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

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A search for new heavy particles manifested as resonances in two-jet final states is presented. The data were produced in 7 TeV proton-proton collisions by the 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 signal acceptance for excited-quark (q^*) production as a function of q^* mass. These exclude at the 95% C.L. the q^* mass interval $0.30 < m_{q^*} < 1.26$ 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 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 flavor-universal color-octet coloron [6,7], or a color-octet techni-ρ meson predicted by models of extended technicolor and top-color-assisted technicolor [8–11].

Particularly sensitive to such new objects is the dijet invariant mass observable, defined as $m^{jj} \equiv \sqrt{(E^{j_1} + E^{j_2})^2 - (\vec{p}^{j_1} + \vec{p}^{j_2})^2}$, where E and $\vec{p}$ are the jet energy and momentum, respectively. Several experiments have examined m^{jj} distributions in search of new resonances [12–17]; recently, 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 $260 < m_{q^*} < 870$ GeV [16]. This Letter reports the first search by the ATLAS experiment [18] at the LHC for such massive particles in pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ 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 the acceptance times cross section to be set for resonant states with intrinsic widths narrower than the experimental resolution.

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The analysis technique consisted of a model-independent 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 signal acceptance ($\mathcal{A}$) for several q^* test masses for a standard set of model parameters.

The ATLAS detector [18] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [19]. 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 [20]. 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 by using the anti-k_T jet clustering algorithm [21] 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 noncompensation 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 [20,22]. The m^{jj} observable was computed without unfolding jets to hadrons or partons.

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 beam line, of $|z| < 10$ cm. Events with at least two jets were retained if the highest p_T jet (the "leading" jet) satisfied $p_T^{j_1} > 80$ GeV and the next-to-leading jet satisfied $p_T^{j_2} > 30$ 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 [23]; this affected the event selection by less than 0.5%. The two leading jets were required to satisfy several quality criteria [23] and to lie outside detector regions where the jet energy was not yet measured in an optimal way, such as the interval $1.3 < |\eta^{\rm jet}| < 1.8$. Finally, both jets were required to be in the pseudorapidity region $|\eta^{\rm jet}| < 2.5$, 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 by using the excited-quark ($qg \to q^*$) production model [2,3]. The excited quark q^* was assumed to have spin 1/2 and quarklike 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 by using PYTHIA [24] 6.4.21, a leading-order parton-shower MC generator, with the modified leading-order MRST2007 [25] 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, which were dominantly qg but also qW, qZ, and $q\gamma$. The MC samples were produced [26] by using the ATLAS MC09 parameter tune [27] and a GEANT4-based detector simulation [28].

Figure 1 shows the predicted signals for q^* masses of 500, 800, and 1200 GeV, after all selection cuts. The signal

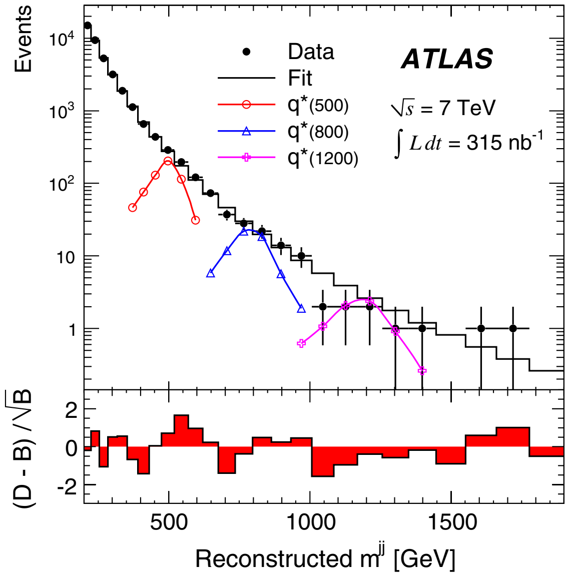

FIG. 1 (color online). The data (D) dijet mass distribution (filled points) fitted by using a binned background (B) distribution described by Eq. (1) (histogram). The predicted q^* signals [2,3] for excited-quark masses of 500, 800, and 1200 GeV are overlaid, and the bin-by-bin significance of the data-background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

acceptance ($\mathcal{A}$), which included reconstruction and trigger efficiencies near 100%, was found to range from ~31% for $m_{q^*} = 300$ GeV to ~48% for $m_{q^*} = 1.7$ TeV [29]. 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 $m_{q^*} = 300$ GeV to $\sigma_{m^{jj}}/m^{jj} \sim 7\%$ at $m_{q^*} = 1.7$ TeV and was dominated by the detector energy resolution.

The background shape was determined by fitting the observed spectrum with the function [16]

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

where $x \equiv m^{jj}/\sqrt{s}$, such that $f(1) = 0$ and $f(0) \to +\infty$, 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 Eq. (1) has been shown to fit the m^{jj} observable well in PYTHIA, HERWIG, and next-to-leading-order perturbative QCD predictions for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [16]. Studies using PYTHIA and the ATLAS GEANT4-based detector simulation were performed to demonstrate that the smooth and monotonic form of Eq. (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 Eq. (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 Eq. (1) are shown in Fig. 1. The presence or absence of detectable 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 [30], the Jeffreys divergence [31], the Kolmogorov-Smirnov test, the likelihood, the Pearson χ^2, and the TailHunter statistic [32]. 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 pseudospectra drawn from Poisson variations seeded by the results of the fit of Eq. (1) to the data. The p value of the background-only hypothesis is defined as the fraction of pseudoexperiments that result 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 (C.L.) upper limits on $\sigma \cdot \mathcal{A}$ for hypothetical new particles decaying into dijets with $|\eta^{\rm jet}| < 2.5$. 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:

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

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 Eq. (1); the fifth parameter consisted of the normalization of the predicted $\nu^{\rm th}$ q^* signal template. To avoid acceptance bias, the lowest q^* test mass used was 300 GeV. For every q^* mass, Eq. (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% probability region 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 pseudoexperiments 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, the background fit parameters, the integrated luminosity, and the jet energy resolution (JER). The jet energy scale uncertainty was quantified as a function of p_T and $\eta^{\rm jet}$, with values in the range 6%–9% [20,33,34]. The jet calibration relied on the MC simulation of the response of the ATLAS detector; its uncertainty was constrained by varying the ATLAS simulation and from *in situ* information. The systematic uncertainty on the determination of the background was taken from the uncertainty on the parameters resulting from the fit of Eq. (1) to the data sample. The uncertainty on $\sigma \cdot \mathcal{A}$ due to integrated luminosity was estimated to be $\pm 11\%$ [35]. The JER uncertainty was treated as uniform in p_T and $\eta^{\rm jet}$ with a value of $\pm 14\%$ on the fractional p_T resolution of each jet [36]. The effects of jet energy scale, background fit, integrated luminosity, and JER were incorporated as nuisance parameters into the likelihood function in Eq. (2) and then marginalized by numerically integrating the product of this modified likelihood, the prior in s, and the priors corresponding to the nuisance parameters to arrive at a modified posterior probability distribution. 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% C.L. upper limits on $\sigma \cdot \mathcal{A}$ as a function of the q^* resonance mass after incorporation of systematic uncertainties. Linear interpolations

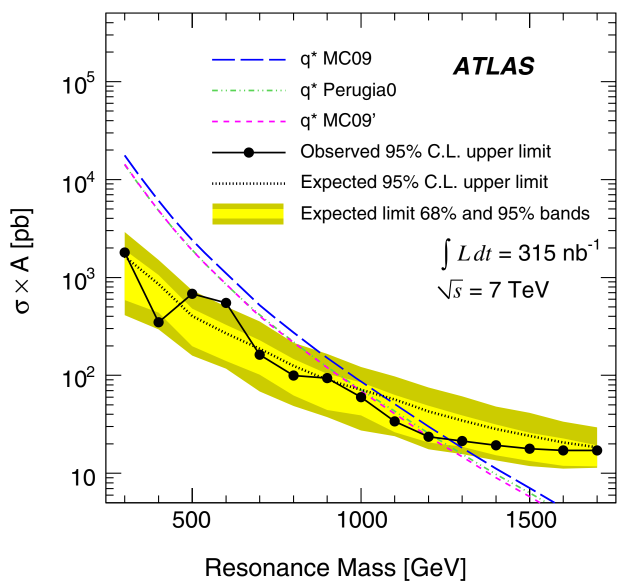

FIG. 2 (color online). The 95% C.L. upper limit on $\sigma \cdot \mathcal{A}$ as a function of dijet resonance mass (black filled circles). The black dotted curve shows the expected 95% C.L. upper limit, and the light and dark yellow shaded bands represent the 68% and 95% credibility intervals of the expected limit, respectively. The dashed curves represent excited-quark $\sigma \cdot \mathcal{A}$ predictions for different MC tunes, each using a different PDF set.

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

MC tune	PDF set	Observed mass limit [TeV] Stat. ⊕ Syst.	Stat. only	Expected mass limit [TeV] Stat. ⊕ Syst.
MC09 [27]	MRST2007 [25]	1.26	1.28	1.06
MC09′[a]	CTEQ6L1 [37]	1.20	1.23	0.99
Perugia0 [38]	CTEQ5L [39]	1.22	1.25	1.00

[a]The MC09′ tune is identical to MC09 except for the PYTHIA [24] parameter PARP(82) = 2.1 and use of the CTEQ6L1 PDF set.

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% C.L. excited-quark mass exclusion region was found to be $0.30 < m_{q^*} < 1.26$ TeV by using MRST2007 PDFs in the ATLAS default MC09 tune. Table I shows the results obtained by using CTEQ6L1 [37] and CTEQ5L [39] 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 by using an analogous approach but replacing the actual data with pseudodata generated by random fluctuations around the smooth function described by fitting the data with Eq. (1); these are shown in Fig. 2, with a resulting expected q^* mass exclusion region of $0.30 < m_{q^*} < 1.06$ 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 ±20%; this changed the observed MRST2007 limit of 1.26 TeV to 1.32 and 1.22 TeV, respectively.

In conclusion, a model-independent search for new heavy particles manifested as 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% C.L. were set on the products of cross section and signal acceptance for hypothetical new q^* particles decaying to dijets. These data exclude at the 95% C.L. excited-quark masses from the lower edge of the search region, 0.30 TeV, to 1.26 TeV for a standard set of model parameters and using the ATLAS default MC09 tune [27]. 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.

