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Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS Detector at the LHC

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By using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally segmented electromagnetic and hadronic calorimeters. The transverse energies of dijets in opposite hemispheres are observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

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Collisions of heavy ions at ultrarelativistic energies are expected to produce an evanescent hot, dense state, with temperatures exceeding 2×10^{12} K, in which the relevant degrees of freedom are not hadrons but quarks and gluons. In this medium, high-energy quarks and gluons are expected to transfer energy to the medium by multiple interactions with the ambient plasma. There is a rich theoretical literature on in-medium QCD energy loss extending back to Bjorken, who proposed to look for "jet quenching" in proton-proton collisions [1]. This work also suggested the observation of highly unbalanced dijets when one jet is produced at the periphery of the collision. For comprehensive reviews of recent theoretical work in this area, see Refs. [2,3].

Single particle measurements made by Relativistic Heavy Ion Collider experiments established that high transverse momentum (p_T) hadrons are produced at rates a factor of 5 or more lower than expected by assuming QCD factorization holds in every binary collision of nucleons in the oncoming nuclei [4,5]. This observation is characterized by measurements of R_{AA}, the ratio of yields in heavy ion collisions to proton-proton collisions, divided by the number of binary collisions. Dihadron measurements also showed a clear absence of back-to-back hadron production in more central heavy ion collisions [5], strongly suggestive of jet suppression. The limited rapidity coverage of the experiment, and jet energies comparable to the underlying event energy, prevented a stronger conclusion being drawn from these data.

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The LHC heavy ion program was foreseen to provide an opportunity to study jet quenching at much higher jet energies than achieved at the Relativistic Heavy Ion Collider. This Letter provides the first measurements of jet production in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV per nucleon-nucleon collision, the highest center of mass energy ever achieved for nuclear collisions. At this energy, next-to-leading-order QCD calculations [6] predict abundant rates of jets above 100 GeV produced in the pseudorapidity region $|\eta| < 4.5$ [7], which can be reconstructed by ATLAS.

The data in this Letter were obtained by ATLAS during the 2010 lead-lead run at the LHC and correspond to an integrated luminosity of approximately 1.7 $\mu\mathrm{b}^{-1}$.

For this study, the focus is on the balance between the highest transverse energy pair of jets in events where those jets have an azimuthal angle separation $\Delta\phi = |\phi_1 - \phi_2| > \pi/2$ to reduce contributions from multijet final states. In this Letter, jets with $\Delta\phi > \pi/2$ are labeled as being in opposite hemispheres. The jet energy imbalance is expressed in terms of the asymmetry A_J:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \qquad \Delta\phi > \frac{\pi}{2}, \tag{1}$$

where the first jet is required to have a transverse energy $E_{T1} > 100$ GeV, and the second jet is the highest transverse energy jet in the opposite hemisphere with $E_{T2} > 25$ GeV. The average contribution of the underlying event energy is subtracted when deriving the individual jet transverse energies. The event selection is chosen such that the first jet has high reconstruction efficiency and the second jet is above the distribution of background fluctuations and the intrinsic soft jets associated with the collision. Dijet events are expected to have A_J near zero, with deviations expected from gluon radiation falling outside the jet cone, as well as from instrumental effects. Energy loss in the medium could lead to much stronger deviations in the reconstructed energy balance.

The ATLAS detector [8] is well-suited for measuring jets due to its large acceptance, highly segmented electromagnetic and hadronic calorimeters. These allow efficient reconstruction of jets over a wide range in the region $|\eta| < 4.5$. The detector also provides precise charged particle and muon tracking. An event display showing the inner detector and calorimeter systems is shown in Fig. 1.

Liquid argon technology providing excellent energy and position resolution is used in the electromagnetic calorimeter that covers the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a sampling calorimeter made of steel and scintillating tiles. In the end caps ($1.5 < |\eta| < 3.2$), liquid argon technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of the electromagnetic calorimeters. To complete the η coverage, the liquid argon forward calorimeters provide both electromagnetic and hadronic energy measurements, extending the coverage up to $|\eta| = 4.9$. The calorimeter (η and ϕ) granularities are 0.1×0.1 for the hadronic calorimeters up to $|\eta| = 2.5$ (except for the third layer of the tile calorimeter, which has a segmentation of 0.2×0.1 up to $|\eta| = 1.7$) and then 0.2×0.2 up to $|\eta| = 4.9$. The electromagnetic calorimeters are longitudinally segmented into three compartments and feature a much finer readout granularity varying by layer, with cells as small as 0.025×0.025 extending to $|\eta| = 2.5$ in the middle layer. In the data-taking period considered, approximately 187 000 calorimeter cells (98% of the total) were usable for event reconstruction.

The bulk of the data reported here were triggered by using coincidence signals from two sets of minimum bias trigger scintillator detectors, positioned at $z = \pm 3.56$ m, covering the full azimuth between $2.09 < |\eta| < 3.84$ and divided into eight ϕ sectors and two η sectors. Coincidences in the zero degree calorimeter and luminosity measurement using a Cherenkov integrating detector were also used as primary triggers, since these detectors were far less susceptible to LHC beam backgrounds. These triggers have a large overlap and are close to fully efficient for the events studied here.

In the offline analysis, events are required to have a time difference between the two sets of minimum bias trigger scintillator counters of $\Delta t < 3$ ns and a reconstructed vertex to efficiently reject beam-halo backgrounds. The primary vertex is derived from the reconstructed tracks in the inner detector, which covers $|\eta| < 2.5$ by using silicon pixel and strip detectors surrounded by straw tubes. These event selection criteria have been estimated to accept over 98% of the total lead-lead inelastic cross section.

The level of event activity or "centrality" is characterized by using the total transverse energy (ΣE_T) deposited in the forward calorimeters (FCal), which cover $3.2 < |\eta| < 4.9$, shown in Fig. 2. Bins are defined in centrality according to fractions of the total lead-lead cross section selected by the trigger and are expressed in terms of percentiles (0%–10%, 10%–20%, 20%–40%, and 40%–100%) with 0% representing the upper end of the ΣE_T distribution. Previous heavy ion experiments have shown a clear correlation of the ΣE_T with the geometry of the overlap region of the colliding nuclei and, correspondingly, the total event multiplicity. This is verified in the bottom panel of Fig. 2, which shows a tight correlation between the energy flow near midrapidity and the forward ΣE_T. The forward ΣE_T is used for this analysis to avoid biasing the centrality measurement with jets.

