} J. Huston,⁹³ J. Huth,⁵⁹ G. Iacobucci,⁵² G. Iakovidis,²⁷ I. Ibragimov,¹⁴³ L. Iconomidou-Fayard,¹¹⁹ Z. Idrissi,^{137e} P. Iengo,³² O. Igonkina,^{109,z} T. Iizawa,¹⁷⁴ Y. Ikegami,⁶⁹ M. Ikeno,⁶⁹ Y. Ilchenko,^{11,aa} D. Iliadis,¹⁵⁶ N. Ilic,¹⁴⁵ G. Introzzi,^{123a,123b} P. Ioannou,^{9,a} M. Iodice,^{136a} K. Iordanidou,³⁸ V. Ippolito,⁵⁹ M. F. Isacson,¹⁶⁸ N. Ishijima,¹²⁰ M. Ishino,¹⁵⁷ M. Ishitsuka,¹⁵⁹ C. Issever,¹²² S. Istin,^{20a} F. Ito,¹⁶⁴ J. M. Iturbe Ponce,^{62a} R. Iuppa,^{162a,162b} H. Iwasaki,⁶⁹ J. M. Izen,⁴⁴ V. Izzo,^{106a} S. Jabbar,³ P. Jackson,¹ R. M. Jacobs,²³ V. Jain,² K. B. Jakobi,⁸⁶ K. Jakobs,⁵¹ S. Jakobsen,⁶⁵ T. Jakoubek,¹²⁹ D. O. Jamin,¹¹⁶ D. K. Jana,⁸² R. Jansky,⁵² J. Janssen,²³ M. Janus,⁵⁷ P. A. Janus,^{41a} G. Jarlskog,⁸⁴ N. Javadov,^{68,c} T. Javůrek,⁵¹ M. Javurkova,⁵¹ F. Jeanneau,¹³⁸ L. Jeanty,¹⁶ J. Jejelava,^{54a,bb} A. Jelinskas,¹⁷³ P. Jenni,^{51,cc} C. Jeske,¹⁷³ S. Jézéquel,⁵ H. Ji,¹⁷⁶ J. Jia,¹⁵⁰ H. Jiang,⁶⁷ Y. Jiang,^{36a} Z. Jiang,¹⁴⁵ S. Jiggins,⁸¹ J. Jimenez Pena,¹⁷⁰ S. Jin,^{35a} A. Jinaru,^{28b} O. Jinnouchi,¹⁵⁹ H. Jivan,^{147c} P. Johansson,¹⁴¹ K. A. Johns,⁷ C. A. Johnson,⁶⁴ W. J. Johnson,¹⁴⁰ K. Jon-And,^{148a,148b} R. W. L. Jones,⁷⁵ S. D. Jones,¹⁵¹ S. Jones,⁷ T. J. Jones,⁷⁷ J. Jongmanns,^{60a} P. M. Jorge,^{128a,128b} J. Jovicevic,^{163a} X. Ju,¹⁷⁶ A. Juste Rozas,^{13,w} M. K. Köhler,¹⁷⁵ A. Kaczmarska,⁴² M. Kado,¹¹⁹ H. Kagan,¹¹³ M. Kagan,¹⁴⁵ S. J. Kahn,⁸⁸ T. Kaji,¹⁷⁴ E. Kajomovitz,⁴⁸ C. W. Kalderon,⁸⁴ A. Kaluza,⁸⁶ S. Kama,⁴³ A. Kamenshchikov,¹³² N. Kanaya,¹⁵⁷ L. Kanjir,⁷⁸ V. A. Kantserov,¹⁰⁰ J. Kanzaki,⁶⁹ B. Kaplan,¹¹² L. S. Kaplan,¹⁷⁶ D. Kar,^{147c} K. Karakostas,¹⁰ N. Karastathis,¹⁰ M. J. Kareem,⁵⁷ E. Karentzos,¹⁰ S. N. Karpov,⁶⁸ Z. M. Karpova,⁶⁸ K. Karthik,¹¹² V. Kartvelishvili,⁷⁵ A. N. Karyukhin,¹³² K. Kasahara,¹⁶⁴ L. Kashif,¹⁷⁶ R. D. Kass,¹¹³ A. Kastanas,¹⁴⁹ Y. Kataoka,¹⁵⁷ C. Kato,¹⁵⁷ A. Katre,⁵² J. Katzy,⁴⁵ K. Kawade,⁷⁰ K. Kawagoe,⁷³ T. Kawamoto,¹⁵⁷ G. Kawamura,⁵⁷ E. F. Kay,⁷⁷ V. F. Kazanin,^{111,d} R. Keeler,¹⁷² R. Kehoe,⁴³ J. S. Keller,³¹ J. J. Kempster,⁸⁰ J. Kendrick,¹⁹ H. Keoshkerian,¹⁶¹ O. Kepka,¹²⁹ B. P. Kerševan,⁷⁸ S. Kersten,¹⁷⁸ R. A. Keyes,⁹⁰ M. Khader,¹⁶⁹ F. Khalil-zada,¹² A. Khanov,¹¹⁶ A. G. Kharlamov,^{111,d} T. Kharlamova,^{111,d} A. Khodinov,¹⁶⁰ T. J. Khoo,⁵² V. Khovanskiy,^{99,a} E. Khramov,⁶⁸ J. Khubua,^{54b,dd} S. Kido,⁷⁰ C. R. Kilby,⁸⁰ H. Y. Kim,⁸ S. H. Kim,¹⁶⁴ Y. K. Kim,³³ N. Kimura,¹⁵⁶ O. M. Kind,¹⁷ B. T. King,⁷⁷ D. Kirchmeier,⁴⁷ J. Kirk,¹³³ A. E. Kiryunin,¹⁰³ T. Kishimoto,¹⁵⁷ D. Kisieleska,^{41a} V. Kitali,⁴⁵ K. Kiuchi,¹⁶⁴ O. Kivernyk,⁵ E. Kladiva,^{146b} T. Klapdor-Kleingrothaus,⁵¹ M. H. Klein,³⁸ M. Klein,⁷⁷ U. Klein,⁷⁷ K. Kleinknecht,⁸⁶ P. Klimek,¹¹⁰ A. Klimentov,²⁷ R. Klingenberg,⁴⁶ T. Klingl,²³ T. Klioutchnikova,³² E.-E. Kluge,^{60a} P. Kluit,¹⁰⁹ S. Kluth,¹⁰³ E. Kneringer,⁶⁵ E. B. F. G. Knoops,⁸⁸ A. Knue,¹⁰³ A. Kobayashi,¹⁵⁷ D. Kobayashi,¹⁵⁹ T. Kobayashi,¹⁵⁷ M. Kobel,⁴⁷ M. Kocian,¹⁴⁵ P. Kodys,¹³¹ T. Koffas,³¹ E. Koffeman,¹⁰⁹ N. M. Köhler,¹⁰³ T. Koi,¹⁴⁵ M. Kolb,^{60b} I. Koletsou,⁵ A. A. Komar,^{98,a} Y. Komori,¹⁵⁷ T. Kondo,⁶⁹ N. Kondrashova,^{36c} K. Köneke,⁵¹ A. C. König,¹⁰⁸ T. Kono,^{69,ee} R. Konoplich,^{112,ff} N. Konstantinidis,⁸¹ R. Kopeliainsky,⁶⁴ S. Koperny,^{41a} A. K. Kopp,⁵¹ K. Korcyl,⁴² K. Kordas,¹⁵⁶ A. Korn,⁸¹ A. A. Korol,^{111,d} I. Korolkov,¹³ E. V. Korolkova,¹⁴¹ O. Kortner,¹⁰³ S. Kortner,¹⁰³ T. Kosek,¹³¹ V. V. Kostyukhin,²³ A. Kotwal,⁴⁸ A. Koulouris,¹⁰ A. Kourkoumeli-Charalampidi,^{123a,123b} C. Kourkoumelis,⁹ E. Kourlitis,¹⁴¹ V. Kouskoura,²⁷ A. B. Kowalewska,⁴² R. Kowalewski,¹⁷² T. Z. Kowalski,^{41a} C. Kozakai,¹⁵⁷ W. Kozanecki,¹³⁸ A. S. Kozhin,¹³² V. A. Kramarenko,¹⁰¹ G. Kramberger,⁷⁸ D. Krasnopevtsev,¹⁰⁰ M. W. Krasny,⁸³ A. Krasznahorkay,³² D. Krauss,¹⁰³ J. A. Kremer,^{41a} J. Kretzschmar,⁷⁷ K. Kreutzfeldt,⁵⁵ P. Krieger,¹⁶¹ K. Krizka,³³ K. Kroeninger,⁴⁶ H. Kroha,¹⁰³ J. Kroll,¹²⁹ J. Kroll,¹²⁴ J. Kröseberg,²³ J. Krstic,¹⁴ U. Kruchonak,⁶⁸ H. Krüger,²³ N. Krumnack,⁶⁷ M. C. Kruse,⁴⁸ T. Kubota,⁹¹ H. Kucuk,⁸¹ S. Kuday,^{4b} J. T. Kuechler,¹⁷⁸ S. Kuehn,³² A. Kugel,^{60a} F. Kuger,¹⁷⁷ T. Kuhl,⁴⁵ V. Kukhtin,⁶⁸ R. Kukla,⁸⁸