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G. Arabidze,[8] I. Aracena,[143] Y. Arai,[66] A. T. H. Arce,[44] J. P. Archambault,[28] S. Arfaoui,[29,e] J-F. Arguin,[14] T. Argyropoulos,[9] E. Arik,[18a,a] M. Arik,[18a] A. J. Armbruster,[87] K. E. Arms,[109] S. R. Armstrong,[24] O. Arnaez,[4] C. Arnault,[115] A. Artamonov,[95] D. Arutinov,[20] M. Asai,[143] S. Asai,[155] R. Asfandiyarov,[172] S. Ask,[27] B. Åsman,[146a,146b] D. Asner,[28] L. Asquith,[77] K. Assamagan,[24] A. Astbury,[169] A. Astvatsatourov,[52] G. Atoian,[175] B. Aubert,[4] B. Auerbach,[175] E. Auge,[115] K. Augsten,[127] M. Aurousseau,[4] N. Austin,[73] G. Avolio,[163] R. Avramidou,[9] D. Axen,[168] C. Ay,[54] G. Azuelos,[93,f] Y. Azuma,[155] M. A. Baak,[29] G. Baccaglioni,[89a] C. Bacci,[134a,134b] A. M. Bach,[14] H. Bachacou,[136] K. Bachas,[29] G. Bachy,[29] M. Backes,[49] E. Badescu,[25a] P. Bagnaia,[132a,132b] Y. Bai,[32a] D. C. Bailey,[158] T. Bain,[158] J. T. Baines,[129] O. K. Baker,[175] M. D. Baker,[24] S Baker,[77] F. Baltasar Dos Santos Pedrosa,[29] E. Banas,[38] P. Banerjee,[93] S. Banerjee,[169] D. Banfi,[89a,89b] A. Bangert,[137] V. Bansal,[169] S. P. Baranov,[94] S. Baranov,[65] A. Barashkou,[65] A. Barbaro Galtieri,[14] T. Barber,[27] E. L. Barberio,[86] D. Barberis,[50a,50b] M. Barbero,[20] D. Y. Bardin,[65] T. Barillari,[99] M. Barisonzi,[174] T. Barklow,[143] N. Barlow,[27] B. M. Barnett,[129] R. M. Barnett,[14] A. Baroncelli,[134a] M. Barone,[47] A. J. Barr,[118] F. Barreiro,[80] J. Barreiro Guimarães da Costa,[57] P. Barrillon,[115] R. Bartoldus,[143] D. Bartsch,[20] R. L. Bates,[53] L. Batkova,[144a] J. R. Batley,[27] A. Battaglia,[16] M. Battistin,[29] G. Battistoni,[89a] F. Bauer,[136] H. S. Bawa,[143] M. Bazalova,[125] B. Beare,[158] T. Beau,[78] P. H. Beauchemin,[118] R. Beccherle,[50a] P. Bechtle,[41] G. A. Beck,[75] H. P. Beck,[16] M. Beckingham,[48] K. H. Becks,[174] A. J. Beddall,[18c] A. Beddall,[18c] V. A. Bednyakov,[65] C. Bee,[83] M. Begel,[24] S. Behar Harpaz,[152] P. K. Behera,[63] M. Beimforde,[99] C. Belanger-Champagne,[166] B. Belhorma,[55] P. J. Bell,[49] W. H. Bell,[49] G. Bella,[153] L. Bellagamba,[19a] F. Bellina,[29] G. Bellomo,[89a,89b] M. Bellomo,[119a] A. Belloni,[57] K. Belotskiy,[96] O. Beltramello,[29] S. Ben Ami,[152] O. Benary,[153] D. Benchekroun,[135a] C. Benchouk,[83] M. Bendel,[81] B. H. Benedict,[163] N. Benekos,[165] Y. Benhammou,[153] G. P. Benincasa,[124a] D. P. Benjamin,[44] M. Benoit,[115] J. R. Bensinger,[22] K. Benslama,[130] S. Bentvelsen,[105] M. Beretta,[47] D. Berge,[29] E. Bergeaas Kuutmann,[41] N. Berger,[4] F. Berghaus,[169] E. Berglund,[49] J. Beringer,[14] K. Bernardet,[83] P. Bernat,[115] R. Bernhard,[48] C. Bernius,[77] T. Berry,[76] A. Bertin,[19a,19b] F. Bertinelli,[29] F. Bertolucci,[122a,122b] S. Bertolucci,[47] M. I. Besana,[89a,89b] N. Besson,[136] S. Bethke,[99] W. Bhimji,[45] R. M. Bianchi,[48] M. Bianco,[72a,72b] O. Biebel,[98] J. Biesiada,[14] M. Biglietti,[132a,132b] H. Bilokon,[47] M. Binder,[98] M. Bindi,[19a,19b] S. Binet,[115] A. Bingul,[18c] C. Bini,[132a,132b] C. Biscarat,[177] R. Bischof,[62] U. Bitenc,[48] K. M. Black,[57] R. E. Blair,[5] J-B Blanchard,[115] G. Blanchot,[29] C. Blocker,[22] J. Blocki,[38] A. Blondel,[49] W. Blum,[81] U. Blumenschein,[54] C. Boaretto,[132a,132b] G. J. Bobbink,[105] A. Bocci,[44] D. Bocian,[38] R. Bock,[29] C. R. Boddy,[118] M. Boehler,[41] J. Boek,[174] N. Boelaert,[79] S. Böser,[77] J. A. Bogaerts,[29] A. Bogouch,[90,a] C. Bohm,[146a] J. Bohm,[125] V. Boisvert,[76] T. Bold,[163,g] V. Boldea,[25a] V. G. Bondarenko,[96] M. Bondioli,[163] M. Boonekamp,[136] G. Boorman,[76] C. N. Booth,[139] P. Booth,[139] J. R. A. Booth,[17] S. Bordoni,[78] C. Borer,[16] A. Borisov,[128] G. Borissov,[71] I. Borjanovic,[12a] S. Borroni,[132a,132b] K. Bos,[105] D. Boscherini,[19a] M. Bosman,[11] H. Boterenbrood,[105] D. Botterill,[129] J. Bouchami,[93] J. Boudreau,[123] E. V. Bouhova-Thacker,[71] C. Boulahouache,[123] C. Bourdarios,[115] A. Boveia,[30] J. Boyd,[29] I. R. Boyko,[65] N. I. Bozhko,[128] I. Bozovic-Jelisavcic,[12b] S. Braccini,[47] J. Bracinik,[17] A. Braem,[29] E. Brambilla,[72a,72b] P. Branchini,[134a] G. W. Brandenburg,[57] A. Brandt,[7] G. Brandt,[41] O. Brandt,[54] U. Bratzler,[156] B. Brau,[84] J. E. Brau,[114] H. M. Braun,[174] B. Brelier,[158] J. Bremer,[29] R. Brenner,[166] S. Bressler,[152] D. Breton,[115] N. D. Brett,[118] P. G. Bright-Thomas,[17] D. Britton,[53] F. M. Brochu,[27] I. Brock,[20] R. Brock,[88] T. J. Brodbeck,[71] E. Brodet,[153] F. Broggi,[89a] C. Bromberg,[88] G. Brooijmans,[34] W. K. Brooks,[31b] G. Brown,[82] E. Brubaker,[30] P. A. Bruckman de Renstrom,[38] D. Bruncko,[144b] R. Bruneliere,[48] S. Brunet,[61] A. Bruni,[19a] G. Bruni,[19a] M. Bruschi,[19a] T. Buanes,[13] F. Bucci,[49] J. Buchanan,[118] N. J. Buchanan,[2] P. Buchholz,[141] R. M. Buckingham,[118] A. G. Buckley,[45] I. A. Budagov,[65] B. Budick,[108] V. Büscher,[81] L. Bugge,[117] D. Buira-Clark,[118] E. J. Buis,[105] O. Bulekov,[96] M. Bunse,[42] T. Buran,[117] H. Burckhart,[29] S. Burdin,[73] T. Burgess,[13] S. Burke,[129] E. Busato,[33] P. Bussey,[53] C. P. Buszello,[166] F. Butin,[29] B. Butler,[143] J. M. Butler,[21] C. M. Buttar,[53] J. M. Butterworth,[77] T. Byatt,[77] J. Caballero,[24] S. Cabrera Urbán,[167] M. Caccia,[89a,89b,h] D. Caforio,[19a,19b] O. Cakir,[3a] P. Calafiura,[14] G. Calderini,[78] P. Calfayan,[98] R. Calkins,[106] L. P. Caloba,[23] R. Caloi,[132a,132b] D. Calvet,[33] A. Camard,[78] P. Camarri,[133a,133b] M. Cambiaghi,[119a,119b] D. Cameron,[117] J. Cammin,[20] S. Campana,[29] M. Campanelli,[77] V. Canale,[102a,102b] F. Canelli,[30] A. Canepa,[159a] J. Cantero,[80] L. Capasso,[102a,102b] M. D. M. Capeans Garrido,[29] I. Caprini,[25a] M. Caprini,[25a] M. Caprio,[102a,102b] D. Capriotti,[99] M. Capua,[36a,36b] R. Caputo,[148] C. Caramarcu,[25a] R. Cardarelli,[133a] T. Carli,[29] G. Carlino,[102a] L. Carminati,[89a,89b] B. Caron,[2,f] S. Caron,[48] C. Carpentieri,[48] G. D. Carrillo Montoya,[172] S. Carron Montero,[158] A. A. Carter,[75] J. R. Carter,[27] J. Carvalho,[124a,i] D. Casadei,[108] M. P. Casado,[11] M. Cascella,[122a,122b] C. Caso,[50a,50b,a] A. M. Castaneda Hernandez,[172] E. Castaneda-Miranda,[172] V. Castillo Gimenez,[167] N. F. Castro,[124b,b] G. Cataldi,[72a] F. Cataneo,[29] A. Catinaccio,[29] J. R. Catmore,[71] A. Cattai,[29]

