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Search for a Supersymmetric Partner to the Top Quark in Final States with Jets and Missing Transverse Momentum at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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A search for direct pair production of supersymmetric top squarks ($\tilde{t}_1$) is presented, assuming the $\tilde{t}_1$ decays into a top quark and the lightest supersymmetric particle, $\tilde{\chi}_1^0$, and that both top quarks decay to purely hadronic final states. A total of 16 (4) events are observed compared to a predicted standard model background of $13.5^{+3.7}_{-3.6}(4.4^{+1.7}_{-1.3})$ events in two signal regions based on $\int \mathcal{L}dt = 4.7$ fb^{-1} of pp collision data taken at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. An exclusion region in the $\tilde{t}_1$ versus $\tilde{\chi}_1^0$ mass plane is evaluated: $370 < m_{\tilde{t}_1} < 465$ GeV is excluded for $m_{\tilde{\chi}_1^0} \sim 0$ GeV while $m_{\tilde{t}_1} = 445$ GeV is excluded for $m_{\tilde{\chi}_1^0} \leq 50$ GeV.

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The standard model (SM) is a successful but incomplete theory of particle interactions. Supersymmetry (SUSY) [1–9] provides an elegant cancellation of the quadratic mass divergences that would accompany a SM Higgs boson by introducing supersymmetric partners of all SM particles, such as a scalar partner of the top quark ($\tilde{t}$). Like $t\bar{t}$, direct $\tilde{t}\tilde{t}^*$ is produced primarily through gluon fusion at the Large Hadron Collider (LHC). The production cross section depends mostly on the mass of the top partner and has minimal dependence on other SUSY parameters [10–12]. The LHC enables searches for direct $\tilde{t}\tilde{t}^*$ production at higher mass scales than previous accelerators [13–27]. The viability of SUSY as a scenario to stabilize the Higgs potential and to be consistent with electroweak naturalness [28,29] is tested by the search for $\tilde{t}$ below the TeV scale.

In this Letter, we present a search for direct $\tilde{t}\tilde{t}^*$ production assuming $\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$, where $\tilde{t}_1$ is the lightest $\tilde{t}$ eigenstate and $\tilde{\chi}_1^0$ represents the lightest supersymmetric particle (LSP) in R-parity conserving models [30–34]. We target events where both W bosons decay hadronically, yielding a final state with six high transverse momentum (p_T) jets from the all-hadronic $t\bar{t}$ final state and large missing transverse momentum (E_T^{miss}) from the LSPs. The kinematics of both top quarks can therefore be fully specified by the visible decay products. Additionally, SM backgrounds from all-hadronic $t\bar{t}$ are suppressed as there is no intrinsic E_T^{miss} except from semileptonic c- and b-quark decays. The dominant background consists of $t\bar{t}$ events that contain a $W \to \ell\nu$ decay where the lepton (ℓ), often of τ flavor, is either lost or misidentified as a jet. These events also have large E_T^{miss} from the neutrino (ν).

The data were acquired during 2011 in LHC pp collisions at a center-of-mass energy of 7 TeV with the ATLAS detector [35], which consists of tracking detectors surrounded by a 2 T superconducting solenoid, calorimeters, and a muon spectrometer in a toroidal magnetic field. The high-granularity calorimeter system, with acceptance covering $|\eta| < 4.9$ [36], is composed of liquid argon with lead, copper, or tungsten absorbers and scintillator tiles with steel absorbers. This data set, composed of events with a high-p_T jet and large E_T^{miss} as selected by the trigger system, corresponds to an integrated luminosity of 4.7 fb^{-1} with a relative uncertainty of 3.9% [37–39].

Jets are constructed from three-dimensional clusters of calorimeter cells using the anti-k_t algorithm with a distance parameter of 0.4 [39,40]. Jet energies are corrected [41] for losses in material in front of the active calorimeter layers, detector inhomogeneities, the noncompensating nature of the calorimeter, and the impact of multiple overlapping pp interactions. These corrections are derived from test beam, cosmic-ray, and pp collision data, and from a detailed GEANT4 [42] detector simulation [43]. Jets containing a b-hadron are identified with an algorithm exploiting both the impact parameter and secondary vertex information [44,45]. A factor correcting for the slight differences in the b-tagging efficiency between data and the GEANT4 simulation is applied to each jet in the simulation. The b-jets are restricted to the fiducial region of the tracker, $|\eta| < 2.5$. Non-$t\bar{t}$ backgrounds are minimized by requiring either ≥ 1 b-jets with a selection corresponding to a 60% efficiency with a low <0.2% misidentification rate (tight), or ≥ 2 b-jets each with 75% efficiency but a higher ≈1.7% misidentification rate per b-jet (loose).

The E_T^{miss} is the magnitude of $\mathbf{p}_T^{\text{miss}}$, the negative vector sum of the p_T of the clusters of calorimeter cells, calibrated according to their associated reconstructed object (e.g., jets and electrons), and of the p_T of muons above 10 GeV

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within $|\eta| < 2.4$. Events containing $E_T^{\rm miss}$ induced by jets associated with calorimeter noise or noncollision backgrounds [46], or by cosmic-ray muons [47,48], are removed from consideration. Large $\mathbf{p}_T^{\rm miss}$ collinear with a high-p_T jet could indicate a significant fluctuation in the reconstructed jet energy or the presence of a semileptonic c- or b-quark decay. Therefore, the difference in azimuthal angle ($\Delta\phi$) between the $\mathbf{p}_t^{\rm miss}$ and any of the three highest-p_T jets in the event, $\Delta\phi(\mathbf{p}_T^{\rm miss}, \text{jet})$, is required to be $>\pi/5$ radians. Fluctuations in the $E_T^{\rm miss}$ are also suppressed by requiring that the $\Delta\phi$ between the above computed $\mathbf{p}_T^{\rm miss}$ and one calculated with the tracking system, using tracks having $p_T > 0.5$ GeV, is $<\pi/3$ radians.

Events are required to have at least one jet with $p_T > 130$ GeV in $|\eta| < 2.8$ and $E_T^{\rm miss} > 150$ GeV to ensure full efficiency of the trigger. At least five other jets having $p_T > 30$ GeV and $|\eta| < 2.8$ must be present. In addition to the jet and $E_T^{\rm miss}$ requirements, events containing "loose" electrons [49,50] with $p_T > 20$ GeV and $|\eta| < 2.47$ that do not overlap with any jet within $\Delta R < 0.4$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, are rejected. Similarly, events with muons [47–51] having $p_T > 10$ GeV and $|\eta| < 2.4$ that are separated by $\Delta R > 0.4$ from the nearest jet are rejected. A jet with 1–4 tracks and $\Delta\phi(\mathbf{p}_T^{\rm miss}, \text{jet}) < \pi/5$ indicates a likely $W \to \tau\nu$ decay. Events with such τ-like jets that have transverse mass $m_T = \sqrt{2p_T E_T^{\rm miss}(1 - \cos\Delta\phi)} < 100$ GeV are rejected.

The presence of high-p_T top quarks that decay through $t \to bW \to bjj$ in the $\tilde{t}_1\tilde{t}_1^*$ final state is exploited to further reduce SM backgrounds by only considering events with reconstructed three-jet invariant masses consistent with the top-quark mass (m_t). A clustering technique resolves the combinatorics associated with high-multiplicity jet events. The three closest jets in the η-ϕ plane are combined to form one triplet; a second triplet is formed from the remaining jets by repeating the procedure. The resulting three-jet mass (m_{jjj}) spectrum is shown in Fig. 1 for the control region constructed from ℓ + jets events (defined below). There is a clear peak associated with the hadronically decaying top quarks above a small non-$t\bar{t}$ background. A requirement of $80 < m_{jjj} < 270$ GeV is placed on each reconstructed triplet in the event. The kinematics of the $t \to bW \to b\ell\nu$ decay is also exploited to further reduce the dominant ℓ + jets $t\bar{t}$ background, as the m_T distribution of the $\mathbf{p}_T^{\rm miss}$ and b-jet ($m_T^{\rm jet}$) has an end point at m_t. When there are ≥ 2 loose b-jets, the $m_T^{\rm jet}$ for the b-jet closest to the $\mathbf{p}_T^{\rm miss}$ is required to be >175 GeV. The largest $m_T^{\rm jet}$, calculated for each of the four highest-p_T jets, is required to be >175 GeV in the case of only one tight b-jet.

Two signal regions (SR) are defined including the above kinematic and mass requirements. The first, which requires $E_T^{\rm miss} > 150$ GeV (SRA), is optimized for low $m_{\tilde{t}_1}$, while the second, requiring $E_T^{\rm miss} > 260$ GeV (SRB), is used for higher $m_{\tilde{t}_1}$. Using these signal regions, the search is most sensitive to $\tilde{t}_1\tilde{t}_1^*$ production with $350 \lesssim m_{\tilde{t}_1} \lesssim 500$ GeV and $m_{\tilde{\chi}_1^0} \ll m_{\tilde{t}_1}$. Signal events are simulated using HERWIG++ [52] with the MRST2007LO* [53] parton distribution functions (PDF) generated with the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ masses at fixed values in a grid with 50 GeV spacing. The mixing between $\tilde{t}_L$ and $\tilde{t}_R$ is chosen such that the lightest scalar top is mostly the partner of the right-handed top quark. The branching fraction of $\tilde{t} \to t\tilde{\chi}_1^0$ is set to 100% and the top-quark mass is set to 172.5 GeV. Signal cross sections are calculated to next-to-leading order in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [10–12]. The nominal production cross section and associated uncertainty are taken from an envelope of cross section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [54]. The $\tilde{t}_1\tilde{t}_1^*$ cross section for $m_{\tilde{t}_1} = 400$ GeV is $\sigma_{\tilde{t}_1\tilde{t}_1^*} = 0.21 \pm 0.03$ pb.