Y. Kulchitsky,⁹⁵ S. Kuleshov,^{34b} Y. P. Kulinich,¹⁶⁹ M. Kuna,^{134a,134b} T. Kunigo,⁷¹ A. Kupco,¹²⁹ T. Kupfer,⁴⁶ O. Kuprash,¹⁵⁵
H. Kurashige,⁷⁰ L. L. Kurchaninov,^{163a} Y. A. Kurochkin,⁹⁵ M. G. Kurth,^{35a} V. Kus,¹²⁹ E. S. Kuwertz,¹⁷² M. Kuze,¹⁵⁹
J. Kvita,¹¹⁷ T. Kwan,¹⁷² D. Kyriazopoulos,¹⁴¹ A. La Rosa,¹⁰³ J. L. La Rosa Navarro,^{26d} L. La Rotonda,^{40a,40b}
F. La Ruffa,^{40a,40b} C. Lacasta,¹⁷⁰ F. Lacava,^{134a,134b} J. Lacey,⁴⁵ H. Lacker,¹⁷ D. Lacour,⁸³ E. Ladygin,⁶⁸ R. Lafaye,⁵
B. Laforge,⁸³ T. Lagouri,¹⁷⁹ S. Lai,⁵⁷ S. Lammers,⁶⁴ W. Lampl,⁷ E. Lançon,²⁷ U. Landgraf,⁵¹ M. P. J. Landon,⁷⁹
M. C. Lanfermann,⁵² V. S. Lang,^{60a} J. C. Lange,¹³ R. J. Langenberg,³² A. J. Lankford,¹⁶⁶ F. Lanni,²⁷ K. Lantsch,²³
A. Lanza,^{123a} A. Lapertosa,^{53a,53b} S. Laplace,⁸³ J. F. Laporte,¹³⁸ T. Lari,^{94a} F. Lasagni Manghi,^{22a,22b} M. Lassnig,³²
P. Laurelli,⁵⁰ W. Lavrijsen,¹⁶ A. T. Law,¹³⁹ P. Laycock,⁷⁷ T. Lazovich,⁵⁹ M. Lazzaroni,^{94a,94b} B. Le,⁹¹ O. Le Dortz,⁸³
E. Le Guirrec,⁸⁸ E. P. Le Quilleuc,¹³⁸ M. LeBlanc,¹⁷² T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁸ C. A. Lee,²⁷ G. R. Lee,^{133,gg}
S. C. Lee,¹⁵³ L. Lee,⁵⁹ B. Lefebvre,⁹⁰ G. Lefebvre,⁸³ M. Lefebvre,¹⁷² F. Legger,¹⁰² C. Leggett,¹⁶ G. Lehmann Miotto,³²
X. Lei,⁷ W. A. Leight,⁴⁵ M. A. L. Leite,^{26d} R. Leitner,¹³¹ D. Lellouch,¹⁷⁵ B. Lemmer,⁵⁷ K. J. C. Leney,⁸¹ T. Lenz,²³
B. Lenzi,³² R. Leone,⁷ S. Leone,^{126a,126b} C. Leonidopoulos,⁴⁹ G. Lerner,¹⁵¹ C. Leroy,⁹⁷ A. A. J. Lesage,¹³⁸ C. G. Lester,³⁰
M. Levchenko,¹²⁵ J. Levêque,⁵ D. Levin,⁹² L. J. Levinson,¹⁷⁵ M. Levy,¹⁹ D. Lewis,⁷⁹ B. Li,^{36a,hh} Changqiao Li,^{36a} H. Li,¹⁵⁰
L. Li,^{36c} Q. Li,^{35a} S. Li,⁴⁸ X. Li,^{36c} Y. Li,¹⁴³ Z. Liang,^{35a} B. Liberti,^{135a} A. Liblong,¹⁶¹ K. Lie,^{62c} J. Liebal,²³ W. Liebig,¹⁵
A. Limosani,¹⁵² S. C. Lin,¹⁸² T. H. Lin,⁸⁶ B. E. Lindquist,¹⁵⁰ A. E. Lioni,⁵² E. Lipeles,¹²⁴ A. Lipniacka,¹⁵ M. Lisovyi,^{60b}
T. M. Liss,^{169,ii} A. Lister,¹⁷¹ A. M. Litke,¹³⁹ B. Liu,^{153,jj} H. Liu,⁹² H. Liu,²⁷ J. K. K. Liu,¹²² J. Liu,^{36b} J. B. Liu,^{36a} K. Liu,⁸⁸
L. Liu,¹⁶⁹ M. Liu,^{36a} Y. L. Liu,^{36a} Y. Liu,^{36a} M. Livan,^{123a,123b} A. Lleres,⁵⁸ J. Llorente Merino,^{35a} S. L. Lloyd,⁷⁹ C. Y. Lo,^{62b}
F. Lo Sterzo,¹⁵³ E. M. Lobodzinska,⁴⁵ P. Loch,⁷ F. K. Loebinger,⁸⁷ A. Loesle,⁵¹ K. M. Loew,²⁵ A. Loginov,^{179,a} T. Lohse,¹⁷
K. Lohwasser,¹⁴¹ M. Lokajicek,¹²⁹ B. A. Long,²⁴ J. D. Long,¹⁶⁹ R. E. Long,⁷⁵ L. Longo,^{76a,76b} K. A. Looper,¹¹³
J. A. Lopez,^{34b} D. Lopez Mateos,⁵⁹ I. Lopez Paz,¹³ A. Lopez Solis,⁸³ J. Lorenz,¹⁰² N. Lorenzo Martinez,⁵ M. Losada,²¹
P. J. Lösel,¹⁰² X. Lou,^{35a} A. Lounis,¹¹⁹ J. Love,⁶ P. A. Love,⁷⁵ H. Lu,^{62a} N. Lu,⁹² Y. J. Lu,⁶³ H. J. Lubatti,¹⁴⁰ C. Luci,^{134a,134b}
A. Lucotte,⁵⁸ C. Luedtke,⁵¹ F. Luehring,⁶⁴ W. Lukas,⁶⁵ L. Luminari,^{134a} O. Lundberg,^{148a,148b} B. Lund-Jensen,¹⁴⁹
M. S. Lutz,⁸⁹ P. M. Luzi,⁸³ D. Lynn,²⁷ R. Lysak,¹²⁹ E. Lytken,⁸⁴ F. Lyu,^{35a} V. Lyubushkin,⁶⁸ H. Ma,²⁷ L. L. Ma,^{36b} Y. Ma,^{36b}
G. Maccarrone,⁵⁰ A. Macchiolo,¹⁰³ C. M. Macdonald,¹⁴¹ B. Maček,⁷⁸ J. Machado Miguens,^{124,128b} D. Madaffari,¹⁷⁰
R. Madar,³⁷ W. F. Mader,⁴⁷ A. Madsen,⁴⁵ J. Maeda,⁷⁰ S. Maeland,¹⁵ T. Maeno,²⁷ A. S. Maevskiy,¹⁰¹ V. Magerl,⁵¹
J. Mahlstedt,¹⁰⁹ C. Maiani,¹¹⁹ C. Maidantchik,^{26a} A. A. Maier,¹⁰³ T. Maier,¹⁰² A. Maio,^{128a,128b,128d} O. Majersky,^{146a}
S. Majewski,¹¹⁸ Y. Makida,⁶⁹ N. Makovec,¹¹⁹ B. Malaescu,⁸³ Pa. Malecki,⁴² V. P. Maleev,¹²⁵ F. Malek,⁵⁸ U. Mallik,⁶⁶
D. Malon,⁶ C. Malone,³⁰ S. Maltezos,¹⁰ S. Malyukov,³² J. Mamuzic,¹⁷⁰ G. Mancini,⁵⁰ I. Mandić,⁷⁸ J. Maneira,^{128a,128b}
L. Manhaes de Andrade Filho,^{26b} J. Manjarres Ramos,⁴⁷ K. H. Mankinen,⁸⁴ A. Mann,¹⁰² A. Manousos,³² B. Mansoulie,¹³⁸
J. D. Mansour,^{35a} R. Mantifel,⁹⁰ M. Mantoani,⁵⁷ S. Manzoni,^{94a,94b} L. Mapelli,³² G. Marceca,²⁹ L. March,⁵² L. Marchese,¹²²
G. Marchiori,⁸³ M. Marcisovsky,¹²⁹ M. Marjanovic,³⁷ D. E. Marley,⁹² F. Marroquim,^{26a} S. P. Marsden,⁸⁷ Z. Marshall,¹⁶
M. U. F. Martensson,¹⁶⁸ S. Marti-Garcia,¹⁷⁰ C. B. Martin,¹¹³ T. A. Martin,¹⁷³ V. J. Martin,⁴⁹ B. Martin dit Latour,¹⁵
M. Martinez,^{13,w} V. I. Martinez Outschoorn,¹⁶⁹ S. Martin-Haugh,¹³³ V. S. Martoiu,^{28b} A. C. Martyniuk,⁸¹ A. Marzin,³²
L. Masetti,⁸⁶ T. Mashimo,¹⁵⁷ R. Mashinistov,⁹⁸ J. Masik,⁸⁷ A. L. Maslennikov,^{111,d} L. Massa,^{135a,135b} P. Mastrandrea,⁵
A. Mastroberardino,^{40a,40b} T. Masubuchi,¹⁵⁷ P. Mättig,¹⁷⁸ J. Maurer,^{28b} S. J. Maxfield,⁷⁷ D. A. Maximov,^{111,d} R. Mazini,¹⁵³
I. Maznas,¹⁵⁶ S. M. Mazza,^{94a,94b} N. C. Mc Fadden,¹⁰⁷ G. Mc Goldrick,¹⁶¹ S. P. Mc Kee,⁹² A. McCarn,⁹² R. L. McCarthy,¹⁵⁰
T. G. McCarthy,¹⁰³ L. I. McClymont,⁸¹ E. F. McDonald,⁹¹ J. A. McFayden,⁸¹ G. Mchedlidze,⁵⁷ S. J. McMahon,¹³³
P. C. McNamara,⁹¹ R. A. McPherson,^{172,p} S. Meehan,¹⁴⁰ T. J. Megy,⁵¹ S. Mehlhase,¹⁰² A. Mehta,⁷⁷ T. Meideck,⁵⁸
K. Meier,^{60a} B. Meirose,⁴⁴ D. Melini,^{170,kk} B. R. Mellado Garcia,^{147c} J. D. Mellenthin,⁵⁷ M. Melo,^{146a} F. Meloni,¹⁸
A. Melzer,²³ S. B. Menary,⁸⁷ L. Meng,⁷⁷ X. T. Meng,⁹² A. Mengarelli,^{22a,22b} S. Menke,¹⁰³ E. Meoni,^{40a,40b} S. Mergelmeyer,¹⁷
P. Mermod,⁵² L. Merola,^{106a,106b} C. Meroni,^{94a} F. S. Merritt,³³ A. Messina,^{134a,134b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁶ C. Meyer,¹²⁴
J-P. Meyer,¹³⁸ J. Meyer,¹⁰⁹ H. Meyer Zu Theenhausen,^{60a} F. Miano,¹⁵¹ R. P. Middleton,¹³³ S. Miglioranza,^{53a,53b} L. Mijović,⁴⁹
G. Mikenberg,¹⁷⁵ M. Mikestikova,¹²⁹ M. Mikuž,⁷⁸ M. Milesi,⁹¹ A. Milic,¹⁶¹ D. W. Miller,³³ C. Mills,⁴⁹ A. Milov,¹⁷⁵
D. A. Milstead,^{148a,148b} A. A. Minaenko,¹³² Y. Minami,¹⁵⁷ I. A. Minashvili,⁶⁸ A. I. Mincer,¹¹² B. Mindur,^{41a} M. Mineev,⁶⁸
Y. Minegishi,¹⁵⁷ Y. Ming,¹⁷⁶ L. M. Mir,¹³ K. P. Mistry,¹²⁴ T. Mitani,¹⁷⁴ J. Mitrevski,¹⁰² V. A. Mitsou,¹⁷⁰ A. Miucci,¹⁸
P. S. Miyagawa,¹⁴¹ A. Mizukami,⁶⁹ J. U. Mjörnmark,⁸⁴ T. Mkrтчyan,¹⁸⁰ M. Mlynarikova,¹³¹ T. Moa,^{148a,148b}
K. Mochizuki,⁹⁷ P. Mogg,⁵¹ S. Mohapatra,³⁸ S. Molander,^{148a,148b} R. Moles-Valls,²³ R. Monden,⁷¹ M. C. Mondragon,⁹³
K. Mönig,⁴⁵ J. Monk,³⁹ E. Monnier,⁸⁸ A. Montalbano,¹⁵⁰ J. Montejo Berlingen,³² F. Monticelli,⁷⁴ S. Monzani,^{94a,94b}
R. W. Moore,³ N. Morange,¹¹⁹ D. Moreno,²¹ M. Moreno Llácer,³² P. Morettini,^{53a} S. Morgenstern,³² D. Mori,¹⁴⁴ T. Mori,¹⁵⁷