G. Cattani,[133a,133b] S. Caughron,[34] D. Cauz,[164a,164c] A. Cavallari,[132a,132b] P. Cavalleri,[78] D. Cavalli,[89a] M. Cavalli-Sforza,[11] V. Cavasinni,[122a,122b] A. Cazzato,[72a,72b] F. Ceradini,[134a,134b] C. Cerna,[83] A. S. Cerqueira,[23] A. Cerri,[29] L. Cerrito,[75] F. Cerutti,[47] M. Cervetto,[50a,50b] S. A. Cetin,[18b] F. Cevenini,[102a,102b] A. Chafaq,[135a] D. Chakraborty,[106] K. Chan,[2] J. D. Chapman,[27] J. W. Chapman,[87] E. Chareyre,[78] D. G. Charlton,[17] V. Chavda,[82] S. Cheatham,[71] S. Chekanov,[5] S. V. Chekulaev,[159a] G. A. Chelkov,[65] H. Chen,[24] L. Chen,[2] S. Chen,[32c] T. Chen,[32c] X. Chen,[172] S. Cheng,[32a] A. Cheplakov,[65] V. F. Chepurnov,[65] R. Cherkaoui El Moursli,[135c] V. Tcherniatine,[24] D. Chesneanu,[25a] E. Cheu,[6] S. L. Cheung,[158] L. Chevalier,[136] F. Chevallier,[136] V. Chiarella,[47] G. Chiefari,[102a,102b] L. Chikovani,[51] J. T. Childers,[58a] A. Chilingarov,[71] G. Chiodini,[72a] M. V. Chizhov,[65] G. Choudalakis,[30] S. Chouridou,[137] I. A. Christidi,[77] A. Christov,[48] D. Chromek-Burckhart,[29] M. L. Chu,[151] J. Chudoba,[125] G. Ciapetti,[132a,132b] A. K. Ciftci,[3a] R. Ciftci,[3a] D. Cinca,[33] V. Cindro,[74] M. D. Ciobotaru,[163] C. Ciocca,[19a,19b] A. Ciocio,[14] M. Cirilli,[87,j] M. Citterio,[89a] A. Clark,[49] P. J. Clark,[45] W. Cleland,[123] J. C. Clemens,[83] B. Clement,[55] C. Clement,[146a,146b] R. W. Clifft,[129] Y. Coadou,[83] M. Cobal,[164a,164c] A. Coccaro,[50a,50b] J. Cochran,[64] P. Coe,[118] S. Coelli,[89a] J. Coggeshall,[165] E. Cogneras,[177] C. D. Cojocaru,[28] J. Colas,[4] B. Cole,[34] A. P. Colijn,[105] C. Collard,[115] N. J. Collins,[17] C. Collins-Tooth,[53] J. Collot,[55] G. Colon,[84] R. Coluccia,[72a,72b] G. Comune,[88] P. Conde Muiño,[124a] E. Coniavitis,[118] M. C. Conidi,[11] M. Consonni,[104] S. Constantinescu,[25a] C. Conta,[119a,119b] F. Conventi,[102a,k] J. Cook,[29] M. Cooke,[34] B. D. Cooper,[75] A. M. Cooper-Sarkar,[118] N. J. Cooper-Smith,[76] K. Copic,[34] T. Cornelissen,[50a,50b] M. Corradi,[19a] S. Correard,[83] F. Corriveau,[85,l] A. Corso-Radu,[163] A. Cortes-Gonzalez,[165] G. Cortiana,[99] G. Costa,[89a] M. J. Costa,[167] D. Costanzo,[139] T. Costin,[30] D. Côté,[29] R. Coura Torres,[23] L. Courneyea,[169] G. Cowan,[76] C. Cowden,[27] B. E. Cox,[82] K. Cranmer,[108] J. Cranshaw,[5] M. Cristinziani,[20] G. Crosetti,[36a,36b] R. Crupi,[72a,72b] S. Crépé-Renaudin,[55] C. Cuenca Almenar,[175] T. Cuhadar Donszelmann,[139] S. Cuneo,[50a,50b] M. Curatolo,[47] C. J. Curtis,[17] P. Cwetanski,[61] H. Czirr,[141] Z. Czyczula,[175] S. D'Auria,[53] M. D'Onofrio,[73] A. D'Orazio,[99] A. Da Rocha Gesualdi Mello,[23] P. V. M. Da Silva,[23] C Da Via,[82] W. Dabrowski,[37] A. Dahlhoff,[48] T. Dai,[87] C. Dallapiccola,[84] S. J. Dallison,[129,a] J. Dalmau,[75] C. H. Daly,[138] M. Dam,[35] M. Dameri,[50a,50b] H. O. Danielsson,[29] R. Dankers,[105] D. Dannheim,[99] V. Dao,[49] G. Darbo,[50a] G. L. Darlea,[25b] C. Daum,[105] J. P. Dauvergne,[29] W. Davey,[86] T. Davidek,[126] N. Davidson,[86] R. Davidson,[71] M. Davies,[93] A. R. Davison,[77] E. Dawe,[142] I. Dawson,[139] J. W. Dawson,[5] R. K. Daya,[39] K. De,[7] R. de Asmundis,[102a] S. De Castro,[19a,19b] P. E. De Castro Faria Salgado,[24] S. De Cecco,[78] J. de Graat,[98] N. De Groot,[104] P. de Jong,[105] E. De La Cruz-Burelo,[87] C. De La Taille,[115] B. De Lotto,[164a,164c] L. De Mora,[71] L. De Nooij,[105] M. De Oliveira Branco,[29] D. De Pedis,[132a] P. de Saintignon,[55] A. De Salvo,[132a] U. De Sanctis,[164a,164c] A. De Santo,[149] J. B. De Vivie De Regie,[115] G. De Zorzi,[132a,132b] S. Dean,[77] G. Dedes,[99] D. V. Dedovich,[65] P. O. Defay,[33] J. Degenhardt,[120] M. Dehchar,[118] M. Deile,[98] C. Del Papa,[164a,164c] J. Del Peso,[80] T. Del Prete,[122a,122b] A. Dell'Acqua,[29] L. Dell'Asta,[89a,89b] M. Della Pietra,[102a,k] D. della Volpe,[102a,102b] M. Delmastro,[29] P. Delpierre,[83] N. Delruelle,[29] P. A. Delsart,[55] C. Deluca,[148] S. Demers,[175] M. Demichev,[65] B. Demirkoz,[11] J. Deng,[163] W. Deng,[24] S. P. Denisov,[128] C. Dennis,[118] J. E. Derkaoui,[135b] F. Derue,[78] P. Dervan,[73] K. Desch,[20] P. O. Deviveiros,[158] A. Dewhurst,[129] B. DeWilde,[148] S. Dhaliwal,[158] R. Dhullipudi,[24,m] A. Di Ciaccio,[133a,133b] L. Di Ciaccio,[4] A. Di Domenico,[132a,132b] A. Di Girolamo,[29] B. Di Girolamo,[29] S. Di Luise,[134a,134b] A. Di Mattia,[88] R. Di Nardo,[133a,133b] A. Di Simone,[133a,133b] R. Di Sipio,[19a,19b] M. A. Diaz,[31a] M. M. Diaz Gomez,[49] F. Diblen,[18c] E. B. Diehl,[87] H. Dietl,[99] J. Dietrich,[48] T. A. Dietzsch,[58a] S. Diglio,[115] K. Dindar Yagci,[39] J. Dingfelder,[20] C. Dionisi,[132a,132b] P. Dita,[25a] S. Dita,[25a] F. Dittus,[29] F. Djama,[83] R. Djilkibaev,[108] T. Djobava,[51] M. A. B. do Vale,[23] A. Do Valle Wemans,[124a] T. K. O. Doan,[4] M. Dobbs,[85] R. Dobinson,[29,a] D. Dobos,[29] E. Dobson,[29] M. Dobson,[163] J. Dodd,[34] O. B. Dogan,[18a,a] C. Doglioni,[118] T. Doherty,[53] Y. Doi,[66] J. Dolejsi,[126] I. Dolenc,[74] Z. Dolezal,[126] B. A. Dolgoshein,[96] T. Dohmae,[155] M. Donega,[120] J. Donini,[55] J. Dopke,[174] A. Doria,[102a] A. Dos Anjos,[172] M. Dosil,[11] A. Dotti,[122a,122b] M. T. Dova,[70] J. D. Dowell,[17] A. Doxiadis,[105] A. T. Doyle,[53] Z. Drasal,[126] J. Drees,[174] N. Dressnandt,[120] H. Drevermann,[29] C. Driouichi,[35] M. Dris,[9] J. G. Drohan,[77] J. Dubbert,[99] T. Dubbs,[137] S. Dube,[14] E. Duchovni,[171] G. Duckeck,[98] A. Dudarev,[29] F. Dudziak,[115] M. Dührssen,[29] I. P. Duerdoth,[82] L. Duflot,[115] M-A. Dufour,[85] M. Dunford,[29] H. Duran Yildiz,[3b] A. Dushkin,[22] R. Duxfield,[139] M. Dwuznik,[37] F. Dydak,[29] D. Dzahini,[55] M. Düren,[52] W. L. Ebenstein,[44] J. Ebke,[98] S. Eckert,[48] S. Eckweiler,[81] K. Edmonds,[81] C. A. Edwards,[76] I. Efthymiopoulos,[49] K. Egorov,[61] W. Ehrenfeld,[41] T. Ehrich,[99] T. Eifert,[29] G. Eigen,[13] K. Einsweiler,[14] E. Eisenhandler,[75] T. Ekelof,[166] M. El Kacimi,[4] M. Ellert,[166] S. Elles,[4] F. Ellinghaus,[81] K. Ellis,[75] N. Ellis,[29] J. Elmsheuser,[98] M. Elsing,[29] R. Ely,[14] D. Emeliyanov,[129] R. Engelmann,[148] A. Engl,[98] B. Epp,[62] A. Eppig,[87] J. Erdmann,[54] A. Ereditato,[16] V. Eremin,[97] D. Eriksson,[146a] I. Ermoline,[88] J. Ernst,[1] M. Ernst,[24] J. Ernwein,[136]