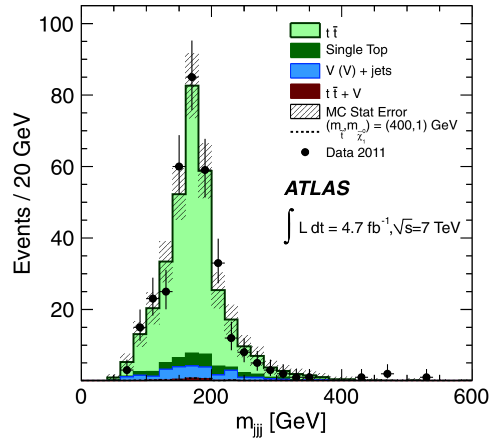

FIG. 1 (color online). Three-jet invariant mass distribution of the hadronic top-quark candidate in the control region constructed from ℓ + jets events where the signal expectation is minimal. Data are indicated by points; shaded histograms represent contributions from several SM sources (with $t\bar{t}$ scaled by 0.66 The hatched error bars indicate the total statistical uncertainty on the expected background. The distribution for the $m_{\tilde{t}_1} = 400$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV signal expectation in this control region is overlaid.

In the signal region, the dominant source of SM background is $t\bar{t} \to \tau$ + jets events where the τ lepton is reconstructed as a jet. Additional, smaller, backgrounds include other $t\bar{t} \to \ell$ + jets final states, $t\bar{t} + V$ where V represents a W or Z boson, single top-quark production, V + jets, and VV + jets. The $t\bar{t}$ events are produced with ALPGEN [55] using the CTEQ6L1 PDF [56] and interfaced to HERWIG [57,58] for particle production and JIMMY [59] for the underlying event model. TAUOLA was used to model the decay of τ leptons [60]. Additional $t\bar{t}$ samples generated with MC@NLO [61,62] and ACERMC [63], interfaced to HERWIG and JIMMY, are used to estimate event generator systematic uncertainties. Samples of $t\bar{t} + V$ are produced with MADGRAPH [64] interfaced to PYTHIA [58,65,66]. Single top events are generated with MC@NLO [67,68] and ACERMC. The associated production of W and Z bosons and light and heavy-flavor jets is simulated using ALPGEN; diboson production is simulated with SHERPA [69].

All samples are passed through the GEANT4 simulation of the ATLAS detector, and are reconstructed in the same manner as the data. The simulation includes the effect of multiple pp interactions and is weighted to reproduce the observed distribution of the number of interactions per bunch crossing. SM event samples are normalized to the results of higher-order calculations using the cross sections cited in Ref. [70] except for the ℓ + jets $t\bar{t}$ background. This sample is normalized by a factor that scales the $t\bar{t}$ expectation to agree with the observed data in a control region (CR) kinematically close to the signal region but with little expected signal. The CR is constructed from events containing one muon or one "tight" electron [49] with $p_T >$ 30 GeV consistent with originating from a W-boson decay ($40 < m_T^{\ell} < 120$ GeV) and ≥ 5 jets, where m_T^{ℓ} is the transverse mass of the electron or muon and $\mathbf{p}_T^{\rm miss}$. The lepton must be isolated such that the scalar p_T sum of tracks in a cone of $\Delta R < 0.2$ around the lepton, excluding the track of the lepton, is $<$1.8 GeV for the muon or is $<$10% of the electron p_T, respectively. The jet, b-jet, and $E_T^{\rm miss}$ requirements remain the same as the standard signal selection; however, some topological constraints are relaxed [$\Delta\phi(\mathbf{p}_T^{\rm miss}, \text{jet}) > \pi/10$ radians and $m_{jjj} < 600$ GeV] and others removed ($m_T^{\rm jet}$) to gain statistics. The $t\bar{t}$ purity in the control region is $>$80%; the expected signal contamination is $<$3%. The lepton is treated as a jet of the same energy and momentum, mimicking the effect of the τ lepton. Effects of the additional $E_T^{\rm miss}$ from the τ neutrino are smaller than the statistical uncertainties. The normalization is scaled by 0.66 ± 0.05 to bring the ≥ 6 jet ℓ + jets ALPGEN $t\bar{t}$ events into agreement with the data after recalculating all quantities except $E_T^{\rm miss}$; the uncertainty quoted here is statistical only. This scale factor is used in Figs. 1–3. The normalization is validated with an orthogonal $t\bar{t}$-dominated sample created from SRA by selecting events with τ-like jets; the requirement on $m_T^{\rm jet}$ is removed to increase the sample size. The m_T of τ-like jets is shown in Fig. 2, where the $t\bar{t}$ sample has been normalized as described above. Expectations from the simulation agree with the data within uncertainties. Contributions to the signal region from QCD multijet and all-hadronic $t\bar{t}$ production are estimated with a data-driven technique [71]. Jets are smeared in a low-$E_T^{\rm miss}$ data sample using response functions derived from control regions dominated by multijet events. The expected number of such events is 0.2 ± 0.2 in SRA after the full event selection.

The $E_T^{\rm miss}$ distribution in SRA is shown in Fig. 3 for data, for the SM backgrounds, and for expectations of $\tilde{t}_1\tilde{t}_1^*$ production with $m_{\tilde{t}_1} = 400$ and $m_{\tilde{\chi}_1^0} = 1$ GeV. Numbers

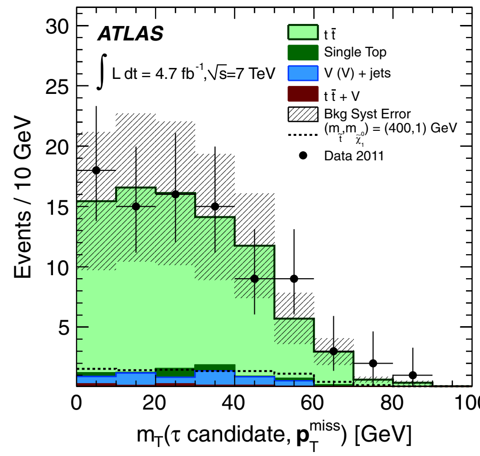

FIG. 2 (color online). The m_T distribution for τ-like jets with the selection described in the text. Data are indicated by points; shaded histograms represent contributions from several SM sources (with $t\bar{t}$ scaled by 0.66). The hatched error bars indicate the systematic uncertainty on the total expected background. The expected signal distribution for $m_{\tilde{t}_1} = 400$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV is overlaid.

of events and combined statistical and systematic uncertainties, for both SRA and SRB, are tabulated in Table I. Uncertainties in the event generators, including the impact of initial- and final-state radiation, are the dominant source of systematic uncertainty of 28% (23%) for the background in SRA (SRB). Other major sources of uncertainty include 22% (32%) for the jet energy calibration, 6.5% (6.8%) for jet energy resolution, 5.9% (6.2%) for b-jet identification, and 1.4% (1.5%) for $E_T^{\rm miss}$ in SRA (SRB).

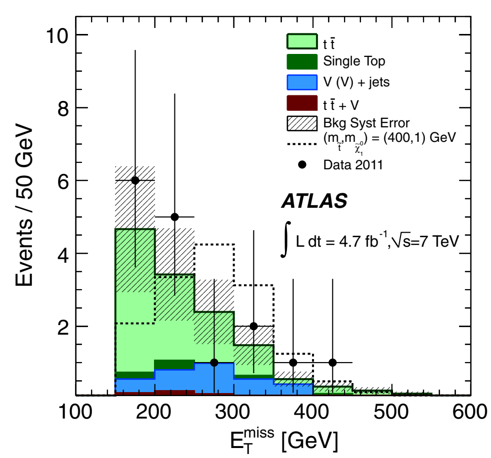

FIG. 3 (color online). The $E_{\rm T}^{\rm miss}$ distribution in data compared to the SM expectation for signal region A. The hatched error bars indicate the systematic uncertainty on the total expected background. The expected signal distribution for $m_{\tilde{t}_1} = 400$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV is overlaid. The SM background distributions do not include the 0.2 ± 0.2 events of all-hadronic $t\bar{t}$ and QCD multijets estimated from data.

TABLE I. The numbers of expected events for the SM backgrounds and an example SUSY signal point, and the observed number of events in data. The 95% C.L. upper limit on the observed (expected) visible cross section, as defined in the text, is appended below.

	SRA $E_T^{\rm miss} > 150$ GeV	SRB >260 GeV
$t\bar{t}$	9.2 ± 2.7	2.3 ± 0.6
$t\bar{t} + W/Z$	0.8 ± 0.2	0.4 ± 0.1
Single top	0.7 ± 0.4	$0.2^{+0.3}_{-0.2}$
Z + jets	$1.3^{+1.1}_{-1.0}$	$0.9^{+0.8}_{-0.7}$
W + jets	$1.2^{+1.4}_{-1.0}$	0.5 ± 0.4
Diboson	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
Multijets	0.2 ± 0.2	0.02 ± 0.02
Total SM	$13.5^{+3.7}_{-3.6}$	$4.4^{+1.7}_{-1.3}$
SUSY $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (400, 1)$ GeV	14.8 ± 4.0	8.9 ± 3.1
Data (observed)	16	4
Visible cross section limit [fb]	2.9 (2.5)	1.3 (1.3)

The number of observed events in the data is well matched by the SM background. These results are interpreted as exclusion limits for $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ using a CL$_s$ likelihood ratio combining Poisson probabilities for signal and background [72]. Systematic uncertainties are treated as nuisance parameters assuming Gaussian distributions. Uncertainties associated with jets, b-jets, $E_T^{\rm miss}$, and luminosity are fully correlated between signal and background; the others are assumed to be uncorrelated. The expected limits for the signal regions are evaluated for each $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ point; the SR with the better expected sensitivity is used for that point. The expected and observed 95% C.L. exclusion limits, interpolating across points, are displayed in Fig. 4. The -1σ observed limit contour that accounts for theoretical uncertainties on the SUSY cross sections is maximum at $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (445, 50)$ GeV. Top squark masses between 370 and 465 GeV are excluded for $m_{\tilde{\chi}_1^0} \sim 0$ GeV. These values are derived from the -1σ observed limit contour to account for theoretical uncertainties on the SUSY cross sections. The 95% C.L. upper limit on the number of events beyond the SM in each signal region, divided by the integrated luminosity, yields limits on the observed (expected) visible cross sections of 2.9 (2.5) fb in SRA and 1.3 (1.3) fb in SRB.