M. Morii,⁵⁹ M. Morinaga,¹⁵⁷ V. Morisbak,¹²¹ A. K. Morley,³² G. Mornacchi,³² J. D. Morris,⁷⁹ L. Morvaj,¹⁵⁰
P. Moschovakos,¹⁰ M. Mosidze,^{54b} H. J. Moss,¹⁴¹ J. Moss,^{145,11} K. Motohashi,¹⁵⁹ R. Mount,¹⁴⁵ E. Mountricha,²⁷
E. J. W. Moyses,⁸⁹ S. Muanza,⁸⁸ F. Mueller,¹⁰³ J. Mueller,¹²⁷ R. S. P. Mueller,¹⁰² D. Muenstermann,⁷⁵ P. Mullen,⁵⁶
G. A. Mullier,¹⁸ F. J. Munoz Sanchez,⁸⁷ W. J. Murray,^{173,133} H. Musheghyan,³² M. Muškinja,⁷⁸ A. G. Myagkov,^{132,mm}
M. Myska,¹³⁰ B. P. Nachman,¹⁶ O. Nackenhorst,⁵² K. Nagai,¹²² R. Nagai,^{69,ee} K. Nagano,⁶⁹ Y. Nagasaka,⁶¹ K. Nagata,¹⁶⁴
M. Nagel,⁵¹ E. Nagy,⁸⁸ A. M. Nairz,³² Y. Nakahama,¹⁰⁵ K. Nakamura,⁶⁹ T. Nakamura,¹⁵⁷ I. Nakano,¹¹⁴
R. F. Naranjo Garcia,⁴⁵ R. Narayan,¹¹ D. I. Narrias Villar,^{60a} I. Naryshkin,¹²⁵ T. Naumann,⁴⁵ G. Navarro,²¹ R. Nayyar,⁷
H. A. Neal,⁹² P. Yu. Nechaeva,⁹⁸ T. J. Neep,¹³⁸ A. Negri,^{123a,123b} M. Negrini,^{22a} S. Nektarijevic,¹⁰⁸ C. Nellist,¹¹⁹ A. Nelson,¹⁶⁶
M. E. Nelson,¹²² S. Nemecek,¹²⁹ P. Nemethy,¹¹² M. Nessi,^{32,nn} M. S. Neubauer,¹⁶⁹ M. Neumann,¹⁷⁸ P. R. Newman,¹⁹
T. Y. Ng,^{62c} T. Nguyen Manh,⁹⁷ R. B. Nickerson,¹²² R. Nicolaidou,¹³⁸ J. Nielsen,¹³⁹ V. Nikolaenko,^{132,mm} I. Nikolic-Audit,⁸³
K. Nikolopoulos,¹⁹ J. K. Nilsen,¹²¹ P. Nilsson,²⁷ Y. Ninomiya,¹⁵⁷ A. Nisati,^{134a} N. Nishu,^{35c} R. Nisius,¹⁰³ I. Nitsche,⁴⁶
T. Nitta,¹⁷⁴ T. Nobe,¹⁵⁷ Y. Noguchi,⁷¹ M. Nomachi,¹²⁰ I. Nomidis,³¹ M. A. Nomura,²⁷ T. Nooney,⁷⁹ M. Nordberg,³²
N. Norjoharuddeen,¹²² O. Novgorodova,⁴⁷ S. Nowak,¹⁰³ M. Nozaki,⁶⁹ L. Nozka,¹¹⁷ K. Ntekas,¹⁶⁶ E. Nurse,⁸¹ F. Nuti,⁹¹
K. O'connor,²⁵ D. C. O'Neil,¹⁴⁴ A. A. O'Rourke,⁴⁵ V. O'Shea,⁵⁶ F. G. Oakham,^{31,e} H. Oberlack,¹⁰³ T. Obermann,²³
J. Ocariz,⁸³ A. Ochi,⁷⁰ I. Ochoa,³⁸ J. P. Ochoa-Ricoux,^{34a} S. Oda,⁷³ S. Odaka,⁶⁹ A. Oh,⁸⁷ S. H. Oh,⁴⁸ C. C. Ohm,¹⁶
H. Ohman,¹⁶⁸ H. Oide,^{53a,53b} H. Okawa,¹⁶⁴ Y. Okumura,¹⁵⁷ T. Okuyama,⁶⁹ A. Olariu,^{28b} L. F. Oleiro Seabra,^{128a}
S. A. Olivares Pino,⁴⁹ D. Oliveira Damazio,²⁷ A. Olszewski,⁴² J. Olszowska,⁴² A. Onofre,^{128a,128e} K. Onogi,¹⁰⁵
P. U. E. Onyisi,^{11,aa} H. Oppen,¹²¹ M. J. Oreglia,³³ Y. Oren,¹⁵⁵ D. Orestano,^{136a,136b} N. Orlando,^{62b} R. S. Orr,¹⁶¹
B. Osculati,^{53a,53b,a} R. Ospanov,^{36a} G. Otero y Garzon,²⁹ H. Otono,⁷³ M. Ouchrif,^{137d} F. Ould-Saada,¹²¹ A. Ouraou,¹³⁸
K. P. Oussoren,¹⁰⁹ Q. Ouyang,^{35a} M. Owen,⁵⁶ R. E. Owen,¹⁹ V. E. Ozcan,^{20a} N. Ozturk,⁸ K. Pachal,¹⁴⁴ A. Pacheco Pages,¹³
L. Pacheco Rodriguez,¹³⁸ C. Padilla Aranda,¹³ S. Pagan Griso,¹⁶ M. Paganini,¹⁷⁹ F. Paige,²⁷ G. Palacino,⁶⁴ S. Palazzo,^{40a,40b}
S. Palestini,³² M. Palka,^{41b} D. Pallin,³⁷ E. St. Panagiotopoulou,¹⁰ I. Panagoulas,¹⁰ C. E. Pandini,⁸³ J. G. Panduro Vazquez,⁸⁰
P. Pani,³² S. Panitkin,²⁷ D. Pantea,^{28b} L. Paolozzi,⁵² Th. D. Papadopoulou,¹⁰ K. Papageorgiou,^{9,i} A. Paramonov,⁶
D. Paredes Hernandez,¹⁷⁹ A. J. Parker,⁷⁵ M. A. Parker,³⁰ K. A. Parker,⁴⁵ F. Parodi,^{53a,53b} J. A. Parsons,³⁸ U. Parzefall,⁵¹
V. R. Pascuzzi,¹⁶¹ J. M. Pasner,¹³⁹ E. Pasqualucci,^{134a} S. Passaggio,^{53a} Fr. Pastore,⁸⁰ S. Pataraja,⁸⁶ J. R. Pater,⁸⁷ T. Pauly,³²
B. Pearson,¹⁰³ S. Pedraza Lopez,¹⁷⁰ R. Pedro,^{128a,128b} S. V. Peleganchuk,^{111,d} O. Penc,¹²⁹ C. Peng,^{35a} H. Peng,^{36a} J. Penwell,⁶⁴
B. S. Peralva,^{26b} M. M. Perego,¹³⁸ D. V. Perepelitsa,²⁷ F. Peri,¹⁷ L. Perini,^{94a,94b} H. Pernegger,³² S. Perrella,^{106a,106b}
R. Peschke,⁴⁵ V. D. Peshekhonov,^{68,a} K. Peters,⁴⁵ R. F. Y. Peters,⁸⁷ B. A. Petersen,³² T. C. Petersen,³⁹ E. Petit,⁵⁸ A. Petridis,¹
C. Petridou,¹⁵⁶ P. Petroff,¹¹⁹ E. Petrolo,^{134a} M. Petrov,¹²² F. Petrucci,^{136a,136b} N. E. Pettersson,⁸⁹ A. Peyaud,¹³⁸ R. Pezoa,^{34b}
F. H. Phillips,⁹³ P. W. Phillips,¹³³ G. Piacquadio,¹⁵⁰ E. Pianori,¹⁷³ A. Picazio,⁸⁹ E. Piccaro,⁷⁹ M. A. Pickering,¹²² R. Piegai,²⁹
J. E. Pilcher,³³ A. D. Pilkington,⁸⁷ A. W. J. Pin,⁸⁷ M. Pinamonti,^{135a,135b} J. L. Pinfold,³ H. Pirumov,⁴⁵ M. Pitt,¹⁷⁵ L. Plazak,^{146a}
M.-A. Pleier,²⁷ V. Pleskot,⁸⁶ E. Plotnikova,⁶⁸ D. Pluth,⁶⁷ P. Podberezko,¹¹¹ R. Poettgen,^{148a,148b} R. Poggi,^{123a,123b}
L. Poggioli,¹¹⁹ D. Pohl,²³ G. Polesello,^{123a} A. Poley,⁴⁵ A. Policicchio,^{40a,40b} R. Polifka,³² A. Polini,^{22a} C. S. Pollard,⁵⁶
V. Polychronakos,²⁷ K. Pommès,³² D. Ponomarenko,¹⁰⁰ L. Pontecorvo,^{134a} G. A. Popeneciu,^{28d} A. Poppleton,³²
S. Pospisil,¹³⁰ K. Potamianos,¹⁶ I. N. Potrap,⁶⁸ C. J. Potter,³⁰ G. Poulard,³² T. Poulsen,⁸⁴ J. Poveda,³²
M. E. Pozo Astigarraga,³² P. Pralavorio,⁸⁸ A. Pranko,¹⁶ S. Prell,⁶⁷ D. Price,⁸⁷ M. Primavera,^{76a} S. Prince,⁹⁰ N. Proklova,¹⁰⁰
K. Prokofiev,^{62c} F. Prokoshin,^{34b} S. Protopopescu,²⁷ J. Proudfoot,⁶ M. Przybycien,^{41a} A. Puri,¹⁶⁹ P. Puzo,¹¹⁹ J. Qian,⁹²
G. Qin,⁵⁶ Y. Qin,⁸⁷ A. Quadt,⁵⁷ M. Queitsch-Maitland,⁴⁵ D. Quilty,⁵⁶ S. Raddum,¹²¹ V. Radeka,²⁷ V. Radescu,¹²²
S. K. Radhakrishnan,¹⁵⁰ P. Radloff,¹¹⁸ P. Rados,⁹¹ F. Ragusa,^{94a,94b} G. Rahal,¹⁸¹ J. A. Raine,⁸⁷ S. Rajagopalan,²⁷
C. Rangel-Smith,¹⁶⁸ T. Rashid,¹¹⁹ S. Raspopov,⁵ M. G. Ratti,^{94a,94b} D. M. Rauch,⁴⁵ F. Rauscher,¹⁰² S. Rave,⁸⁶
I. Ravinovich,¹⁷⁵ J. H. Rawling,⁸⁷ M. Raymond,³² A. L. Read,¹²¹ N. P. Readioff,⁵⁸ M. Reale,^{76a,76b} D. M. Rebuffi,^{123a,123b}
A. Redelbach,¹⁷⁷ G. Redlinger,²⁷ R. Reece,¹³⁹ R. G. Reed,^{147c} K. Reeves,⁴⁴ L. Rehnisch,¹⁷ J. Reichert,¹²⁴ A. Reiss,⁸⁶
C. Rembser,³² H. Ren,^{35a} M. Rescigno,^{134a} S. Resconi,^{94a} E. D. Resseguie,¹²⁴ S. Rettie,¹⁷¹ E. Reynolds,¹⁹
O. L. Rezanova,^{111,d} P. Reznicek,¹³¹ R. Rezvani,⁹⁷ R. Richter,¹⁰³ S. Richter,⁸¹ E. Richter-Was,^{41b} O. Ricken,²³ M. Ridel,⁸³
P. Rieck,¹⁰³ C. J. Riegel,¹⁷⁸ J. Rieger,⁵⁷ O. Rifki,¹¹⁵ M. Rijssenbeek,¹⁵⁰ A. Rimoldi,^{123a,123b} M. Rimoldi,¹⁸ L. Rinaldi,^{22a}
G. Ripellino,¹⁴⁹ B. Ristić,³² E. Ritsch,³² I. Riu,¹³ F. Rizatdinova,¹¹⁶ E. Rizvi,⁷⁹ C. Rizzi,¹³ R. T. Roberts,⁸⁷
S. H. Robertson,^{90,p} A. Robichaud-Veronneau,⁹⁰ D. Robinson,³⁰ J. E. M. Robinson,⁴⁵ A. Robson,⁵⁶ E. Rocco,⁸⁶
C. Roda,^{126a,126b} Y. Rodina,^{88,oo} S. Rodriguez Bosca,¹⁷⁰ A. Rodriguez Perez,¹³ D. Rodriguez Rodriguez,¹⁷⁰ S. Roe,³²
C. S. Rogan,⁵⁹ O. Røhne,¹²¹ J. Roloff,⁵⁹ A. Romaniouk,¹⁰⁰ M. Romano,^{22a,22b} S. M. Romano Saez,³⁷ E. Romero Adam,¹⁷⁰

