

Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC

The ATLAS Collaboration

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A search for new heavy particles manifested as narrow resonances in two-jet final states is presented. The data were produced in 7 TeV proton-proton collisions by the Large Hadron Collider (LHC) and correspond to an integrated luminosity of 315 nb^{-1} collected by the ATLAS detector. No resonances were observed. Upper limits were set on the product of cross section and detector acceptance for excited-quark (q^*) production as a function of q^* mass. These exclude at the 95% CL the q^* mass interval $0.40 < m_{q^*} < 1.26 \text{ TeV}$, extending the reach of previous experiments.

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Two-jet (dijet) events in high-energy proton-proton (pp) collisions are usually described in the Standard Model (SM) by applying quantum chromodynamics (QCD) to the scattering of beam-constituent quarks and gluons. Several extensions beyond the SM predict new heavy particles, accessible at LHC energies, that decay into two energetic partons. Such new states may include an excited composite quark q^* , exemplifying quark substructure [1–3]; an axigluon predicted by chiral color models [4, 5]; a flavour-universal color-octet coloron [6, 7]; or a color-octet techni- ρ meson predicted by models of extended technicolor and topcolor-assisted technicolor [8–11].

The dijet invariant mass (m^{jj}) observable is particularly sensitive to such new objects. Studies using 1.13 fb^{-1} of $p\bar{p}$ collision data at the Fermilab Tevatron collider have excluded the existence of excited quarks q^* with mass $260 < m_{q^*} < 870 \text{ GeV}$ [12]. This Letter reports the first search by the ATLAS experiment [13] at the LHC for such massive particles in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$, based on a data sample corresponding to an integrated luminosity of 315 nb^{-1} . The analysis presented here focused on a search for excited quarks because of the accessible predicted cross section [2, 3] for such particles and the benchmark nature of the model that allows limits on acceptance times cross section to be set for narrow-width resonances.

The analysis technique consisted of a search for a dijet mass resonance on top of a smooth and rapidly falling spectrum and relied on the measured m^{jj} distribution to estimate the background level to this new possible signal. In the absence of an observed new physics signal, upper limits were determined on products of cross section (σ) and detector acceptance (\mathcal{A}) for several q^* test masses.

The ATLAS detector [13] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [14]. The overall layout of the detector is dominated by its four superconducting magnet systems, which comprise a thin solenoid surrounding inner tracking detectors

and three large toroids with an eightfold azimuthal symmetry.

The calorimeters, which are surrounded by an extensive muon system, are of particular importance to this analysis. In the pseudorapidity region $|\eta| < 3.2$, high-granularity liquid-argon (LAr) electromagnetic sampling calorimeters are used. An iron-scintillator tile calorimeter provides hadronic coverage in the range $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements.

The data sample was collected during stable periods of 7 TeV pp collisions using a trigger configuration requiring the lowest-level hardware-based calorimeter jet trigger to satisfy a nominal transverse energy threshold of 15 GeV [15]. This trigger had an efficiency greater than 99% for events with at least one jet with transverse energy higher than 80 GeV.

Jets were reconstructed using the anti- k_T jet clustering algorithm [16] with a radius parameter $R = 0.6$. The inputs to this algorithm were clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jet four-vectors were constructed by performing a four-vector sum over these cell clusters, treating each as an (E, \vec{p}) four-vector with zero mass. These were corrected for the effects of calorimeter non-compensation and inhomogeneities by using transverse-momentum (p_T) and η -dependent calibration factors based on Monte Carlo (MC) corrections and validated with extensive test-beam and collision-data studies [15, 17].

In order to suppress cosmic-ray and beam-related backgrounds, events were required to contain at least one primary collision vertex, defined by at least five reconstructed charged-particle tracks, each with a position, when extrapolated to the beamline, of $|z| < 10 \text{ cm}$. Events with at least two jets were retained if the highest p_T jet (the “leading” jet) satisfied $p_T^{j_1} > 80 \text{ GeV}$ and the next-to-leading jet satisfied $p_T^{j_2} > 30 \text{ GeV}$; this ensured that the data sample had high and unbiased trigger and jet reconstruction efficiencies. Those events containing a

poorly measured jet with $p_T > 15$ GeV were vetoed to prevent cases where a jet was incorrectly identified as one of the two leading jets [18]; this affected the event selection by less than 0.5%. The two leading jets were required to satisfy several quality criteria [18] and to lie outside detector regions where the jet energy was not yet measured in an optimal way, such as the interval $1.3 < |\eta^{\text{jet}}| < 1.8$. Finally, both jets were required to be in the pseudorapidity region $|\eta^{\text{jet}}| < 2.5$, and their pseudorapidity difference was required to satisfy $|\eta^{j_1} - \eta^{j_2}| < 1.3$. These cuts, which suppress high-mass SM multijet background, were determined by performing an optimization of the potential signal from q^* decays (using a q^* mass of 1 TeV) compared with the SM background. There were 132,433 candidates that satisfied these requirements.

The final event sample was selected by requiring the dijet invariant mass to satisfy $m^{jj} > 200$ GeV in order to eliminate any potential kinematic bias in the m^{jj} distributions from the selection requirements on the jet candidates. There were 37,805 events in this sample, which formed the m^{jj} distribution shown in Fig. 1.

MC signal events were generated using the excited-quark ($qg \rightarrow q^*$) production model [2, 3]. The excited quark q^* was assumed to have spin 1/2 and quark-like couplings, relative to those of the SM $SU(2)$, $U(1)$, and $SU(3)$ gauge groups, of $f = f' = f_s = 1$, respectively. The compositeness scale (Λ) was set to the q^* mass. Signal events were generated using PYTHIA [19] 6.4.21, a leading-order parton-shower MC generator, with the modified leading-order MRST2007 [20] parton distribution functions (PDFs) and with the renormalization and factorization scales set to the mean p_T of the two leading jets. PYTHIA was also used to decay the excited quarks to all possible SM final states. The MC samples were produced [21] using the ATLAS MC09 parameter tune [22] and a GEANT4-based detector simulation [23].

Figure 1 shows the predicted signals for q^* masses of 500, 800, and 1200 GeV, after all selection cuts. The signal acceptance (\mathcal{A}), which included reconstruction and trigger efficiencies near 100%, was found to range from $\sim 36\%$ for $m_{q^*} = 400$ GeV to $\sim 49\%$ for $m_{q^*} = 1.5$ TeV. The choice of dijet mass binning was motivated by the dijet mass resolution of the signal. The predicted experimental width ranged from $\sigma_{m^{jj}}/m^{jj} \sim 11\%$ at $m_{q^*} = 400$ GeV to $\sigma_{m^{jj}}/m^{jj} \sim 7\%$ at $m_{q^*} = 1.5$ TeV and was dominated by the not-yet-optimized detector energy resolution.

The background shape was determined by fitting the observed spectrum with the function [12]

$$f(x) = p_1 \frac{(1-x)^{p_2}}{x^{p_3+p_4 \ln x}}, \quad (1)$$

where $x \equiv m^{jj}/\sqrt{s}$ such that $f(1) = 0$ and $f(0) \rightarrow +\infty$, and $p_{\{1,2,3,4\}}$ are free parameters. The $x^{-p_4 \ln x}$ factor was included to describe the high- m^{jj} part of the spectrum. The function in Eqn. 1 has been shown to fit the

m^{jj} observable well in PYTHIA, HERWIG, and next-to-leading-order (NLO) perturbative QCD predictions for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [12]. Studies using PYTHIA and the ATLAS GEANT4-based detector simulation, scaled to the same number of events as the data, were performed to demonstrate that the smooth and monotonic form of Eqn. 1 describes QCD-predicted dijet mass distributions in pp collisions at $\sqrt{s} = 7$ TeV. There is good agreement between the MC prediction and the fitted parametrization in Eqn. 1, as evidenced by a χ^2 per degree of freedom of 27/22 over the dijet mass range $200 < m^{jj} < 1900$ GeV.

The results of fitting the data with Eqn. 1 are shown in Fig. 1. The presence or absence of detectable narrow m^{jj} resonances in this distribution was determined by performing several statistical tests of the background-only hypothesis. A suite of six tests was employed: the BumpHunter [24], the Jeffreys divergence [25], the Kolmogorov-Smirnov test, the likelihood, the Pearson χ^2 , and the TailHunter statistic [26]. The agreement of the data with the background-only hypothesis of a smoothly varying and monotonic distribution was determined for each statistic by calculating the p -value for the data using 10^3 pseudo-spectra drawn from Poisson variations seeded by the results of the fit of Eqn. 1 to the data. The p -value of the background-only hypothesis is defined as the fraction of pseudo-experiments that results in a value of the given statistic greater than the value of the same statistic found by the fit to the data. The results of all six tests were consistent with the conclusion that the fitted parametrization described the observed data distribution well, with p -values in excess of 51%. These observations supported the background-only hypothesis.

In the absence of any observed discrepancy with the zero-signal hypothesis, a Bayesian approach was used to set 95% credibility-level (CL) upper limits on $\sigma \cdot \mathcal{A}$ for hypothetical new particles decaying into dijets with $|\eta^{\text{jet}}| < 2.5$. For each of the test masses (indexed by ν) corresponding to the excited-quark q^* predictions, a likelihood function L_ν was defined as a product of Poisson factors computed for each bin (i) of the m^{jj} distribution:

$$L_\nu(d|b_\nu, s) \equiv \prod_i \frac{[b_{\nu i} + s_i(\nu)]^{d_i}}{d_i!} e^{-[b_{\nu i} + s_i(\nu)]}, \quad (2)$$

where d_i is the observed number of data events in bin i , $b_{\nu i}$ is the background in bin i obtained as described below, and $s_i(\nu)$ is the predicted signal added in bin i by the signal template; the latter was normalized to the total number of predicted signal events $s = \sum_i s_i(\nu)$. For each ν , the backgrounds in the bins $b_{\nu i}$ were evaluated from a simultaneous five-parameter fit of the signal and background distributions to ensure that the background determination would not be biased by the presence of any signal. The four background parameters were those in Eqn. 1; the fifth parameter consisted of the normal-

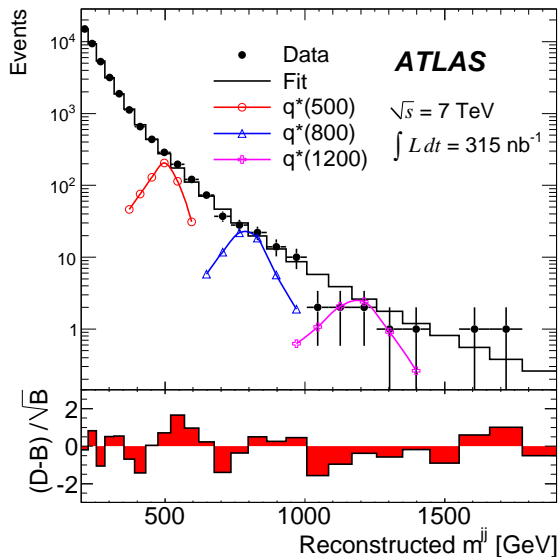


FIG. 1. The data (D) dijet mass distribution (filled points) fitted using a binned background (B) distribution described by Eqn. 1 (histogram). The predicted q^* signals [2, 3] for excited-quark masses of 500, 800, and 1200 GeV are overlaid, and the bin-by-bin significance of the data-background difference is shown.

ization of the predicted $\nu^{\text{th}} q^*$ signal template. To allow for a low-mass background sideband, the lowest q^* test mass used was 400 GeV. For every q^* mass, Eqn. 2 was computed for a range of possible signal yields, s , and the resulting likelihood function was multiplied by a flat prior in s to give a posterior probability density in s . The 95% quantile was then determined by integration of the posterior probability distribution. This Bayesian technique was found to yield credibility intervals that corresponded well with frequentist confidence intervals. This was verified by performing a series of pseudo-experiments to determine, by way of a standard frequentist calculation, the coverage, or the fraction of times that the 95% Bayesian credibility interval contained the true number of signal events.

The dominant sources of systematic uncertainty, in decreasing order of importance, were the absolute jet energy scale (JES), the background fit parameters, the integrated luminosity, and the jet energy resolution (JER). The JES uncertainty was quantified as a function of p_T and η^{jet} , with values in the range $6 \sim 9\%$ [15, 27, 28]. The statistical uncertainty on the determination of the background was taken from the uncertainty on the parameters resulting from the fit of Eqn. 1 to the data sample. The uncertainty on $\sigma \cdot \mathcal{A}$ due to integrated luminosity was estimated to be $\pm 11\%$ [29]. The JER uncertainty was treated as uniform in p_T and η^{jet} with a value of $\pm 14\%$ on the fractional p_T resolution of each jet [30]. The effects of JES, background fit, integrated luminosity, and

JER were incorporated as nuisance parameters into the likelihood function and then marginalized by integrating over each variable. In the course of applying this convolution technique, the JER was found to make a negligible contribution to the overall systematic uncertainty.