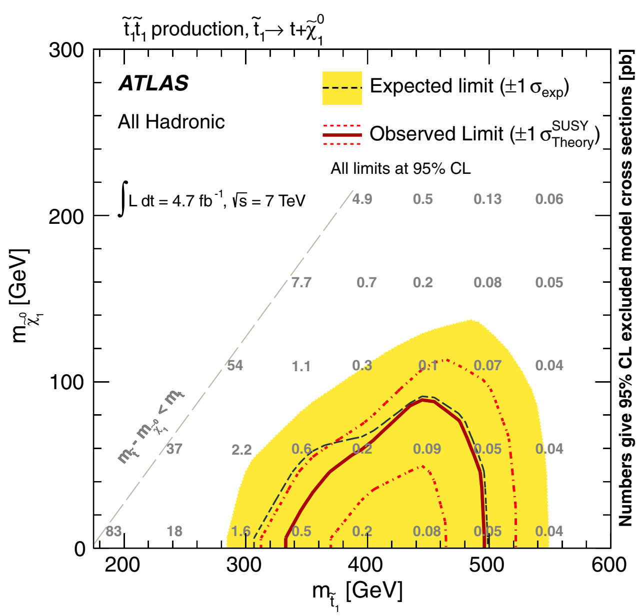

FIG. 4 (color online). Expected and observed 95% C.L. exclusion limits in the plane of $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{t}_1}$, assuming 100% branching fraction for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. The dashed line shows the expected limit at 95% C.L. with the shaded region indicating the $\pm1\sigma$ exclusions due to experimental uncertainties. Observed limits are indicated by the solid contour (nominal) and the dotted contours (obtained by varying the SUSY cross section by the theoretical uncertainties). The inner dotted contour indicates the excluded region. The dashed diagonal line represents the kinematic limit for the $t\tilde{\chi}_1^0$ final state. The numbers overlaid on the plot represent the 95% C.L. excluded visible cross sections in pb.

In conclusion, we have presented a search for the direct production of $\tilde{t}_1\tilde{t}_1^*$ in the $t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$ decay channel, assuming 100% branching fraction for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. A total of 16 (4) events are observed compared to a predicted standard model background of $13.5^{+3.7}_{-3.6}(4.4^{+1.7}_{-1.3})$ events in two signal regions based on $\int \mathcal{L}dt = 4.7$ fb^{-1} of pp collision data taken at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. No evidence for $\tilde{t}_1\tilde{t}_1^*$ is observed in data and 95% C.L. limits are set on $\tilde{t}_1\tilde{t}_1^*$ production as a function of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$.

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G. J. Bobbink,[105] V. B. Bobrovnikov,[107] S. S. Bocchetta,[79] A. Bocci,[45] C. R. Boddy,[118] M. Boehler,[48] J. Boek,[175] N. Boelaert,[36] J. A. Bogaerts,[30] A. Bogdanchikov,[107] A. Bogouch,[90,a] C. Bohm,[146a] J. Bohm,[125] V. Boisvert,[76] T. Bold,[38] V. Boldea,[26a] N. M. Bolnet,[136] M. Bomben,[78] M. Bona,[75] M. Boonekamp,[136] S. Bordoni,[78] C. Borer,[17] A. Borisov,[128] G. Borissov,[71] I. Borjanovic,[13a] M. Borri,[82] S. Borroni,[87] V. Bortolotto,[134a,134b] K. Bos,[105] D. Boscherini,[20a] M. Bosman,[12] H. Boterenbrood,[105] J. Bouchami,[93] J. Boudreau,[123] E. V. Bouhova-Thacker,[71] D. Boumediene,[34] C. Bourdarios,[115] N. Bousson,[83] A. Boveia,[31] J. Boyd,[30] I. R. Boyko,[64] I. Bozovic-Jelisavcic,[13b] J. Bracinik,[18] P. Branchini,[134a] A. Brandt,[8] G. Brandt,[118] O. Brandt,[54] U. Bratzler,[156] B. Brau,[84] J. E. Brau,[114] H. M. Braun,[175,a] S. F. Brazzale,[164a,164c] B. Brelier,[158] J. Bremer,[30] K. Brendlinger,[120] R. Brenner,[166] S. Bressler,[172] D. Britton,[53] F. M. Brochu,[28] I. Brock,[21] R. Brock,[88] F. Broggi,[89a] C. Bromberg,[88] J. Bronner,[99] G. Brooijmans,[35] T. Brooks,[76] W. K. Brooks,[32b] G. Brown,[82] H. Brown,[8] P. A. Bruckman de Renstrom,[39] D. Bruncko,[144b] R. Bruneliere,[48] S. Brunet,[60] A. Bruni,[20a] G. Bruni,[20a] M. Bruschi,[20a] T. Buanes,[14] Q. Buat,[55] F. Bucci,[49] J. Buchanan,[118] P. Buchholz,[141] R. M. Buckingham,[118] A. G. Buckley,[46] S. I. Buda,[26a] I. A. Budagov,[64] B. Budick,[108] V. Büscher,[81] L. Bugge,[117] O. Bulekov,[96] A. C. Bundock,[73] M. Bunse,[43] T. Buran,[117] H. Burckhart,[30] S. Burdin,[73] T. Burgess,[14] S. Burke,[129] E. Busato,[34] P. Bussey,[53] C. P. Buszello,[166] B. Butler,[143] J. M. Butler,[22] C. M. Buttar,[53] J. M. Butterworth,[77] W. Buttinger,[28] S. Cabrera Urbán,[167] D. Caforio,[20a,20b] O. Cakir,[4a] P. Calafiura,[15] G. Calderini,[78] P. Calfayan,[98] R. Calkins,[106] L. P. Caloba,[24a] R. Caloi,[132a,132b] D. Calvet,[34] S. Calvet,[34] R. Camacho Toro,[34] P. Camarri,[133a,133b] D. Cameron,[117] L. M. Caminada,[15] R. Caminal Armadans,[12] S. Campana,[30] M. Campanelli,[77] V. Canale,[102a,102b] F. Canelli,[31,h] A. Canepa,[159a] J. Cantero,[80] R. Cantrill,[76] L. Capasso,[102a,102b] M. D. M. Capeans Garrido,[30] I. Caprini,[26a] M. Caprini,[26a] D. Capriotti,[99] M. Capua,[37a,37b] R. Caputo,[81] R. Cardarelli,[133a] T. Carli,[30] G. Carlino,[102a] L. Carminati,[89a,89b] B. Caron,[85] S. Caron,[104] E. Carquin,[32b] G. D. Carrillo Montoya,[173] A. A. Carter,[75] J. R. Carter,[28] J. Carvalho,[124a,i] D. Casadei,[108] M. P. Casado,[12] M. Cascella,[122a,122b] C. Caso,[50a,50b,a] A. M. Castaneda Hernandez,[173,j] E. Castaneda-Miranda,[173] V. Castillo Gimenez,[167] N. F. Castro,[124a] G. Cataldi,[72a] P. Catastini,[57] A. Catinaccio,[30] J. R. Catmore,[30] A. Cattai,[30] G. Cattani,[133a,133b] S. Caughron,[88] V. Cavaliere,[165] P. Cavalleri,[78] D. Cavalli,[89a] M. Cavalli-Sforza,[12] V. Cavasinni,[122a,122b] F. Ceradini,[134a,134b] A. S. Cerqueira,[24b] A. Cerri,[30] L. Cerrito,[75] F. Cerutti,[47] S. A. Cetin,[19b] A. Chafaq,[135a] D. Chakraborty,[106] I. Chalupkova,[126] K. Chan,[3] P. Chang,[165] B. Chapleau,[85] J. D. Chapman,[28] J. W. Chapman,[87] E. Chareyre,[78] D. G. Charlton,[18] V. Chavda,[82] C. A. Chavez Barajas,[30] S. Cheatham,[85] S. Chekanov,[6] S. V. Chekulaev,[159a] G. A. Chelkov,[64] M. A. Chelstowska,[104] C. Chen,[63] H. Chen,[25] S. Chen,[33c] X. Chen,[173] Y. Chen,[35] A. Cheplakov,[64] R. Cherkaoui El Moursli,[135e] V. Chernyatin,[25] E. Cheu,[7] S. L. Cheung,[158] L. Chevalier,[136] G. Chiefari,[102a,102b] L. Chikovani,[51a,a] J. T. Childers,[30] A. Chilingarov,[71] G. Chiodini,[72a] A. S. Chisholm,[18] R. T. Chislett,[77] A. Chitan,[26a] M. V. Chizhov,[64] G. Choudalakis,[31] S. Chouridou,[137] I. A. Christidi,[77] A. Christov,[48] D. Chromek-Burckhart,[30] M. L. Chu,[151] J. Chudoba,[125] G. Ciapetti,[132a,132b] A. K. Ciftci,[4a] R. Ciftci,[4a] D. Cinca,[34] V. Cindro,[74] C. Ciocca,[20a,20b] A. Ciocio,[15] M. Cirilli,[87] P. Cirkovic,[13b] Z. H. Citron,[172] M. Citterio,[89a] M. Ciubancan,[26a] A. Clark,[49] P. J. Clark,[46] R. N. Clarke,[15] W. Cleland,[123] J. C. Clemens,[83] B. Clement,[55] C. Clement,[146a,146b] Y. Coadou,[83] M. Cobal,[164a,164c] A. Coccaro,[138] J. Cochran,[63] L. Coffey,[23] J. G. Cogan,[143] J. Coggeshall,[165] E. Cogneras,[178] J. Colas,[5] S. Cole,[106] A. P. Colijn,[105] N. J. Collins,[18] C. Collins-Tooth,[53] J. Collot,[55] T. Colombo,[119a,119b] G. Colon,[84] P. Conde Muiño,[124a] E. Coniavitis,[118] M. C. Conidi,[12] S. M. Consonni,[89a,89b] V. Consorti,[48] S. Constantinescu,[26a] C. Conta,[119a,119b] G. Conti,[57] F. Conventi,[102a,k] M. Cooke,[15] B. D. Cooper,[77] A. M. Cooper-Sarkar,[118] K. Copic,[15] T. Cornelissen,[175] M. Corradi,[20a] F. Corriveau,[85,l] A. Cortes-Gonzalez,[165] G. Cortiana,[99] G. Costa,[89a] M. J. Costa,[167] D. Costanzo,[139] D. Côté,[30] L. Courneyea,[169] G. Cowan,[76] C. Cowden,[28] B. E. Cox,[82] K. Cranmer,[108] F. Crescioli,[122a,122b] M. Cristinziani,[21] G. Crosetti,[37a,37b] S. Crépé-Renaudin,[55] C.-M. Cuciuc,[26a] C. Cuenca Almenar,[176] T. Cuhadar Donszelmann,[139] M. Curatolo,[47] C. J. Curtis,[18] C. Cuthbert,[150] P. Cwetanski,[60] H. Czirr,[141] P. Czodrowski,[44] Z. Czyczula,[176] S. D'Auria,[53] M. D'Onofrio,[73] A. D'Orazio,[132a,132b] M. J. Da Cunha Sargedas De Sousa,[124a] C. Da Via,[82] W. Dabrowski,[38] A. Dafinca,[118] T. Dai,[87] C. Dallapiccola,[84] M. Dam,[36] M. Dameri,[50a,50b] D. S. Damiani,[137] H. O. Danielsson,[30] V. Dao,[49] G. Darbo,[50a] G. L. Darlea,[26b] J. A. Dassoulas,[42] W. Davey,[21] T. Davidek,[126] N. Davidson,[86] R. Davidson,[71] E. Davies,[118,d] M. Davies,[93] O. Davignon,[78] A. R. Davison,[77] Y. Davygora,[58a] E. Dawe,[142] I. Dawson,[139] R. K. Daya-Ishmukhametova,[23] K. De,[8] R. de Asmundis,[102a] S. De Castro,[20a,20b] S. De Cecco,[78] J. de Graat,[98] N. De Groot,[104] P. de Jong,[105] C. De La Taille,[115] H. De la Torre,[80] F. De Lorenzi,[63] L. de Mora,[71] L. De Nooij,[105] D. De Pedis,[132a] 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] W. J. Dearnaley,[71] R. Debbe,[25] C. Debenedetti,[46] B. Dechenaux,[55]