N. Rompotis,⁷⁷ M. Ronzani,⁵¹ L. Roos,⁸³ S. Rosati,^{134a} K. Rosbach,⁵¹ P. Rose,¹³⁹ N.-A. Rosien,⁵⁷ E. Rossi,^{106a,106b}
L. P. Rossi,^{53a} J. H. N. Rosten,³⁰ R. Rosten,¹⁴⁰ M. Rotaru,^{28b} J. Rothberg,¹⁴⁰ D. Rousseau,¹¹⁹ A. Rozanov,⁸⁸ Y. Rozen,¹⁵⁴
X. Ruan,^{147c} F. Rubbo,¹⁴⁵ F. Rühr,⁵¹ A. Ruiz-Martinez,³¹ Z. Rurikova,⁵¹ N. A. Rusakovich,⁶⁸ H. L. Russell,⁹⁰
J. P. Rutherford,⁷ N. Ruthmann,³² Y. F. Ryabov,¹²⁵ M. Rybar,¹⁶⁹ G. Rybkin,¹¹⁹ S. Ryu,⁶ A. Ryzhov,¹³² G. F. Rzehorz,⁵⁷
A. F. Saavedra,¹⁵² G. Sabato,¹⁰⁹ S. Sacerdoti,²⁹ H. F.-W. Sadrozinski,¹³⁹ R. Sadykov,⁶⁸ F. Safai Tehrani,^{134a} P. Saha,¹¹⁰
M. Sahinsoy,^{60a} M. Saimpert,⁴⁵ M. Saito,¹⁵⁷ T. Saito,¹⁵⁷ H. Sakamoto,¹⁵⁷ Y. Sakurai,¹⁷⁴ G. Salamanna,^{136a,136b}
J. E. Salazar Loyola,^{34b} D. Salek,¹⁰⁹ P. H. Sales De Bruin,¹⁶⁸ D. Salihagic,¹⁰³ A. Salnikov,¹⁴⁵ J. Salt,¹⁷⁰ D. Salvatore,^{40a,40b}
F. Salvatore,¹⁵¹ A. Salvucci,^{62a,62b,62c} A. Salzburger,³² D. Sammel,⁵¹ D. Sampsonidis,¹⁵⁶ D. Sampsonidou,¹⁵⁶ J. Sánchez,¹⁷⁰
V. Sanchez Martinez,¹⁷⁰ A. Sanchez Pineda,^{167a,167c} H. Sandaker,¹²¹ R. L. Sandbach,⁷⁹ C. O. Sander,⁴⁵ M. Sandhoff,¹⁷⁸
C. Sandoval,²¹ D. P. C. Sankey,¹³³ M. Sannino,^{53a,53b} Y. Sano,¹⁰⁵ A. Sansoni,⁵⁰ C. Santoni,³⁷ H. Santos,^{128a}
I. Santoyo Castillo,¹⁵¹ A. Sapronov,⁶⁸ J. G. Saraiva,^{128a,128d} B. Sarrazin,²³ O. Sasaki,⁶⁹ K. Sato,¹⁶⁴ E. Sauvan,⁵ G. Savage,⁸⁰
P. Savard,^{161,e} N. Savic,¹⁰³ C. Sawyer,¹³³ L. Sawyer,^{82,v} J. Saxon,³³ C. Sbarra,^{22a} A. Sbrizzi,^{22a,22b} T. Scanlon,⁸¹
D. A. Scannicchio,¹⁶⁶ M. Scarella,¹⁵² J. Schaarschmidt,¹⁴⁰ P. Schacht,¹⁰³ B. M. Schachtner,¹⁰² D. Schaefer,³² L. Schaefer,¹²⁴
R. Schaefer,⁴⁵ J. Schaeffer,⁸⁶ S. Schaepe,²³ S. Schatzel,^{60b} U. Schäfer,⁸⁶ A. C. Schaffer,¹¹⁹ D. Schaile,¹⁰²
R. D. Schamberger,¹⁵⁰ V. A. Schegelsky,¹²⁵ D. Scheirich,¹³¹ M. Schernau,¹⁶⁶ C. Schiavi,^{53a,53b} S. Schier,¹³⁹
L. K. Schildgen,²³ C. Schillo,⁵¹ M. Schioppa,^{40a,40b} S. Schlenker,³² K. R. Schmidt-Sommerfeld,¹⁰³ K. Schmieden,³²
C. Schmitt,⁸⁶ S. Schmitt,⁴⁵ S. Schmitz,⁸⁶ U. Schnoor,⁵¹ L. Schoeffel,¹³⁸ A. Schoening,^{60b} B. D. Schoenrock,⁹³ E. Schopf,²³
M. Schott,⁸⁶ J. F. P. Schouwenberg,¹⁰⁸ J. Schovancova,³² S. Schramm,⁵² N. Schuh,⁸⁶ A. Schulte,⁸⁶ M. J. Schultens,²³
H.-C. Schultz-Coulon,^{60a} H. Schulz,¹⁷ M. Schumacher,⁵¹ B. A. Schumm,¹³⁹ Ph. Schune,¹³⁸ A. Schwartzman,¹⁴⁵
T. A. Schwarz,⁹² H. Schweiger,⁸⁷ Ph. Schwemling,¹³⁸ R. Schwienhorst,⁹³ J. Schwindling,¹³⁸ A. Sciandra,²³ G. Sciolla,²⁵
M. Scornajenghi,^{40a,40b} F. Scuri,^{126a,126b} F. Scutti,⁹¹ J. Searcy,⁹² P. Seema,²³ S. C. Seidel,¹⁰⁷ A. Seiden,¹³⁹ J. M. Seixas,^{26a}
G. Sekhniaidze,^{106a} K. Sekhon,⁹² S. J. Sekula,⁴³ N. Semprini-Cesari,^{22a,22b} S. Senkin,³⁷ C. Serfon,¹²¹ L. Serin,¹¹⁹
L. Serkin,^{167a,167b} M. Sessa,^{136a,136b} R. Seuster,¹⁷² H. Severini,¹¹⁵ T. Sfiligoj,⁷⁸ F. Sforza,³² A. Sfyrla,⁵² E. Shabalina,⁵⁷
N. W. Shaikh,^{148a,148b} L. Y. Shan,^{35a} R. Shang,¹⁶⁹ J. T. Shank,²⁴ M. Shapiro,¹⁶ P. B. Shatalov,⁹⁹ K. Shaw,^{167a,167b}
S. M. Shaw,⁸⁷ A. Shcherbakova,^{148a,148b} C. Y. Shehu,¹⁵¹ Y. Shen,¹¹⁵ N. Sherafati,³¹ P. Sherwood,⁸¹ L. Shi,^{153,pp} S. Shimizu,⁷⁰