Figure 2 depicts the resulting 95% CL upper limits on $\sigma \cdot \mathcal{A}$ as a function of the q^* resonance mass after incorporation of systematic uncertainties. Linear interpolations between test masses were used to determine where the experimental bound intersected with a theoretical prediction to yield a lower limit on allowed mass. The corresponding observed 95% CL excited-quark mass exclusion region was found to be $0.40 < m_{q^*} < 1.26$ TeV using MRST2007 PDFs in the ATLAS default MC09 tune. Table I shows the results obtained using CTEQ6L1 [31] and CTEQ5L [32] PDF sets. The variations in the observed limit associated with the error eigenvectors of a CTEQ PDF set were found to be smaller than the spread displayed in Table I. The excluded regions were ~ 30 GeV greater when only statistical uncertainties were taken into account. The expected limits corresponding to the data sample were computed using an analogous approach, but replacing the actual data with pseudo-data generated by random fluctuations around the smooth function described by fitting the data with Eqn. 1; these are shown in Fig. 2, with a resulting expected q^* mass exclusion region of $0.40 < m_{q^*} < 1.06$ TeV using MRST2007 PDFs. As indicated in Table I, the two other PDF sets yielded similar results, with expected exclusion regions extending to near 1 TeV. An indication of the dependence of the m_{q^*} limits on the theoretical prediction for the q^* signal was obtained by simultaneously varying both the renormalization and factorization scales by factors of 0.5 and 2, which was tantamount to modifying the predicted cross section by approximately $\pm 20\%$; this changed the observed MRST2007 limit of 1.26 TeV to 1.32 TeV and 1.22 TeV, respectively.

In conclusion, a search for new heavy particles manifested as narrow mass resonances in dijet final states was conducted using a 315 nb^{-1} sample of 7 TeV proton-proton collisions produced by the LHC and recorded by the ATLAS detector. No evidence of a resonance structure was found and upper limits at the 95% CL were set on the products of cross section and detector acceptance for hypothetical new q^* particles decaying to dijets. These data exclude at the 95% CL excited-quark masses from the lower edge of our search region, 0.40 TeV, to 1.26 TeV for a standard set of model parameters and using the ATLAS default MC09 tune [22]. This result extends the reach of previous experiments and constitutes the first exclusion of physics beyond the Standard Model by the ATLAS experiment. In the future, such searches will be extended to exclude or discover additional hypothetical particles over greater mass ranges.

TABLE I. The 95% CL lower limits on the allowed q^* mass obtained using different PDF sets.

MC Tune	PDF Set	Observed Mass Limit [TeV]		Expected Mass Limit [TeV]
		Stat. \oplus Syst.	Stat. only	Stat. \oplus Syst.
MC09 [22]	MRST2007 [20]	1.26	1.29	1.06
MC09' ^a	CTEQ6L1 [31]	1.20	1.23	0.99
Perugia0 [33]	CTEQ5L [32]	1.22	1.25	1.00

^a The MC09' tune is identical to MC09 except for the PYTHIA parameter PARP(82)= 2.1 and use of the CTEQ6L1 PDF set.

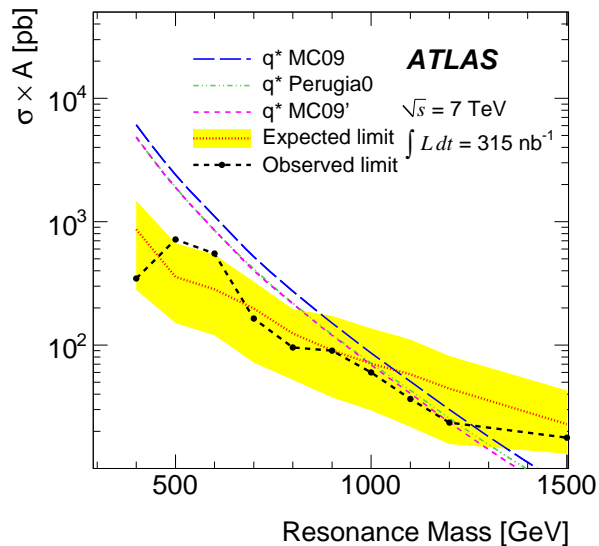


FIG. 2. The 95% CL upper limit on $\sigma \cdot \mathcal{A}$ as a function of dijet resonance mass (dots), including the effects of systematic uncertainties. The red dotted curve shows the expected 95% CL upper limit and the yellow band represents the 95% credibility interval of the expected limit. The dashed curves represent excited-quark $\sigma \cdot \mathcal{A}$ predictions for different MC tunes, each using a different PDF set.

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The ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, A.A. Abdelalim⁴⁹, A. Abdesselam¹¹⁸, O. Abidinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, H. Abramowicz¹⁵³, H. Abreu¹¹⁵, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, M. Ackers²⁰, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁵, M. Aderholz⁹⁹, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, H. Ahmed², M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, A. Aktas⁴⁸, M.S. Alam¹, M.A. Alam⁷⁶, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁵, M. Aleppo^{89a,89b}, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob²⁰, M. Aliev¹⁵, G. Alimonti^{89a}, J. Alison¹²⁰, M. Aliyev¹⁰, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, A. Aloisio^{102a,102b}, R. Alon¹⁷¹, A. Alonso⁷⁹, J. Alonso¹⁴, M.G. Alvigi^{102a,102b}, K. Amako⁶⁶, P. Amaral²⁹, G. Ambrosio^{89a,b}, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,c}, G. Amorós¹⁶⁷, N. Amram¹⁵³, C. Anastopoulos¹³⁹, T. Andeen³⁴, C.F. Anders²⁰, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, M-L. Andrieux⁵⁵, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, S. Antonelli^{19a,19b}, J. Antos^{144b}, B. Antunovic⁴¹, F. Anulli^{132a}, S. Aoun⁸³, G. Arabidze⁸, I. Aracena¹⁴³, Y. Arai⁶⁶, A.T.H. Arce⁴⁴, J.P. Archambault²⁸, S. Arfaoui^{29,d}, J-F. Arguin¹⁴, T. Argyropoulos⁹, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, K.E. Arms¹⁰⁹, S.R. Armstrong²⁴, O. Arnaez⁴, C. Arnault¹¹⁵, A. Artamonov⁹⁵, D. Arutinov²⁰, M. Asai¹⁴³, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷², S. Ask²⁷, B. Åsman^{146a,146b}, D. Asner²⁸, L. Asquith⁷⁷, K. Assamagan²⁴, A. Astvatsatourov⁵², G. Atoian¹⁷⁵, B. Aubert⁴, B. Auerbach¹⁷⁵, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Aurousseau⁴, N. Austin⁷³, G. Avolio¹⁶³, R. Avramidou⁹, C. Ay⁵⁴, G. Azuelos^{93,e}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, G. Bachy²⁹, M. Backes⁴⁹, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁵, M.D. Baker²⁴, S. Baker⁷⁷, F. Baltasar Dos Santos Pedrosa²⁹, E. Banas³⁸, P. Banerjee⁹³, S. Banerjee¹⁶⁹, D. Banfi^{89a,89b}, A. Bangert¹³⁷, V. Bansal¹⁶⁹, S.P. Baranov⁹⁴, A. Barashkou⁶⁵, A. Barbaro Galtieri¹⁴, T. Barber²⁷, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁵, T. Barillari⁹⁹, M. Barisonzi¹⁷⁴, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, M. Barone⁴⁷, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, D. Bartsch²⁰, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, G. Battistoni^{89a}, F. Bauer¹³⁶,

H.S. Bawa¹⁴³, B. Beare¹⁵⁸, T. Beau⁷⁸, P.H. Beauchemin¹¹⁸, R. Beccherle^{50a}, P. Bechtle⁴¹, G.A. Beck⁷⁵, H.P. Beck¹⁶, M. Beckingham⁴⁸, K.H. Becks¹⁷⁴, A.J. Beddall^{18c}, A. Beddall^{18c}, V.A. Bednyakov⁶⁵, C. Bee⁸³, M. Begel²⁴, S. Behar Harpaz¹⁵², P.K. Behera⁶³, M. Beimforde⁹⁹, C. Belanger-Champagne¹⁶⁶, B. Belhorma⁵⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹, G. Bellomo^{89a,89b}, M. Bellomo^{119a}, A. Belloni⁵⁷, K. Belotskiy⁹⁶, O. Beltramello²⁹, S. Ben Ami¹⁵², O. Benary¹⁵³, D. Benčekroun^{135a}, C. Benchouk⁸³, M. Bendel⁸¹, B.H. Benedict¹⁶³, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²², K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, M. Beretta⁴⁷, D. Berge²⁹, E. Bergeaas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹, E. Berglund⁴⁹, J. Beringer¹⁴, K. Bernardet⁸³, P. Bernat¹¹⁵, R. Bernhard⁴⁸, C. Bernius⁷⁷, T. Berry⁷⁶, A. Bertin^{19a,19b}, F. Bertinelli²⁹, F. Bertolucci^{122a,122b}, S. Bertolucci⁴⁷, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁵, R.M. Bianchi⁴⁸, M. Bianco^{72a,72b}, O. Biebel⁹⁸, J. Biesiada¹⁴, M. Biglietti^{132a,132b}, H. Bilokon⁴⁷, M. Binder⁹⁸, M. Bindi^{19a,19b}, A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁸⁰, R. Bischof⁶², U. Bitenc⁴⁸, K.M. Black⁵⁷, R.E. Blair⁵, J-B Blanchard¹¹⁵, G. Blanchot²⁹, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, C. Boaretto^{132a,132b}, G.J. Bobbink¹⁰⁵, A. Bocci⁴⁴, D. Bocian³⁸, R. Bock²⁹, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁴, N. Boelaert⁷⁹, S. Böser⁷⁷, J.A. Bogaerts²⁹, A. Bogouch^{90,*}, C. Bohm^{146a}, V. Boisvert⁷⁶, T. Bold^{163,f}, V. Boldea^{25a}, M. Bondioli¹⁶³, M. Boonekamp¹³⁶, G. Boorman⁷⁶, C.N. Booth¹³⁹, P. Booth¹³⁹, J.R.A. Booth¹⁷, S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borisso⁷¹, I. Borjanovic^{12a}, S. Borroni^{132a,132b}, K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, C. Boulahouache¹²³, C. Bourdarios¹¹⁵, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁵, N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, S. Braccini⁴⁷, J. Bracinik¹⁷, A. Braem²⁹, E. Brambilla^{72a,72b}, G.W. Brandenburg⁵⁷, A. Brandt⁷, G. Brandt⁴¹, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun¹⁷⁴, B. Brelier¹⁵⁸, J. Bremer²⁹, R. Brenner¹⁶⁶, S. Bressler¹⁵², D. Breton¹¹⁵, N.D. Brett¹¹⁸, P.G. Bright-Thomas¹⁷, D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, T.J. Brodbeck⁷¹, E. Brodet¹⁵³, F. Broggi^{89a}, C. Bromberg⁸⁸, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², E. Brubaker³⁰, P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶¹, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³, F. Bucci⁴⁹, J. Buchanan¹¹⁸, N.J. Buchanan², P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, I.A. Budagov⁶⁵, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, D. Buira-Clark¹¹⁸, E.J. Buis¹⁰⁵, O. Bulekov⁹⁶, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³, T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶, F. Butin²⁹, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, T. Byatt⁷⁷, J. Caballero²⁴, S. Cabrera Urbán¹⁶⁷, M. Caccia^{89a,89b,g}, D. Caforio^{19a,19b}, O. Cakin^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, A. Camard⁷⁸, P. Camarri^{133a,133b}, M. Cambiaghi^{119a,119b}, D. Cameron¹¹⁷, J. Cammin²⁰, S. Campana²⁹, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli³⁰, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, M. Caprio^{102a,102b}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo¹⁴⁸, C. Caramarcu^{25a}, R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron^{2,h}, S. Caron⁴⁸, C. Carpentieri⁴⁸, G.D. Carrillo Montoya¹⁷², S. Carron Montero¹⁵⁸, A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,i}, D. Casadei¹⁰⁸, M.P. Casado¹¹, M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷², E. Castaneda-Miranda¹⁷², V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124b,a}, G. Cataldi^{72a}, F. Cataneo²⁹, A. Catinaccio²⁹, J.R. Catmore⁷¹, A. Cattai²⁹, G. Cattani^{133a,133b}, S. Caughron³⁴, A. Cavallari^{132a,132b}, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b}, A. Cazzato^{72a,72b}, F. Ceradini^{134a,134b}, C. Cerna⁸³, A.S. Cerqueira^{23a}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷, M. Cervetto^{50a,50b}, S.A. Cetin^{18b}, F. Cevenini^{102a,102b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, K. Chan², J.D. Chapman²⁷, J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁷, S. Cheatham⁷¹, S. Chekanov⁵, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁵, H. Chen²⁴, L. Chen², S. Chen^{32c}, T. Chen^{32c}, X. Chen¹⁷², S. Cheng^{32a}, A. Cheplakov⁶⁵, V.F. Chepurnov⁶⁵, R. Cherkaoui El Moursli^{135d}, V. Tcherniatine²⁴, D. Chesneau^{25a}, E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, F. Chevallier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani⁵¹, J.T. Childers^{58a}, A. Chilingarov⁷¹, G. Chiodini^{72a}, M.V. Chizhov⁶⁵, G. Choudalakis³⁰, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, M.D. Ciobotaru¹⁶³, C. Ciocca^{19a,19b}, A. Ciocio¹⁴, M. Cirilli^{87,j}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, R.W. Clift¹²⁹, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro^{50a,50b}, J. Cochran⁶⁴, P. Coe¹¹⁸, J. Coggeshall¹⁶⁵, E. Cogneras¹⁸⁰, C.D. Cojocar²⁸, J. Colas⁴, A.P. Colijn¹⁰⁵, C. Collard¹¹⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵, G. Colon⁸⁴, R. Coluccia^{72a,72b}, G. Comune⁸⁸, P. Conde Muino^{124a}, E. Coniavitis¹¹⁸, M.C. Conidi¹¹, M. Consonni¹⁰⁴, S. Constantinescu^{25a}, C. Conta^{119a,119b}, F. Conventi^{102a,k}, J. Cook²⁹, M. Cooke³⁴, B.D. Cooper⁷⁵, A.M. Cooper-Sarkar¹¹⁸, N.J. Cooper-Smith⁷⁶, K. Copic³⁴, T. Cornelissen^{50a,50b}, M. Corradi^{19a}, S. Correard⁸³, F. Corriveau^{85,l}, A. Corso-Radu¹⁶³, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹, R. Coura Torres^{23a}, L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸, J. Cranshaw⁵, M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b},