D. V. Dedovich,[64] J. Degenhardt,[120] C. Del Papa,[164a,164c] J. Del Peso,[80] T. Del Prete,[122a,122b] T. Delemontex,[55] M. Deliyergiyev,[74] A. Dell'Acqua,[30] L. Dell'Asta,[22] M. Della Pietra,[102a,k] D. della Volpe,[102a,102b] M. Delmastro,[5] P. A. Delsart,[55] C. Deluca,[105] S. Demers,[176] M. Demichev,[64] B. Demirkoz,[12,m] J. Deng,[163] S. P. Denisov,[128] D. Derendarz,[39] J. E. Derkaoui,[135d] F. Derue,[78] P. Dervan,[73] K. Desch,[21] E. Devetak,[148] P. O. Deviveiros,[105] A. Dewhurst,[129] B. DeWilde,[148] S. Dhaliwal,[158] R. Dhullipudi,[25,n] A. Di Ciaccio,[133a,133b] L. Di Ciaccio,[5] A. Di Girolamo,[30] B. Di Girolamo,[30] S. Di Luise,[134a,134b] A. Di Mattia,[173] B. Di Micco,[30] R. Di Nardo,[47] A. Di Simone,[133a,133b] R. Di Sipio,[20a,20b] M. A. Diaz,[32a] E. B. Diehl,[87] J. Dietrich,[42] T. A. Dietzsch,[58a] S. Diglio,[86] K. Dindar Yagci,[40] J. Dingfelder,[21] F. Dinut,[26a] C. Dionisi,[132a,132b] P. Dita,[26a] S. Dita,[26a] F. Dittus,[30] F. Djama,[83] T. Djobava,[51b] M. A. B. do Vale,[24c] A. Do Valle Wemans,[124a,o] T. K. O. Doan,[5] M. Dobbs,[85] R. Dobinson,[30,a] D. Dobos,[30] E. Dobson,[30,p] J. Dodd,[35] C. Doglioni,[49] T. Doherty,[53] Y. Doi,[65,a] J. Dolejsi,[126] I. Dolenc,[74] Z. Dolezal,[126] B. A. Dolgoshein,[96,a] T. Dohmae,[155] M. Donadelli,[24d] J. Donini,[34] J. Dopke,[30] A. Doria,[102a] A. Dos Anjos,[173] A. Dotti,[122a,122b] M. T. Dova,[70] A. D. Doxiadis,[105] A. T. Doyle,[53] M. Dris,[10] J. Dubbert,[99] S. Dube,[15] E. Duchovni,[172] G. Duckeck,[98] D. Duda,[175] A. Dudarev,[30] F. Dudziak,[63] M. Dührssen,[30] I. P. Duerdoth,[82] L. Duflot,[115] M-A. Dufour,[85] L. Duguid,[76] M. Dunford,[30] H. Duran Yildiz,[4a] R. Duxfield,[139] M. Dwuznik,[38] F. Dydak,[30] M. Düren,[52] J. Ebke,[98] S. Eckweiler,[81] K. Edmonds,[81] W. Edson,[2] C. A. Edwards,[76] N. C. Edwards,[53] W. Ehrenfeld,[42] T. Eifert,[143] G. Eigen,[14] K. Einsweiler,[15] E. Eisenhandler,[75] T. Ekelof,[166] M. El Kacimi,[135c] M. Ellert,[166] S. Elles,[5] F. Ellinghaus,[81] K. Ellis,[75] N. Ellis,[30] J. Elmsheuser,[98] M. Elsing,[30] D. Emeliyanov,[129] R. Engelmann,[148] A. Engl,[98] B. Epp,[61] J. Erdmann,[54] A. Ereditato,[17] D. Eriksson,[146a] J. Ernst,[2] M. Ernst,[25] J. Ernwein,[136] D. Errede,[165] S. Errede,[165] E. Ertel,[81] M. Escalier,[115] H. Esch,[43] C. Escobar,[123] X. Espinal Curull,[12] B. Esposito,[47] F. Etienne,[83] A. I. Etienvre,[136] E. Etzion,[153] D. Evangelakou,[54] H. Evans,[60] L. Fabbri,[20a,20b] C. Fabre,[30] R. M. Fakhrutdinov,[128] S. Falciano,[132a] Y. Fang,[173] M. Fanti,[89a,89b] A. Farbin,[8] A. Farilla,[134a] J. Farley,[148] T. Farooque,[158] S. Farrell,[163] S. M. Farrington,[170] P. Farthouat,[30] F. Fassi,[167] P. Fassnacht,[30] D. Fassouliotis,[9] B. Fatholahzadeh,[158] A. Favareto,[89a,89b] L. Fayard,[115] S. Fazio,[37a,37b] R. Febbraro,[34] P. Federic,[144a] O. L. Fedin,[121] W. Fedorko,[88] M. Fehling-Kaschek,[48] L. Feligioni,[83] D. Fellmann,[6] C. Feng,[33d] E. J. Feng,[6] A. B. Fenyuk,[128] J. Ferencei,[144b] W. Fernando,[6] S. Ferrag,[53] J. Ferrando,[53] V. Ferrara,[42] A. Ferrari,[166] P. Ferrari,[105] R. Ferrari,[119a] D. E. Ferreira de Lima,[53] A. Ferrer,[167] D. Ferrere,[49] C. Ferretti,[87] A. Ferretto Parodi,[50a,50b] M. Fiascaris,[31] F. Fiedler,[81] A. Filipčič,[74] F. Filthaut,[104] M. Fincke-Keeler,[169] M. C. N. Fiolhais,[124a,i] L. Fiorini,[167] A. Firan,[40] G. Fischer,[42] M. J. Fisher,[109] M. Flechl,[48] I. Fleck,[141] J. Fleckner,[81] P. Fleischmann,[174] S. Fleischmann,[175] T. Flick,[175] A. Floderus,[79] L. R. Flores Castillo,[173] M. J. Flowerdew,[99] T. Fonseca Martin,[17] A. Formica,[136] A. Forti,[82] D. Fortin,[159a] D. Fournier,[115] H. Fox,[71] P. Francavilla,[12] M. Franchini,[20a,20b] S. Franchino,[119a,119b] D. Francis,[30] T. Frank,[172] S. Franz,[30] M. Fraternali,[119a,119b] S. Fratina,[120] S. T. French,[28] C. Friedrich,[42] F. Friedrich,[44] R. Froeschl,[30] D. Froidevaux,[30] J. A. Frost,[28] C. Fukunaga,[156] E. Fullana Torregrosa,[30] B. G. Fulsom,[143] J. Fuster,[167] C. Gabaldon,[30] O. Gabizon,[172] T. Gadfort,[25] S. Gadomski,[49] G. Gagliardi,[50a,50b] P. Gagnon,[60] C. Galea,[98] B. Galhardo,[124a] E. J. Gallas,[118] V. Gallo,[17] B. J. Gallop,[129] P. Gallus,[125] K. K. Gan,[109] Y. S. Gao,[143,f] A. Gaponenko,[15] F. Garberson,[176] M. Garcia-Sciveres,[15] C. García,[167] J. E. García Navarro,[167] R. W. Gardner,[31] N. Garelli,[30] H. Garitaonandia,[105] V. Garonne,[30] C. Gatti,[47] G. Gaudio,[119a] B. Gaur,[141] L. Gauthier,[136] P. Gauzzi,[132a,132b] I. L. Gavrilenko,[94] C. Gay,[168] G. Gaycken,[21] E. N. Gazis,[10] P. Ge,[33d] Z. Gecse,[168] C. N. P. Gee,[129] D. A. A. Geerts,[105] Ch. Geich-Gimbel,[21] K. Gellerstedt,[146a,146b] C. Gemme,[50a] A. Gemmell,[53] M. H. Genest,[55] S. Gentile,[132a,132b] M. George,[54] S. George,[76] P. Gerlach,[175] A. Gershon,[153] C. Geweniger,[58a] H. Ghazlane,[135b] N. Ghodbane,[34] B. Giacobbe,[20a] S. Giagu,[132a,132b] V. Giakoumopoulou,[9] V. Giangiobbe,[12] F. Gianotti,[30] B. Gibbard,[25] A. Gibson,[158] S. M. Gibson,[30] D. Gillberg,[29] A. R. Gillman,[129] D. M. Gingrich,[3,e] J. Ginzburg,[153] N. Giokaris,[9] M. P. Giordani,[164c] R. Giordano,[102a,102b] F. M. Giorgi,[16] P. Giovannini,[99] P. F. Giraud,[136] D. Giugni,[89a] M. Giunta,[93] P. Giusti,[20a] B. K. Gjelsten,[117] L. K. Gladilin,[97] C. Glasman,[80] J. Glatzer,[48] A. Glazov,[42] K. W. Glitza,[175] G. L. Glonti,[64] J. R. Goddard,[75] J. Godfrey,[142] J. Godlewski,[30] M. Goebel,[42] T. Göpfert,[44] C. Goeringer,[81] C. Gössling,[43] S. Goldfarb,[87] T. Golling,[176] A. Gomes,[124a,c] L. S. Gomez Fajardo,[42] R. Gonçalo,[76] J. Goncalves Pinto Firmino Da Costa,[42] L. Gonella,[21] S. González de la Hoz,[167] G. Gonzalez Parra,[12] M. L. Gonzalez Silva,[27] S. Gonzalez-Sevilla,[49] J. J. Goodson,[148] L. Goossens,[30] P. A. Gorbounov,[95] H. A. Gordon,[25] I. Gorelov,[103] G. Gorfine,[175] B. Gorini,[30] E. Gorini,[72a,72b] A. Gorišek,[74] E. Gornicki,[39] B. Gosdzik,[42] A. T. Goshaw,[6] M. Gosselink,[105] M. I. Gostkin,[64] I. Gough Eschrich,[163] M. Gouighri,[135a] D. Goujdami,[135c] M. P. Goulette,[49] A. G. Goussiou,[138] C. Goy,[5] S. Gozpinar,[23] I. Grabowska-Bold,[38] P. Grafström,[20a,20b] K-J. Grahn,[42] F. Grancagnolo,[72a] S. Grancagnolo,[16] V. Grassi,[148] V. Gratchev,[121] N. Grau,[35] H. M. Gray,[30] J. A. Gray,[148]