C. O. Shimmin,¹⁷⁹ M. Shimojima,¹⁰⁴ I. P. J. Shipsey,¹²² S. Shirabe,⁷³ M. Shiyakova,^{68,qq} J. Shlomi,¹⁷⁵ A. Shmeleva,⁹⁸
D. Shoaleh Saadi,⁹⁷ M. J. Shochet,³³ S. Shojaii,^{94a} D. R. Shope,¹¹⁵ S. Shrestha,¹¹³ E. Shulga,¹⁰⁰ M. A. Shupe,⁷ P. Sicho,¹²⁹
A. M. Sickles,¹⁶⁹ P. E. Sidebo,¹⁴⁹ E. Sideras Haddad,^{147c} O. Sidiropoulou,¹⁷⁷ A. Sidoti,^{22a,22b} F. Siegert,⁴⁷ Dj. Sijacki,¹⁴
J. Silva,^{128a,128d} S. B. Silverstein,^{148a} V. Simak,¹³⁰ Lj. Simic,¹⁴ S. Simion,¹¹⁹ E. Simioni,⁸⁶ B. Simmons,⁸¹ M. Simon,⁸⁶
P. Sinervo,¹⁶¹ N. B. Sinev,¹¹⁸ M. Sioli,^{22a,22b} G. Siragusa,¹⁷⁷ I. Siral,⁹² S. Yu. Sivoklov,¹⁰¹ J. Sjölin,^{148a,148b} M. B. Skinner,⁷⁵
P. Skubic,¹¹⁵ M. Slater,¹⁹ T. Slavicek,¹³⁰ M. Slawinska,⁴² K. Sliwa,¹⁶⁵ R. Slovak,¹³¹ V. Smakhtin,¹⁷⁵ B. H. Smart,⁵
J. Smiesko,^{146a} N. Smirnov,¹⁰⁰ S. Yu. Smirnov,¹⁰⁰ Y. Smirnov,¹⁰⁰ L. N. Smirnova,^{101,rr} O. Smirnova,⁸⁴ J. W. Smith,⁵⁷
M. N. K. Smith,³⁸ R. W. Smith,³⁸ M. Smizanska,⁷⁵ K. Smolek,¹³⁰ A. A. Snesarev,⁹⁸ I. M. Snyder,¹¹⁸ S. Snyder,²⁷
R. Sobie,^{172,p} F. Socher,⁴⁷ A. Soffer,¹⁵⁵ A. Søggaard,⁴⁹ D. A. Soh,¹⁵³ G. Sokhrannyi,⁷⁸ C. A. Solans Sanchez,³² M. Solar,¹³⁰
E. Yu. Soldatov,¹⁰⁰ U. Soldevila,¹⁷⁰ A. A. Solodkov,¹³² A. Soloshenko,⁶⁸ O. V. Solovyanov,¹³² V. Solovyev,¹²⁵ P. Sommer,⁵¹
H. Son,¹⁶⁵ A. Sopczak,¹³⁰ D. Sosa,^{60b} C. L. Sotiropoulou,^{126a,126b} R. Soualah,^{167a,167c} A. M. Soukharev,^{111,d} D. South,⁴⁵
B. C. Sowden,⁸⁰ S. Spagnolo,^{76a,76b} M. Spalla,^{126a,126b} M. Spangenberg,¹⁷³ F. Spanò,⁸⁰ D. Sperlich,¹⁷ F. Spettel,¹⁰³
T. M. Spieker,^{60a} R. Spighi,^{22a} G. Spigo,³² L. A. Spiller,⁹¹ M. Spousta,¹³¹ R. D. St. Denis,^{56a} A. Stabile,^{94a} R. Stamen,^{60a}
S. Stamm,¹⁷ E. Stanecka,⁴² R. W. Staneck,⁶ C. Stanescu,^{136a} M. M. Stanitzki,⁴⁵ B. S. Stapf,¹⁰⁹ S. Stapnes,¹²¹
E. A. Starchenko,¹³² G. H. Stark,³³ J. Stark,⁵⁸ S. H. Stark,³⁹ P. Staroba,¹²⁹ P. Starovoitov,^{60a} S. Stärz,³² R. Staszewski,⁴²
P. Steinberg,²⁷ B. Stelzer,¹⁴⁴ H. J. Stelzer,³² O. Stelzer-Chilton,^{163a} H. Stenzel,⁵⁵ G. A. Stewart,⁵⁶ M. C. Stockton,¹¹⁸
M. Stoebe,⁹⁰ G. Stoicea,^{28b} P. Stolte,⁵⁷ S. Stonjek,¹⁰³ A. R. Stradling,⁸ A. Straessner,⁴⁷ M. E. Stramaglia,¹⁸ J. Strandberg,¹⁴⁹
S. Strandberg,^{148a,148b} M. Strauss,¹¹⁵ P. Strizenec,^{146b} R. Ströhmer,¹⁷⁷ D. M. Strom,¹¹⁸ R. Stroynowski,⁴³ A. Strubig,⁴⁹
S. A. Stucci,²⁷ B. Stugu,¹⁵ N. A. Styles,⁴⁵ D. Su,¹⁴⁵ J. Su,¹²⁷ S. Suchek,^{60a} Y. Sugaya,¹²⁰ M. Suk,¹³⁰ V. V. Sulin,⁹⁸
DMS Sultan,^{162a,162b} S. Sultansoy,^{4c} T. Sumida,⁷¹ S. Sun,⁵⁹ X. Sun,³ K. Suruliz,¹⁵¹ C. J. E. Suster,¹⁵² M. R. Sutton,¹⁵¹
S. Suzuki,⁶⁹ M. Svatos,¹²⁹ M. Swiatlowski,³³ S. P. Swift,² I. Sykora,^{146a} T. Sykora,¹³¹ D. Ta,⁵¹ K. Tackmann,⁴⁵ J. Taenzer,¹⁵⁵
A. Taffard,¹⁶⁶ R. Tafirout,^{163a} N. Taiblum,¹⁵⁵ H. Takai,²⁷ R. Takashima,⁷² E. H. Takasugi,¹⁰³ T. Takeshita,¹⁴² Y. Takubo,⁶⁹
M. Talby,⁸⁸ A. A. Talyshev,^{111,d} J. Tanaka,¹⁵⁷ M. Tanaka,¹⁵⁹ R. Tanaka,¹¹⁹ S. Tanaka,⁶⁹ R. Tanioka,⁷⁰ B. B. Tannenwald,¹¹³
S. Tapia Araya,^{34b} S. Tapprogge,⁸⁶ S. Tarem,¹⁵⁴ G. F. Tartarelli,^{94a} P. Tas,¹³¹ M. Tasevsky,¹²⁹ T. Tashiro,⁷¹ E. Tassi,^{40a,40b}