S. Crépé-Renaudin⁵⁵, C. Cuenca Almenar¹⁷⁵, T. Cuhadar Donszelmann¹³⁹, S. Cuneo^{50a,50b}, M. Curatolo⁴⁷, C.J. Curtis¹⁷, P. Cwetanski⁶¹, H. Cziri¹⁴¹, Z. Czyczula¹⁷⁵, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio⁹⁹, A. Da Rocha Gesualdi Mello^{23a}, P.V.M. Da Silva^{23a}, C Da Via⁸², W. Dabrowski³⁷, A. Dahlhoff⁴⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴, S.J. Dallison^{129,*}, J. Dalmau⁷⁵, C.H. Daly¹³⁸, M. Dam³⁵, M. Dameri^{50a,50b}, H.O. Danielsson²⁹, R. Dankers¹⁰⁵, D. Dannheim⁹⁹, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b}, C. Daum¹⁰⁵, J.P. Dauvergne²⁹, W. Davey⁸⁶, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, M. Davies⁹³, A.R. Davison⁷⁷, E. Dawe¹⁴², I. Dawson¹³⁹, J.W. Dawson⁵, R.K. Daya³⁹, K. De⁷, R. de Asmundis^{102a}, S. De Castro^{19a,19b}, P.E. De Castro Faria Salgado²⁴, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, E. De La Cruz-Burelo⁸⁷, C. De La Taille¹¹⁵, B. De Lotto^{164a,164c}, L. De Mora⁷¹, L. De Nooij¹⁰⁵, M. De Oliveira Branco²⁹, D. De Pedis^{132a}, P. de Saintignon⁵⁵, A. De Salvo^{132a}, U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, S. Dean⁷⁷, G. Dedes⁹⁹, D.V. Dedovich⁶⁵, P.O. Defay³³, J. Degenhardt¹²⁰, M. Dehchar¹¹⁸, M. Deile⁹⁸, C. Del Papa^{164a,164c}, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, A. Dell'Acqua²⁹, L. Dell'Asta^{89a,89b}, M. Della Pietra^{102a,m}, D. della Volpe^{102a,102b}, M. Delmastro²⁹, P. Delpierre⁸³, N. Delruelle²⁹, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸, S. Demers¹⁷⁵, M. Demichev⁶⁵, B. Demirkoz¹¹, J. Deng¹⁶³, W. Deng²⁴, S.P. Denisov¹²⁸, C. Dennis¹¹⁸, J.E. Derkaoui^{135c}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²⁰, P.O. Deviveiros¹⁵⁸, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,n}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹, B. Di Girolamo²⁹, S. Di Luise^{134a,134b}, A. Di Mattia⁸⁸, R. Di Nardo^{133a,133b}, A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, M.M. Diaz Gomez⁴⁹, F. Diblen^{18c}, E.B. Diehl⁸⁷, H. Dietl⁹⁹, J. Dietrich⁴⁸, T.A. Dietzsch^{58a}, S. Diglio¹¹⁵, K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a}, F. Dittus²⁹, F. Djama⁸³, R. Djilkibaev¹⁰⁸, T. Djobava⁵¹, M.A.B. do Vale^{23a}, A. Do Valle Wemans^{124a}, T.K.O. Doan⁴, M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos²⁹, E. Dobson²⁹, M. Dobson¹⁶³, J. Dodd³⁴, O.B. Dogan^{18a,*}, C. Doglioni¹¹⁸, T. Doherty⁵³, Y. Doi⁶⁶, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshin⁹⁶, T. Dohmae¹⁵⁵, M. Donega¹²⁰, J. Donini⁵⁵, J. Dopke¹⁷⁴, A. Doria^{102a}, A. Dos Anjos¹⁷², M. Dosil¹¹, A. Dotti^{122a,122b}, M.T. Dova⁷⁰, J.D. Dowell¹⁷, A. Doxiadis¹⁰⁵, A.T. Doyle⁵³, Z. Drasal¹²⁶, J. Drees¹⁷⁴, N. Dressnandt¹²⁰, H. Drevermann²⁹, C. Driouichi³⁵, M. Dris⁹, J.G. Drohan⁷⁷, J. Dubbert⁹⁹, T. Dubbs¹³⁷, S. Dube¹⁴, E. Duchovni¹⁷¹, G. Duckeck⁹⁸, A. Dudarev²⁹, F. Dudziak¹¹⁵, M. Dührssen²⁹, I.P. Duerdoth⁸², L. Dufлот¹¹⁵, M-A. Dufour⁸⁵, M. Dunford²⁹, H. Duran Yildiz^{3b}, R. Duxfield¹³⁹, M. Dwuznik³⁷, F. Dydak²⁹, D. Dzahini⁵⁵, M. Düren⁵², J. Ebke⁹⁸, S. Eckert⁴⁸, S. Eckweiler⁸¹, K. Edmonds⁸¹, C.A. Edwards⁷⁶, I. Efthymiopoulos⁴⁹, W. Ehrenfeld⁴¹, T. Ehrich⁹⁹, T. Eifert²⁹, G. Eigen¹³, K. Einsweiler¹⁴, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi⁴, M. Ellert¹⁶⁶, S. Elles⁴, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹, R. Ely¹⁴, D. Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶², A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, V. Eremimov⁹⁷, D. Eriksson^{146a}, J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, C. Escobar¹⁶⁷, X. Espinal Curull¹¹, B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etiennevire¹³⁶, E. Etzion¹⁵³, H. Evans⁶¹, V.N. Evdokimov¹²⁸, L. Fabbri^{19a,19b}, C. Fabre²⁹, K. Facius³⁵, R.M. Fakhrutdinov¹²⁸, S. Falciano^{132a}, A.C. Falou¹¹⁵, Y. Fang¹⁷², M. Fanti^{89a,89b}, A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S.M. Farrington¹¹⁸, P. Farthouat²⁹, D. Fasching¹⁷², P. Fassnacht²⁹, D. Fassouliotis⁸, B. Fatholahzadeh¹⁵⁸, L. Fayard¹¹⁵, S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a}, O.L. Fedin¹²¹, I. Fedorko²⁹, W. Fedorko²⁹, M. Fehling⁴⁸, L. Feligioni⁸³, C.U. Felzmann⁸⁶, C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, D. Ferguson¹⁷², J. Ferland⁹³, B. Fernandes^{124a,o}, W. Fernando¹⁰⁹, S. Ferrag⁵³, J. Ferrando¹¹⁸, V. Ferrara⁴¹, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, A. Ferrer¹⁶⁷, M.L. Ferrer⁴⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, F. Ferro^{50a,50b}, M. Fiassarini¹¹⁸, F. Fiedler⁸¹, A. Filipčić⁷⁴, A. Filippas⁹, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,i}, L. Fiorini¹¹, A. Firan³⁹, G. Fischer⁴¹, P. Fischer²⁰, M.J. Fisher¹⁰⁹, S.M. Fisher¹²⁹, J. Flammer²⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷³, S. Fleischmann²⁰, T. Flick¹⁷⁴, L.R. Flores Castillo¹⁷², M.J. Flowerdew⁹⁹, F. Föhlich^{58a}, M. Fokitis⁹, T. Fonseca Martin¹⁶, J. Fopma¹¹⁸, D.A. Forbush¹³⁸, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, J.M. Foster⁸², D. Fournier¹¹⁵, A. Foussat²⁹, A.J. Fowler⁴⁴, K. Fowler¹³⁷, H. Fox⁷¹, P. Francavilla^{122a,122b}, S. Franchino^{119a,119b}, D. Francis²⁹, M. Franklin⁵⁷, S. Franz²⁹, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, J. Freestone⁸², S.T. French²⁷, R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa⁵, J. Fuster¹⁶⁷, C. Gabaldon⁸⁰, O. Gabizon¹⁷¹, T. Gadfort²⁴, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea⁹⁸, E.J. Gallas¹¹⁸, M.V. Gallas²⁹, V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, E. Galyaev⁴⁰, K.K. Gan¹⁰⁹, Y.S. Gao^{143,p}, V.A. Gapienko¹²⁸, A. Gaponenko¹⁴, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro⁴⁹, R.W. Gardner³⁰, N. Garelli²⁹, H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, O. Gaumer⁴⁹, P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, J-C. Gayde²⁹, E.N. Gazis⁹, P. Ge^{32d}, C.N.P. Gee¹²⁹, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, M.H. Genest⁹⁸, S. Gentile^{132a,132b}, F. Georgatos⁹, S. George⁷⁶, P. Gerlach¹⁷⁴, A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135d}, P. Ghez⁴, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b}, V. Giakoumopoulou⁸, V. Giangiobbe^{122a,122b}, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson¹¹⁸, G.F. Gieraltowski⁵, L.M. Gilbert¹¹⁸, M. Gilchriese¹⁴, O. Gildemeister²⁹, V. Gilevsky⁹¹, D. Gillberg²⁸,