Jets have been reconstructed by using the infrared-safe anti-k_t jet clustering algorithm [9] with the radius parame-

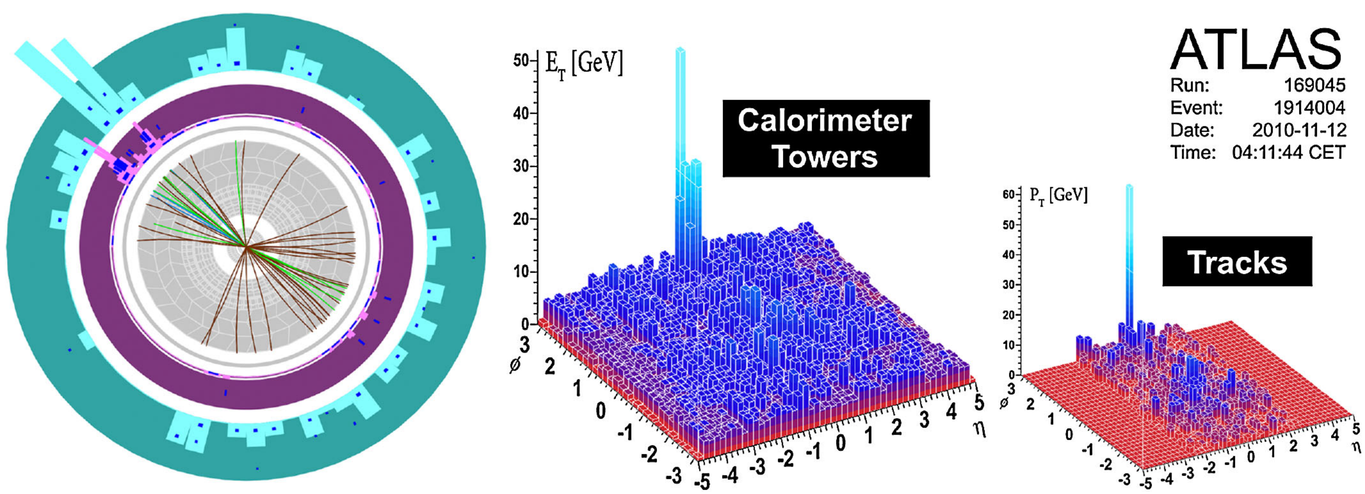
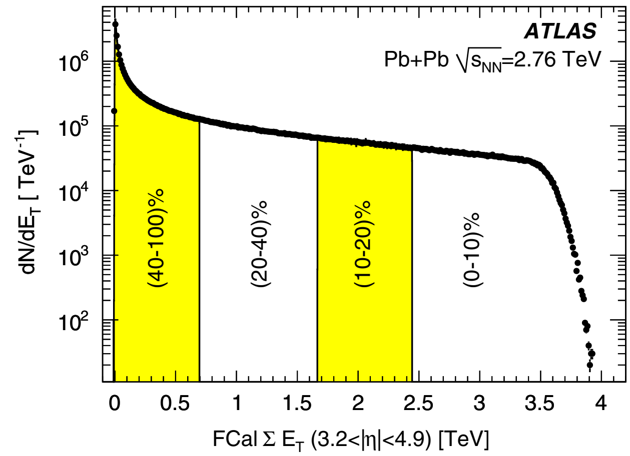


FIG. 1 (color online). Event display of a highly asymmetric dijet event, with one jet with $E_T > 100$ GeV and no evident recoiling jet and with high-energy calorimeter cell deposits distributed over a wide azimuthal region. By selecting tracks with $p_T > 2.6$ GeV and applying cell thresholds in the calorimeters ($E_T > 700$ MeV in the electromagnetic calorimeter, and $E > 1$ GeV in the hadronic calorimeter), the recoil can be seen dispersed widely over the azimuth.



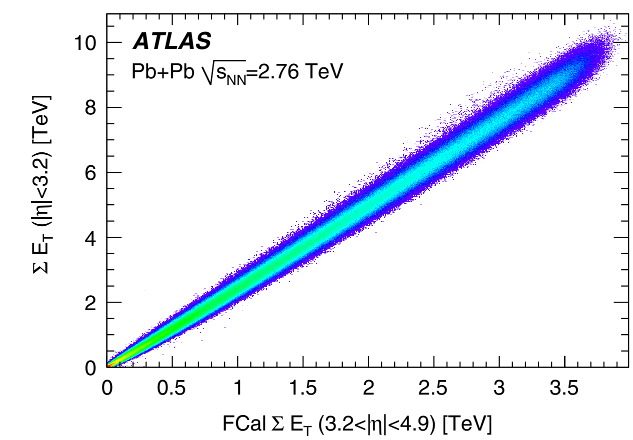


FIG. 2 (color online). (Top) Distribution of uncorrected ΣE_T in the FCal. Bins in event activity or centrality are indicated by the alternating bands (see text for details) and labeled according to increasing fraction of lead-lead total cross section starting from the largest measured ΣE_T. (Bottom) Correlation of uncorrected ΣE_T in $|\eta| < 3.2$ with that measured in the FCal ($3.2 < |\eta| < 4.9$).

ter $R = 0.4$. The inputs to this algorithm are "towers" of calorimeter cells of size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ with the input cells weighted by using energy-density-dependent factors to correct for calorimeter noncompensation and other energy losses. Jet four-momenta are constructed by the vectorial addition of cells, treating each cell as an $(E, \vec{p})$ four-vector with zero mass.

The jets reconstructed by using the anti-k_t algorithm contain a mix of genuine jets and jet-sized patches of the underlying event. For each event, we estimate the average transverse energy density in each calorimeter layer in bins of width $\Delta\eta = 0.1$ and averaged over the azimuth. In the averaging, we exclude jets with $D = E_T(\max)/\langle E_T \rangle$, the ratio of the maximum tower energy over the mean tower energy, greater than 5. The value $D_{\rm cut} = 5$ is chosen based upon simulation studies, and the results have been tested to be stable against variations in this parameter. These average energies are subtracted layer by layer from the cells that make up each jet, scaling appropriately for the cell area. The final reported four-momentum for each jet is then recalculated from the remaining energy in the cells.