E. Graziani,[134a] O. G. Grebenyuk,[121] T. Greenshaw,[73] Z. D. Greenwood,[25,n] K. Gregersen,[36] I. M. Gregor,[42] P. Grenier,[143] J. Griffiths,[8] N. Grigalashvili,[64] A. A. Grillo,[137] S. Grinstein,[12] Ph. Gris,[34] Y. V. Grishkevich,[97] J.-F. Grivaz,[115] E. Gross,[172] J. Grosse-Knetter,[54] J. Groth-Jensen,[172] K. Grybel,[141] D. Guest,[176] C. Guicheney,[34] S. Guindon,[54] U. Gul,[53] H. Guler,[85,q] J. Gunther,[125] B. Guo,[158] J. Guo,[35] P. Gutierrez,[111] N. Guttman,[153] O. Gutzwiller,[173] C. Guyot,[136] C. Gwenlan,[118] C. B. Gwilliam,[73] A. Haas,[143] S. Haas,[30] C. Haber,[15] H. K. Hadavand,[40] D. R. Hadley,[18] P. Haefner,[21] F. Hahn,[30] S. Haider,[30] Z. Hajduk,[39] H. Hakobyan,[177] D. Hall,[118] J. Haller,[54] K. Hamacher,[175] P. Hamal,[113] M. Hamer,[54] A. Hamilton,[145b,r] S. Hamilton,[161] L. Han,[33b] K. Hanagaki,[116] K. Hanawa,[160] M. Hance,[15] C. Handel,[81] P. Hanke,[58a] J. R. Hansen,[36] J. B. Hansen,[36] J. D. Hansen,[36] P. H. Hansen,[36] P. Hansson,[143] K. Hara,[160] G. A. Hare,[137] T. Harenberg,[175] S. Harkusha,[90] D. Harper,[87] R. D. Harrington,[46] O. M. Harris,[138] J. Hartert,[48] F. Hartjes,[105] T. Haruyama,[65] A. Harvey,[56] S. Hasegawa,[101] Y. Hasegawa,[140] S. Hassani,[136] S. Haug,[17] M. Hauschild,[30] R. Hauser,[88] M. Havranek,[21] C. M. Hawkes,[18] R. J. Hawkings,[30] A. D. Hawkins,[79] T. Hayakawa,[66] T. Hayashi,[160] D. Hayden,[76] C. P. Hays,[118] H. S. Hayward,[73] S. J. Haywood,[129] S. J. Head,[18] V. Hedberg,[79] L. Heelan,[8] S. Heim,[88] B. Heinemann,[15] S. Heisterkamp,[36] L. Helary,[22] C. Heller,[98] M. Heller,[30] S. Hellman,[146a,146b] D. Hellmich,[21] C. Helsens,[12] R. C. W. Henderson,[71] M. Henke,[58a] A. Henrichs,[54] A. M. Henriques Correia,[30] S. Henrot-Versille,[115] C. Hensel,[54] T. Henß,[175] C. M. Hernandez,[8] Y. Hernández Jiménez,[167] R. Herrberg,[16] G. Herten,[48] R. Hertenberger,[98] L. Hervas,[30] G. G. Hesketh,[77] N. P. Hessey,[105] E. Higón-Rodriguez,[167] J. C. Hill,[28] K. H. Hiller,[42] S. Hillert,[21] S. J. Hillier,[18] I. Hinchliffe,[15] E. Hines,[120] M. Hirose,[116] F. Hirsch,[43] D. Hirschbuehl,[175] J. Hobbs,[148] N. Hod,[153] M. C. Hodgkinson,[139] P. Hodgson,[139] A. Hoecker,[30] M. R. Hoeferkamp,[103] J. Hoffman,[40] D. Hoffmann,[83] M. Hohlfeld,[81] M. Holder,[141] S. O. Holmgren,[146a] T. Holy,[127] J. L. Holzbauer,[88] T. M. Hong,[120] L. Hooft van Huysduynen,[108] S. Horner,[48] J-Y. Hostachy,[55] S. Hou,[151] A. Hoummada,[135a] J. Howard,[118] J. Howarth,[82] I. Hristova,[16] J. Hrivnac,[115] T. Hryn'ova,[5] P. J. Hsu,[81] S.-C. Hsu,[15] D. Hu,[35] Z. Hubacek,[127] F. Hubaut,[83] F. Huegging,[21] A. Huettmann,[42] T. B. Huffman,[118] E. W. Hughes,[35] G. Hughes,[71] M. Huhtinen,[30] M. Hurwitz,[15] U. Husemann,[42] N. Huseynov,[64,s] J. Huston,[88] J. Huth,[57] G. Iacobucci,[49] G. Iakovidis,[10] M. Ibbotson,[82] I. Ibragimov,[141] L. Iconomidou-Fayard,[115] J. Idarraga,[115] P. Iengo,[102a] O. Igonkina,[105] Y. Ikegami,[65] M. Ikeno,[65] D. Iliadis,[154] N. Ilic,[158] T. Ince,[21] J. Inigo-Golfin,[30] P. Ioannou,[9] M. Iodice,[134a] K. Iordanidou,[9] V. Ippolito,[132a,132b] A. Irles Quiles,[167] C. Isaksson,[166] M. Ishino,[67] M. Ishitsuka,[157] R. Ishmukhametov,[40] C. Issever,[118] S. Istin,[19a] A. V. Ivashin,[128] W. Iwanski,[39] H. Iwasaki,[65] J. M. Izen,[41] V. Izzo,[102a] B. Jackson,[120] J. N. Jackson,[73] P. Jackson,[1] M. R. Jaekel,[30] V. Jain,[60] K. Jakobs,[48] S. Jakobsen,[36] T. Jakoubek,[125] J. Jakubek,[127] D. K. Jana,[111] E. Jansen,[77] H. Jansen,[30] A. Jantsch,[99] M. Janus,[48] G. Jarlskog,[79] L. Jeanty,[57] I. Jen-La Plante,[31] D. Jennens,[86] P. Jenni,[30] A. E. Loevschall-Jensen,[36] P. Jež,[36] S. Jézéquel,[5] M. K. Jha,[20a] H. Ji,[173] W. Ji,[81] J. Jia,[148] Y. Jiang,[33b] M. Jimenez Belenguer,[42] S. Jin,[33a] O. Jinnouchi,[157] M. D. Joergensen,[36] D. Joffe,[40] M. Johansen,[146a,146b] K. E. Johansson,[146a] P. Johansson,[139] S. Johnert,[42] K. A. Johns,[7] K. Jon-And,[146a,146b] G. Jones,[170] R. W. L. Jones,[71] T. J. Jones,[73] C. Joram,[30] P. M. Jorge,[124a] K. D. Joshi,[82] J. Jovicevic,[147] T. Jovin,[13b] X. Ju,[173] C. A. Jung,[43] R. M. Jungst,[30] V. Juranek,[125] P. Jussel,[61] A. Juste Rozas,[12] S. Kabana,[17] M. Kaci,[167] A. Kaczmarska,[39] P. Kadlecik,[36] M. Kado,[115] H. Kagan,[109] M. Kagan,[57] E. Kajomovitz,[152] S. Kalinin,[175] L. V. Kalinovskaya,[64] S. Kama,[40] N. Kanaya,[155] M. Kaneda,[30] S. Kaneti,[28] T. Kanno,[157] V. A. Kantserov,[96] J. Kanzaki,[65] B. Kaplan,[108] A. Kapliy,[31] J. Kaplon,[30] D. Kar,[53] M. Karagounis,[21] K. Karakostas,[10] M. Karnevskiy,[42] V. Kartvelishvili,[71] A. N. Karyukhin,[128] L. Kashif,[173] G. Kasieczka,[58b] R. D. Kass,[109] A. Kastanas,[14] M. Kataoka,[5] Y. Kataoka,[155] E. Katsoufis,[10] J. Katzy,[42] V. Kaushik,[7] K. Kawagoe,[69] T. Kawamoto,[155] G. Kawamura,[81] M. S. Kayl,[105] S. Kazama,[155] V. A. Kazanin,[107] M. Y. Kazarinov,[64] R. Keeler,[169] R. Kehoe,[40] M. Keil,[54] G. D. Kekelidze,[64] J. S. Keller,[138] M. Kenyon,[53] O. Kepka,[125] N. Kerschen,[30] B. P. Kerševan,[74] S. Kersten,[175] K. Kessoku,[155] J. Keung,[158] F. Khalil-zada,[11] H. Khandanyan,[146a,146b] A. Khanov,[112] D. Kharchenko,[64] A. Khodinov,[96] A. Khomich,[58a] T. J. Khoo,[28] G. Khoriauli,[21] A. Khoroshilov,[175] V. Khovanskiy,[95] E. Khramov,[64] J. Khubua,[51b] H. Kim,[146a,146b] S. H. Kim,[160] N. Kimura,[171] O. Kind,[16] B. T. King,[73] M. King,[66] R. S. B. King,[118] J. Kirk,[129] A. E. Kiryunin,[99] T. Kishimoto,[66] D. Kisielewska,[38] T. Kitamura,[66] T. Kittelmann,[123] K. Kiuchi,[160] E. Kladiva,[144b] M. Klein,[73] U. Klein,[73] K. Kleinknecht,[81] M. Klemetti,[85] A. Klier,[172] P. Klimek,[146a,146b] A. Klimentov,[25] R. Klingenberg,[43] J. A. Klinger,[82] E. B. Klinkby,[36] T. Klioutchnikova,[30] 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,[61] E. B. F. G. Knoops,[83] A. Knue,[54] B. R. Ko,[45] T. Kobayashi,[155] M. Kobel,[44] M. Kocian,[143] P. Kodys,[126] K. Köneke,[30] A. C. König,[104] S. Koenig,[81] L. Köpke,[81] F. Koetsveld,[104] P. Koevesarki,[21] T. Koffas,[29] E. Koffeman,[105] L. A. Kogan,[118] S. Kohlmann,[175] F. Kohn,[54] Z. Kohout,[127] T. Kohriki,[65] T. Koi,[143] G. M. Kolachev,[107,a] H. Kolanoski,[16] V. Kolesnikov,[64]