A.R. Gillman¹²⁹, D.M. Gingrich^{2,g}, J. Ginzburg¹⁵³, N. Giokaris⁸, M.P. Giordani^{164a,164c}, R. Giordano^{102a,102b},
 F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷,
 C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁴, G.L. Glonti⁶⁵, K.G. Gnanvo⁷⁵, J. Godfrey¹⁴²,
 J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷, D. Goldin³⁹,
 T. Golling¹⁷⁵, N.P. Gollub²⁹, S.N. Golovnia¹²⁸, A. Gomes^{124a,r}, L.S. Gomez Fajardo⁴¹, R. Gonçalo⁷⁶, L. Gonella²⁰,
 C. Gong^{32b}, A. Gonidec²⁹, S. Gonzalez¹⁷², S. González de la Hoz¹⁶⁷, M.L. Gonzalez Silva²⁶, B. Gonzalez-Pineiro⁸⁸,
 S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³,
 G. Gorfine¹⁷⁴, B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸, S.A. Gorokhov¹²⁸, B.T. Gorski²⁹,
 V.N. Goryachev¹²⁸, B. Gosdzik⁴¹, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁵, M. Gouanère⁴, I. Gough Eschrich¹⁶³,
 M. Gouighri^{135a}, D. Goujdami^{135a}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸, C. Goy⁴, I. Grabowska-Bold^{163,s},
 V. Grabski¹⁷⁶, P. Grafström²⁹, C. Grah¹⁷⁴, K-J. Grahn¹⁴⁷, F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸,
 V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray^{34,t}, J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, B. Green⁷⁶,
 D. Greenfield¹²⁹, T. Greenshaw⁷³, Z.D. Greenwood^{24,u}, I.M. Gregor⁴¹, P. Grenier¹⁴³, A. Grewal¹¹⁸,
 E. Griesmayer⁴⁶, J. Griffiths¹³⁸, N. Grigalashvili⁶⁵, A.A. Grillo¹³⁷, K. Grimm¹⁴⁸, S. Grinstein¹¹, P.L.Y. Gris³³,
 Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, J. Grognuz²⁹, M. Groh⁹⁹, M. Groll⁸¹, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁴,
 J. Groth-Jensen⁷⁹, M. Gruwe²⁹, K. Grybel¹⁴¹, V.J. Guarino⁵, C. Guicheney³³, A. Guida^{72a,72b}, T. Guillemin⁴,
 H. Guler^{85,v}, B. Guo¹⁵⁸, A. Gupta³⁰, Y. Gusakov⁶⁵, V.N. Gushchin¹²⁸, A. Gutierrez⁹³, P. Gutierrez¹¹¹,
 N. Guttman¹⁵³, O. Gutzwiller¹⁷², C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴,
 G. Haboubi¹²³, R. Hackenburg²⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, C. Haeblerli¹⁶, P. Haefner⁹⁹, R. Härtel⁹⁹,
 F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁶, J. Haller^{41,w}, K. Hamacher¹⁷⁴, A. Hamilton⁴⁹,
 S. Hamilton¹⁶¹, H. Han^{32a}, L. Han^{32b}, K. Hanagaki¹¹⁶, M. Hance¹²⁰, C. Handel⁸¹, P. Hanke^{58a}, C.J. Hansen¹⁶⁶,
 J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵, P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷,
 T. Harenberg¹⁷⁴, R. Harper¹³⁹, R.D. Harrington²¹, O.M. Harris¹³⁸, K. Harrison¹⁷, J.C. Hart¹²⁹, J. Hartert⁴⁸,
 F. Hartjes¹⁰⁵, T. Haruyama⁶⁶, A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, M. Hatch²⁹, D. Hauff⁹⁹,
 S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁸, M. Havranek¹²⁵, B.M. Hawes¹¹⁸, C.M. Hawkes¹⁷, R.J. Hawkins²⁹,
 D. Hawkins¹⁶³, T. Hayakawa⁶⁷, H.S. Hayward⁷³, S.J. Haywood¹²⁹, E. Hazen²¹, M. He^{32d}, S.J. Head¹⁷,
 V. Hedberg⁷⁹, L. Heelan²⁸, S. Heim⁸⁸, B. Heinemann¹⁴, F.E.W. Heinemann¹¹⁸, S. Heisterkamp³⁵, L. Helary⁴,
 M. Heldmann⁴⁸, M. Heller¹¹⁵, S. Hellman^{146a,146b}, C. Helsens¹¹, T. Hemperek²⁰, R.C.W. Henderson⁷¹,
 P.J. Hendriks¹⁰⁵, M. Henke^{58a}, A. Henrichs⁵⁴, A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵,
 F. Henry-Couannier⁸³, C. Hensel⁵⁴, T. Henß¹⁷⁴, Y. Hernández Jiménez¹⁶⁷, A.D. Hershenhorn¹⁵², G. Herten⁴⁸,
 R. Hertenberger⁹⁸, L. Hervas²⁹, N.P. Hessey¹⁰⁵, A. Hidvegi^{146a}, E. Higón-Rodríguez¹⁶⁷, D. Hill^{5,*}, J.C. Hill²⁷,
 N. Hill⁵, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, D. Hindson¹¹⁸, E. Hines¹²⁰, M. Hirose¹¹⁶,
 F. Hirsch⁴², D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹,
 M.R. Hoefkamp¹⁰³, J. Hoffman³⁹, D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, T.I. Hollins¹⁷, G. Hollyman⁷⁶,
 A. Holmes¹¹⁸, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, R.J. Homer¹⁷, Y. Homma⁶⁷, T. Horazdovsky¹²⁷,
 C. Horn¹⁴³, S. Horner⁴⁸, S. Horvat⁹⁹, J.-Y. Hostachy⁵⁵, T. Hott⁹⁹, S. Hou¹⁵¹, M.A. Houlden⁷³, A. Houmada^{135a},
 D.F. Howell¹¹⁸, J. Hrivnac¹¹⁵, I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu¹⁷⁵, S.-C. Hsu¹⁴, G.S. Huang¹¹¹, Z. Hubacek¹²⁷,
 F. Hubaut⁸³, F. Huegging²⁰, T.B. Huffman¹¹⁸, E.W. Hughes³⁴, G. Hughes⁷¹, R.E. Hughes-Jones⁸², M. Huhtinen²⁹,
 P. Hurst⁵⁷, M. Hurwitz³⁰, U. Husemann⁴¹, N. Huseynov¹⁰, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci^{102a}, G. Iakovidis⁹,
 M. Ibbotson⁸², I. Ibragimov¹⁴¹, R. Ichimiya⁶⁷, L. Iconomidou-Fayard¹¹⁵, J. Idarraga^{159b}, M. Idzik³⁷, P. Iengo⁴,
 O. Igonkina¹⁰⁵, Y. Ikegami⁶⁶, M. Ikeno⁶⁶, Y. Ilchenko³⁹, D. Iliadis¹⁵⁴, D. Imbault⁷⁸, M. Imhaeuser¹⁷⁴, M. Imori¹⁵⁵,
 T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{134a}, G. Ionescu⁴, A. Irls Quiles¹⁶⁷, K. Ishii⁶⁶, A. Ishikawa⁶⁷,
 M. Ishino⁶⁶, R. Ishmukhametov³⁹, T. Isobe¹⁵⁵, V. Issakov^{175,*}, C. Issever¹¹⁸, S. Istin^{18a}, Y. Itoh¹⁰¹, A.V. Ivashin¹²⁸,
 W. Iwanski³⁸, H. Iwasaki⁶⁶, J.M. Izen⁴⁰, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹,
 M. Jahoda¹²⁵, V. Jain⁶¹, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jankowski¹⁵⁸, E. Jansen⁷⁷,
 A. Jantsch⁹⁹, M. Janus²⁰, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, K. Jelen³⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴,
 P. Jež³⁵, S. Jézéquel⁴, H. Ji¹⁷², W. Ji⁷⁹, J. Jia¹⁴⁸, Y. Jiang^{32b}, M. Jimenez Belenguer²⁹, G. Jin^{32b}, S. Jin^{32a},
 O. Jinnouchi¹⁵⁷, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹,
 S. Johnert⁴¹, K.A. Johns⁶, K. Jon-And^{146a,146b}, G. Jones⁸², M. Jones¹¹⁸, R.W.L. Jones⁷¹, T.W. Jones⁷⁷,
 T.J. Jones⁷³, O. Jonsson²⁹, K.K. Joo^{158,x}, D. Joos⁴⁸, C. Joram²⁹, P.M. Jorge^{124a,c}, S. Jorgensen¹¹, J. Joseph¹⁴,
 V. Juranek¹²⁵, P. Jussel⁶², V.V. Kabachenko¹²⁸, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarzka³⁸, P. Kadlecik³⁵,
 M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, S. Kaiser⁹⁹, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁴, L.V. Kalinovskaya⁶⁵,
 S. Kama⁴¹, N. Kanaya¹⁵⁵, M. Kaneda¹⁵⁵, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁶, B. Kaplan¹⁷⁵, A. Kapliy³⁰, J. Kaplon²⁹,
 D. Kar⁴³, M. Karagounis²⁰, M. Karagoz Unel¹¹⁸, M. Karnevskiy⁴¹, K. Karr⁵, V. Kartvelishvili⁷¹,
 A.N. Karyukhin¹²⁸, L. Kashif⁵⁷, A. Kasmi³⁹, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kastoryano¹⁷⁵, M. Kataoka⁴,
 Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁷, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹,

M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁵, S.I. Kazi⁸⁶, J.R. Keates⁸², R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁵, M. Kelly⁸², J. Kennedy⁹⁸, C.J. Kenney¹⁴³, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁴, K. Kessoku¹⁵⁵, C. Ketterer⁴⁸, M. Khakzad²⁸, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁵, A. Khodinov¹⁴⁸, A.G. Kholodenko¹²⁸, A. Khomich^{58a}, G. Khorauli²⁰, N. Khovanskiy⁶⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁵, J. Khubua⁵¹, G. Kilvington⁷⁶, H. Kim⁷, M.S. Kim², P.C. Kim¹⁴³, S.H. Kim¹⁶⁰, N. Kimura¹⁷⁰, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁷, J. Kirk¹²⁹, G.P. Kirsch¹¹⁸, L.E. Kirsch²², A.E. Kiryumin⁹⁹, D. Kisielewska³⁷, B. Kisielewski³⁸, T. Kittelmann¹²³, A.M. Kiver¹²⁸, H. Kiyamura⁶⁷, E. Kladiva^{144b}, J. Klaiber-Lodewigs⁴², M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷¹, A. Klimentov²⁴, R. Klingenberg⁴², E.B. Klinkby⁴⁴, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, N.S. Knecht¹⁵⁸, E. Kneringer⁶², J. Knobloch²⁹, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, B. Koblitz²⁹, M. Kocian¹⁴³, A. Kocnar¹¹³, P. Kodys¹²⁶, K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, S. König⁴⁸, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁹, E. Koffeman¹⁰⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁶, T. Koj¹⁴³, T. Kokott²⁰, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁵, I. Koletsou⁴, J. Koll⁸⁸, D. Kollar²⁹, M. Kollefrath⁴⁸, S.D. Kolya⁸², A.A. Komar⁹⁴, J.R. Komaragiri¹⁴², T. Kondo⁶⁶, T. Kono^{41,y}, A.I. Kononov⁴⁸, R. Konoplich¹⁰⁸, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁴, S. Koperny³⁷, S.V. Kopikov¹²⁸, K. Korcyl³⁸, K. Kordas¹⁵⁴, V. Koreshev¹²⁸, A. Korn¹⁴, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, P. Kostka⁴¹, V.V. Kostyukhin²⁰, M.J. Kotamäki²⁹, S. Kotov⁹⁹, V.M. Kotov⁶⁵, C. Kourkoumelis⁸, A. Koutsman¹⁰⁵, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, O. Krasel⁴², M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, A. Kreisel¹⁵³, F. Krejci¹²⁷, J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, G. Krobath⁹⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁵, H. Krüger²⁰, Z.V. Krumshteyn⁶⁵, A. Kruth²⁰, T. Kubota¹⁵⁵, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl¹⁷⁴, D. Kuhn⁶², V. Kukhtin⁶⁵, Y. Kulchitsky⁹⁰, S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁸³, N. Kundu¹¹⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁷, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, W. Kuykendall¹³⁸, M. Kuze¹⁵⁷, P. Kuzhir⁹¹, O. Kvasnicka¹²⁵, R. Kwee¹⁵, A. La Rosa²⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁵, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, M. Lamanna²⁹, M. Lambacher⁹⁸, C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, H. Landsman¹⁵², J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzsch²⁹, A. Lanza^{119a}, V.V. Lapin^{128,*}, S. Laplace⁴, C. Lapoire⁸³, J.F. Laporte¹³⁶, T. Lari^{89a}, A.V. Larionov¹²⁸, A. Lerner¹¹⁸, C. Lasseur²⁹, M. Lassnig²⁹, W. Lau¹¹⁸, P. Laurelli⁴⁷, A. Lavorato¹¹⁸, W. Lavrijsen¹⁴, P. Laycock⁷³, A.B. Lazarev⁶⁵, A. Lazzaro^{89a,89b}, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹³⁶, M. Leahu²⁹, A. Lebedev⁶⁴, C. Lebel⁹³, M. Lechowski¹¹⁵, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹⁵⁰, S.C. Lee¹⁵¹, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, A. Leger⁴⁹, B.C. LeGeyt¹²⁰, F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, M. Lehto¹³⁹, X. Lei⁶, R. Leitner¹²⁶, D. Lellouch¹⁷¹, J. Lellouch⁷⁸, M. Leltchouk³⁴, V. Lendermann^{58a}, K.J.C. Leney⁷³, T. Lenz¹⁷⁴, G. Lenzen¹⁷⁴, B. Lenzi¹³⁶, K. Leonhardt⁴³, J. Lepidis¹⁷⁴, C. Leroy⁹³, J-R. Lessard¹⁶⁹, J. Lesser^{146a}, C.G. Lester²⁷, A. Leung Fook Cheong¹⁷², J. Levêque⁸³, D. Levin⁸⁷, L.J. Levinson¹⁷¹, M.S. Levitski¹²⁸, M. Lewandowska²¹, M. Leyton¹⁵, H. Li¹⁷², X. Li⁸⁷, Z. Liang³⁹, Z. Liang^{118,z}, B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹⁷³, R. Lifshitz¹⁵², J.N. Lilley¹⁷, H. Lim⁵, A. Limosani⁸⁶, M. Limper⁶³, S.C. Lin¹⁵¹, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, L. Lipinsky¹²⁵, A. Lipniacka¹³, T.M. Liss¹⁶⁵, D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu^{151,aa}, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, S. Liu², Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, S. Lockwitz¹⁷⁵, T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁵, C.W. Loh¹⁶⁸, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, J. Loken¹¹⁸, R.E. Long⁷¹, L. Lopes^{124a,c}, D. Lopez Mateos^{34,ab}, M. Losada¹⁶², P. Loscutoff¹⁴, M.J. Losty^{159a}, X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², L. Lovas^{144a}, J. Love²¹, P.A. Love⁷¹, A.J. Lowe¹⁴³, F. Lu^{32a}, J. Lu², L. Lu³⁹, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶¹, G. Luijckx¹⁰⁵, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹, J. Lundberg²⁹, J. Lundquist³⁵, A. Lupi^{122a,122b}, G. Lutz⁹⁹, D. Lynn²⁴, J. Lynn¹¹⁸, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷², M. Maaßen⁴⁸, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a,c}, D. Macina⁴⁹, R. Mackeprang³⁵, D. MacQueen², R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁴, S. Mättig⁴¹, P.J. Magalhaes Martins^{124a,i}, L. Magnoni²⁹, E. Magradze⁵¹, C.A. Magrath¹⁰⁴, Y. Mahalalel¹⁵³, K. Mahboubi⁴⁸, A. Mahmood¹, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a}, A. Maio^{124a,r}, S. Majewski²⁴, Y. Makida⁶⁶, M. Makouski¹²⁸, N. Makovec¹¹⁵, P. Mal⁶, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶³, D. Malon⁵, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov⁶⁵, R. Mameghani⁹⁸, J. Mamuzic⁴¹, A. Manabe⁶⁶, A. Manara⁶¹, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangeard⁸⁸, M. Mangin-Brinet⁴⁹, I.D. Manjavidze⁶⁵, A. Mann⁵⁴, W.A. Mann¹⁶¹, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Manz⁹⁹, A. Mapelli²⁹,