The efficiency of the jet reconstruction algorithm and other event properties have been studied by using PYTHIA [10] events superimposed on HIJING events [11]. There is no parton-level interference between the PYTHIA and HIJING generated events. A GEANT4 [12] simulation models the detector response [13] to all the final state particles from the two generated events. The HIJING parameters used do not include jet quenching, but variations in flow as a function of centrality are added. It is found that jets with $E_T > 100$ GeV are reconstructed with nearly 100% efficiency at all centralities.

Simulations have been used to check the overall linearity and resolution of the reconstruction with respect to the primary jet energy, assuming jet shapes similar to those found in proton-proton collisions [14]. However, the efficiency, linearity, and resolution for reconstructing jets may be poorer if the jets are substantially modified by the medium. To check the sensitivity to such effects, the jet shape, characterized here as the ratio of the "core" energy (integrated over $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$) to the total energy, has been studied. This ratio shows only a weak dependence on centrality, providing evidence that the high-energy jets do look approximately like jets measured in proton-proton collisions and that the energy subtraction procedure does not introduce significant biases.

After event selection, the requirement of a leading jet with $E_T > 100$ GeV and $|\eta| < 2.8$ yields a sample of 1693 events. These are called the "jet-selected events." The lead-lead data are also compared with a sample of 17 nb^{-1} of proton-proton collision data [14], which yields 6732 events.

A striking feature of this sample is the appearance of events with only one high E_T jet clearly visible in the calorimeter and no high E_T jet opposite to it in azimuth. Such an event is shown in Fig. 1. The calorimeter E_T and charged particle Σp_T are shown in regions of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. Inspection of this event shows a highly asymmetric pair of jets with the particles recoiling against the leading jet being widely distributed in the azimuth.

To quantify the transverse energy balance between jets in these events, we calculate the dijet asymmetry A_J in different centrality bins between the highest E_T (leading) jet and the highest E_T jet in the opposite hemisphere (second jet). The second jet is required to have $E_T > 25$ GeV in order to discriminate against background from the underlying event. This excludes around 5% of the jet-selected events in the most central 40% of the cross section and accepts nearly all of the more peripheral events.

The dijet asymmetry and $\Delta\phi$ distributions are shown in four centrality bins in Fig. 3, where they are compared with proton-proton data and with fully reconstructed HIJING + PYTHIA simulated events. The simulated events are in-

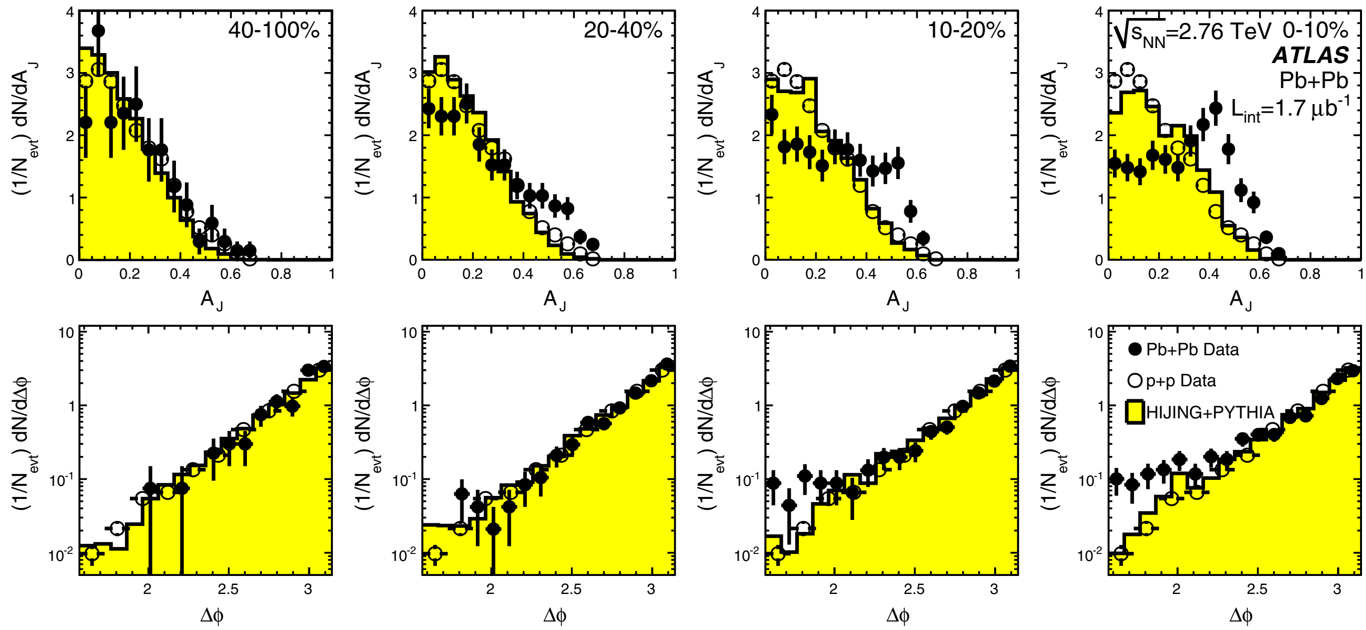


FIG. 3 (color online). (Top) Dijet asymmetry distributions for data (points) and unquenched HIJING with superimposed PYTHIA dijets (solid yellow histograms), as a function of collision centrality (left to right from peripheral to central events). Proton-proton data from $\sqrt{s} = 7$ TeV, analyzed with the same jet selection, are shown as open circles. (Bottom) Distribution of $\Delta\phi$, the azimuthal angle between the two jets, for data and HIJING + PYTHIA, also as a function of centrality.

tended to illustrate the effect of the heavy ion background on jet reconstruction, not any underlying physics process. The dijet asymmetry in peripheral lead-lead events is similar to that in both proton-proton and simulated events; however, as the events become more central, the lead-lead data distributions develop different characteristics, indicating an increased rate of highly asymmetric dijet events. The asymmetry distribution broadens; the mean shifts to higher values; the peak at zero asymmetry is no longer visible; and for the most central events a peak is visible at higher asymmetry values (asymmetries larger than 0.6 can exist only for leading jets substantially above the kinematic threshold of 100 GeV transverse energy). The $\Delta\phi$ distributions show that the leading and second jets are primarily back-to-back in all centrality bins; however, a systematic increase is observed in the rate of second jets at large angles relative to the recoil direction as the events become more central.