I. Koletsou,[89a] J. Koll,[88] A. A. Komar,[94] Y. Komori,[155] T. Kondo,[65] T. Kono,[42,t] A. I. Kononov,[48] R. Konoplich,[108,u] N. Konstantinidis,[77] S. Koperny,[38] K. Korcyl,[39] K. Kordas,[154] A. Korn,[118] A. Korol,[107] I. Korolkov,[12] E. V. Korolkova,[139] V. A. Korotkov,[128] O. Kortner,[99] S. Kortner,[99] V. V. Kostyukhin,[21] S. Kotov,[99] V. M. Kotov,[64] A. Kotwal,[45] C. Kourkoumelis,[9] V. Kouskoura,[154] A. Koutsman,[159a] R. Kowalewski,[169] T. Z. Kowalski,[38] W. Kozanecki,[136] A. S. Kozhin,[128] V. Kral,[127] V. A. Kramarenko,[97] G. Kramberger,[74] M. W. Krasny,[78] A. Krasznahorkay,[108] J. K. Kraus,[21] S. Kreiss,[108] F. Krejci,[127] J. Kretzschmar,[73] N. Krieger,[54] P. Krieger,[158] K. Kroeninger,[54] H. Kroha,[99] J. Kroll,[120] J. Kroseberg,[21] J. Krstic,[13a] U. Kruchonak,[64] H. Krüger,[21] T. Kruker,[17] N. Krumnack,[63] Z. V. Krumshteyn,[64] T. Kubota,[86] S. Kuday,[4a] S. Kuehn,[48] A. Kugel,[58c] T. Kuhl,[42] D. Kuhn,[61] V. Kukhtin,[64] Y. Kulchitsky,[90] S. Kuleshov,[32b] C. Kummer,[98] M. Kuna,[78] J. Kunkle,[120] A. Kupco,[125] H. Kurashige,[66] M. Kurata,[160] Y. A. Kurochkin,[90] V. Kus,[125] E. S. Kuwertz,[147] M. Kuze,[157] J. Kvita,[142] R. Kwee,[16] A. La Rosa,[49] L. La Rotonda,[37a,37b] L. Labarga,[80] J. Labbe,[5] S. Lablak,[135a] C. Lacasta,[167] F. Lacava,[132a,132b] H. Lacker,[16] D. Lacour,[78] V. R. Lacuesta,[167] E. Ladygin,[64] R. Lafaye,[5] B. Laforge,[78] T. Lagouri,[176] S. Lai,[48] E. Laisne,[55] M. Lamanna,[30] L. Lambourne,[77] C. L. Lampen,[7] W. Lampl,[7] E. Lancon,[136] U. Landgraf,[48] M. P. J. Landon,[75] J. L. Lane,[82] V. S. Lang,[58a] C. Lange,[42] A. J. Lankford,[163] F. Lanni,[25] K. Lantzsch,[175] S. Laplace,[78] C. Lapoire,[21] J. F. Laporte,[136] T. Lari,[89a] A. Larner,[118] M. Lassnig,[30] P. Laurelli,[47] V. Lavorini,[37a,37b] W. Lavrijsen,[15] P. Laycock,[73] O. Le Dortz,[78] E. Le Guirriec,[83] E. Le Menedeu,[12] T. LeCompte,[6] F. Ledroit-Guillon,[55] H. Lee,[105] J. S. H. Lee,[116] S. C. Lee,[151] L. Lee,[176] M. Lefebvre,[169] M. Legendre,[136] F. Legger,[98] C. Leggett,[15] M. Lehmacher,[21] G. Lehmann Miotto,[30] X. Lei,[7] M. A. L. Leite,[24d] R. Leitner,[126] D. Lellouch,[172] B. Lemmer,[54] V. Lendermann,[58a] K. J. C. Leney,[145b] T. Lenz,[105] G. Lenzen,[175] B. Lenzi,[30] K. Leonhardt,[44] S. Leontsinis,[10] F. Lepold,[58a] C. Leroy,[93] J-R. Lessard,[169] C. G. Lester,[28] C. M. Lester,[120] J. Levêque,[5] D. Levin,[87] L. J. Levinson,[172] A. Lewis,[118] G. H. Lewis,[108] A. M. Leyko,[21] M. Leyton,[16] B. Li,[83] H. Li,[173,v] S. Li,[33b,w] X. Li,[87] Z. Liang,[118,x] H. Liao,[34] B. Liberti,[133a] P. Lichard,[30] M. Lichtnecker,[98] K. Lie,[165] W. Liebig,[14] C. Limbach,[21] A. Limosani,[86] M. Limper,[62] S. C. Lin,[151,y] F. Linde,[105] J. T. Linnemann,[88] E. Lipeles,[120] A. Lipniacka,[14] T. M. Liss,[165] D. Lissauer,[25] A. Lister,[49] A. M. Litke,[137] C. Liu,[29] D. Liu,[151] H. Liu,[87] J. B. Liu,[87] L. Liu,[87] M. Liu,[33b] Y. Liu,[33b] M. Livan,[119a,119b] S. S. A. Livermore,[118] A. Lleres,[55] J. Llorente Merino,[80] S. L. Lloyd,[75] E. Lobodzinska,[42] P. Loch,[7] W. S. Lockman,[137] T. Loddenkoetter,[21] F. K. Loebinger,[82] A. Loginov,[176] C. W. Loh,[168] T. Lohse,[16] K. Lohwasser,[48] M. Lokajicek,[125] V. P. Lombardo,[5] R. E. Long,[71] L. Lopes,[124a] D. Lopez Mateos,[57] J. Lorenz,[98] N. Lorenzo Martinez,[115] M. Losada,[162] P. Loscutoff,[15] F. Lo Sterzo,[132a,132b] M. J. Losty,[159a,a] X. Lou,[41] A. Lounis,[115] K. F. Loureiro,[162] J. Love,[6] P. A. Love,[71] A. J. Lowe,[143,f] F. Lu,[33a] H. J. Lubatti,[138] C. Luci,[132a,132b] A. Lucotte,[55] A. Ludwig,[44] D. Ludwig,[42] I. Ludwig,[48] J. Ludwig,[48] F. Luehring,[60] G. Luijckx,[105] W. Lukas,[61] D. Lumb,[48] L. Luminari,[132a] E. Lund,[117] B. Lund-Jensen,[147] B. Lundberg,[79] J. Lundberg,[146a,146b] O. Lundberg,[146a,146b] J. Lundquist,[36] M. Lungwitz,[81] D. Lynn,[25] E. Lytken,[79] H. Ma,[25] L. L. Ma,[173] G. Maccarrone,[47] A. Macchiolo,[99] B. Maček,[74] J. Machado Miguens,[124a] R. Mackeprang,[36] R. J. Madaras,[15] H. J. Maddocks,[71] W. F. Mader,[44] R. Maenner,[58c] T. Maeno,[25] P. Mättig,[175] S. Mättig,[81] L. Magnoni,[163] E. Magradze,[54] K. Mahboubi,[48] J. Mahlstedt,[105] S. Mahmoud,[73] G. Mahout,[18] C. Maiani,[136] C. Maidantchik,[24a] A. Maio,[124a,c] S. Majewski,[25] Y. Makida,[65] N. Makovec,[115] P. Mal,[136] B. Malaescu,[30] Pa. Malecki,[39] P. Malecki,[39] V. P. Maleev,[121] F. Malek,[55] U. Mallik,[62] D. Malon,[6] C. Malone,[143] S. Maltezos,[10] V. Malyshev,[107] S. Malyukov,[30] R. Mameghani,[98] J. Mamuzic,[13b] A. Manabe,[65] L. Mandelli,[89a] I. Mandić,[74] R. Mandrysch,[16] J. Maneira,[124a] A. Manfredini,[99] P. S. Mangeard,[88] L. Manhaes de Andrade Filho,[24b] J. A. Manjarres Ramos,[136] A. Mann,[54] P. M. Manning,[137] A. Manousakis-Katsikakis,[9] B. Mansoulie,[136] A. Mapelli,[30] L. Mapelli,[30] L. March,[80] J. F. Marchand,[29] F. Marchese,[133a,133b] G. Marchiori,[78] M. Marcisovsky,[125] C. P. Marino,[169] F. Marroquim,[24a] Z. Marshall,[30] F. K. Martens,[158] L. F. Marti,[17] S. Marti-Garcia,[167] B. Martin,[30] B. Martin,[88] J. P. Martin,[93] T. A. Martin,[18] V. J. Martin,[46] B. Martin dit Latour,[49] S. Martin-Haugh,[149] M. Martinez,[12] V. Martinez Outschoorn,[57] A. C. Martyniuk,[169] 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] I. Massa,[20a,20b] G. Massaro,[105] N. Massol,[5] P. Mastrandrea,[148] A. Mastroberardino,[37a,37b] T. Masubuchi,[155] P. Matricon,[115] H. Matsunaga,[155] T. Matsushita,[66] C. Mattravers,[118,d] J. Maurer,[83] S. J. Maxfield,[73] A. Mayne,[139] R. Mazini,[151] M. Mazur,[21] L. Mazzaferro,[133a,133b] M. Mazzanti,[89a] J. Mc Donald,[85] S. P. Mc Kee,[87] A. McCarn,[165] R. L. McCarthy,[148] T. G. McCarthy,[29] N. A. McCubbin,[129] K. W. McFarlane,[56,a] J. A. Mcfayden,[139] G. Mchedlidze,[51b] T. Mclaughlan,[18] S. J. McMahon,[129] R. A. McPherson,[169,l] A. Meade,[84] J. Mechnich,[105] M. Mechtel,[175] M. Medinnis,[42] R. Meera-Lebbai,[111] T. Meguro,[116] R. Mehdiyev,[93] S. Mehlhase,[36] A. Mehta,[73] K. Meier,[58a] B. Meirose,[79] C. Melachrinos,[31]