D. Errede,[165] S. Errede,[165] E. Ertel,[81] M. Escalier,[115] C. Escobar,[167] X. Espinal Curull,[11] B. Esposito,[47] F. Etienne,[83] A. I. Etienvre,[136] E. Etzion,[153] H. Evans,[61] V. N. Evdokimov,[128] L. Fabbri,[19a,19b] C. Fabre,[29] K. Facius,[35] R. M. Fakhrutdinov,[128] S. Falciano,[132a] A. C. Falou,[115] Y. Fang,[172] M. Fanti,[89a,89b] A. Farbin,[7] A. Farilla,[134a] J. Farley,[148] T. Farooque,[158] S. M. Farrington,[118] P. Farthouat,[29] D. Fasching,[172] P. Fassnacht,[29] D. Fassouliotis,[8] B. Fatholahzadeh,[158] L. Fayard,[115] S. Fazio,[36a,36b] R. Febbraro,[33] P. Federic,[144a] O. L. Fedin,[121] I. Fedorko,[29] W. Fedorko,[29] M. Fehling-Kaschek,[48] L. Feligioni,[83] C. U. Felzmann,[86] C. Feng,[32d] E. J. Feng,[30] A. B. Fenyuk,[128] J. Ferencei,[144b] D. Ferguson,[172] J. Ferland,[93] B. Fernandes,[124a,n] W. Fernando,[109] S. Ferrag,[53] J. Ferrando,[118] V. Ferrara,[41] A. Ferrari,[166] P. Ferrari,[105] R. Ferrari,[119a] A. Ferrer,[167] M. L. Ferrer,[47] D. Ferrere,[49] C. Ferretti,[87] A. Ferretto Parodi,[50a,50b] F. Ferro,[50a,50b] M. Fiascaris,[118] F. Fiedler,[81] A. Filipčič,[74] A. Filippas,[9] F. Filthaut,[104] M. Fincke-Keeler,[169] M. C. N. Fiolhais,[124a,i] L. Fiorini,[11] A. Firan,[39] G. Fischer,[41] P. Fischer,[20] M. J. Fisher,[109] S. M. Fisher,[129] J. Flammer,[29] M. Flechl,[48] I. Fleck,[141] J. Fleckner,[81] P. Fleischmann,[173] S. Fleischmann,[20] T. Flick,[174] L. R. Flores Castillo,[172] M. J. Flowerdew,[99] F. Föhlisch,[58a] M. Fokitis,[9] T. Fonseca Martin,[16] J. Fopma,[118] D. A. Forbush,[138] A. Formica,[136] A. Forti,[82] D. Fortin,[159a] J. M. Foster,[82] D. Fournier,[115] A. Foussat,[29] A. J. Fowler,[44] K. Fowler,[137] H. Fox,[71] P. Francavilla,[122a,122b] S. Franchino,[119a,119b] D. Francis,[29] M. Franklin,[57] S. Franz,[29] M. Fraternali,[119a,119b] S. Fratina,[120] J. Freestone,[82] S. T. French,[27] R. Froeschl,[29] D. Froidevaux,[29] J. A. Frost,[27] C. Fukunaga,[156] E. Fullana Torregrosa,[5] J. Fuster,[167] C. Gabaldon,[80] O. Gabizon,[171] T. Gadfort,[24] S. Gadomski,[49] G. Gagliardi,[50a,50b] P. Gagnon,[61] C. Galea,[98] E. J. Gallas,[118] M. V. Gallas,[29] V. Gallo,[16] B. J. Gallop,[129] P. Gallus,[125] E. Galyaev,[40] K. K. Gan,[109] Y. S. Gao,[143,o] V. A. Gapienko,[128] A. Gaponenko,[14] M. Garcia-Sciveres,[14] C. García,[167] J. E. García Navarro,[49] R. W. Gardner,[30] N. Garelli,[29] H. Garitaonandia,[105] V. Garonne,[29] J. Garvey,[17] C. Gatti,[47] G. Gaudio,[119a] O. Gaumer,[49] V. Gautard,[136] P. Gauzzi,[132a,132b] I. L. Gavrilenko,[94] C. Gay,[168] G. Gaycken,[20] J-C. Gayde,[29] E. N. Gazis,[9] P. Ge,[32d] C. N. P. Gee,[129] Ch. Geich-Gimbel,[20] K. Gellerstedt,[146a,146b] C. Gemme,[50a] M. H. Genest,[98] S. Gentile,[132a,132b] F. Georgatos,[9] S. George,[76] P. Gerlach,[174] A. Gershon,[153] C. Geweniger,[58a] H. Ghazlane,[135c] P. Ghez,[4] N. Ghodbane,[33] B. Giacobbe,[19a] S. Giagu,[132a,132b] V. Giakoumopoulou,[8] V. Giangiobbe,[122a,122b] F. Gianotti,[29] B. Gibbard,[24] A. Gibson,[158] S. M. Gibson,[118] G. F. Gieraltowski,[5] L. M. Gilbert,[118] M. Gilchriese,[14] O. Gildemeister,[29] V. Gilewsky,[91] D. Gillberg,[28] A. R. Gillman,[129] D. M. Gingrich,[2,f] J. Ginzburg,[153] N. Giokaris,[8] M. P. Giordani,[164a,164c] R. Giordano,[102a,102b] F. M. Giorgi,[15] P. Giovannini,[99] P. F. Giraud,[136] P. Girtler,[62] D. Giugni,[89a] P. Giusti,[19a] B. K. Gjelsten,[117] L. K. Gladilin,[97] C. Glasman,[80] J Glatzer,[48] A. Glazov,[41] K. W. Glitza,[174] G. L. Glonti,[65] K. G. Gnanvo,[75] J. Godfrey,[142] J. Godlewski,[29] M. Goebel,[41] T. Göpfert,[43] C. Goeringer,[81] C. Gössling,[42] T. Göttfert,[99] V. Goggi,[119a,119b,p] S. Goldfarb,[87] D. Goldin,[39] T. Golling,[175] N. P. Gollub,[29] S. N. Golovnia,[128] A. Gomes,[124a,q] L. S. Gomez Fajardo,[41] R. Gonçalo,[76] L. Gonella,[20] C. Gong,[32b] A. Gonidec,[29] S. Gonzalez,[172] S. González de la Hoz,[167] M. L. Gonzalez Silva,[26] B. Gonzalez-Pineiro,[88] S. Gonzalez-Sevilla,[49] J. J. Goodson,[148] L. Goossens,[29] P. A. Gorbounov,[95] H. A. Gordon,[24] I. Gorelov,[103] G. Gorfine,[174] B. Gorini,[29] E. Gorini,[72a,72b] A. Gorišek,[74] E. Gornicki,[38] S. A. Gorokhov,[128] B. T. Gorski,[29] V. N. Goryachev,[128] B. Gosdzik,[41] M. Gosselink,[105] M. I. Gostkin,[65] M. Gouanère,[4] I. Gough Eschrich,[163] M. Gouighri,[135a] D. Goujdami,[135a] M. P. Goulette,[49] A. G. Goussiou,[138] C. Goy,[4] I. Grabowska-Bold,[163,g] V. Grabski,[176] P. Grafström,[29] C. Grah,[174] K-J. Grahn,[147] F. Grancagnolo,[72a] S. Grancagnolo,[15] V. Grassi,[148] V. Gratchev,[121] N. Grau,[34] H. M. Gray,[34,r] J. A. Gray,[148] E. Graziani,[134a] O. G. Grebenyuk,[121] B. Green,[76] D. Greenfield,[129] T. Greenshaw,[73] Z. D. Greenwood,[24,m] I. M. Gregor,[41] P. Grenier,[143] A. Grewal,[118] E. Griesmayer,[46] J. Griffiths,[138] N. Grigalashvili,[65] A. A. Grillo,[137] K. Grimm,[148] S. Grinstein,[11] P. L. Y. Gris,[33] Y. V. Grishkevich,[97] J.-F. Grivaz,[115] L. S. Groer,[158] J. Grognuz,[29] M. Groh,[99] M. Groll,[81] E. Gross,[171] J. Grosse-Knetter,[54] J. Groth-Jensen,[79] M. Gruwe,[29] K. Grybel,[141] V. J. Guarino,[5] C. Guicheney,[33] A. Guida,[72a,72b] T. Guillemin,[4] H. Guler,[85,s] J. Gunther,[125] B. Guo,[158] A. Gupta,[30] Y. Gusakov,[65] V. N. Gushchin,[128] A. Gutierrez,[93] P. Gutierrez,[111] N. Guttman,[153] O. Gutzwiller,[172] C. Guyot,[136] C. Gwenlan,[118] C. B. Gwilliam,[73] A. Haas,[143] S. Haas,[29] C. Haber,[14] G. Haboubi,[123] R. Hackenburg,[24] H. K. Hadavand,[39] D. R. Hadley,[17] C. Haeberli,[16] P. Haefner,[99] R. Härtel,[99] F. Hahn,[29] S. Haider,[29] Z. Hajduk,[38] H. Hakobyan,[176] J. Haller,[41,t] G. D. Hallewell,[83] K. Hamacher,[174] A. Hamilton,[49] S. Hamilton,[161] H. Han,[32a] L. Han,[32b] K. Hanagaki,[116] M. Hance,[120] C. Handel,[81] P. Hanke,[58a] C. J. Hansen,[166] J. R. Hansen,[35] J. B. Hansen,[35] J. D. Hansen,[35] P. H. Hansen,[35] T. Hansl-Kozanecka,[137] P. Hansson,[143] K. Hara,[160] G. A. Hare,[137] T. Harenberg,[174] R. Harper,[139] R. D. Harrington,[21] O. M. Harris,[138] K Harrison,[17] J. C. Hart,[129] J. Hartert,[48] F. Hartjes,[105] T. Haruyama,[66] A. Harvey,[56] S. Hasegawa,[101] Y. Hasegawa,[140] K. Hashemi,[22] S. Hassani,[136] M. Hatch,[29] D. Hauff,[99] S. Haug,[16] M. Hauschild,[29] R. Hauser,[88] M. Havranek,[125] B. M. Hawes,[118] C. M. Hawkes,[17] R. J. Hawkings,[29]