Numerous studies have been performed to verify that the events with large asymmetry are not produced by backgrounds or detector effects. Detector effects primarily include readout errors and local acceptance loss due to dead channels and detector cracks. All of the jet events in this sample were checked, and no events were flagged as problematic. The analysis was repeated first by requiring both jets to be within $|\eta| < 1$ and $|\eta| < 2$, to see if there is any effect related to boundaries between the calorimeter sections, and no change to the distribution was observed. Furthermore, the highly asymmetric dijets were not found to populate any specific region of the calorimeter, indicating that no substantial fraction of produced energy was lost in an inefficient or uncovered region.

To investigate the effect of the underlying event, the jet radius parameter R was varied from 0.4 to 0.2 and 0.6 with the result that the large asymmetry was not reduced. In fact, the asymmetry increased for the smaller radius, which would not be expected if detector effects are dominant. The analysis was independently corroborated by a study of "track jets," reconstructed with inner detector tracks of $p_T > 4$ GeV using the same jet algorithms. The inner detector has an estimated efficiency for reconstructing charged hadrons above $p_T > 1$ GeV of approximately 80% in the most peripheral events (the same as that found in 7 TeV proton-proton operation) and 70% in the most central events, due to the approximately 10% occupancy reached in the silicon strips. A similar asymmetry effect is also observed with track jets. The jet energy scale and underlying event subtraction were also validated by correlating calorimeter and track-based jet measurements.

The missing E_T distribution was measured for minimum bias heavy ion events as a function of the total E_T deposited in the calorimeters up to about $\Sigma E_T = 10$ TeV. The resolution as a function of total E_T shows the same behavior as in proton-proton collisions. None of the events in the jet-selected sample was found to have an anomalously large missing E_T.

The events containing high-p_T jets were studied for the presence of high-p_T muons that could carry a large fraction of the recoil energy. Fewer than 2% of the events have a muon with $p_T > 10$ GeV, potentially recoiling against the leading jet, so this can not explain the prevalence of highly asymmetric dijet topologies in more central events.

None of these investigations indicate that the highly asymmetric dijet events arise from backgrounds or detector-related effects.

In summary, first results are presented on jet reconstruction in lead-lead collisions, with the ATLAS detector at the LHC. In a sample of events with a reconstructed jet with transverse energy of 100 GeV or more, an asymmetry is observed between the transverse energies of the leading and second jets that increases with the centrality of the collisions. This has a natural interpretation in terms of QCD energy loss, where the second jet is attenuated, in some cases leading to striking highly asymmetric dijet events. This observation is the first of an enhancement of such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