A. Tavares Delgado,^{128a,128b} Y. Tayalati,^{137e} A. C. Taylor,¹⁰⁷ G. N. Taylor,⁹¹ P. T. E. Taylor,⁹¹ W. Taylor,^{163b}
P. Teixeira-Dias,⁸⁰ D. Temple,¹⁴⁴ H. Ten Kate,³² P. K. Teng,¹⁵³ J. J. Teoh,¹²⁰ F. Tepel,¹⁷⁸ S. Terada,⁶⁹ K. Terashi,¹⁵⁷
J. Terron,⁸⁵ S. Terzo,¹³ M. Testa,⁵⁰ R. J. Teuscher,^{161,p} T. Theveneaux-Pelzer,⁸⁸ F. Thiele,³⁹ J. P. Thomas,¹⁹
J. Thomas-Wilsker,⁸⁰ P. D. Thompson,¹⁹ A. S. Thompson,⁵⁶ L. A. Thomsen,¹⁷⁹ E. Thomson,¹²⁴ M. J. Tibbetts,¹⁶
R. E. Tisce Torres,⁸⁸ V. O. Tikhomirov,^{98,ss} Yu. A. Tikhonov,^{111,d} S. Timoshenko,¹⁰⁰ P. Tipton,¹⁷⁹ S. Tisserant,⁸⁸
K. Todome,¹⁵⁹ S. Todorova-Nova,⁵ S. Todt,⁴⁷ J. Tojo,⁷³ S. Tokár,^{146a} K. Tokushuku,⁶⁹ E. Tolley,⁵⁹ L. Tomlinson,⁸⁷
M. Tomoto,¹⁰⁵ L. Tompkins,^{145,tt} K. Toms,¹⁰⁷ B. Tong,⁵⁹ P. Tornambe,⁵¹ E. Torrence,¹¹⁸ H. Torres,¹⁴⁴ E. Torr  Pastor,¹⁴⁰
J. Toth,^{88,uu} F. Touchard,⁸⁸ D. R. Tovey,¹⁴¹ C. J. Treado,¹¹² T. Trefzger,¹⁷⁷ F. Tresoldi,¹⁵¹ A. Tricoli,²⁷ I. M. Trigger,^{163a}
S. Trincaz-Duvoid,⁸³ M. F. Tripania,¹³ W. Trischuk,¹⁶¹ B. Trocm ,⁵⁸ A. Trofymov,⁴⁵ C. Troncon,^{94a}
M. Trotter-McDonald,¹⁶ M. Trovatelli,¹⁷² L. Truong,^{147b} M. Trzebinski,⁴² A. Trzupek,⁴² K. W. Tsang,^{62a} J. C-L. Tseng,¹²²
P. V. Tsiareshka,⁹⁵ G. Tsipolitis,¹⁰ N. Tsirintanis,⁹ S. Tsiskaridze,¹³ V. Tsiskaridze,⁵¹ E. G. Tskhadadze,^{54a} K. M. Tsui,^{62a}
I. I. Tsukerman,⁹⁹ V. Tsulaia,¹⁶ S. Tsuno,⁶⁹ D. Tsybychev,¹⁵⁰ Y. Tu,^{62b} A. Tudorache,^{28b} V. Tudorache,^{28b} T. T. Tulbure,^{28a}
A. N. Tuna,⁵⁹ S. A. Tuppuri,^{22a,22b} S. Turchikhin,⁶⁸ D. Turgeman,¹⁷⁵ I. Turk Cakir,^{4b,vv} R. Turra,^{94a} P. M. Tuts,³⁸
G. Uccielli,^{22a,22b} I. Ueda,⁶⁹ M. Ughetto,^{148a,148b} F. Ukegawa,¹⁶⁴ G. Unal,³² A. Undrus,²⁷ G. Unel,¹⁶⁶ F. C. Ungaro,⁹¹
Y. Unno,⁶⁹ C. Unverdorben,¹⁰² J. Urban,^{146b} P. Urquijo,⁹¹ P. Urrejola,⁸⁶ G. Usai,⁸ J. Usui,⁶⁹ L. Vacavant,⁸⁸ V. Vacek,¹³⁰
B. Vachon,⁹⁰ K. O. H. Vadla,¹²¹ A. Vaidya,⁸¹ C. Valderanis,¹⁰² E. Valdes Santurio,^{148a,148b} S. Valentineti,^{22a,22b} A. Valero,¹⁷⁰
L. Val ry,¹³ S. Valkar,¹³¹ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷⁰ W. Van Den Wollenberg,¹⁰⁹ H. van der Graaf,¹⁰⁹
P. van Gemmeren,⁶ J. Van Nieuwkoop,¹⁴⁴ I. van Vulpen,¹⁰⁹ M. C. van Woerden,¹⁰⁹ M. Vanadia,^{135a,135b} W. Vandelli,³²
A. Vaniachine,¹⁶⁰ P. Vankov,¹⁰⁹ G. Vardanyan,¹⁸⁰ R. Vari,^{134a} E. W. Varnes,⁷ C. Varni,^{53a,53b} T. Varol,⁴³ D. Varouchas,¹¹⁹
A. Vartapetian,⁸ K. E. Varvell,¹⁵² J. G. Vasquez,¹⁷⁹ G. A. Vasquez,^{34b} F. Vazeille,³⁷ T. Vazquez Schroeder,⁹⁰ J. Veatch,⁵⁷
V. Veeraraghavan,⁷ L. M. Veloce,¹⁶¹ F. Veloso,^{128a,128c} S. Veneziano,^{134a} A. Ventura,^{76a,76b} M. Venturi,¹⁷² N. Venturi,³²
A. Venturini,²⁵ V. Vercesi,^{123a} M. Verducci,^{136a,136b} W. Verkerke,¹⁰⁹ A. T. Vermeulen,¹⁰⁹ J. C. Vermeulen,¹⁰⁹
M. C. Vetterli,^{144,e} N. Viaux Maira,^{34b} O. Viazlo,⁸⁴ I. Vichou,^{169,a} T. Vickey,¹⁴¹ O. E. Vickey Boeriu,¹⁴¹
G. H. A. Viehhauser,¹²² S. Viel,¹⁶ L. Vigani,¹²² M. Villa,^{22a,22b} M. Villaplana Perez,^{94a,94b} E. Vilucchi,⁵⁰ M. G. Vincker,³¹