D. Hawkins,[163] T. Hayakawa,[67] H. S. Hayward,[73] S. J. Haywood,[129] E. Hazen,[21] M. He,[32d] S. J. Head,[17] V. Hedberg,[79] L. Heelan,[28] S. Heim,[88] B. Heinemann,[14] F. E. W. Heinemann,[118] S. Heisterkamp,[35] L. Helary,[4] M. Heldmann,[48] M. Heller,[115] S. Hellman,[146a,146b] C. Helsens,[11] T. Hemperek,[20] R. C. W. Henderson,[71] P. J. Hendriks,[105] M. Henke,[58a] A. Henrichs,[54] A. M. Henriques Correia,[29] S. Henrot-Versille,[115] F. Henry-Couannier,[83] C. Hensel,[54] T. Henß,[174] Y. Hernández Jiménez,[167] A. D. Hershenhorn,[152] G. Herten,[48] R. Hertenberger,[98] L. Hervas,[29] N. P. Hessey,[105] A. Hidvegi,[146a] E. Higón-Rodriguez,[167] D. Hill,[5,a] J. C. Hill,[27] N. Hill,[5] K. H. Hiller,[41] S. Hillert,[20] S. J. Hillier,[17] I. Hinchliffe,[14] D. Hindson,[118] E. Hines,[120] M. Hirose,[116] F. Hirsch,[42] D. Hirschbuehl,[174] J. Hobbs,[148] N. Hod,[153] M. C. Hodgkinson,[139] P. Hodgson,[139] A. Hoecker,[29] M. R. Hoeferkamp,[103] J. Hoffman,[39] D. Hoffmann,[83] M. Hohlfeld,[81] M. Holder,[141] T. I. Hollins,[17] G. Hollyman,[76] A. Holmes,[118] S. O. Holmgren,[146a] T. Holy,[127] J. L. Holzbauer,[88] R. J. Homer,[17] Y. Homma,[67] T. Horazdovsky,[127] C. Horn,[143] S. Horner,[48] S. Horvat,[99] J-Y. Hostachy,[55] T. Hott,[99] S. Hou,[151] M. A. Houlden,[73] A. Hoummada,[135a] D. F. Howell,[118] J. Hrivnac,[115] I. Hruska,[125] T. Hryn'ova,[4] P. J. Hsu,[175] S.-C. Hsu,[14] G. S. Huang,[111] Z. Hubacek,[127] F. Hubaut,[83] F. Huegging,[20] T. B. Huffman,[118] E. W. Hughes,[34] G. Hughes,[71] R. E. Hughes-Jones,[82] M. Huhtinen,[29] P. Hurst,[57] M. Hurwitz,[30] U. Husemann,[41] N. Huseynov,[10] J. Huston,[88] J. Huth,[57] G. Iacobucci,[102a] G. Iakovidis,[9] M. Ibbotson,[82] I. Ibragimov,[141] R. Ichimiya,[67] L. Iconomidou-Fayard,[115] J. Idarraga,[159b] M. Idzik,[37] P. Iengo,[4] O. Igonkina,[105] Y. Ikegami,[66] M. Ikeno,[66] Y. Ilchenko,[39] D. Iliadis,[154] D. Imbault,[78] M. Imhaeuser,[174] M. Imori,[155] T. Ince,[20] J. Inigo-Golfin,[29] P. Ioannou,[8] M. Iodice,[134a] G. Ionescu,[4] A. Irles Quiles,[167] K. Ishii,[66] A. Ishikawa,[67] M. Ishino,[66] R. Ishmukhametov,[39] T. Isobe,[155] V. Issakov,[175,a] C. Issever,[118] S. Istin,[18a] Y. Itoh,[101] A. V. Ivashin,[128] W. Iwanski,[38] H. Iwasaki,[66] J. M. Izen,[40] V. Izzo,[102a] B. Jackson,[120] J. N. Jackson,[73] P. Jackson,[143] M. R. Jaekel,[29] M. Jahoda,[125] V. Jain,[61] K. Jakobs,[48] S. Jakobsen,[35] J. Jakubek,[127] D. K. Jana,[111] E. Jankowski,[158] E. Jansen,[77] A. Jantsch,[99] M. Janus,[20] R. C. Jared,[172] G. Jarlskog,[79] L. Jeanty,[57] K. Jelen,[37] I. Jen-La Plante,[30] P. Jenni,[29] A. Jeremie,[4] P. Jež,[35] S. Jézéquel,[4] H. Ji,[172] W. Ji,[79] J. Jia,[148] Y. Jiang,[32b] M. Jimenez Belenguer,[29] G. Jin,[32b] S. Jin,[32a] O. Jinnouchi,[157] D. Joffe,[39] L. G. Johansen,[13] M. Johansen,[146a,146b] K. E. Johansson,[146a] P. Johansson,[139] S. Johnert,[41] K. A. Johns,[6] K. Jon-And,[146a,146b] G. Jones,[82] M. Jones,[118] R. W. L. Jones,[71] T. W. Jones,[77] T. J. Jones,[73] O. Jonsson,[29] K. K. Joo,[158,u] D. Joos,[48] C. Joram,[29] P. M. Jorge,[124a,d] S. Jorgensen,[11] J. Joseph,[14] V. Juranek,[125] P. Jussel,[62] V. V. Kabachenko,[128] S. Kabana,[16] M. Kaci,[167] A. Kaczmarska,[38] P. Kadlecik,[35] M. Kado,[115] H. Kagan,[109] M. Kagan,[57] S. Kaiser,[99] E. Kajomovitz,[152] S. Kalinin,[174] L. V. Kalinovskaya,[65] S. Kama,[39] N. Kanaya,[155] M. Kaneda,[155] V. A. Kantserov,[96] J. Kanzaki,[66] B. Kaplan,[175] A. Kapliy,[30] J. Kaplon,[29] D. Kar,[43] M. Karagounis,[20] M. Karagoz,[118] M. Karnevskiy,[41] K. Karr,[5] V. Kartvelishvili,[71] A. N. Karyukhin,[128] L. Kashif,[57] A. Kasmi,[39] R. D. Kass,[109] A. Kastanas,[13] M. Kastoryano,[175] M. Kataoka,[4] Y. Kataoka,[155] E. Katsoufis,[9] J. Katzy,[41] V. Kaushik,[6] K. Kawagoe,[67] T. Kawamoto,[155] G. Kawamura,[81] M. S. Kayl,[105] F. Kayumov,[94] V. A. Kazanin,[107] M. Y. Kazarinov,[65] S. I. Kazi,[86] J. R. Keates,[82] R. Keeler,[169] P. T. Keener,[120] R. Kehoe,[39] M. Keil,[54] G. D. Kekelidze,[65] M. Kelly,[82] J. Kennedy,[98] C. J. Kenney,[143] M. Kenyon,[53] O. Kepka,[125] N. Kerschen,[29] B. P. Kerševan,[74] S. Kersten,[174] K. Kessoku,[155] C. Ketterer,[48] M. Khakzad,[28] F. Khalil-zada,[10] H. Khandanyan,[165] A. Khanov,[112] D. Kharchenko,[65] A. Khodinov,[148] A. G. Kholodenko,[128] A. Khomich,[58a] G. Khoriauli,[20] N. Khovanskiy,[65] V. Khovanskiy,[95] E. Khramov,[65] J. Khubua,[51] G. Kilvington,[76] H. Kim,[7] M. S. Kim,[2] P. C. Kim,[143] S. H. Kim,[160] N. Kimura,[170] O. Kind,[15] P. Kind,[174] B. T. King,[73] M. King,[67] J. Kirk,[129] G. P. Kirsch,[118] L. E. Kirsch,[22] A. E. Kiryunin,[99] D. Kisielewska,[37] B. Kisielewski,[38] T. Kittelmann,[123] A. M. Kiver,[128] H. Kiyamura,[67] E. Kladiva,[144b] J. Klaiber-Lodewigs,[42] M. Klein,[73] U. Klein,[73] K. Kleinknecht,[81] M. Klemetti,[85] A. Klier,[171] A. Klimentov,[24] R. Klingenberg,[42] E. B. Klinkby,[44] T. Klioutchnikova,[29] P. F. Klok,[104] S. Klous,[105] E.-E. Kluge,[58a] T. Kluge,[73] P. Kluit,[105] S. Kluth,[99] N. S. Knecht,[158] E. Kneringer,[62] J. Knobloch,[29] B. R. Ko,[44] T. Kobayashi,[155] M. Kobel,[43] B. Koblitz,[29] M. Kocian,[143] A. Kocnar,[113] P. Kodys,[126] K. Köneke,[29] A. C. König,[104] S. Koenig,[81] S. König,[48] L. Köpke,[81] F. Koetsveld,[104] P. Koevesarki,[20] T. Koffas,[29] E. Koffeman,[105] F. Kohn,[54] Z. Kohout,[127] T. Kohriki,[66] T. Koi,[143] T. Kokott,[20] G. M. Kolachev,[107] H. Kolanoski,[15] V. Kolesnikov,[65] I. Koletsou,[4] J. Koll,[88] D. Kollar,[29] M. Kollefrath,[48] S. Kolos,[163,v] S. D. Kolya,[82] A. A. Komar,[94] J. R. Komaragiri,[142] T. Kondo,[66] T. Kono,[41,t] A. I. Kononov,[48] R. Konoplich,[108] S. P. Konovalov,[94] N. Konstantinidis,[77] A. Kootz,[174] S. Koperny,[37] S. V. Kopikov,[128] K. Korcyl,[38] K. Kordas,[154] V. Koreshev,[128] A. Korn,[14] A. Korol,[107] I. Korolkov,[11] E. V. Korolkova,[139] V. A. Korotkov,[128] O. Kortner,[99] P. Kostka,[41] V. V. Kostyukhin,[20] M. J. Kotamäki,[29] S. Kotov,[99] V. M. Kotov,[65] K. Y. Kotov,[107] C. Kourkoumelis,[8] A. Koutsman,[105] R. Kowalewski,[169] H. Kowalski,[41] T. Z. Kowalski,[37] W. Kozanecki,[136] A. S. Kozhin,[128] V. Kral,[127] V. A. Kramarenko,[97] G. Kramberger,[74] O. Krasel,[42] M. W. Krasny,[78] A. Krasznahorkay,[108] J. Kraus,[88] A. Kreisel,[153] F. Krejci,[127] J. Kretzschmar,[73] N. Krieger,[54]