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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] S. Bahinipati,[2] Y. Bai,[32a] D. C. Bailey,[158] T. Bain,[158] J. T. Baines,[129] O. K. Baker,[175] S Baker,[77] F. Baltasar Dos Santos Pedrosa,[29] E. Banas,[38] P. Banerjee,[93] Sw. Banerjee,[169] D. Banfi,[89a,89b] A. Bangert,[137] V. Bansal,[169] H. S. Bansil,[17] L. Barak,[171] S. P. Baranov,[94] 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] A. J. Barr,[118] F. Barreiro,[80] J. Barreiro Guimarães da Costa,[57] P. Barrillon,[115] R. Bartoldus,[143] A. E. Barton,[71] 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] B. Beare,[158] T. Beau,[78] P. H. Beauchemin,[118] R. Beccherle,[50a] P. Bechtle,[41] 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] 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] D. P. Benjamin,[44] M. Benoit,[115] J. R. Bensinger,[22] K. Benslama,[130] S. Bentvelsen,[105] 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,[24] T. Berry,[76] A. Bertin,[19a,19b] F. Bertinelli,[29] F. Bertolucci,[122a,122b] M. I. Besana,[89a,89b] N. Besson,[136] S. Bethke,[99] W. Bhimji,[45] R. M. Bianchi,[29] M. Bianco,[72a,72b] O. Biebel,[98] J. Biesiada,[14] M. Biglietti,[132a,132b] H. Bilokon,[47] M. Bindi,[19a,19b] A. Bingul,[18c] C. Bini,[132a,132b] C. Biscarat,[177] U. Bitenc,[48] K. M. Black,[21] 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] G. J. Bobbink,[105] V. B. Bobrovnikov,[107] A. Bocci,[44] R. Bock,[29] C. R. Boddy,[118] M. Boehler,[41] J. Boek,[174] N. Boelaert,[35] S. Böser,[77] J. A. Bogaerts,[29] A. Bogdanchikov,[107] A. Bogouch,[90,a] C. Bohm,[146a] V. Boisvert,[76] T. Bold,[163,g] V. Boldea,[25a] 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] N. Bousson,[83] A. Boveia,[30] J. Boyd,[29] I. R. Boyko,[65] N. I. Bozhko,[128] I. Bozovic-Jelisavcic,[12b] 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] S. I. Buda,[25a] 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] W. Buttinger,[27] T. Byatt,[77] S. Cabrera Urbán,[167] M. Caccia,[89a,89b] D. Caforio,[19a,19b] O. Cakir,[3a] P. Calafiura,[14] G. Calderini,[78] P. Calfayan,[98] R. Calkins,[106] L. P. Caloba,[23a] R. Caloi,[132a,132b] D. Calvet,[33] S. 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] 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,[159a] 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,h] 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,[88] 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,[23a] A. Cerri,[29] L. Cerrito,[75] F. Cerutti,[47] S. A. Cetin,[18b] F. Cevenini,[102a,102b] A. Chafaq,[135a] D. Chakraborty,[106] K. Chan,[2] B Chapleau,[85] 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,[135d] V. Tcherniatine,[24] E. Cheu,[6] S. L. Cheung,[158] L. Chevalier,[136] F. Chevallier,[136] 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] M. Ciubancan,[25a] 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] J. G. Cogan,[143] 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,i] J. Cook,[29] M. Cooke,[14] 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,j] 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,[23a] L. Courneyea,[169] G. Cowan,[76] C. Cowden,[27] B. E. Cox,[82] K. Cranmer,[108] 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,[117] S. D'Auria,[53] M. D'Onofrio,[73] A. D'Orazio,[132a,132b] A. Da Rocha Gesualdi Mello,[23a] P. V. M. Da Silva,[23a] C Da Via,[82] W. Dabrowski,[37] A. Dahlhoff,[48] T. Dai,[87] C. Dallapiccola,[84] S. J. Dallison,[129,a] M. Dam,[35] M. Dameri,[50a,50b] D. S. Damiani,[137] 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,a] R. K. Daya,[39] K. De,[7] R. de Asmundis,[102a] S. De Castro,[19a,19b] 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] S. Dean,[77] R. Debbe,[24] G. Dedes,[99] D. V. Dedovich,[65] 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] S. P. Denisov,[128] C. Dennis,[118] D. Derendarz,[38] J. E. Derkaoui,[135c] F. Derue,[78] P. Dervan,[73] K. Desch,[20] E. Devetak,[148] P. O. Deviveiros,[158] A. Dewhurst,[129] B. DeWilde,[148] S. Dhaliwal,[158] R. Dhullipudi,[24,l] A. Di Ciaccio,[133a,133b] L. Di Ciaccio,[4] 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] 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,[23a] A. Do Valle Wemans,[124a] T. K. O. Doan,[4] M. Dobbs,[85] R. Dobinson,[29,a] D. Dobos,[42] E. Dobson,[29] M. Dobson,[163] J. Dodd,[34] O. B. Dogan,[18a,a] C. Doglioni,[118] T. Doherty,[53] Y. Doi,[66,a] J. Dolejsi,[126] I. Dolenc,[74] Z. Dolezal,[126] B. A. Dolgoshein,[96] T. Dohmae,[155] M. Donadelli,[23b] 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. D. 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] R. Duxfield,[139] M. Dwuznik,[37] F. Dydak,[29] D. Dzahini,[55] M. Düren,[52] J. Ebke,[98] S. Eckert,[48] S. Eckweiler,[81] K. Edmonds,[81] C. A. Edwards,[76] I. Efthymiopoulos,[49] 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] D. Eriksson,[146a] 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] D. Evangelakou,[54] H. Evans,[61] 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] A. Favareto,[89a,89b] L. Fayard,[115] S. Fazio,[36a,36b] R. Febbraro,[33] P. Federic,[144a] O. L. Fedin,[121] I. Fedorko,[29] W. Fedorko,[88] M. Fehling-Kaschek,[48] L. Feligioni,[83] D. Fellmann,[5] 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,m] 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] M. Fiascaris,[30] F. Fiedler,[81] A. Filipčič,[74] A. Filippas,[9] F. Filthaut,[104] M. Fincke-Keeler,[169] M. C. N. Fiolhais,[124a,h] 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] 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] T. Frank,[171] M. Franklin,[57] S. Franz,[29] M. Fraternali,[119a,119b] S. Fratina,[120] S. T. French,[27] R. Froeschl,[29] D. Froidevaux,[29] J. A. Frost,[27] C. Fukunaga,[156] E. Fullana Torregrosa,[29] J. Fuster,[167] C. Gabaldon,[29] 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,n] V. A. Gapienko,[128] A. Gaponenko,[14] F. Garberson,[175] 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] B. Gaur,[141] L. Gauthier,[136] 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,[135d] 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,[29] 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,o] J. Ginzburg,[153] N. Giokaris,[8] R. Giordano,[102a,102b] F. M. Giorgi,[15] P. Giovannini,[99] P. F. Giraud,[136] 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] J. Godfrey,[142] J. Godlewski,[29] M. Goebel,[41] T. Göpfert,[43] C. Goeringer,[81] C. Gössling,[42] T. Göttfert,[99] S. Goldfarb,[87] D. Goldin,[39] T. Golling,[175] N. P. Gollub,[29] S. N. Golovnia,[128] A. Gomes,[124a,p] 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] 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,q] J. A. Gray,[148] E. Graziani,[134a] O. G. Grebenyuk,[121] D. Greenfield,[129] T. Greenshaw,[73] Z. D. Greenwood,[24,r] I. M. Gregor,[41] P. Grenier,[143] 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] J. Grognuz,[29] M. Groh,[99] 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] S. Guindon,[54] H. Guler,[85,s] J. Gunther,[125] B. Guo,[158] J. Guo,[34] 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] R. Hackenburg,[24] H. K. Hadavand,[39] D. R. Hadley,[17] P. Haefner,[99] F. Hahn,[29] S. Haider,[29] Z. Hajduk,[38] H. Hakobyan,[176] J. Haller,[54,t] 