V. B. Vinogradov,⁶⁸ A. Vishwakarma,⁴⁵ C. Vittori,^{22a,22b} I. Vivarelli,¹⁵¹ S. Vlachos,¹⁰ M. Vogel,¹⁷⁸ P. Vokac,¹³⁰
G. Volpi,^{126a,126b} H. von der Schmitt,¹⁰³ E. von Toerne,²³ V. Vorobel,¹³¹ K. Vorobev,¹⁰⁰ M. Vos,¹⁷⁰ R. Voss,³²
J. H. Vossebeld,⁷⁷ N. Vranjes,¹⁴ M. Vranjes Milosavljevic,¹⁴ V. Vrba,¹³⁰ M. Vreeswijk,¹⁰⁹ R. Vuillermet,³² I. Vukotic,³³
P. Wagner,²³ W. Wagner,¹⁷⁸ J. Wagner-Kuhr,¹⁰² H. Wahlberg,⁷⁴ S. Wahrmund,⁴⁷ J. Wakabayashi,¹⁰⁵ J. Walder,⁷⁵
R. Walker,¹⁰² W. Walkowiak,¹⁴³ V. Wallangen,^{148a,148b} C. Wang,^{35b} C. Wang,^{36b,ww} F. Wang,¹⁷⁶ H. Wang,¹⁶ H. Wang,³
J. Wang,⁴⁵ J. Wang,¹⁵² Q. Wang,¹¹⁵ R. Wang,⁶ S. M. Wang,¹⁵³ T. Wang,³⁸ W. Wang,^{153,xx} W. Wang,^{36a} Z. Wang,^{36c}
C. Wanotayaroj,¹¹⁸ A. Warburton,⁹⁰ C. P. Ward,³⁰ D. R. Wardrope,⁸¹ A. Washbrook,⁴⁹ P. M. Watkins,¹⁹ A. T. Watson,¹⁹
M. F. Watson,¹⁹ G. Watts,¹⁴⁰ S. Watts,⁸⁷ B. M. Waugh,⁸¹ A. F. Webb,¹¹ S. Webb,⁸⁶ M. S. Weber,¹⁸ S. W. Weber,¹⁷⁷
S. A. Weber,³¹ J. S. Webster,⁶ A. R. Weidberg,¹²² B. Weinert,⁶⁴ J. Weingarten,⁵⁷ M. Weirich,⁸⁶ C. Weiser,⁵¹ H. Weits,¹⁰⁹
P. S. Wells,³² T. Wenaus,²⁷ T. Wengler,³² S. Wenig,³² N. Wermes,²³ M. D. Werner,⁶⁷ P. Werner,³² M. Wessels,^{60a}
K. Whalen,¹¹⁸ N. L. Whallon,¹⁴⁰ A. M. Wharton,⁷⁵ A. S. White,⁹² A. White,⁸ M. J. White,¹ R. White,^{34b} D. Whiteson,¹⁶⁶
B. W. Whitmore,⁷⁵ F. J. Wickens,¹³³ W. Wiedenmann,¹⁷⁶ M. Wielers,¹³³ C. Wiglesworth,³⁹ L. A. M. Wiik-Fuchs,⁵¹
A. Wildauer,¹⁰³ F. Wilk,⁸⁷ H. G. Wilkens,³² H. H. Williams,¹²⁴ S. Williams,¹⁰⁹ C. Willis,⁹³ S. Willocq,⁸⁹ J. A. Wilson,¹⁹
I. Wingerter-Seez,⁵ E. Winkels,¹⁵¹ F. Winklmeier,¹¹⁸ O. J. Winston,¹⁵¹ B. T. Winter,²³ M. Wittgen,¹⁴⁵ M. Wobisch,^{82,v}
T. M. H. Wolf,¹⁰⁹ R. Wolff,⁸⁸ M. W. Wolter,⁴² H. Wolters,^{128a,128c} V. W. S. Wong,¹⁷¹ S. D. Worm,¹⁹ B. K. Wosiek,⁴²
J. Wotschack,³² K. W. Wozniak,⁴² M. Wu,³³ S. L. Wu,¹⁷⁶ X. Wu,⁵² Y. Wu,⁹² T. R. Wyatt,⁸⁷ B. M. Wynne,⁴⁹ S. Xella,³⁹
Z. Xi,⁹² L. Xia,^{35c} D. Xu,^{35a} L. Xu,²⁷ T. Xu,¹³⁸ B. Yabsley,¹⁵² S. Yacoob,^{147a} D. Yamaguchi,¹⁵⁹ Y. Yamaguchi,¹²⁰
A. Yamamoto,⁶⁹ S. Yamamoto,¹⁵⁷ T. Yamanaka,¹⁵⁷ M. Yamatani,¹⁵⁷ K. Yamauchi,¹⁰⁵ Y. Yamazaki,⁷⁰ Z. Yan,²⁴ H. Yang,^{36c}
H. Yang,¹⁶ Y. Yang,¹⁵³ Z. Yang,¹⁵ W-M. Yao,¹⁶ Y. C. Yap,⁸³ Y. Yasu,⁶⁹ E. Yatsenko,⁵ K. H. Yau Wong,²³ J. Ye,⁴³ S. Ye,²⁷
I. Yeletsikh,⁶⁸ E. Yigitbasi,²⁴ E. Yildirim,⁸⁶ K. Yorita,¹⁷⁴ K. Yoshihara,¹²⁴ C. Young,¹⁴⁵ C. J. S. Young,³² J. Yu,⁸ J. Yu,⁶⁷
S. P. Y. Yuen,²³ I. Yusuff,^{30,yy} B. Zabinski,⁴² G. Zacharis,¹⁰ R. Zaidan,¹³ A. M. Zaitsev,^{132,mmm} N. Zakharchuk,⁴⁵
J. Zalieckas,¹⁵ A. Zaman,¹⁵⁰ S. Zambito,⁵⁹ D. Zanzi,⁹¹ C. Zeitnitz,¹⁷⁸ G. Zemaityte,¹²² A. Zemla,^{41a} J. C. Zeng,¹⁶⁹
Q. Zeng,¹⁴⁵ O. Zenin,¹³² T.  eniš,^{146a} D. Zerwas,¹¹⁹ D. Zhang,⁹² F. Zhang,¹⁷⁶ G. Zhang,^{36a,zz} H. Zhang,^{35b} J. Zhang,⁶
L. Zhang,⁵¹ L. Zhang,^{36a} M. Zhang,¹⁶⁹ P. Zhang,^{35b} R. Zhang,²³ R. Zhang,^{36a,ww} X. Zhang,^{36b} Y. Zhang,^{35a} Z. Zhang,¹¹⁹
X. Zhao,⁴³ Y. Zhao,^{36b,aaa} Z. Zhao,^{36a} A. Zhemchugov,⁶⁸ B. Zhou,⁹² C. Zhou,¹⁷⁶ L. Zhou,⁴³ M. Zhou,^{35a} M. Zhou,¹⁵⁰