L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand⁴, F. Marchese^{133a,133b}, M. Marchesotti²⁹, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, A. Marin^{21,*}, C.P. Marino⁶¹, F. Marroquim^{23a}, R. Marshall⁸², Z. Marshall^{34,ab}, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, A.J. Martin⁷⁵, B. Martin²⁹, B. Martin⁸⁸, F.F. Martin¹²⁰, J.P. Martin⁹³, Ph. Martin⁵⁵, T.A. Martin¹⁷, B. Martin dit Latour⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷, A.C. Martyniuk⁸², F. Marzano^{132a}, A. Marzin¹³⁶, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, M. Maß⁴², I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, M. Mathes²⁰, P. Matricon¹¹⁵, H. Matsumoto¹⁵⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁷, C. Mattravers^{118,ac}, J.M. Maugain²⁹, S.J. Maxfield⁷³, E.N. May⁵, J.K. Mayer¹⁵⁸, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰, E. Mazzoni^{122a,122b}, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶, S. McGarvie⁷⁶, H. McGlone⁵³, G. Mchedlize⁵¹, R.A. McLaren²⁹, S.J. McMahon¹²⁹, T.R. McMahon⁷⁶, T.J. McMahon¹⁷, R.A. McPherson^{169,l}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁴, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T.M. Meguro¹¹⁶, R. Mehdiyev⁹³, S. Mehlhase⁴¹, A. Mehta⁷³, K. Meier^{58a}, J. Meinhardt⁴⁸, B. Meirose⁴⁸, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷², L. Mendoza Navas¹⁶², Z. Meng^{151,ad}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹, C. Menot²⁹, E. Meoni¹¹, D. Merkl⁹⁸, P. Mermod¹¹⁸, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰, A.M. Messina²⁹, I. Messmer⁴⁸, J. Metcalfe¹⁰³, A.S. Mete⁶⁴, S. Meuser²⁰, C. Meyer⁸¹, J-P. Meyer¹³⁶, J. Meyer¹⁷³, J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶⁴, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹, P. Miele²⁹, S. Migas⁷³, A. Migliaccio^{102a,102b}, L. Mijović⁴¹, G. Mikenberg¹⁷¹, M. Mikestikova¹²⁵, B. Mikulec⁴⁹, M. Mikuz⁷⁴, D.W. Miller¹⁴³, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, D. Milstein¹⁷¹, S. Mima¹¹⁰, A.A. Minaenko¹²⁸, M. Miñano¹⁶⁷, I.A. Minashvili⁶⁵, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁵, Y. Ming¹³⁰, L.M. Mir¹¹, G. Mirabelli^{132a}, L. Miralles Verge¹¹, S. Misawa²⁴, A. Misiejuk⁷⁶, A. Mitra¹¹⁸, J. Mitrevski¹³⁷, G.Y. Mitrofanov¹²⁸, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁶, P.S. Miyagawa⁸², K. Miyazaki⁶⁷, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, M. Moch^{132a,132b}, P. Mockett¹³⁸, S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, B. Mohn¹³, W. Mohr⁴⁸, S. Mohrdieck-Möck⁹⁹, A.M. Moiseev^{128,*}, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, L. Moneta⁴⁹, J. Monk⁷⁷, E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰, R.W. Moore², G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, A. Morais^{124a,c}, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹, M. Moreno Llacer¹⁶⁷, P. Morettini^{50a}, D. Morgan¹³⁹, M. Morii⁵⁷, J. Morin⁷⁵, Y. Morita⁶⁶, A.K. Morley²⁹, G. Mornacchi²⁹, M-C. Morone⁴⁹, J.D. Morris⁷⁵, H.G. Moser⁹⁹, M. Mosidze⁵¹, J. Moss¹⁰⁹, A. Moszczynski³⁸, R. Mount¹⁴³, E. Mountricha⁹, S.V. Mouraviev⁹⁴, T.H. Moyer¹⁷, E.J.W. Moyses⁸⁴, M. Mudrinic^{12b}, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰, T.A. Müller⁹⁸, D. Muenstermann⁴², A. Muijs¹⁰⁵, A. Muir¹⁶⁸, A. Mumar¹²⁰, Y. Munwes¹⁵³, K. Murakami⁶⁶, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁶, Y. Nagasaka⁶⁰, A.M. Nairz²⁹, D. Naito¹¹⁰, K. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, M. Nash^{77,ae}, I. Nasteva⁸², N.R. Nation²¹, T. Nattermann²⁰, T. Naumann⁴¹, F. Nauyock⁸², G. Navarro¹⁶², H.A. Neal⁸⁷, E. Nebot⁸⁰, P. Nechaeva⁹⁴, A. Negri^{119a,119b}, G. Negri²⁹, S. Negroni³⁴, A. Nelson⁶⁴, S. Nelson¹⁴³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi²⁹, S.Y. Nesterov¹²¹, M.S. Neubauer¹⁶⁵, L. Neukermans⁴, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, C. Nicholson⁵³, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, G. Nicoletti⁴⁷, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, T. Niinikoski²⁹, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, K. Nikolaev⁶⁵, I. Nikolic-Audit⁷⁸, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁷, R. Nisius⁹⁹, L. Nodulman⁵, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, H. Nomoto¹⁵⁵, M. Nordberg²⁹, B. Nordkvist^{146a,146b}, O. Norniella Francisco¹¹, P.R. Norton¹²⁹, D. Notz⁴¹, J. Novakova¹²⁶, M. Nozaki⁶⁶, M. Nožička⁴¹, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Haninger²⁰, T. Nunnemann⁹⁸, E. Nurse⁷⁷, T. Nyman²⁹, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, F.G. Oakham^{28,h}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁷, S. Oda¹⁵⁵, S. Odaka⁶⁶, J. Odier⁸³, G.A. Odino^{50a,50b}, H. Ogren⁶¹, A. Oh⁸², S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, H. Ohshita¹⁴⁰, T.K. Ohska⁶⁶, T. Ohsugi⁵⁹, S. Okada⁶⁷, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵, M. Olcese^{50a}, A.G. Olchevski⁶⁵, M. Oliveira^{124a,i}, D. Oliveira Damazio²⁴, C. Oliver⁸⁰, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, C. Omachi^{67,af}, A. Onofre^{124a,ag}, P.U.E. Onyisi³⁰, C.J. Oram^{159a}, G. Ordóñez¹⁰⁴, M.J. Oreglia³⁰, F. Orellana⁴⁹, Y. Oren¹⁵³, D. Orestano^{134a,134b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, E.O. Ortega¹³⁰, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁵, B. Ottewell¹¹⁸, M. Ouchrif^{135c}, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a}, M. Owen⁸², S. Owen¹³⁹, A. Oyarzun^{31b}, O.K. Øye¹³, V.E. Ozcan⁷⁷, K. Ozone⁶⁶, N. Ozturk⁷, A. Pacheco Pages¹¹, C. Padilla Aranda¹¹, E. Paganis¹³⁹, C. Pahl⁶³, F. Paige²⁴, K. Pajchel¹¹⁷, S. Palestini²⁹, J. Palla²⁹, D. Pallin³³, A. Palma^{124a,c}, J.D. Palmer¹⁷, M.J. Palmer²⁷, Y.B. Pan¹⁷², E. Panagiotopoulou⁹, B. Panes^{31a}, N. Panikashvili⁸⁷, V.N. Panin¹⁰⁷, S. Panitkin²⁴, D. Pantea^{25a}, M. Panuskova¹²⁵, V. Paolone¹²³, A. Paoloni^{133a,133b}, Th.D. Papadopoulou⁹, A. Paramonov⁵, S.J. Park⁵⁴, W. Park^{24,ah}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸, E. Pasqualucci^{132a}, A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore²⁹, G. Pásztor^{49,ai}, S. Patariaia¹⁷², N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsý^{144a}, M.I. Pedraza Morales¹⁷², S.J.M. Peeters¹⁰⁵, S.V. Peleganchuk¹⁰⁷, H. Peng¹⁷², R. Pengo²⁹, A. Penson³⁴, J. Penwell⁶¹,