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] P. Hansson,[143] K. Hara,[160] G. A. Hare,[137] T. Harenberg,[174] D. Harper,[87] 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] 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] D Hayden,[76] 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] S. Heisterkamp,[35] L. Helary,[4] M. Heldmann,[48] M. Heller,[115] S. Hellman,[146a,146b] C. Helsens,[11] R. C. W. Henderson,[71] 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] R. Herrberg,[15] 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] 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] 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] K. Horton,[118] J-Y. Hostachy,[55] T. Hott,[99] S. Hou,[151] M. A. Houlden,[73] A. Hoummada,[135a] J. Howarth,[82] D. F. Howell,[118] I. Hristova,[41] 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,[14] 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,[115] 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] 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] 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] 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,[81] Y. Jiang,[32b] M. Jimenez Belenguer,[29] G. Jin,[32b] S. Jin,[32a] O. Jinnouchi,[157] M. D. Joergensen,[35] 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] R. W. L. Jones,[71] T. W. Jones,[77] T. J. Jones,[73] O. Jonsson,[29] K. K. Joo,[158] C. Joram,[29] P. M. Jorge,[124a,c] J. Joseph,[14] X. Ju,[130] 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] T. Kanno,[157] V. A. Kantserov,[96] J. Kanzaki,[66] B. Kaplan,[175] A. Kapliy,[30] J. Kaplon,[29] D. Kar,[43] 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. 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] V. A. Kazanin,[107] M. Y. Kazarinov,[65] S. I. Kazi,[86] J. R. Keates,[82] R. Keeler,[169] 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] T. J. Khoo,[27] 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] B. T. King,[73] M. King,[67] R. S. B. King,[118] J. Kirk,[129] G. P. Kirsch,[118] L. E. Kirsch,[22] A. E. Kiryunin,[99] D. Kisielewska,[37] 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,[35] T. Klioutchnikova,[29] P. F. Klok,[104] S. Klous,[105] E.-E. Kluge,[58a] T. Kluge,[73] P. Kluit,[105] S. Kluth,[99] E. Kneringer,[62] J. Knobloch,[29] A. Knue,[54] 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,[89a,89b] J. Koll,[88] D. Kollar,[29] M. Kollefrath,[48] S. D. Kolya,[82] A. A. Komar,[94] J. R. Komaragiri,[142] T. Kondo,[66] T. Kono,[41,u] A. I. Kononov,[48] R. Konoplich,[108,v] 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] S. Kortner,[99] V. V. Kostyukhin,[20] M. J. Kotamäki,[29] S. Kotov,[99] V. M. Kotov,[65] C. Kourkoumelis,[8] A. Koutsman,[105] R. Kowalewski,[169] 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] 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] 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] E. Laisne,[55] M. Lamanna,[29] 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] V. V. Lapin,[128,a] S. Laplace,[4] C. Lapoire,[20] 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. Leahu,[29] A. Lebedev,[64] C. Lebel,[93] T. LeCompte,[5] F. Ledroit-Guillon,[55] H. Lee,[105] J. S. H. Lee,[150] S. C. Lee,[151] L. Lee JR,[175] 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] M. A. L. Leite,[23b] R. Leitner,[126] D. Lellouch,[171] J. Lellouch,[78] M. Leltchouk,[34] V. Lendermann,[58a] K. J. C. Leney,[145b] T. Lenz,[174] G. Lenzen,[174] B. Lenzi,[136] K. Leonhardt,[43] 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] B. Li,[83] H. Li,[172] S. Li,[32b] X. Li,[87] Z. Liang,[39] Z. Liang,[118,w] B. Liberti,[133a] P. Lichard,[29] M. Lichtnecker,[98] K. Lie,[165] W. Liebig,[13] R. Lifshitz,[152] J. N. Lilley,[17] A. Limosani,[86] M. Limper,[63] S. C. Lin,[151,x] F. Linde,[105] J. T. Linnemann,[88] E. Lipeles,[120] L. Lipinsky,[125] A. Lipniacka,[13] T. M. Liss,[165] A. Lister,[49] A. M. Litke,[137] C. Liu,[28] D. Liu,[151,y] H. Liu,[87] J. B. Liu,[87] M. Liu,[32b] S. Liu,[2] 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] V. P. Lombardo,[89a,89b] R. E. Long,[71] L. Lopes,[124a,c] D. Lopez Mateos,[34,q] M. Losada,[162] P. Loscutoff,[14] F. Losterzo,[132a,132b] M. J. Losty,[159a] X. Lou,[40] A. Lounis,[115] K. F. Loureiro,[162] 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] M. Lungwitz,[81] A. Lupi,[122a,122b] G. Lutz,[99] D. Lynn,[24] 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,c] D. Macina,[49] R. Mackeprang,[35] 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,h] L. Magnoni,[29] E. Magradze,[51] C. A. Magrath,[104] Y. Mahalalel,[153] K. Mahboubi,[48] G. Mahout,[17] C. Maiani,[132a,132b] C. Maidantchik,[23a] A. Maio,[124a,p] S. Majewski,[24] Y. Makida,[66] 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] R. Mameghani,[98] J. Mamuzic,[12b] A. Manabe,[66] L. Mandelli,[89a] I. Mandić,[74] R. Mandrysch,[15] J. Maneira,[124a] P. S. Mangeard,[88] I. D. Manjavidze,[65] A. Mann,[54] 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,[29] F. Marchese,[133a,133b] M. Marchesotti,[29] G. Marchiori,[78] M. Marcisovsky,[125] A. Marin,[21,a] C. P. Marino,[61] F. Marroquim,[23a] R. Marshall,[82] Z. Marshall,[34,q] F. K. Martens,[158] S. Marti-Garcia,[167] 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. C. Martyniuk,[82] M. Marx,[82] F. Marzano,[132a] A. Marzin,[111] 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,z] J. M. Maugain,[29] S. J. Maxfield,[73] E. N. May,[5] A. Mayne,[139] R. Mazini,[151] M. Mazur,[20] M. Mazzanti,[89a] E. Mazzoni,[122a,122b] S. P. Mc Kee,[87] A. McCarn,[165] R. L. McCarthy,[148] T. G. McCarthy,[28] N. A. McCubbin,[129] K. W. McFarlane,[56] J. A. Mcfayden,[139] H. McGlone,[53] G. Mchedlidze,[51] R. A. McLaren,[29] T. Mclaughlan,[17] S. J. McMahon,[129] T. R. McMahon,[76] T. J. McMahon,[17] R. A. McPherson,[169,j] 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,[79] C. Melachrinos,[30] B. R. Mellado Garcia,[172] L. Mendoza Navas,[162] Z. Meng,[151,y] 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. Messina,[29] 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] 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] 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] 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] T. Moa,[146a,146b] P. Mockett,[138] S. Moed,[57] V. Moeller,[27] K. Mönig,[41] N. Möser,[20] S. Mohapatra,[148] 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] S. Monzani,[19a,19b] R. W. Moore,[2] G. F. Moorhead,[86] C. Mora Herrera,[49] A. Moraes,[53] A. Morais,[124a,c] N. Morange,[136] J. Morel,[54] G. Morello,[36a,36b] D. Moreno,[81] M. Moreno Llácer,[167] P. Morettini,[50a] M. Morii,[57] J. Morin,[75] Y. Morita,[66] A. K. Morley,[29] G. Mornacchi,[29] M-C. Morone,[49] J. D. Morris,[75] H. G. Moser,[99] M. Mosidze,[51] J. Moss,[109] R. Mount,[143] E. Mountricha,[9] S. V. Mouraviev,[94] 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] Y. Munwes,[153] K. Murakami,[66] 