B. R. Mellado Garcia,[173] F. Meloni,[89a,89b] L. Mendoza Navas,[162] Z. Meng,[151,v] A. Mengarelli,[20a,20b] S. Menke,[99] E. Meoni,[161] K. M. Mercurio,[57] P. Mermod,[49] L. Merola,[102a,102b] C. Meroni,[89a] F. S. Merritt,[31] H. Merritt,[109] A. Messina,[30,z] J. Metcalfe,[25] A. S. Mete,[163] C. Meyer,[81] C. Meyer,[31] J-P. Meyer,[136] J. Meyer,[174] J. Meyer,[54] T. C. Meyer,[30] J. Miao,[33d] S. Michal,[30] L. Micu,[26a] R. P. Middleton,[129] S. Migas,[73] L. Mijović,[136] G. Mikenberg,[172] M. Mikestikova,[125] M. Mikuž,[74] D. W. Miller,[31] R. J. Miller,[88] W. J. Mills,[168] C. Mills,[57] A. Milov,[172] D. A. Milstead,[146a,146b] D. Milstein,[172] A. A. Minaenko,[128] M. Miñano Moya,[167] I. A. Minashvili,[64] A. I. Mincer,[108] B. Mindur,[38] M. Mineev,[64] Y. Ming,[173] L. M. Mir,[12] G. Mirabelli,[132a] J. Mitrevski,[137] V. A. Mitsou,[167] S. Mitsui,[65] P. S. Miyagawa,[139] J. U. Mjörnmark,[79] T. Moa,[146a,146b] V. Moeller,[28] K. Mönig,[42] N. Möser,[21] S. Mohapatra,[148] W. Mohr,[48] R. Moles-Valls,[167] J. Monk,[77] E. Monnier,[83] J. Montejo Berlingen,[12] F. Monticelli,[70] S. Monzani,[20a,20b] R. W. Moore,[3] G. F. Moorhead,[86] C. Mora Herrera,[49] A. Moraes,[53] N. Morange,[136] J. Morel,[54] G. Morello,[37a,37b] D. Moreno,[81] M. Moreno Llácer,[167] P. Morettini,[50a] M. Morgenstern,[44] M. Morii,[57] A. K. Morley,[30] G. Mornacchi,[30] J. D. Morris,[75] L. Morvaj,[101] H. G. Moser,[99] M. Mosidze,[51b] J. Moss,[109] R. Mount,[143] E. Mountricha,[10,aa] S. V. Mouraviev,[94,a] E. J. W. Moyse,[84] F. Mueller,[58a] J. Mueller,[123] K. Mueller,[21] T. A. Müller,[98] T. Mueller,[81] D. Muenstermann,[30] Y. Munwes,[153] W. J. Murray,[129] I. Mussche,[105] E. Musto,[102a,102b] A. G. Myagkov,[128] M. Myska,[125] J. Nadal,[12] K. Nagai,[160] R. Nagai,[157] K. Nagano,[65] A. Nagarkar,[109] Y. Nagasaka,[59] M. Nagel,[99] A. M. Nairz,[30] Y. Nakahama,[30] K. Nakamura,[155] T. Nakamura,[155] I. Nakano,[110] G. Nanava,[21] A. Napier,[161] R. Narayan,[58b] M. Nash,[77,d] T. Nattermann,[21] T. Naumann,[42] G. Navarro,[162] H. A. Neal,[87] P. Yu. Nechaeva,[94] T. J. Neep,[82] A. Negri,[119a,119b] G. Negri,[30] M. Negrini,[20a] S. Nektarijevic,[49] A. Nelson,[163] T. K. Nelson,[143] S. Nemecek,[125] P. Nemethy,[108] A. A. Nepomuceno,[24a] M. Nessi,[30,bb] M. S. Neubauer,[165] M. Neumann,[175] A. Neusiedl,[81] R. M. Neves,[108] P. Nevski,[25] P. R. Newman,[18] V. Nguyen Thi Hong,[136] R. B. Nickerson,[118] R. Nicolaidou,[136] B. Nicquevert,[30] F. Niedercorn,[115] J. Nielsen,[137] N. Nikiforou,[35] A. Nikiforov,[16] V. Nikolaenko,[128] I. Nikolic-Audit,[78] K. Nikolics,[49] K. Nikolopoulos,[18] H. Nilsen,[48] P. Nilsson,[8] Y. Ninomiya,[155] A. Nisati,[132a] R. Nisius,[99] T. Nobe,[157] L. Nodulman,[6] M. Nomachi,[116] I. Nomidis,[154] S. Norberg,[111] M. Nordberg,[30] P. R. Norton,[129] J. Novakova,[126] M. Nozaki,[65] L. Nozka,[113] I. M. Nugent,[159a] A.-E. Nuncio-Quiroz,[21] G. Nunes Hanninger,[86] T. Nunnemann,[98] E. Nurse,[77] B. J. O'Brien,[46] D. C. O'Neil,[142] V. O'Shea,[53] L. B. Oakes,[98] F. G. Oakham,[29,e] H. Oberlack,[99] J. Ocariz,[78] A. Ochi,[66] S. Oda,[69] S. Odaka,[65] J. Odier,[83] H. Ogren,[60] A. Oh,[82] S. H. Oh,[45] C. C. Ohm,[30] T. Ohshima,[101] H. Okawa,[25] Y. Okumura,[31] T. Okuyama,[155] A. Olariu,[26a] A. G. Olchevski,[64] S. A. Olivares Pino,[32a] M. Oliveira,[124a,i] D. Oliveira Damazio,[25] E. Oliver Garcia,[167] D. Olivito,[120] A. Olszewski,[39] J. Olszowska,[39] A. Onofre,[124a,cc] P. U. E. Onyisi,[31] C. J. Oram,[159a] M. J. Oreglia,[31] Y. Oren,[153] D. Orestano,[134a,134b] N. Orlando,[72a,72b] I. Orlov,[107] C. Oropeza Barrera,[53] R. S. Orr,[158] B. Osculati,[50a,50b] R. Ospanov,[120] C. Osuna,[12] G. Otero y Garzon,[27] J. P. Ottersbach,[105] M. Ouchrif,[135d] E. A. Ouellette,[169] F. Ould-Saada,[117] A. Ouraou,[136] Q. Ouyang,[33a] A. Ovcharova,[15] M. Owen,[82] S. Owen,[139] V. E. Ozcan,[19a] N. Ozturk,[8] A. Pacheco Pages,[12] C. Padilla Aranda,[12] S. Pagan Griso,[15] E. Paganis,[139] C. Pahl,[99] F. Paige,[25] P. Pais,[84] K. Pajchel,[117] G. Palacino,[159b] C. P. Paleari,[7] S. Palestini,[30] D. Pallin,[34] A. Palma,[124a] J. D. Palmer,[18] Y. B. Pan,[173] E. Panagiotopoulou,[10] P. Pani,[105] N. Panikashvili,[87] S. Panitkin,[25] D. Pantea,[26a] A. Papadelis,[146a] Th. D. Papadopoulou,[10] A. Paramonov,[6] D. Paredes Hernandez,[34] W. Park,[25,dd] M. A. Parker,[28] F. Parodi,[50a,50b] J. A. Parsons,[35] U. Parzefall,[48] S. Pashapour,[54] E. Pasqualucci,[132a] S. Passaggio,[50a] A. Passeri,[134a] F. Pastore,[134a,134b,a] Fr. Pastore,[76] G. Pásztor,[49,ee] S. Pataraia,[175] N. Patel,[150] J. R. Pater,[82] S. Patricelli,[102a,102b] T. Pauly,[30] M. Pecsy,[144a] S. Pedraza Lopez,[167] M. I. Pedraza Morales,[173] S. V. Peleganchuk,[107] D. Pelikan,[166] H. Peng,[33b] B. Penning,[31] A. Penson,[35] J. Penwell,[60] M. Perantoni,[24a] K. Perez,[35,ff] T. Perez Cavalcanti,[42] E. Perez Codina,[159a] M. T. Pérez García-Estañ,[167] V. Perez Reale,[35] L. Perini,[89a,89b] H. Pernegger,[30] R. Perrino,[72a] P. Perrodo,[5] V. D. Peshekhonov,[64] K. Peters,[30] B. A. Petersen,[30] J. Petersen,[30] T. C. Petersen,[36] E. Petit,[5] A. Petridis,[154] C. Petridou,[154] E. Petrolo,[132a] F. Petrucci,[134a,134b] D. Petschull,[42] M. Petteni,[142] R. Pezoa,[32b] A. Phan,[86] P. W. Phillips,[129] G. Piacquadio,[30] A. Picazio,[49] E. Piccaro,[75] M. Piccinini,[20a,20b] S. M. Piec,[42] R. Piegaia,[27] D. T. Pignotti,[109] J. E. Pilcher,[31] A. D. Pilkington,[82] J. Pina,[124a,c] M. Pinamonti,[164a,164c] A. Pinder,[118] J. L. Pinfold,[3] B. Pinto,[124a] C. Pizio,[89a,89b] M. Plamondon,[169] M.-A. Pleier,[25] E. Plotnikova,[64] A. Poblaguev,[25] S. Poddar,[58a] F. Podlyski,[34] L. Poggioli,[115] D. Pohl,[21] M. Pohl,[49] G. Polesello,[119a] A. Policicchio,[37a,37b] A. Polini,[20a] J. Poll,[75] V. Polychronakos,[25] D. Pomeroy,[23] K. Pommès,[30] L. Pontecorvo,[132a] B. G. Pope,[88] G. A. Popeneciu,[26a] D. S. Popovic,[13a] A. Poppleton,[30] X. Portell Bueso,[30] G. E. Pospelov,[99] S. Pospisil,[127] I. N. Potrap,[99] C. J. Potter,[149] C. T. Potter,[114] G. Poulard,[30] J. Poveda,[60] V. Pozdnyakov,[64] R. Prabhu,[77] P. Pralavorio,[83] A. Pranko,[15] S. Prasad,[30] R. Pravahan,[25] S. Prell,[63] K. Pretzl,[17] D. Price,[60] J. Price,[73] L. E. Price,[6] D. Prieur,[123] M. Primavera,[72a]