N. Zhou,^{35c} C. G. Zhu,^{36b} H. Zhu,^{35a} J. Zhu,⁹² Y. Zhu,^{36a} X. Zhuang,^{35a} K. Zhukov,⁹⁸ A. Zibell,¹⁷⁷ D. Zieminska,⁶⁴
 N. I. Zimine,⁶⁸ C. Zimmermann,⁸⁶ S. Zimmermann,⁵¹ Z. Zinonos,¹⁰³ M. Zinser,⁸⁶ M. Ziolkowski,¹⁴³ L. Živković,¹⁴
 G. Zoernig,¹⁷⁶ A. Zoccoli,^{22a,22b} R. Zou,³³ M. zur Nedden,¹⁷ and L. Zwalinski³²

(ATLAS Collaboration)

- ¹Department of Physics, University of Adelaide, Adelaide, Australia
²Physics Department, SUNY Albany, Albany, New York, USA
³Department of Physics, University of Alberta, Edmonton, Alberta, Canada
^{4a}Department of Physics, Ankara University, Ankara, Turkey
^{4b}Istanbul Aydin University, Istanbul, Turkey
^{4c}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
⁵LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
⁶High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
⁷Department of Physics, University of Arizona, Tucson, Arizona, USA
⁸Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
⁹Physics Department, National and Kapodistrian University of Athens, Athens, Greece
¹⁰Physics Department, National Technical University of Athens, Zografou, Greece
¹¹Department of Physics, The University of Texas at Austin, Austin, Texas, USA
¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
¹³Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
¹⁴Institute of Physics, University of Belgrade, Belgrade, Serbia
¹⁵Department for Physics and Technology, University of Bergen, Bergen, Norway
¹⁶Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
¹⁷Department of Physics, Humboldt University, Berlin, Germany
¹⁸Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
¹⁹School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
^{20a}Department of Physics, Bogazici University, Istanbul, Turkey
^{20b}Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
^{20d}Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
^{20e}Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
²¹Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
^{22a}INFN Sezione di Bologna, Italy
^{22b}Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
²³Physikalisches Institut, University of Bonn, Bonn, Germany
²⁴Department of Physics, Boston University, Boston, Massachusetts, USA
²⁵Department of Physics, Brandeis University, Waltham, Massachusetts, USA
^{26a}Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
^{26b}Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
^{26c}Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
^{26d}Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
²⁷Physics Department, Brookhaven National Laboratory, Upton, New York, USA
^{28a}Transilvania University of Brasov, Brasov, Romania
^{28b}Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
^{28c}Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
^{28d}National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
^{28e}University Politehnica Bucharest, Bucharest, Romania
^{28f}West University in Timisoara, Timisoara, Romania
²⁹Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
³⁰Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
³¹Department of Physics, Carleton University, Ottawa, Ontario, Canada
³²CERN, Geneva, Switzerland
³³Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
^{34a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
^{34b}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
^{35a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
^{35b}Department of Physics, Nanjing University, Jiangsu, China

- ^{35c}Physics Department, Tsinghua University, Beijing, China
- ^{36a}Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
- ^{36b}School of Physics, Shandong University, Shandong, China
- ^{36c}Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China
- ³⁷Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ³⁸Nevis Laboratory, Columbia University, Irvington, New York, USA
- ³⁹Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ^{40a}INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ^{40b}Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ^{41a}AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ^{41b}Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ⁴²Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴³Physics Department, Southern Methodist University, Dallas, Texas, USA
- ⁴⁴Physics Department, University of Texas at Dallas, Richardson, Texas, USA
- ⁴⁵DESY, Hamburg and Zeuthen, Germany
- ⁴⁶Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁷Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁸Department of Physics, Duke University, Durham North Carolina, USA
- ⁴⁹SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵⁰INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵¹Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁵²Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- ^{53a}INFN Sezione di Genova, Italy
- ^{53b}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{54a}E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia
- ^{54b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵⁵II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁶SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁷II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁸Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
- ^{60a}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{60b}Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁶¹Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ^{62a}Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
- ^{62b}Department of Physics, The University of Hong Kong, Hong Kong, China
- ^{62c}Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶³Department of Physics, National Tsing Hua University, Taiwan, Taiwan
- ⁶⁴Department of Physics, Indiana University, Bloomington, Indiana, USA
- ⁶⁵Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁶University of Iowa, Iowa City, Iowa, USA
- ⁶⁷Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA
- ⁶⁸Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁹KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁷⁰Graduate School of Science, Kobe University, Kobe, Japan
- ⁷¹Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷²Kyoto University of Education, Kyoto, Japan
- ⁷³Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁴Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁵Physics Department, Lancaster University, Lancaster, United Kingdom
- ^{76a}INFN Sezione di Lecce, Italy
- ^{76b}Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁷Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁸Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- ⁷⁹School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

- ⁸⁰*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- ⁸¹*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁸²*Louisiana Tech University, Ruston, Louisiana, USA*
- ⁸³*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- ⁸⁴*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁸⁵*Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- ⁸⁶*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁸⁷*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁸⁸*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
- ⁸⁹*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ⁹⁰*Department of Physics, McGill University, Montreal Québec, Canada*
- ⁹¹*School of Physics, University of Melbourne, Victoria, Australia*
- ⁹²*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
- ⁹³*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ^{94a}*INFN Sezione di Milano, Italy*
- ^{94b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ⁹⁵*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
- ⁹⁶*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus*
- ⁹⁷*Group of Particle Physics, University of Montreal, Montreal Québec, Canada*
- ⁹⁸*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- ⁹⁹*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ¹⁰⁰*National Research Nuclear University MEPhI, Moscow, Russia*
- ¹⁰¹*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ¹⁰²*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹⁰³*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹⁰⁴*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹⁰⁵*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ^{106a}*INFN Sezione di Napoli, Italy*
- ^{106b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ¹⁰⁷*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹⁰⁸*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹⁰⁹*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁰*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ¹¹¹*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ¹¹²*Department of Physics, New York University, New York, New York, USA*
- ¹¹³*Ohio State University, Columbus, Ohio, USA*
- ¹¹⁴*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹⁵*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹¹⁶*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹¹⁷*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹⁸*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹¹⁹*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹²⁰*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹²¹*Department of Physics, University of Oslo, Oslo, Norway*
- ¹²²*Department of Physics, Oxford University, Oxford, United Kingdom*
- ^{123a}*INFN Sezione di Pavia, Italy*
- ^{123b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ¹²⁴*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹²⁵*National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
- ^{126a}*INFN Sezione di Pisa, Italy*
- ^{126b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ¹²⁷*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{128a}*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal*
- ^{128b}*Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{128c}*Department of Physics, University of Coimbra, Coimbra, Portugal*
- ^{128d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{128e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{128f}*Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal*
- ^{128g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- ¹²⁹*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*

- ¹³⁰*Czech Technical University in Prague, Praha, Czech Republic*
- ¹³¹*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹³²*State Research Center Institute for High Energy Physics (Protvino), NRC KI, Protvino, Russia*
- ¹³³*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ^{134a}*INFN Sezione di Roma, Italy*
- ^{134b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ^{135a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{135b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{136a}*INFN Sezione di Roma Tre, Italy*
- ^{136b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{137a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco*
- ^{137b}*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
- ^{137c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{137d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
- ^{137e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ¹³⁸*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*
- ¹³⁹*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ¹⁴⁰*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹⁴¹*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴²*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴³*Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴⁴*Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada*
- ¹⁴⁵*SLAC National Accelerator Laboratory, Stanford, California, USA*
- ^{146a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{146b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ^{147a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{147b}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- ^{147c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{148a}*Department of Physics, Stockholm University, Sweden*
- ^{148b}*The Oskar Klein Centre, Stockholm, Sweden*
- ¹⁴⁹*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁵⁰*Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA*
- ¹⁵¹*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵²*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵³*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ¹⁵⁴*Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
- ¹⁵⁵*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁶*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁷*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁸*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁹*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁶⁰*Tomsk State University, Tomsk, Russia*
- ¹⁶¹*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
- ^{162a}*INFN-TIFPA, Italy*
- ^{162b}*University of Trento, Trento, Italy*
- ^{163a}*TRIUMF, Vancouver, British Columbia, Canada*
- ^{163b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
- ¹⁶⁴*Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*
- ¹⁶⁵*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- ¹⁶⁶*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ^{167a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{167b}*ICTP, Trieste, Italy*
- ^{167c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ¹⁶⁸*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁹*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁷⁰*Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- ¹⁷¹*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*

¹⁷²*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*

¹⁷³*Department of Physics, University of Warwick, Coventry, United Kingdom*

¹⁷⁴*Waseda University, Tokyo, Japan*

¹⁷⁵*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*

¹⁷⁶*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*

¹⁷⁷*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*

¹⁷⁸*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*

¹⁷⁹*Department of Physics, Yale University, New Haven, Connecticut, USA*

¹⁸⁰*Yerevan Physics Institute, Yerevan, Armenia*

¹⁸¹*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

¹⁸²*Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan*

^aDeceased.

^bAlso at Department of Physics, King's College London, London, United Kingdom.

^cAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^dAlso at Novosibirsk State University, Novosibirsk, Russia.

^eAlso at TRIUMF, Vancouver BC, Canada.

^fAlso at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.

^gAlso at Physics Department, An-Najah National University, Nablus, Palestine.

^hAlso at Department of Physics, California State University, Fresno CA, USA.

ⁱAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^jAlso at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.

^kAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^lAlso at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^mAlso at Tomsk State University, Tomsk, Russia.

ⁿAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

^oAlso at Università di Napoli Parthenope, Napoli, Italy.

^pAlso at Institute of Particle Physics (IPP), Canada.

^qAlso at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^rAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^sAlso at Borough of Manhattan Community College, City University of New York, New York City, USA.

^tAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^uAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

^vAlso at Louisiana Tech University, Ruston LA, USA.

^wAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^xAlso at Graduate School of Science, Osaka University, Osaka, Japan.

^yAlso at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.

^zAlso at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

^{aa}Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.

^{bb}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^{cc}Also at CERN, Geneva, Switzerland

^{dd}Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^{ee}Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

^{ff}Also at Manhattan College, New York NY, USA.

^{gg}Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile.

^{hh}Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.

ⁱⁱAlso at The City College of New York, New York NY, USA.

^{jj}Also at School of Physics, Shandong University, Shandong, China.

^{kk}Also at Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal.

^{ll}Also at Department of Physics, California State University, Sacramento CA, USA.

^{mmm}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

ⁿⁿAlso at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

^{oo}Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

^{pp}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

^{qq}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

^{rr}Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.

^{ss}Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{tt}Also at Department of Physics, Stanford University, Stanford CA, USA.

^{uu}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{vv}Also at Giresun University, Faculty of Engineering, Turkey.

^{ww}Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^{xx}Also at Department of Physics, Nanjing University, Jiangsu, China.

^{yy}Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

^{zz}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{aaa}Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.