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] Y. Nakahama,[115] K. Nakamura,[155] I. Nakano,[110] G. Nanava,[20] A. Napier,[161] M. Nash,[77,z] I. Nasteva,[82] N. R. Nation,[21] T. Nattermann,[20] T. Naumann,[41] G. Navarro,[162] H. A. Neal,[87] E. Nebot,[80] P. Nechaeva,[94] A. Negri,[119a,119b] G. Negri,[29] S. Nektarijevic,[49] A. Nelson,[64] S. Nelson,[143] T. K. Nelson,[143] S. Nemecek,[125] P. Nemethy,[108] A. A. Nepomuceno,[23a] M. Nessi,[29] S. Y. Nesterov,[121] M. S. Neubauer,[165] A. Neusiedl,[81] R. M. Neves,[108] P. Nevski,[24] P. R. Newman,[17] R. B. Nickerson,[118] R. Nicolaidou,[136] L. Nicolas,[139] 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] 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] B. J. O'Brien,[45] 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,h] D. Oliveira Damazio,[24] E. Oliver Garcia,[167] D. Olivito,[120] A. Olszewski,[38] J. Olszowska,[38] C. Omachi,[67] 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] M. Ouchrif,[135c] 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] N. Ozturk,[7] A. Pacheco Pages,[11] C. Padilla Aranda,[11] E. Paganis,[139] F. Paige,[24] K. Pajchel,[117] S. Palestini,[29] D. Pallin,[33] A. Palma,[124a,c] J. D. Palmer,[17] Y. B. Pan,[172] E. Panagiotopoulou,[9] B. Panes,[31a] N. Panikashvili,[87] 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] 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] M. Pecsy,[144a] M. I. Pedraza Morales,[172] S. V. Peleganchuk,[107] H. Peng,[172] R. Pengo,[29] A. Penson,[34] J. Penwell,[61] M. Perantoni,[23a] K. Perez,[34,q] T. Perez Cavalcanti,[41] 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] O. Peters,[105] B. A. Petersen,[29] J. Petersen,[29] T. C. Petersen,[35] E. Petit,[83] A. Petridis,[154] C. Petridou,[154] E. Petrolo,[132a] F. Petrucci,[134a,134b] D Petschull,[41] M. Petteni,[142] R. Pezoa,[31b] A. Phan,[86] A. W. Phillips,[27] P. W. Phillips,[129] 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,p] M. Pinamonti,[164a,164c] J. L. Pinfold,[2] J. Ping,[32c] B. Pinto,[124a,c] 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,[24] S. Poddar,[58a] F. Podlyski,[33] 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] L. Pontecorvo,[132a] B. G. Pope,[88] G. A. Popeneciu,[25a] D. S. Popovic,[12a] A. Poppleton,[29] X. Portell Bueso,[48] R. Porter,[163] C. Posch,[21] G. E. Pospelov,[99] S. Pospisil,[127] I. N. Potrap,[99] C. J. Potter,[149] C. T. Potter,[85] G. Poulard,[29] J. Poveda,[172] R. Prabhu,[77] P. Pralavorio,[83] S. Prasad,[57] R. Pravahan,[7] S. Prell,[64] 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] J. Purdham,[87] M. Purohit,[24,dd] P. Puzo,[115] Y. Pylypchenko,[117] J. Qian,[87] Z. Qian,[83] Z. Qin,[41] A. Quadt,[54] D. R. Quarrie,[14] W. B. Quayle,[172] F. Quinonez,[31a] M. Raas,[104] V. Radescu,[58b] B. Radics,[20] T. Rador,[18a] F. Ragusa,[89a,89b] G. Rahal,[177] A. M. Rahimi,[109] S. Rajagopalan,[24] S. Rajek,[42] M. Rammensee,[48] M. Rammes,[141] M. Ramstedt,[146a,146b] K. Randrianarivony,[28] 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] A. Renaud,[115] P. Renkel,[39] B. Rensch,[35] M. Rescigno,[132a] S. Resconi,[89a] B. Resende,[136] P. Reznicek,[98] R. Rezvani,[158] A. Richards,[77] R. Richter,[99] E. Richter-Was,[38,ee] 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] S. H. Robertson,[85,j] A. Robichaud-Veronneau,[49] D. Robinson,[27] J. E. M. 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] A. Roe,[54] 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] M Rose,[76] G. A. Rosenbaum,[158] E. I. Rosenberg,[64] P. L. Rosendahl,[13] L. Rosselet,[49] V. Rossetti,[11] E. Rossi,[102a,102b] L. P. Rossi,[50a] L. Rossi,[89a,89b] M. Rotaru,[25a] I. Roth,[171] J. Rothberg,[138] I. Rottländer,[20] D. Rousseau,[115] C. R. Royon,[136] A. Rozanov,[83] Y. Rozen,[152] X. Ruan,[115] I. Rubinskiy,[41] B. Ruckert,[98] N. Ruckstuhl,[105] V. I. Rud,[97] G. Rudolph,[62] F. Rühr,[6] 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,[14] P. Ruzicka,[125] Y. F. Ryabov,[121] V. Ryadovikov,[128] P. Ryan,[88] G. Rybkin,[115] N. C. Ryder,[118] S. Rzaeva,[10] A. F. Saavedra,[150] I. Sadeh,[153] H. F-W. Sadrozinski,[137] R. Sadykov,[65] F. Safai Tehrani,[132a,132b] H. Sakamoto,[155] G. Salamanna,[105] A. Salamon,[133a] M. Saleem,[111] D. Salihagic,[99] A. Salnikov,[143] J. Salt,[167] B. M. Salvachua Ferrando,[5] D. Salvatore,[36a,36b] F. Salvatore,[149] 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] A. Sansoni,[47] C. Santamarina Rios,[85] C. Santoni,[33] R. Santonico,[133a,133b] H. Santos,[124a] J. G. Saraiva,[124a,p] 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] V. Savinov,[123] P. Savva,[9] L. Sawyer,[24,r] D. H. Saxon,[53] L. P. Says,[33] C. Sbarra,[19a,19b] A. Sbrizzi,[19a,19b] O. Scallon,[93] D. A. Scannicchio,[163] J. Schaarschmidt,[43] P. Schacht,[99] U. Schäfer,[81] S. Schaetzel,[58b] A. C. Schaffer,[115] D. Schaile,[98] R. D. Schamberger,[148] A. G. Schamov,[107] V. Scharf,[58a] V. A. Schegelsky,[121] D. Scheirich,[87] M. I. Scherzer,[14] C. Schiavi,[50a,50b] J. Schieck,[98] 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] A. Schöning,[58b] M. Schott,[29] D. Schouten,[142] J. Schovancova,[125] M. Schram,[85] A. Schreiner,[63] C. Schroeder,[81] N. Schroer,[58c] S. Schuh,[29] G. Schuler,[29] J. Schultes,[174] H.-C. Schultz-Coulon,[58a] H. Schulz,[15] J. W. Schumacher,[20] M. Schumacher,[48] B. A. Schumm,[137] Ph. Schune,[136] C. Schwanenberger,[82] A. Schwartzman,[143] 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,[23a] 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,[164a,164c] D. Sherman,[175] P. Sherwood,[77] A. Shibata,[108] S. Shimizu,[29] M. Shimojima,[100] T. Shin,[56] A. Shmeleva,[94] M. J. Shochet,[30] D. Short,[118] M. A. Shupe,[6] P. Sicho,[125] A. Sidoti,[15] A. Siebel,[174] F Siegert,[48] J. Siegrist,[14] Dj. Sijacki,[12a] O. Silbert,[171] 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] 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,j] J. Sodomka,[127] A. Soffer,[153] C. A. Solans,[167] M. Solar,[127] J. Solc,[127] U. Soldevila,[167] E. Solfaroli Camillocci,[132a,132b] A. A. Solodkov,[128] O. V. Solovyanov,[128] 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] R. Spighi,[19a] G. Spigo,[29] F. Spila,[132a,132b] E. Spiriti,[134a] R. Spiwoks,[29] M. Spousta,[126] T. Spreitzer,[158] B. Spurlock,[7] R. D. St. Denis,[53] T. Stahl,[141] J. Stahlman,[120] R. Stamen,[58a] E. Stanecka,[29] R. W. Stanek,[5] C. Stanescu,[134a] S. Stapnes,[117] E. A. Starchenko,[128] J. Stark,[55] P. Staroba,[125] P. Starovoitov,[91] A. Staude,[98] P. Stavina,[144a] G. Stavropoulos,[14] G. Steele,[53] P. Steinbach,[43] P. Steinberg,[24] I. Stekl,[127] B. Stelzer,[142] H. J. Stelzer,[41] O. Stelzer-Chilton,[159a] H. Stenzel,[52] K. Stevenson,[75] G. A. Stewart,[53] T. Stockmanns,[20] M. C. Stockton,[29] K. Stoerig,[48] G. Stoicea,[25a] S. Stonjek,[99] P. Strachota,[126] A. R. Stradling,[7] A. Straessner,[43] J. Strandberg,[87] S. Strandberg,[146a,146b] A. Strandlie,[117] M. Strang,[109] E. Strauss,[143] M. Strauss,[111] P. Strizenec,[144b] R. Ströhmer,[173] D. M. Strom,[114] J. A. Strong,[76,a] R. Stroynowski,[39] J. Strube,[129] B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[148] P. Sturm,[174] D. A. Soh,[151,w] D. Su,[143] S. Subramania,[2] Y. Sugaya,[116] T. Sugimoto,[101] C. Suhr,[106] K. Suita,[67] M. Suk,[126] V. V. Sulin,[94] S. Sultansoy,[3d]