M. Perantoni^{23a}, K. Perez^{34,ab}, E. Perez Codina¹¹, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, I. Peric²⁰, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴, S. Persembe^{3a}, P. Perus¹¹⁵, V.D. Peshekhonov⁶⁵, E. Peteret⁵, O. Peters¹⁰⁵, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁸³, C. Petridou¹⁵⁴, E. Petrollo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, B. Pfeifer⁴⁸, A. Phan⁸⁶, A.W. Phillips²⁷, G. Piacquadio²⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b}, A. Pickford⁵³, R. Piegai²⁶, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,r}, M. Pinamonti^{164a,164c}, J.L. Pinfeld², J. Ping^{32c}, B. Pinto^{124a,c}, O. Pirotte²⁹, C. Pizio^{89a,89b}, R. Placakyte⁴¹, M. Plamondon¹⁶⁹, W.G. Plano⁸², M.-A. Pleier²⁴, A.V. Pleskach¹²⁸, A. Poblaguev¹⁷⁵, S. Poddar^{58a}, F. Podlyski³³, L. Poggioli¹¹⁵, T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio¹³⁸, A. Polini^{19a}, J. Poll⁷⁵, V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, R. Popescu²⁴, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso⁴⁸, R. Porter¹⁶³, C. Posch²¹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷, M. Potekhin²⁴, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter⁸⁵, K.P. Potter⁸², G. Poulard²⁹, J. Poveda¹⁷², R. Prabhu²⁰, P. Pralavorio⁸³, S. Prasad⁵⁷, M. Prata^{119a,119b}, R. Pravahan⁷, K. Pretzl¹⁶, L. Pribyl²⁹, D. Price⁶¹, L.E. Price⁵, M.J. Price²⁹, P.M. Prichard⁷³, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev²⁹, F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³, H. Przysieszniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴, J. Purdham⁸⁷, M. Purohit^{24,aj}, P. Puzo¹¹⁵, Y. Pylypchenko¹¹⁷, M. Qi^{32c}, J. Qian⁸⁷, W. Qian¹²⁹, Z. Qian⁸³, Z. Qin⁴¹, A. Quadri⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷², F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radeka²⁴, V. Radescu^{58b}, B. Radics²⁰, T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁸⁰, A.M. Rahimi¹⁰⁹, C. Raine^{53,*}, B. Raith²⁰, S. Rajagopalan²⁴, S. Rajek⁴², M. Rammensee⁴⁸, M. Rammes¹⁴¹, M. Ramstedt^{146a,146b}, P.N. Ratoff⁷¹, F. Rauscher⁹⁸, E. Rauter⁹⁹, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuffi^{119a,119b}, A. Redelbach¹⁷³, G. Redlinger²⁴, R. Reece¹²⁰, K. Reeves⁴⁰, A. Reichold¹⁰⁵, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², D. Reljic^{12a}, C. Rembser²⁹, Z.L. Ren¹⁵¹, P. Renkel³⁹, B. Rensch³⁵, S. Rescia²⁴, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek¹²⁶, R. Rezvani¹⁵⁸, A. Richards⁷⁷, R. Richter⁹⁹, E. Richter-Was^{38,ak}, M. Ridel⁷⁸, S. Rieke⁸¹, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, D.A. Roa Romero¹⁶², S.H. Robertson^{85,l}, A. Robichaud-Veronneau⁴⁹, D. Robinson²⁷, JEM Robinson⁷⁷, M. Robinson¹¹⁴, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, S. Rodier⁸⁰, D. Rodriguez¹⁶², Y. Rodriguez Garcia¹⁵, S. Roe²⁹, O. Røhne¹¹⁷, V. Rojo¹, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, V.M. Romanov⁶⁵, G. Romeo²⁶, D. Romero Maltrana^{31a}, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati¹³⁸, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶⁴, P.L. Rosendahl¹³, L. Rossetlet⁴⁹, V. Rossetti¹¹, L.P. Rossi^{50a}, L. Rossi^{89a,89b}, M. Rotaru^{25a}, J. Rothberg¹³⁸, I. Rottländer²⁰, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan¹¹⁵, B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, G. Rudolph⁶², F. Rühr⁶, A. Ruiz-Martinez⁶⁴, E. Rulikowska-Zarebska³⁷, V. Rumiantsev^{91,*}, L. Rumyantsev⁶⁵, K. Runge⁴⁸, O. Runolfsson²⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵, D.R. Rust⁶¹, J.P. Rutherford⁶, C. Ruwiedel²⁰, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, V. Ryadovikov¹²⁸, P. Ryan⁸⁸, G. Rybkin¹¹⁵, S. Rzaeva¹⁰, A.F. Saavedra¹⁵⁰, H.F.W. Sadrozinski¹³⁷, R. Sadykov⁶⁵, F. Safai Tehrani^{132a,132b}, H. Sakamoto¹⁵⁵, P. Sala^{89a}, G. Salamanna¹⁰⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, O. Saltó Bauza¹¹, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salvucci⁴⁷, A. Salzburger²⁹, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁴, P. Sandhu¹⁵⁸, T. Sandoval²⁷, R. Sandstroem¹⁰⁵, S. Sandvoss¹⁷⁴, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a,r}, T. Sarangi¹⁷², E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁴, O. Sasaki⁶⁶, T. Sasaki⁶⁶, N. Sasao⁶⁸, I. Satsounkevitch⁹⁰, G. Sauvage⁴, P. Savard^{158,h}, A.Y. Savine⁶, V. Savinov¹²³, P. Savva⁹, L. Sawyer^{24,al}, D.H. Saxon⁵³, L.P. SAYS³³, C. Sbarra^{19a,19b}, A. Sbrizzi^{19a,19b}, O. Scallion⁹³, D.A. Scannicchio²⁹, J. Schaarschmidt⁴³, P. Schacht⁹⁹, U. Schäfer⁸¹, S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, M. Schaller²⁹, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer¹⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁹, M. Schioppa^{36a,36b}, S. Schlenker²⁹, J.L. Schlereth⁵, E. Schmidt⁴⁸, M.P. Schmidt^{175,*}, K. Schmieden²⁰, C. Schmitt⁸¹, M. Schmitz²⁰, R.C. Scholte¹⁰⁵, A. Schönig^{58b}, M. Schott²⁹, D. Schouten¹⁴², J. Schovancova¹²⁵, M. Schram⁸⁵, A. Schreiner⁶³, C. Schroeder⁸¹, N. Schroer^{58c}, M. Schroers¹⁷⁴, D. Schroff⁴⁸, S. Schuh²⁹, G. Schuler²⁹, J. Schultes¹⁷⁴, H.-C. Schultz-Coulon^{58a}, J.W. Schumacher⁴³, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, D. Schweiger²⁹, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³, J. Schwindling¹³⁶, W.G. Scott¹²⁹, J. Searcy¹¹⁴, E. Sedykh¹²¹, E. Segura¹¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, R. Seuster⁹⁹, H. Severini¹¹¹, M.E. Sevir⁸⁶, A. Sfyrta¹⁶⁵, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵, L. Shaver⁶, C. Shaw⁵³, K. Shaw¹³⁹, D. Sherman²⁹, P. Sherwood⁷⁷, A. Shibata¹⁰⁸, P. Shield¹¹⁸, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, A. Shmeleva⁹⁴, M.J. Shochet³⁰, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti¹⁵, A. Siebel¹⁷⁴, M. Siebel²⁹, F. Siegert⁷⁷, J. Siegrist¹⁴, Dj. Sijacki^{12a}, O. Silbert¹⁷¹, J. Silva^{124a,am}, Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, M. Simonyan³⁵, P. Sinervo¹⁵⁸,

N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa⁸¹, A.N. Sisakyan⁶⁵, S.Yu. Sivoklokov⁹⁷, J. Sjoelin^{146a,146b}, T.B. Sjrursen¹³, L.A. Skinnari¹⁴, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, N. Skvorodnev²², M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, T.J. Sloan⁷¹, J. Sloper²⁹, V. Smakhtin¹⁷¹, S.Yu. Smirnov⁹⁶, Y. Smirnov²⁴, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, J. Snuverink¹⁰⁵, S. Snyder²⁴, M. Soares^{124a}, R. Sobie^{169,l}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, J. Sondericker²⁴, N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sorbi^{89a,89b}, M. Sosebee⁷, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spano³⁴, P. Speckmayer²⁹, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, E. Spiriti^{134a}, R. Spiwoks²⁹, L. Spogli^{134a,134b}, M. Spousta¹²⁶, T. Spreitzer¹⁴², B. Spurlock⁷, R.D. St. Denis⁵³, T. Stahl¹⁴¹, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka²⁹, R.W. Stanek⁵, C. Stanescu^{134a}, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁹¹, A. Staude⁹⁸, P. Stavina^{144a}, G. Stavropoulos¹⁴, G. Steele⁵³, E. Stefanidis⁷⁷, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁴¹, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², K. Stevenson⁷⁵, G.A. Stewart⁵³, W. Stiller⁹⁹, T. Stockmanns²⁰, M.C. Stockton²⁹, M. Stodulski³⁸, K. Stoerig⁴⁸, G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg⁸⁷, S. Strandberg¹⁴, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷³, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹, J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, P. Sturm¹⁷⁴, D.A. Soh^{151,an}, D. Su¹⁴³, S. Subramania⁶¹, Y. Sugaya¹¹⁶, T. Sugimoto¹⁰¹, C. Suhr¹⁰⁶, K. Suita⁶⁷, M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{3d}, T. Sumida²⁹, X.H. Sun^{32d}, J.E. Sundermann⁴⁸, K. Suruliz^{164a,164b}, S. Sushkov¹¹, G. Susinno^{36a,36b}, M.R. Sutton¹³⁹, Y. Suzuki⁶⁶, Yu.M. Sviridov¹²⁸, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶, R.R. Szczygiel³⁸, B. Szeless²⁹, T. Szymocha³⁸, J. Sánchez¹⁶⁷, D. Ta²⁰, S. Taboada Gameiro²⁹, K. Tackmann²⁹, A. Taffard¹⁶³, R. Tafirout^{159a}, A. Taga¹¹⁷, Y. Takahashi¹⁰¹, H. Takai²⁴, R. Takashima⁶⁹, H. Takeda⁶⁷, T. Takeshita¹⁴⁰, M. Talby⁸³, A. Talyshev¹⁰⁷, M.C. Tamssett⁷⁶, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁶, Y. Tanaka¹⁰⁰, K. Tani⁶⁷, G.P. Tappern²⁹, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁴, G.F. Tartarelli^{89a}, P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarikhanov¹⁴, C. Taylor⁷⁷, F.E. Taylor⁹², G. Taylor¹³⁷, G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, Y.D. Tennenbaum-Katan¹⁵², S. Terada⁶⁶, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Terwort^{41,w}, M. Testa⁴⁷, R.J. Teuscher^{158,l}, C.M. Tevlin⁸², J. Thadome¹⁷⁴, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸, M. Thioye¹⁷⁵, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson⁸⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, R.J. Thompson⁸², A.S. Thompson⁵³, E. Thomson¹²⁰, R.P. Thun⁸⁷, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov¹⁰⁷, C.J.W.P. Timmermans¹⁰⁴, P. Tipton¹⁷⁵, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, J. Tobias⁴⁸, B. Toczec³⁷, T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁶, S. Tokár^{144a}, K. Tokunaga⁶⁷, K. Tokushuku⁶⁶, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins¹⁴, K. Toms¹⁰³, A. Tonazzo^{134a,134b}, G. Tong^{32a}, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁵, I. Torchiani²⁹, E. Torrence¹¹⁴, E. Torró Pastor¹⁶⁷, J. Toth^{83,ai}, F. Touchard⁸³, D.R. Tovey¹³⁹, D. Traynor⁷⁵, T. Trefzger¹⁷³, J. Treis²⁰, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvoid⁷⁸, T.N. Trinh⁷⁸, M.F. Tripiana⁷⁰, N. Triplett⁶⁴, W. Trischuk¹⁵⁸, A. Trivedi^{24,ao}, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trotter-McDonald¹⁴², A. Trzupek³⁸, C. Tsarouchas⁹, J.C-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiareshka⁹⁰, D. Tsiou¹³⁹, G. Tsipolitis⁹, V. Tsiskaridze⁵¹, E.G. Tskhadadze⁵¹, I.I. Tsukerman⁹⁵, V. Tsulaia¹²³, J.-W. Tsung²⁰, S. Tsuno⁶⁶, D. Tsybychev¹⁴⁸, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, P.M. Tuts³⁴, M.S. Twomey¹³⁸, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, D. Typaldos¹⁷, H. Tyrvaainen²⁹, E. Tzamarioudaki⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Uglan¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, D.G. Underwood⁵, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁶, D. Urbaniec³⁴, E. Urkovsky¹⁵³, P. Urquijo^{49,ap}, P. Urrejola^{31a}, G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, C. Valderanis⁹⁹, J. Valenta¹²⁵, P. Valente^{132a}, S. Valentinetti^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster²⁹, B. Van Eijk¹⁰⁵, N. van Eldik⁸⁴, P. van Gemmeren⁵, Z. van Kesteren¹⁰⁵, I. van Vulpen¹⁰⁵, W. Vandelli²⁹, G. Vandoni²⁹, A. Vaniachine⁵, P. Vankov⁷³, F. Vannucci⁷⁸, F. Varela Rodriguez²⁹, R. Vari^{132a}, E.W. Varnes⁶, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, C. Vellidis⁸, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura¹³⁸, S. Ventura⁴⁷, M. Venturi⁴⁸, N. Venturi¹⁶, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, L. Vertogardov¹¹⁸, M.C. Vetterli^{142,h}, I. Vichou¹⁶⁵, T. Vickey^{145b,aq}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, E.G. Villani¹²⁹, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincter²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁵, M. Virchaux^{136,*}, S. Viret³³, J. Virzi¹⁴, A. Vitale^{19a,19b}, O. Vitells¹⁷¹, I. Vivarelli⁴⁸, F. Vives Vaque¹¹, S. Vlachos⁹, M. Vlasak¹²⁷, N. Vlasov²⁰, A. Vogel²⁰, H. Vogt⁴¹, P. Vokac¹²⁷, M. Volpi¹¹, G. Volpini^{89a}, H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶, A.P. Vorobiev¹²⁸, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁴, J.H. Vosseveld⁷³, A.S. Vovenko¹²⁸, N. Vranjes^{12a}, M. Vranjes Milosavljevic^{12a}, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁸¹, D. Vudragovic^{12a},