P. Krieger,[158] G. Krobath,[98] K. Kroeninger,[54] H. Kroha,[99] J. Kroll,[120] J. Kroseberg,[20] J. Krstic,[12a] U. Kruchonak,[65] H. Krüger,[20] Z. V. Krumshteyn,[65] A. Kruth,[20] T. Kubota,[155] S. Kuehn,[48] A. Kugel,[58c] T. Kuhl,[174] D. Kuhn,[62] V. Kukhtin,[65] Y. Kulchitsky,[90] S. Kuleshov,[31b] C. Kummer,[98] M. Kuna,[83] N. Kundu,[118] J. Kunkle,[120] A. Kupco,[125] H. Kurashige,[67] M. Kurata,[160] L. L. Kurchaninov,[159a] Y. A. Kurochkin,[90] V. Kus,[125] W. Kuykendall,[138] M. Kuze,[157] P. Kuzhir,[91] O. Kvasnicka,[125] R. Kwee,[15] A. La Rosa,[29] L. La Rotonda,[36a,36b] L. Labarga,[80] J. Labbe,[4] C. Lacasta,[167] F. Lacava,[132a,132b] H. Lacker,[15] D. Lacour,[78] V. R. Lacuesta,[167] E. Ladygin,[65] R. Lafaye,[4] B. Laforge,[78] T. Lagouri,[80] S. Lai,[48] M. Lamanna,[29] M. Lambacher,[98] C. L. Lampen,[6] W. Lampl,[6] E. Lancon,[136] U. Landgraf,[48] M. P. J. Landon,[75] H. Landsman,[152] J. L. Lane,[82] C. Lange,[41] A. J. Lankford,[163] F. Lanni,[24] K. Lantzsch,[29] A. Lanza,[119a] V. V. Lapin,[128,a] S. Laplace,[4] C. Lapoire,[83] J. F. Laporte,[136] T. Lari,[89a] A. V. Larionov,[128] A. Larner,[118] C. Lasseur,[29] M. Lassnig,[29] W. Lau,[118] P. Laurelli,[47] A. Lavorato,[118] W. Lavrijsen,[14] P. Laycock,[73] A. B. Lazarev,[65] A. Lazzaro,[89a,89b] O. Le Dortz,[78] E. Le Guirriec,[83] C. Le Maner,[158] E. Le Menedeu,[136] M. Le Vine,[24] M. Leahu,[29] A. Lebedev,[64] C. Lebel,[93] M. Lechowski,[115] T. LeCompte,[5] F. Ledroit-Guillon,[55] H. Lee,[105] J. S. H. Lee,[150] S. C. Lee,[151] M. Lefebvre,[169] M. Legendre,[136] A. Leger,[49] B. C. LeGeyt,[120] F. Legger,[98] C. Leggett,[14] M. Lehmacher,[20] G. Lehmann Miotto,[29] M. Lehto,[139] X. Lei,[6] R. Leitner,[126] D. Lellouch,[171] J. Lellouch,[78] M. Leltchouk,[34] V. Lendermann,[58a] K. J. C. Leney,[73] T. Lenz,[174] G. Lenzen,[174] B. Lenzi,[136] K. Leonhardt,[43] J. Lepidis,[174] C. Leroy,[93] J-R. Lessard,[169] J. Lesser,[146a] C. G. Lester,[27] A. Leung Fook Cheong,[172] J. Levêque,[83] D. Levin,[87] L. J. Levinson,[171] M. S. Levitski,[128] M. Lewandowska,[21] M. Leyton,[15] H. Li,[172] X. Li,[87] Z. Liang,[39] Z. Liang,[118,w] B. Liberti,[133a] P. Lichard,[29] M. Lichtnecker,[98] K. Lie,[165] W. Liebig,[173] R. Lifshitz,[152] J. N. Lilley,[17] H. Lim,[5] A. Limosani,[86] M. Limper,[63] S. C. Lin,[151] F. Linde,[105] J. T. Linnemann,[88] E. Lipeles,[120] L. Lipinsky,[125] A. Lipniacka,[13] T. M. Liss,[165] D. Lissauer,[24] A. Lister,[49] A. M. Litke,[137] C. Liu,[28] D. Liu,[151,x] H. Liu,[87] J. B. Liu,[87] M. Liu,[32b] S. Liu,[2] T. Liu,[39] Y. Liu,[32b] M. Livan,[119a,119b] S. S. A. Livermore,[118] A. Lleres,[55] S. L. Lloyd,[75] E. Lobodzinska,[41] P. Loch,[6] W. S. Lockman,[137] S. Lockwitz,[175] T. Loddenkoetter,[20] F. K. Loebinger,[82] A. Loginov,[175] C. W. Loh,[168] T. Lohse,[15] K. Lohwasser,[48] M. Lokajicek,[125] J. Loken,[118] R. E. Long,[71] L. Lopes,[124a,d] D. Lopez Mateos,[34,r] M. Losada,[162] P. Loscutoff,[14] M. J. Losty,[159a] X. Lou,[40] A. Lounis,[115] K. F. Loureiro,[162] L. Lovas,[144a] J. Love,[21] P. A. Love,[71] A. J. Lowe,[143] F. Lu,[32a] J. Lu,[2] L. Lu,[39] H. J. Lubatti,[138] C. Luci,[132a,132b] A. Lucotte,[55] A. Ludwig,[43] D. Ludwig,[41] I. Ludwig,[48] J. Ludwig,[48] F. Luehring,[61] G. Luijckx,[105] D. Lumb,[48] L. Luminari,[132a] E. Lund,[117] B. Lund-Jensen,[147] B. Lundberg,[79] J. Lundberg,[29] J. Lundquist,[35] A. Lupi,[122a,122b] G. Lutz,[99] D. Lynn,[24] J. Lynn,[118] J. Lys,[14] E. Lytken,[79] H. Ma,[24] L. L. Ma,[172] M. Maaßen,[48] J. A. Macana Goia,[93] G. Maccarrone,[47] A. Macchiolo,[99] B. Maček,[74] J. Machado Miguens,[124a,d] D. Macina,[49] R. Mackeprang,[35] D. MacQueen,[2] R. J. Madaras,[14] W. F. Mader,[43] R. Maenner,[58c] T. Maeno,[24] P. Mättig,[174] S. Mättig,[41] P. J. Magalhaes Martins,[124a,i] L. Magnoni,[29] E. Magradze,[51] C. A. Magrath,[104] Y. Mahalalel,[153] K. Mahboubi,[48] A. Mahmood,[1] G. Mahout,[17] C. Maiani,[132a,132b] C. Maidantchik,[23] A. Maio,[124a,q] S. Majewski,[24] Y. Makida,[66] M. Makouski,[128] N. Makovec,[115] P. Mal,[6] Pa. Malecki,[38] P. Malecki,[38] V. P. Maleev,[121] F. Malek,[55] U. Mallik,[63] D. Malon,[5] S. Maltezos,[9] V. Malyshev,[107] S. Malyukov,[65] M. Mambelli,[30] R. Mameghani,[98] J. Mamuzic,[41] A. Manabe,[66] A. Manara,[61] L. Mandelli,[89a] I. Mandić,[74] R. Mandrysch,[15] J. Maneira,[124a] P. S. Mangeard,[88] M. Mangin-Brinet,[49] I. D. Manjavidze,[65] A. Mann,[54] W. A. Mann,[161] P. M. Manning,[137] A. Manousakis-Katsikakis,[8] B. Mansoulie,[136] A. Manz,[99] A. Mapelli,[29] L. Mapelli,[29] L. March,[80] J. F. Marchand,[4] F. Marchese,[133a,133b] M. Marchesotti,[29] G. Marchiori,[78] M. Marcisovsky,[125] A. Marin,[21,a] C. P. Marino,[61] F. Marroquim,[23] R. Marshall,[82] Z. Marshall,[34,r] F. K. Martens,[158] S. Marti-Garcia,[167] A. J. Martin,[75] A. J. Martin,[175] B. Martin,[29] B. Martin,[88] F. F. Martin,[120] J. P. Martin,[93] Ph. Martin,[55] T. A. Martin,[17] B. Martin dit Latour,[49] M. Martinez,[11] V. Martinez Outschoorn,[57] A. Martini,[47] A. C. Martyniuk,[82] F. Marzano,[132a] A. Marzin,[136] L. Masetti,[81] T. Mashimo,[155] R. Mashinistov,[94] J. Masik,[82] A. L. Maslennikov,[107] M. Maß,[42] I. Massa,[19a,19b] G. Massaro,[105] N. Massol,[4] A. Mastroberardino,[36a,36b] T. Masubuchi,[155] M. Mathes,[20] P. Matricon,[115] H. Matsumoto,[155] H. Matsunaga,[155] T. Matsushita,[67] C. Mattravers,[118,y] J. M. Maugain,[29] S. J. Maxfield,[73] E. N. May,[5] J. K. Mayer,[158] A. Mayne,[139] R. Mazini,[151] M. Mazur,[20] M. Mazzanti,[89a] E. Mazzoni,[122a,122b] J. Mc Donald,[85] S. P. Mc Kee,[87] A. McCarn,[165] R. L. McCarthy,[148] T. G. McCarthy,[28] N. A. McCubbin,[129] K. W. McFarlane,[56] S. McGarvie,[76] H. McGlone,[53] G. Mchedlidze,[51] R. A. McLaren,[29] S. J. McMahon,[129] T. R. McMahon,[76] T. J. McMahon,[17] R. A. McPherson,[169,l] A. Meade,[84] J. Mechnich,[105] M. Mechtel,[174] M. Medinnis,[41] R. Meera-Lebbai,[111] T. Meguro,[116] R. Mehdiyev,[93] S. Mehlhase,[41] A. Mehta,[73] K. Meier,[58a] J. Meinhardt,[48] B. Meirose,[48] C. Melachrinos,[30] B. R. Mellado Garcia,[172] L. Mendoza Navas,[162] Z. Meng,[151,x] A. Mengarelli,[19a,19b] S. Menke,[99] C. Menot,[29] E. Meoni,[11] D. Merkl,[98] P. Mermod,[118] L. Merola,[102a,102b] C. Meroni,[89a] F. S. Merritt,[30]