T. Sumida,[29] X. Sun,[55] J. E. Sundermann,[48] K. Suruliz,[164a,164b] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[139] Y. Suzuki,[66] Yu. M. Sviridov,[128] S. Swedish,[168] I. Sykora,[144a] T. Sykora,[126] B. Szeless,[29] J. Sánchez,[167] D. Ta,[105] K. Tackmann,[29] A. Taffard,[163] R. Tafirout,[159a] A. Taga,[117] N. Taiblum,[153] Y. Takahashi,[101] H. Takai,[24] R. Takashima,[69] H. Takeda,[67] T. Takeshita,[140] M. Talby,[83] A. Talyshev,[107] M. C. Tamsett,[24] J. Tanaka,[155] R. Tanaka,[115] S. Tanaka,[131] S. Tanaka,[66] Y. Tanaka,[100] K. Tani,[67] N. Tannoury,[83] G. P. Tappern,[29] S. Tapprogge,[81] D. Tardif,[158] S. Tarem,[152] F. Tarrade,[24] G. F. Tartarelli,[89a] P. Tas,[126] M. Tasevsky,[125] E. Tassi,[36a,36b] M. Tatarkhanov,[14] C. Taylor,[77] F. E. Taylor,[92] G. Taylor,[137] G. N. Taylor,[86] W. Taylor,[159b] M. Teixeira Dias Castanheira,[75] P. Teixeira-Dias,[76] K. K. Temming,[48] H. Ten Kate,[29] P. K. Teng,[151] Y. D. Tennenbaum-Katan,[152] S. Terada,[66] K. Terashi,[155] J. Terron,[80] M. Terwort,[41,t] M. Testa,[47] R. J. Teuscher,[158,j] C. M. Tevlin,[82] J. Thadome,[174] J. Therhaag,[20] T. Theveneaux-Pelzer,[78] M. Thioye,[175] S. Thoma,[48] J. P. Thomas,[17] E. N. Thompson,[84] P. D. Thompson,[17] P. D. Thompson,[158] A. S. Thompson,[53] E. Thomson,[120] M. Thomson,[27] R. P. Thun,[87] T. Tic,[125] V. O. Tikhomirov,[94] Y. A. Tikhonov,[107] C. J. W. P. Timmermans,[104] P. Tipton,[175] F. J. Tique Aires Viegas,[29] S. Tisserant,[83] J. Tobias,[48] B. Toczek,[37] T. Todorov,[4] S. Todorova-Nova,[161] B. Toggerson,[163] J. Tojo,[66] S. Tokár,[144a] K. Tokunaga,[67] K. Tokushuku,[66] K. Tollefson,[88] M. Tomoto,[101] L. Tompkins,[14] K. Toms,[103] A. Tonazzo,[134a,134b] G. Tong,[32a] A. Tonoyan,[13] C. Topfel,[16] N. D. Topilin,[65] I. Torchiani,[29] E. Torrence,[114] E. Torró Pastor,[167] J. Toth,[83,cc] F. Touchard,[83] D. R. Tovey,[139] D. Traynor,[75] T. Trefzger,[173] J. Treis,[20] L. Tremblet,[29] A. Tricoli,[29] I. 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