R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁴, P. Wagner¹²⁰, H. Wahlen¹⁷⁴, J. Walbersloh⁴², J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁵, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷², J. Wang^{32d}, J.C. Wang¹³⁸, S.M. Wang¹⁵¹, A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸, R. Wastie¹¹⁸, P.M. Watkins¹⁷, A.T. Watson¹⁷, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M. Weber⁴⁸, J. Weber⁴², M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²², H.P. Wellisch^{159a}, P.S. Wells²⁹, T. Wenaus²⁴, Z. Weng^{151,ar}, T. Wengler⁸², S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, U. Werthenbach¹⁴¹, M. Wessels^{58a}, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, S.P. Whitaker²¹, A. White⁷, M.J. White²⁷, S. White²⁴, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶¹, F. Wicek¹¹⁵, D. Wicke⁸¹, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷², M. Wielers¹²⁹, P. Wienemann²⁰, C. Wiglesworth⁷³, L.A.M. Wiik⁴⁸, A. Wildauer¹⁶⁷, M.A. Wildt^{41,w}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, E. Woehrling¹⁷, M.W. Wolter³⁸, H. Wolters^{124a,i}, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸⁴, K. Wraight⁵³, C. Wright⁵³, D. Wright¹⁴³, B. Wrona⁷³, S.L. Wu¹⁷², X. Wu⁴⁹, J. Wuestenfeld⁴², E. Wulf³⁴, R. Wunstorff⁴², B.M. Wynne⁴⁵, L. Xaplanteris⁹, S. Xella³⁵, S. Xie⁴⁸, Y. Xie^{32a}, C. Xu^{32b}, D. Xu¹³⁹, G. Xu^{32a}, B. Yabsley¹⁵⁰, M. Yamada⁶⁶, A. Yamamoto⁶⁶, K. Yamamoto⁶⁴, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁷, Z. Yan²¹, H. Yang⁸⁷, S. Yang¹¹⁸, U.K. Yang⁸², Y. Yang⁶¹, Y. Yang^{32a}, Z. Yang^{146a,146b}, W-M. Yao¹⁴, Y. Yao¹⁴, Y. Yasu⁶⁶, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosofmiya¹²³, K. Yorita¹⁷⁰, R. Yoshida⁵, C. Young¹⁴³, S.P. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu^{32c,as}, J. Yuan⁹⁹, L. Yuan^{32a,at}, A. Yurkewicz¹⁴⁸, V.G. Zaets¹²⁸, R. Zaidan⁶³, A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, Yo.K. Zalite¹²¹, V. Zambrano⁴⁷, L. Zanello^{132a,132b}, P. Zarzhitsky³⁹, A. Zaytsev¹⁰⁷, M. Zdrzil¹⁴, C. Zeitnitz¹⁷⁴, M. Zeller¹⁷⁵, P.F. Zema²⁹, A. Zemla³⁸, C. Zender²⁰, A.V. Zenin¹²⁸, O. Zenin¹²⁸, T. Zenis^{144a}, Z. Zenonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, H. Zhang⁸³, J. Zhang⁵, Q. Zhang⁵, X. Zhang^{32d}, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁵, S. Zheng^{32a}, J. Zhong^{151,au}, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹, Y. Zhu¹⁷², X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, B. Zilka^{144a}, R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷², A. Zoccoli^{19a,19b}, Y. Zolnierowski⁴, A. Zsenei²⁹, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶.

¹ University at Albany, 1400 Washington Ave, Albany, NY 12222, United States of America

² University of Alberta, Department of Physics, Centre for Particle Physics, Edmonton, AB T6G 2G7, Canada

³ Ankara University^(a), Faculty of Sciences, Department of Physics, TR 061000 Tandogan, Ankara; Dumlupinar University^(b), Faculty of Arts and Sciences, Department of Physics, Kutahya; Gazi University^(c), Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara; TOBB University of Economics and Technology^(d), Faculty of Arts and Sciences, Division of Physics, 06560, Sogutozu, Ankara; Turkish Atomic Energy Authority^(e), 06530, Lodumlu, Ankara, Turkey

⁴ LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux, France

⁵ Argonne National Laboratory, High Energy Physics Division, 9700 S. Cass Avenue, Argonne IL 60439, United States of America

⁶ University of Arizona, Department of Physics, Tucson, AZ 85721, United States of America

⁷ The University of Texas at Arlington, Department of Physics, Box 19059, Arlington, TX 76019, United States of America

⁸ University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopouli, Zografou, GR 15771 Athens, Greece

⁹ National Technical University of Athens, Physics Department, 9-Iroon Polytechniou, GR 15780 Zografou, Greece

¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan

¹¹ Institut de Física d'Altes Energies, IFAE, Edifici Cn, Universitat Autònoma de Barcelona, ES - 08193 Bellaterra (Barcelona), Spain

¹² University of Belgrade^(a), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences^(b)M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia, Serbia

¹³ University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway

¹⁴ Lawrence Berkeley National Laboratory and University of California, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, United States of America

¹⁵ Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany

¹⁶ University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern, Switzerland

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

¹⁸ Bogazici University^(a), Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul; Dogus

- University^(b), Faculty of Arts and Sciences, Department of Physics, 34722, Kadikoy, Istanbul; ^(c)Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Sehitkamil, Gaziantep, Turkey; Istanbul Technical University^(d), Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, Istanbul, Turkey
- ¹⁹ INFN Sezione di Bologna^(a); Università di Bologna, Dipartimento di Fisica^(b), viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy
- ²⁰ University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany
- ²¹ Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States of America
- ²² Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States of America
- ²³ Universidade Federal do Rio De Janeiro, COPPE/EE/IF ^(a), Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro; ^(b)Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil
- ²⁴ Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States of America
- ²⁵ National Institute of Physics and Nuclear Engineering^(a), Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania; University Politehnica Bucharest^(b), Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University^(c) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania
- ²⁶ Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina
- ²⁷ University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom
- ²⁸ Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada
- ²⁹ CERN, CH - 1211 Geneva 23, Switzerland
- ³⁰ University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States of America
- ³¹ Pontificia Universidad Católica de Chile, Facultad de Fisica, Departamento de Fisica^(a), Avda. Vicuna Mackenna 4860, San Joaquin, Santiago; Universidad Técnica Federico Santa María, Departamento de Física^(b), Avda. España 1680, Casilla 110-V, Valparaíso, Chile
- ³² Institute of High Energy Physics, Chinese Academy of Sciences^(a), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics^(b), Hefei, CN - Anhui 230026; Nanjing University, Department of Physics^(c), 22 Hankou Road, Nanjing, 210093; Shandong University, High Energy Physics Group^(d), Jinan, CN - Shandong 250100, China
- ³³ Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubiere Cedex, France
- ³⁴ Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States of America
- ³⁵ University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 Kobenhavn 0, Denmark
- ³⁶ INFN Gruppo Collegato di Cosenza^(a); Università della Calabria, Dipartimento di Fisica^(b), IT-87036 Arcavacata di Rende, Italy
- ³⁷ Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland
- ³⁹ Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States of America
- ⁴⁰ University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States of America
- ⁴¹ DESY, Notkestr. 85, D-22603 Hamburg and Platanenallee 6, D-15738 Zeuthen, Germany
- ⁴² TU Dortmund, Experimentelle Physik IV, DE - 44221 Dortmund, Germany
- ⁴³ Technical University Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, D-01069 Dresden, Germany
- ⁴⁴ Duke University, Department of Physics, Durham, NC 27708, United States of America
- ⁴⁵ University of Edinburgh, School of Physics & Astronomy, James Clerk Maxwell Building, The Kings Buildings, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt; Johannes Gutenbergstrasse 3 AT - 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, via Enrico Fermi 40, IT-00044 Frascati, Italy
- ⁴⁸ Albert-Ludwigs-Universität, Fakultät für Mathematik und Physik, Hermann-Herder Str. 3, D - 79104 Freiburg i.Br., Germany
- ⁴⁹ Université de Genève, Section de Physique, 24 rue Ernest Ansermet, CH - 1211 Geneve 4, Switzerland
- ⁵⁰ INFN Sezione di Genova^(a); Università di Genova, Dipartimento di Fisica^(b), via Dodecaneso 33, IT - 16146

Genova, Italy

⁵¹ Institute of Physics of the Georgian Academy of Sciences, 6 Tamarashvili St., GE - 380077 Tbilisi; Tbilisi State University, HEP Institute, University St. 9, GE - 380086 Tbilisi, Georgia

⁵² Justus-Liebig-Universität Giessen, II Physikalisches Institut, Heinrich-Buff Ring 16, D-35392 Giessen, Germany

⁵³ University of Glasgow, Department of Physics and Astronomy, Glasgow G12 8QQ, United Kingdom

⁵⁴ Georg-August-Universität, II. Physikalisches Institut, Friedrich-Hund Platz 1, D-37077 Göttingen, Germany

⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3, Université Joseph Fourier, INPG, 53 avenue des Martyrs, FR - 38026 Grenoble Cedex, France

⁵⁶ Hampton University, Department of Physics, Hampton, VA 23668, United States of America

⁵⁷ Harvard University, Laboratory for Particle Physics and Cosmology, 18 Hammond Street, Cambridge, MA 02138, United States of America

⁵⁸ Ruprecht-Karls-Universität Heidelberg: Kirchhoff-Institut für Physik^(a), Im Neuenheimer Feld 227, D-69120 Heidelberg; Physikalisches Institut^(b), Philosophenweg 12, D-69120 Heidelberg; ZITI Ruprecht-Karls-Universität Heidelberg^(c), Lehrstuhl für Informatik V, B6, 23-29, DE - 68131 Mannheim, Germany

⁵⁹ Hiroshima University, Faculty of Science, 1-3-1 Kagamiyama, Higashihiroshima-shi, JP - Hiroshima 739-8526, Japan

⁶⁰ Hiroshima Institute of Technology, Faculty of Applied Information Science, 2-1-1 Miyake Saeki-ku, Hiroshima-shi, JP - Hiroshima 731-5193, Japan

⁶¹ Indiana University, Department of Physics, Swain Hall West 117, Bloomington, IN 47405-7105, United States of America

⁶² Institut für Astro- und Teilchenphysik, Technikerstrasse 25, A - 6020 Innsbruck, Austria

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

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

⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, RU - 141 980 Moscow Region, Russia

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

⁸¹ Universität Mainz, Institut für Physik, Staudinger Weg 7, DE - 55099 Mainz, Germany

⁸² University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom

⁸³ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

⁸⁴ University of Massachusetts, Department of Physics, 710 North Pleasant Street, Amherst, MA 01003, United States of America

⁸⁵ McGill University, High Energy Physics Group, 3600 University Street, Montreal, Quebec H3A 2T8, Canada

⁸⁶ University of Melbourne, School of Physics, AU - Parkville, Victoria 3010, Australia

⁸⁷ The University of Michigan, Department of Physics, 2477 Randall Laboratory, 500 East University, Ann Arbor, MI 48109-1120, United States of America

- ⁸⁸ Michigan State University, Department of Physics and Astronomy, High Energy Physics Group, East Lansing, MI 48824-2320, United States of America
- ⁸⁹ INFN Sezione di Milano^(a); Università di Milano, Dipartimento di Fisica^(b), via Celoria 16, IT - 20133 Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Independence Avenue 68, Minsk 220072, Republic of Belarus
- ⁹¹ National Scientific & Educational Centre for Particle & High Energy Physics, NC PHEP BSU, M. Bogdanovich St. 153, Minsk 220040, Republic of Belarus
- ⁹² Massachusetts Institute of Technology, Department of Physics, Room 24-516, Cambridge, MA 02139, United States of America
- ⁹³ University of Montreal, Group of Particle Physics, C.P. 6128, Succursale Centre-Ville, Montreal, Quebec, H3C 3J7, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Leninsky pr. 53, RU - 117 924 Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), B. Cheremushkinskaya ul. 25, RU 117 218 Moscow, Russia
- ⁹⁶ Moscow Engineering & Physics Institute (MEPhI), Kashirskoe Shosse 31, RU - 115409 Moscow, Russia
- ⁹⁷ Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP), 1(2), Leninskie gory, GSP-1, Moscow 119991 Russian Federation, Russia
- ⁹⁸ Ludwig-Maximilians-Universität München, Fakultät für Physik, Am Coulombwall 1, DE - 85748 Garching, Germany
- ⁹⁹ Max-Planck-Institut für Physik, (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, 536 Aba-machi, JP Nagasaki 851-0193, Japan
- ¹⁰¹ Nagoya University, Graduate School of Science, Furo-Cho, Chikusa-ku, Nagoya, 464-8602, Japan
- ¹⁰² INFN Sezione di Napoli^(a); Università di Napoli, Dipartimento di Scienze Fisiche^(b), Complesso Universitario di Monte Sant'Angelo, via Cinthia, IT - 80126 Napoli, Italy
- ¹⁰³ University of New Mexico, Department of Physics and Astronomy, MSC07 4220, Albuquerque, NM 87131 USA, United States of America
- ¹⁰⁴ Radboud University Nijmegen/NIKHEF, Department of Experimental High Energy Physics, Heyendaalseweg 135, NL-6525 AJ, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics, and University of Amsterdam, Science Park 105, 1098 XG Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, LaTourette Hall Normal Road, DeKalb, IL 60115, United States of America
- ¹⁰⁷ Budker Institute of Nuclear Physics (BINP), RU - Novosibirsk 630 090, Russia
- ¹⁰⁸ New York University, Department of Physics, 4 Washington Place, New York NY 10003, USA, United States of America
- ¹⁰⁹ Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, United States of America
- ¹¹⁰ Okayama University, Faculty of Science, Tsushimanaka 3-1-1, Okayama 700-8530, Japan
- ¹¹¹ University of Oklahoma, Homer L. Dodge Department of Physics and Astronomy, 440 West Brooks, Room 100, Norman, OK 73019-0225, United States of America
- ¹¹² Oklahoma State University, Department of Physics, 145 Physical Sciences Building, Stillwater, OK 74078-3072, United States of America
- ¹¹³ Palacký University, 17.listopadu 50a, 772 07 Olomouc, Czech Republic
- ¹¹⁴ University of Oregon, Center for High Energy Physics, Eugene, OR 97403-1274, United States of America
- ¹¹⁵ LAL, Univ. Paris-Sud, IN2P3/CNRS, Orsay, France
- ¹¹⁶ Osaka University, Graduate School of Science, Machikaneyama-machi 1-1, Toyonaka, Osaka 560-0043, Japan
- ¹¹⁷ University of Oslo, Department of Physics, P.O. Box 1048, Blindern, NO - 0316 Oslo 3, Norway
- ¹¹⁸ Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
- ¹¹⁹ INFN Sezione di Pavia^(a); Università di Pavia, Dipartimento di Fisica Nucleare e Teorica^(b), Via Bassi 6, IT-27100 Pavia, Italy
- ¹²⁰ University of Pennsylvania, Department of Physics, High Energy Physics Group, 209 S. 33rd Street, Philadelphia, PA 19104, United States of America
- ¹²¹ Petersburg Nuclear Physics Institute, RU - 188 300 Gatchina, Russia
- ¹²² INFN Sezione di Pisa^(a); Università di Pisa, Dipartimento di Fisica E. Fermi^(b), Largo B. Pontecorvo 3, IT - 56127 Pisa, Italy