A. M. Messina,[29] I. Messmer,[48] J. Metcalfe,[103] A. S. Mete,[64] S. Meuser,[20] C. Meyer,[81] J-P. Meyer,[136] J. Meyer,[173] J. Meyer,[54] T. C. Meyer,[29] W. T. Meyer,[64] J. Miao,[32d] S. Michal,[29] L. Micu,[25a] R. P. Middleton,[129] P. Miele,[29] S. Migas,[73] A. Migliaccio,[102a,102b] L. Mijović,[41] G. Mikenberg,[171] M. Mikestikova,[125] B. Mikulec,[49] M. Mikuž,[74] D. W. Miller,[143] R. J. Miller,[88] W. J. Mills,[168] C. Mills,[57] A. Milov,[171] D. A. Milstead,[146a,146b] D. Milstein,[171] S. Mima,[110] A. A. Minaenko,[128] M. Miñano,[167] I. A. Minashvili,[65] A. I. Mincer,[108] B. Mindur,[37] M. Mineev,[65] Y. Ming,[130] L. M. Mir,[11] G. Mirabelli,[132a] L. Miralles Verge,[11] S. Misawa,[24] S. Miscetti,[47] A. Misiejuk,[76] A. Mitra,[118] J. Mitrevski,[137] G. Y. Mitrofanov,[128] V. A. Mitsou,[167] S. Mitsui,[66] P. S. Miyagawa,[82] K. Miyazaki,[67] J. U. Mjörnmark,[79] D. Mladenov,[22] T. Moa,[146a,146b] M. Moch,[132a,132b] P. Mockett,[138] S. Moed,[57] V. Moeller,[27] K. Mönig,[41] N. Möser,[20] B. Mohn,[13] W. Mohr,[48] S. Mohrdieck-Möck,[99] A. M. Moisseev,[128,a] R. Moles-Valls,[167] J. Molina-Perez,[29] L. Moneta,[49] J. Monk,[77] E. Monnier,[83] S. Montesano,[89a,89b] F. Monticelli,[70] R. W. Moore,[2] G. F. Moorhead,[86] C. Mora Herrera,[49] A. Moraes,[53] A. Morais,[124a,d] J. Morel,[54] G. Morello,[36a,36b] D. Moreno,[81] M. Moreno Llácer,[167] P. Morettini,[50a] D. Morgan,[139] M. Morii,[57] J. Morin,[75] Y. Morita,[66] A. K. Morley,[29] G. Mornacchi,[29] M-C. Morone,[49] S. V. Morozov,[96] J. D. Morris,[75] H. G. Moser,[99] M. Mosidze,[51] J. Moss,[109] A. Moszczynski,[38] R. Mount,[143] E. Mountricha,[9] S. V. Mouraviev,[94] T. H. Moye,[17] E. J. W. Moyse,[84] M. Mudrinic,[12b] F. Mueller,[58a] J. Mueller,[123] K. Mueller,[20] T. A. Müller,[98] D. Muenstermann,[42] A. Muijs,[105] A. Muir,[168] A. Munar,[120] Y. Munwes,[153] K. Murakami,[66] R. Murillo Garcia,[163] W. J. Murray,[129] I. Mussche,[105] E. Musto,[102a,102b] A. G. Myagkov,[128] M. Myska,[125] J. Nadal,[11] K. Nagai,[160] K. Nagano,[66] Y. Nagasaka,[60] A. M. Nairz,[29] D. Naito,[110] K. Nakamura,[155] I. Nakano,[110] G. Nanava,[20] A. Napier,[161] M. Nash,[77,y] I. Nasteva,[82] N. R. Nation,[21] T. Nattermann,[20] T. Naumann,[41] F. Nauyock,[82] G. Navarro,[162] S. K. Nderitu,[85] H. A. Neal,[87] E. Nebot,[80] P. Nechaeva,[94] A. Negri,[119a,119b] G. Negri,[29] S. Negroni,[34] A. Nelson,[64] S. Nelson,[143] T. K. Nelson,[143] S. Nemecek,[125] P. Nemethy,[108] A. A. Nepomuceno,[23] M. Nessi,[29] S. Y. Nesterov,[121] M. S. Neubauer,[165] L. Neukermans,[4] A. Neusiedl,[81] R. M. Neves,[108] P. Nevski,[24] F. M. Newcomer,[120] C. Nicholson,[53] R. B. Nickerson,[118] R. Nicolaidou,[136] L. Nicolas,[139] G. Nicoletti,[47] B. Nicquevert,[29] F. Niedercorn,[115] J. Nielsen,[137] T. Niinikoski,[29] A. Nikiforov,[15] V. Nikolaenko,[128] K. Nikolaev,[65] I. Nikolic-Audit,[78] K. Nikolopoulos,[24] H. Nilsen,[48] P. Nilsson,[7] Y. Ninomiya,[155] A. Nisati,[132a] T. Nishiyama,[67] R. Nisius,[99] L. Nodulman,[5] M. Nomachi,[116] I. Nomidis,[154] H. Nomoto,[155] M. Nordberg,[29] B. Nordkvist,[146a,146b] O. Norniella Francisco,[11] P. R. Norton,[129] D. Notz,[41] J. Novakova,[126] M. Nozaki,[66] M. Nožička,[41] I. M. Nugent,[159a] A.-E. Nuncio-Quiroz,[20] G. Nunes Hanninger,[20] T. Nunnemann,[98] E. Nurse,[77] T. Nyman,[29] S. W. O'Neale,[17,a] D. C. O'Neil,[142] V. O'Shea,[53] F. G. Oakham,[28,f] H. Oberlack,[99] J. Ocariz,[78] A. Ochi,[67] S. Oda,[155] S. Odaka,[66] J. Odier,[83] G. A. Odino,[50a,50b] H. Ogren,[61] A. Oh,[82] S. H. Oh,[44] C. C. Ohm,[146a,146b] T. Ohshima,[101] H. Ohshita,[140] T. K. Ohska,[66] T. Ohsugi,[59] S. Okada,[67] H. Okawa,[163] Y. Okumura,[101] T. Okuyama,[155] M. Olcese,[50a] A. G. Olchevski,[65] M. Oliveira,[124a,i] D. Oliveira Damazio,[24] C. Oliver,[80] J. Oliver,[57] E. Oliver Garcia,[167] D. Olivito,[120] A. Olszewski,[38] J. Olszowska,[38] C. Omachi,[67,z] A. Onofre,[124a,aa] P. U. E. Onyisi,[30] C. J. Oram,[159a] G. Ordonez,[104] M. J. Oreglia,[30] F. Orellana,[49] Y. Oren,[153] D. Orestano,[134a,134b] I. Orlov,[107] C. Oropeza Barrera,[53] R. S. Orr,[158] E. O. Ortega,[130] B. Osculati,[50a,50b] R. Ospanov,[120] C. Osuna,[11] G. Otero y Garzon,[26] J. P. Ottersbach,[105] B. Ottewell,[118] M. Ouchrif,[135b] F. Ould-Saada,[117] A. Ouraou,[136] Q. Ouyang,[32a] M. Owen,[82] S. Owen,[139] A Oyarzun,[31b] O. K. Øye,[13] V. E. Ozcan,[77] K. Ozone,[66] N. Ozturk,[7] A. Pacheco Pages,[11] C. Padilla Aranda,[11] E. Paganis,[139] F. Paige,[24] K. Pajchel,[117] S. Palestini,[29] J. Palla,[29] D. Pallin,[33] A. Palma,[124a,d] J. D. Palmer,[17] M. J. Palmer,[27] Y. B. Pan,[172] E. Panagiotopoulou,[9] B. Panes,[31a] N. Panikashvili,[87] V. N. Panin,[107] S. Panitkin,[24] D. Pantea,[25a] M. Panuskova,[125] V. Paolone,[123] A. Paoloni,[133a,133b] Th. D. Papadopoulou,[9] A. Paramonov,[5] S. J. Park,[54] W. Park,[24,bb] M. A. Parker,[27] S. I. Parker,[14] F. Parodi,[50a,50b] J. A. Parsons,[34] U. Parzefall,[48] E. Pasqualucci,[132a] A. Passeri,[134a] F. Pastore,[134a,134b] Fr. Pastore,[29] G. Pásztor,[49,cc] S. Pataraia,[172] N. Patel,[150] J. R. Pater,[82] S. Patricelli,[102a,102b] T. Pauly,[29] L. S. Peak,[150] M. Pecsy,[144a] M. I. Pedraza Morales,[172] S. J. M. Peeters,[105] S. V. Peleganchuk,[107] H. Peng,[172] R. Pengo,[29] A. Penson,[34] J. Penwell,[61] M. Perantoni,[23] K. Perez,[34,r] E. Perez Codina,[11] M. T. Pérez García-Estañ,[167] V. Perez Reale,[34] I. Peric,[20] L. Perini,[89a,89b] H. Pernegger,[29] R. Perrino,[72a] P. Perrodo,[4] S. Persembe,[3a] P. Perus,[115] V. D. Peshekhonov,[65] E. Petereit,[5] O. Peters,[105] B. A. Petersen,[29] J. Petersen,[29] T. C. Petersen,[35] E. Petit,[83] C. Petridou,[154] E. Petrolo,[132a] F. Petrucci,[134a,134b] D Petschull,[41] M. Petteni,[142] R. Pezoa,[31b] B. Pfeifer,[48] A. Phan,[86] A. W. Phillips,[27] G. Piacquadio,[29] E. Piccaro,[75] M. Piccinini,[19a,19b] A. Pickford,[53] R. Piegaia,[26] J. E. Pilcher,[30] A. D. Pilkington,[82] J. Pina,[124a,q] M. Pinamonti,[164a,164c] J. L. Pinfold,[2] J. Ping,[32c] B. Pinto,[124a,d] O. Pirotte,[29] C. Pizio,[89a,89b] R. Placakyte,[41] M. Plamondon,[169] W. G. Plano,[82] M.-A. Pleier,[24] A. V. Pleskach,[128] A. Poblaguev,[175] S. Poddar,[58a] F. Podlyski,[33] P. Poffenberger,[169] L. Poggioli,[115] T. Poghosyan,[20] M. Pohl,[49] F. Polci,[55] G. Polesello,[119a]