- ¹²³ University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, PA 15260, United States of America
- ¹²⁴ Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP^(a), Avenida Elias Garcia 14-1, PT - 1000-149 Lisboa, Portugal; Universidad de Granada, Departamento de Fisica Teorica y del Cosmos and CAFPE^(b), E-18071 Granada, Spain
- ¹²⁵ Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ - 18221 Praha 8, Czech Republic
- ¹²⁶ Charles University in Prague, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, V Holesovickach 2, CZ - 18000 Praha 8, Czech Republic
- ¹²⁷ Czech Technical University in Prague, Zikova 4, CZ - 166 35 Praha 6, Czech Republic
- ¹²⁸ State Research Center Institute for High Energy Physics, Moscow Region, 142281, Protvino, Pobeda street, 1, Russia
- ¹²⁹ Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom
- ¹³⁰ University of Regina, Physics Department, Canada
- ¹³¹ Ritsumeikan University, Noji Higashi 1 chome 1-1, JP - Kusatsu, Shiga 525-8577, Japan
- ¹³² INFN Sezione di Roma I^(a); Università La Sapienza, Dipartimento di Fisica^(b), Piazzale A. Moro 2, IT- 00185 Roma, Italy
- ¹³³ INFN Sezione di Roma Tor Vergata^(a); Università di Roma Tor Vergata, Dipartimento di Fisica^(b), via della Ricerca Scientifica, IT-00133 Roma, Italy
- ¹³⁴ INFN Sezione di Roma Tre^(a); Università Roma Tre, Dipartimento di Fisica^(b), via della Vasca Navale 84, IT-00146 Roma, Italy
- ¹³⁵ Réseau Universitaire de Physique des Hautes Energies (RUPHE): Université Hassan II, Faculté des Sciences Ain Chock^(a), B.P. 5366, MA - Casablanca; Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN)^(b), B.P. 1382 R.P. 10001 Rabat 10001; Université Mohamed Premier^(c), LPTPM, Faculté des Sciences, B.P.717. Bd. Mohamed VI, 60000, Oujda ; Université Mohammed V, Faculté des Sciences^(d) 4 Avenue Ibn Battouta, BP 1014 RP, 10000 Rabat, Morocco
- ¹³⁶ CEA, DSM/IRFU, Centre d'Etudes de Saclay, FR - 91191 Gif-sur-Yvette, France
- ¹³⁷ University of California Santa Cruz, Santa Cruz Institute for Particle Physics (SCIPP), Santa Cruz, CA 95064, United States of America
- ¹³⁸ University of Washington, Seattle, Department of Physics, Box 351560, Seattle, WA 98195-1560, United States of America
- ¹³⁹ University of Sheffield, Department of Physics & Astronomy, Hounsfield Road, Sheffield S3 7RH, United Kingdom
- ¹⁴⁰ Shinshu University, Department of Physics, Faculty of Science, 3-1-1 Asahi, Matsumoto-shi, JP - Nagano 390-8621, Japan
- ¹⁴¹ Universität Siegen, Fachbereich Physik, D 57068 Siegen, Germany
- ¹⁴² Simon Fraser University, Department of Physics, 8888 University Drive, CA - Burnaby, BC V5A 1S6, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford, California 94309, United States of America
- ¹⁴⁴ Comenius University, Faculty of Mathematics, Physics & Informatics^(a), Mlynska dolina F2, SK - 84248 Bratislava; Institute of Experimental Physics of the Slovak Academy of Sciences, Dept. of Subnuclear Physics^(b), Watsonova 47, SK - 04353 Kosice, Slovak Republic
- ¹⁴⁵ ^(a)University of Johannesburg, Department of Physics, PO Box 524, Auckland Park, Johannesburg 2006; ^(b)School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, Johannesburg, South Africa, South Africa
- ¹⁴⁶ Stockholm University: Department of Physics^(a); The Oskar Klein Centre^(b), AlbaNova, SE - 106 91 Stockholm, Sweden
- ¹⁴⁷ Royal Institute of Technology (KTH), Physics Department, SE - 106 91 Stockholm, Sweden
- ¹⁴⁸ Stony Brook University, Department of Physics and Astronomy, Nicolls Road, Stony Brook, NY 11794-3800, United States of America
- ¹⁴⁹ University of Sussex, Department of Physics and Astronomy Pevensey 2 Building, Falmer, Brighton BN1 9QH, United Kingdom
- ¹⁵⁰ University of Sydney, School of Physics, AU - Sydney NSW 2006, Australia
- ¹⁵¹ Insitute of Physics, Academia Sinica, TW - Taipei 11529, Taiwan
- ¹⁵² Technion, Israel Inst. of Technology, Department of Physics, Technion City, IL - Haifa 32000, Israel
- ¹⁵³ Tel Aviv University, Raymond and Beverly Sackler School of Physics and Astronomy, Ramat Aviv, IL - Tel Aviv

69978, Israel

¹⁵⁴ Aristotle University of Thessaloniki, Faculty of Science, Department of Physics, Division of Nuclear & Particle Physics, University Campus, GR - 54124, Thessaloniki, Greece

¹⁵⁵ The University of Tokyo, International Center for Elementary Particle Physics and Department of Physics, 7-3-1 Hongo, Bunkyo-ku, JP - Tokyo 113-0033, Japan

¹⁵⁶ Tokyo Metropolitan University, Graduate School of Science and Technology, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan

¹⁵⁷ Tokyo Institute of Technology, 2-12-1-H-34 O-Okayama, Meguro, Tokyo 152-8551, Japan

¹⁵⁸ University of Toronto, Department of Physics, 60 Saint George Street, Toronto M5S 1A7, Ontario, Canada

¹⁵⁹ TRIUMF^(a), 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3; ^(b)York University, Department of Physics and Astronomy, 4700 Keele St., Toronto, Ontario, M3J 1P3, Canada

¹⁶⁰ University of Tsukuba, Institute of Pure and Applied Sciences, 1-1-1 Tennoudai, Tsukuba-shi, JP - Ibaraki 305-8571, Japan

¹⁶¹ Tufts University, Science & Technology Center, 4 Colby Street, Medford, MA 02155, United States of America

¹⁶² Universidad Antonio Narino, Centro de Investigaciones, Cra 3 Este No.47A-15, Bogota, Colombia

¹⁶³ University of California, Irvine, Department of Physics & Astronomy, CA 92697-4575, United States of America

¹⁶⁴ INFN Gruppo Collegato di Udine^(a); ICTP^(b), Strada Costiera 11, IT-34014, Trieste; Università di Udine, Dipartimento di Fisica^(c), via delle Scienze 208, IT - 33100 Udine, Italy

¹⁶⁵ University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of America

¹⁶⁶ University of Uppsala, Department of Physics and Astronomy, P.O. Box 516, SE -751 20 Uppsala, Sweden

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

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

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

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

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

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

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

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

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

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

¹⁷⁷ ATLAS-Canada Tier-1 Data Centre, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada

¹⁷⁸ GridKA Tier-1 FZK, Forschungszentrum Karlsruhe GmbH, Steinbuch Centre for Computing (SCC), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

¹⁷⁹ Port d'Informació Científica (PIC), Universitat Autònoma de Barcelona (UAB), Edifici D, E-08193 Bellaterra, Spain

¹⁸⁰ Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France

¹⁸¹ INFN-CNAF, Viale Berti Pichat 6/2, 40127 Bologna, Italy

¹⁸² Nordic Data Grid Facility, NORDUnet A/S, Kastruplundgade 22, 1, DK-2770 Kastrup, Denmark

¹⁸³ SARA Reken- en Netwerkdiensten, Science Park 121, 1098 XG Amsterdam, Netherlands

¹⁸⁴ Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, No.128, Sec. 2, Academia Rd., Nankang, Taipei, Taiwan 11529, Taiwan

¹⁸⁵ UK-T1-RAL Tier-1, Rutherford Appleton Laboratory, Science and Technology Facilities Council, Harwell Science and Innovation Campus, Didcot OX11 0QX, United Kingdom

¹⁸⁶ RHIC and ATLAS Computing Facility, Physics Department, Building 510, Brookhaven National Laboratory, Upton, New York 11973, United States of America

^a Also at LIP, Portugal

^b Present address FermiLab, USA

^c Also at Faculdade de Ciências, Universidade de Lisboa, Portugal

^d Also at CPPM, Marseille, France.

^e Also at TRIUMF, Vancouver, Canada

- f* Also at FPACS, AGH-UST, Cracow, Poland
- g* Now at Università dell'Insubria, Dipartimento di Fisica e Matematica
- h* Also at TRIUMF, Vancouver, Canada
- i* Also at Department of Physics, University of Coimbra, Portugal
- j* Now at CERN
- k* Also at Università di Napoli Parthenope, Napoli, Italy
- l* Also at Institute of Particle Physics (IPP), Canada
- m* Also at Università di Napoli Parthenope, via A. Acton 38, IT - 80133 Napoli, Italy
- n* Louisiana Tech University, 305 Wisteria Street, P.O. Box 3178, Ruston, LA 71272, United States of America
- o* Also at Universidade de Lisboa, Portugal
- p* At California State University, Fresno, USA
- q* Also at TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada
- r* Also at Faculdade de Ciências, Universidade de Lisboa, Portugal and at Centro de Física Nuclear da Universidade de Lisboa, Portugal
- s* Also at FPACS, AGH-UST, Cracow, Poland
- t* Also at California Institute of Technology, Pasadena, USA
- u* Louisiana Tech University, Ruston, USA
- v* Also at University of Montreal, Montreal, Canada
- w* Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- x* Now at Chonnam National University, Chonnam, Korea 500-757
- y* Also at Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
- z* Also at School of Physics and Engineering, Sun Yat-sen University, China
- aa* Also at School of Physics, Shandong University, Jinan, China
- ab* Also at California Institute of Technology, Pasadena, USA
- ac* Also at Rutherford Appleton Laboratory, Didcot, UK
- ad* Also at school of physics, Shandong University, Jinan
- ae* Also at Rutherford Appleton Laboratory, Didcot, UK
- af* Now at KEK
- ag* Also at Departamento de Física, Universidade de Minho, Portugal
- ah* University of South Carolina, Columbia, USA
- ai* Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- aj* University of South Carolina, Dept. of Physics and Astronomy, 700 S. Main St, Columbia, SC 29208, United States of America
- ak* Also at Institute of Physics, Jagiellonian University, Cracow, Poland
- al* Louisiana Tech University, Ruston, USA
- am* Also at Centro de Física Nuclear da Universidade de Lisboa, Portugal
- an* Also at School of Physics and Engineering, Sun Yat-sen University, Taiwan
- ao* University of South Carolina, Columbia, USA
- ap* Transfer to LHCb 31.01.2010
- aq* Also at Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom
- ar* Also at school of physics and engineering, Sun Yat-sen University
- as* Also at CEA
- at* Also at LPNHE, Paris, France
- au* Also at Nanjing University, China
- * Deceased
-