A. Policicchio,[138] A. Polini,[19a] J. Poll,[75] V. Polychronakos,[24] D. M. Pomarede,[136] D. Pomeroy,[22] K. Pommès,[29] P. Ponsot,[136] L. Pontecorvo,[132a] B. G. Pope,[88] G. A. Popeneciu,[25a] R. Popescu,[24] D. S. Popovic,[12a] A. Poppleton,[29] J. Popule,[125] X. Portell Bueso,[48] R. Porter,[163] C. Posch,[21] G. E. Pospelov,[99] S. Pospisil,[127] M. Potekhin,[24] I. N. Potrap,[99] C. J. Potter,[149] C. T. Potter,[85] K. P. Potter,[82] G. Poulard,[29] J. Poveda,[172] R. Prabhu,[20] P. Pralavorio,[83] S. Prasad,[57] M. Prata,[119a,119b] R. Pravahan,[7] K. Pretzl,[16] L. Pribyl,[29] D. Price,[61] L. E. Price,[5] M. J. Price,[29] P. M. Prichard,[73] D. Prieur,[123] M. Primavera,[72a] K. Prokofiev,[29] F. Prokoshin,[31b] S. Protopopescu,[24] J. Proudfoot,[5] X. Prudent,[43] H. Przysiezniak,[4] S. Psoroulas,[20] E. Ptacek,[114] C. Puigdengoles,[11] J. Purdham,[87] M. Purohit,[24,dd] P. Puzo,[115] Y. Pylypchenko,[117] M. Qi,[32c] J. Qian,[87] W. Qian,[129] Z. Qian,[83] Z. Qin,[41] D. Qing,[151,ee] A. Quadt,[54] D. R. Quarrie,[14] W. B. Quayle,[172] F. Quinonez,[31a] M. Raas,[104] V. Radeka,[24] V. Radescu,[58b] B. Radics,[20] T. Rador,[18a] F. Ragusa,[89a,89b] G. Rahal,[177] A. M. Rahimi,[109] D. Rahm,[24] C. Raine,[53,a] B. Raith,[20] S. Rajagopalan,[24] S. Rajek,[42] M. Rammensee,[48] M. Rammes,[141] M. Ramstedt,[146a,146b] P. N. Ratoff,[71] F. Rauscher,[98] E. Rauter,[99] M. Raymond,[29] A. L. Read,[117] D. M. Rebuzzi,[119a,119b] A. Redelbach,[173] G. Redlinger,[24] R. Reece,[120] K. Reeves,[40] A. Reichold,[105] E. Reinherz-Aronis,[153] A Reinsch,[114] I. Reisinger,[42] D. Reljic,[12a] C. Rembser,[29] Z. L. Ren,[151] P. Renkel,[39] B. Rensch,[35] S. Rescia,[24] M. Rescigno,[132a] S. Resconi,[89a] B. Resende,[136] P. Reznicek,[126] R. Rezvani,[158] A. Richards,[77] R. A. Richards,[88] R. Richter,[99] E. Richter-Was,[38,ff] M. Ridel,[78] S. Rieke,[81] M. Rijpstra,[105] M. Rijssenbeek,[148] A. Rimoldi,[119a,119b] L. Rinaldi,[19a] R. R. Rios,[39] I. Riu,[11] G. Rivoltella,[89a,89b] F. Rizatdinova,[112] E. Rizvi,[75] D. A. Roa Romero,[162] S. H. Robertson,[85,l] A. Robichaud-Veronneau,[49] D. Robinson,[27] JEM Robinson,[77] M. Robinson,[114] A. Robson,[53] J. G. Rocha de Lima,[106] C. Roda,[122a,122b] D. Roda Dos Santos,[29] S. Rodier,[80] D. Rodriguez,[162] Y. Rodriguez Garcia,[15] S. Roe,[29] O. Røhne,[117] V. Rojo,[1] S. Rolli,[161] A. Romaniouk,[96] V. M. Romanov,[65] G. Romeo,[26] D. Romero Maltrana,[31a] L. Roos,[78] E. Ros,[167] S. Rosati,[138] G. A. Rosenbaum,[158] E. I. Rosenberg,[64] P. L. Rosendahl,[13] L. Rosselet,[49] V. Rossetti,[11] L. P. Rossi,[50a] L. Rossi,[89a,89b] M. Rotaru,[25a] J. Rothberg,[138] I. Rottländer,[20] D. Rousseau,[115] C. R. Royon,[136] A. Rozanov,[83] Y. Rozen,[152] X. Ruan,[115] B. Ruckert,[98] N. Ruckstuhl,[105] V. I. Rud,[97] G. Rudolph,[62] F. Rühr,[6] F. Ruggieri,[134a] A. Ruiz-Martinez,[64] E. Rulikowska-Zarebska,[37] V. Rumiantsev,[91,a] L. Rumyantsev,[65] K. Runge,[48] O. Runolfsson,[20] Z. Rurikova,[48] N. A. Rusakovich,[65] D. R. Rust,[61] J. P. Rutherfoord,[6] C. Ruwiedel,[20] P. Ruzicka,[125] Y. F. Ryabov,[121] V. Ryadovikov,[128] P. Ryan,[88] G. Rybkin,[115] S. Rzaeva,[10] A. F. Saavedra,[150] H. F-W. Sadrozinski,[137] R. Sadykov,[65] F. Safai Tehrani,[132a,132b] H. Sakamoto,[155] P. Sala,[89a] G. Salamanna,[105] A. Salamon,[133a] M. Saleem,[111] D. Salihagic,[99] A. Salnikov,[143] J. Salt,[167] O. Saltó Bauza,[11] B. M. Salvachua Ferrando,[5] D. Salvatore,[36a,36b] F. Salvatore,[149] A. Salvucci,[47] A. Salzburger,[29] D. Sampsonidis,[154] B. H. Samset,[117] H. Sandaker,[13] H. G. Sander,[81] M. P. Sanders,[98] M. Sandhoff,[174] P. Sandhu,[158] T. Sandoval,[27] R. Sandstroem,[105] S. Sandvoss,[174] D. P. C. Sankey,[129] B. Sanny,[174] A. Sansoni,[47] C. Santamarina Rios,[85] C. Santoni,[33] R. Santonico,[133a,133b] H. Santos,[124a] J. G. Saraiva,[124a,q] T. Sarangi,[172] E. Sarkisyan-Grinbaum,[7] F. Sarri,[122a,122b] G. Sartisohn,[174] O. Sasaki,[66] T. Sasaki,[66] N. Sasao,[68] I. Satsounkevitch,[90] G. Sauvage,[4] P. Savard,[158,f] A. Y. Savine,[6] V. Savinov,[123] P. Savva,[9] L. Sawyer,[24,m] D. H. Saxon,[53] L. P. Says,[33] C. Sbarra,[19a,19b] A. Sbrizzi,[19a,19b] O. Scallon,[93] D. A. Scannicchio,[29] J. Schaarschmidt,[43] P. Schacht,[99] U. Schäfer,[81] S. Schaetzel,[58b] A. C. Schaffer,[115] D. Schaile,[98] M. Schaller,[29] R. D. Schamberger,[148] A. G. Schamov,[107] V. Scharf,[58a] V. A. Schegelsky,[121] D. Scheirich,[87] M. Schernau,[163] M. I. Scherzer,[14] C. Schiavi,[50a,50b] J. Schieck,[99] M. Schioppa,[36a,36b] S. Schlenker,[29] J. L. Schlereth,[5] E. Schmidt,[48] M. P. Schmidt,[175,a] K. Schmieden,[20] C. Schmitt,[81] M. Schmitz,[20] R. C. Scholte,[105] A. Schöning,[58b] M. Schott,[29] D. Schouten,[142] J. Schovancova,[125] M. Schram,[85] A. Schreiner,[63] C. Schroeder,[81] N. Schroer,[58c] M. Schroers,[174] D. Schroff,[48] S. Schuh,[29] G. Schuler,[29] J. Schultes,[174] H.-C. Schultz-Coulon,[58a] J. W. Schumacher,[43] M. Schumacher,[48] B. A. Schumm,[137] Ph. Schune,[136] C. Schwanenberger,[82] A. Schwartzman,[143] D. Schweiger,[29] Ph. Schwemling,[78] R. Schwienhorst,[88] R. Schwierz,[43] J. Schwindling,[136] W. G. Scott,[129] J. Searcy,[114] E. Sedykh,[121] E. Segura,[11] S. C. Seidel,[103] A. Seiden,[137] F. Seifert,[43] J. M. Seixas,[23] G. Sekhniaidze,[102a] D. M. Seliverstov,[121] B. Sellden,[146a] G. Sellers,[73] M. Seman,[144b] N. Semprini-Cesari,[19a,19b] C. Serfon,[98] L. Serin,[115] R. Seuster,[99] H. Severini,[111] M. E. Sevior,[86] A. Sfyrla,[29] E. Shabalina,[54] M. Shamim,[114] L. Y. Shan,[32a] J. T. Shank,[21] Q. T. Shao,[86] M. Shapiro,[14] P. B. Shatalov,[95] L. Shaver,[6] C. Shaw,[53] K. Shaw,[139] D. Sherman,[29] P. Sherwood,[77] A. Shibata,[108] P. Shield,[118] S. Shimizu,[29] M. Shimojima,[100] T. Shin,[56] A. Shmeleva,[94] M. J. Shochet,[30] M. A. Shupe,[6] P. Sicho,[125] A. Sidoti,[15] A. Siebel,[174] M. Siebel,[29] F Siegert,[77] J. Siegrist,[14] Dj. Sijacki,[12a] O. Silbert,[171] J. Silva,[124a,gg] Y. Silver,[153] D. Silverstein,[143] S. B. Silverstein,[146a] V. Simak,[127] Lj. Simic,[12a] S. Simion,[115] B. Simmons,[77] M. Simonyan,[35] P. Sinervo,[158] N. B. Sinev,[114] V. Sipica,[141] G. Siragusa,[81] A. N. Sisakyan,[65] S. Yu. Sivoklokov,[97] J. Sjölin,[146a,146b] T. B. Sjursen,[13] L. A. Skinnari,[14] K. Skovpen,[107] P. Skubic,[111] N. Skvorodnev,[22] M. Slater,[17] T. Slavicek,[127]

K. Sliwa,[161] T. J. Sloan,[71] J. Sloper,[29] V. Smakhtin,[171] S. Yu. Smirnov,[96] Y. Smirnov,[24] L. N. Smirnova,[97] O. Smirnova,[79] B. C. Smith,[57] D. Smith,[143] K. M. Smith,[53] M. Smizanska,[71] K. Smolek,[127] A. A. Snesarev,[94] S. W. Snow,[82] J. Snow,[111] J. Snuverink,[105] S. Snyder,[24] M. Soares,[124a] R. Sobie,[169,l] J. Sodomka,[127] A. Soffer,[153] C. A. Solans,[167] M. Solar,[127] J. Solc,[127] E. Solfaroli Camillocci,[132a,132b] A. A. Solodkov,[128] O. V. Solovyanov,[128] R. Soluk,[2] J. Sondericker,[24] N. Soni,[2] V. Sopko,[127] B. Sopko,[127] M. Sorbi,[89a,89b] M. Sosebee,[7] A. Soukharev,[107] S. Spagnolo,[72a,72b] F. Spanò,[34] P. Speckmayer,[29] E. Spencer,[137] R. Spighi,[19a] G. Spigo,[29] F. Spila,[132a,132b] E. Spiriti,[134a] R. Spiwoks,[29] L. Spogli,[134a,134b] M. Spousta,[126] T. Spreitzer,[158] B. Spurlock,[7] R. D. St. Denis,[53] T. Stahl,[141] J. Stahlman,[120] R. Stamen,[58a] S. N. Stancu,[163] E. Stanecka,[29] R. W. Stanek,[5] C. 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D. Whiteson,[163] D. Whittington,[61] F. Wicek,[115] D. Wicke,[81] F. J. Wickens,[129] W. Wiedenmann,[172] M. Wielers,[129]
P. Wienemann,[20] C. Wiglesworth,[73] L. A. M. Wiik,[48] A. Wildauer,[167] M. A. Wildt,[41,t] I. Wilhelm,[126] H. G. Wilkens,[29]
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