K. Prokofiev,[108] F. Prokoshin,[32b] S. Protopopescu,[25] J. Proudfoot,[6] X. Prudent,[44] M. Przybycien,[38] H. Przysiezniak,[5] S. Psoroulas,[21] E. Ptacek,[114] E. Pueschel,[84] J. Purdham,[87] M. Purohit,[25,dd] P. Puzo,[115] Y. Pylypchenko,[62] J. Qian,[87] A. Quadt,[54] D. R. Quarrie,[15] W. B. Quayle,[173] F. Quinonez,[32a] M. Raas,[104] V. Radescu,[42] P. Radloff,[114] T. Rador,[19a] F. Ragusa,[89a,89b] G. Rahal,[178] A. M. Rahimi,[109] D. Rahm,[25] S. Rajagopalan,[25] M. Rammensee,[48] M. Rammes,[141] A. S. Randle-Conde,[40] K. Randrianarivony,[29] F. Rauscher,[98] T. C. Rave,[48] M. Raymond,[30] A. L. Read,[117] D. M. Rebuzzi,[119a,119b] A. Redelbach,[174] G. Redlinger,[25] R. Reece,[120] K. Reeves,[41] E. Reinherz-Aronis,[153] A. Reinsch,[114] I. Reisinger,[43] C. Rembser,[30] Z. L. Ren,[151] A. Renaud,[115] M. Rescigno,[132a] S. Resconi,[89a] B. Resende,[136] P. Reznicek,[98] R. Rezvani,[158] R. Richter,[99] E. Richter-Was,[5,gg] M. Ridel,[78] M. Rijpstra,[105] M. Rijssenbeek,[148] A. Rimoldi,[119a,119b] L. Rinaldi,[20a] R. R. Rios,[40] I. Riu,[12] G. Rivoltella,[89a,89b] F. Rizatdinova,[112] E. Rizvi,[75] S. H. Robertson,[85,l] A. Robichaud-Veronneau,[118] D. Robinson,[28] J. E. M. Robinson,[82] A. Robson,[53] J. G. Rocha de Lima,[106] C. Roda,[122a,122b] D. Roda Dos Santos,[30] A. Roe,[54] S. Roe,[30] O. Røhne,[117] S. Rolli,[161] A. Romaniouk,[96] M. Romano,[20a,20b] G. Romeo,[27] E. Romero Adam,[167] N. Rompotis,[138] L. Roos,[78] E. Ros,[167] S. Rosati,[132a] K. Rosbach,[49] A. Rose,[149] M. Rose,[76] G. A. Rosenbaum,[158] E. I. Rosenberg,[63] P. L. Rosendahl,[14] O. Rosenthal,[141] L. Rosselet,[49] V. Rossetti,[12] E. Rossi,[132a,132b] L. P. Rossi,[50a] M. Rotaru,[26a] I. Roth,[172] J. Rothberg,[138] D. Rousseau,[115] C. R. Royon,[136] A. Rozanov,[83] Y. Rozen,[152] X. Ruan,[33a,hh] F. Rubbo,[12] I. Rubinskiy,[42] N. Ruckstuhl,[105] V. I. Rud,[97] C. Rudolph,[44] G. Rudolph,[61] F. Rühr,[7] A. Ruiz-Martinez,[63] L. Rumyantsev,[64] Z. Rurikova,[48] N. A. Rusakovich,[64] J. P. Rutherfoord,[7] C. Ruwiedel,[15,a] P. Ruzicka,[125] Y. F. Ryabov,[121] M. Rybar,[126] G. Rybkin,[115] N. C. Ryder,[118] A. F. Saavedra,[150] I. Sadeh,[153] H. F-W. Sadrozinski,[137] R. Sadykov,[64] F. Safai Tehrani,[132a] H. Sakamoto,[155] G. Salamanna,[75] A. Salamon,[133a] M. Saleem,[111] D. Salek,[30] D. Salihagic,[99] A. Salnikov,[143] J. Salt,[167] B. M. Salvachua Ferrando,[6] D. Salvatore,[37a,37b] F. Salvatore,[149] A. Salvucci,[104] A. Salzburger,[30] D. Sampsonidis,[154] B. H. Samset,[117] A. Sanchez,[102a,102b] V. Sanchez Martinez,[167] H. Sandaker,[14] H. G. Sander,[81] M. P. Sanders,[98] M. Sandhoff,[175] T. Sandoval,[28] C. Sandoval,[162] R. Sandstroem,[99] D. P. C. Sankey,[129] A. Sansoni,[47] C. Santamarina Rios,[85] C. Santoni,[34] R. Santonico,[133a,133b] H. Santos,[124a] J. G. Saraiva,[124a] T. Sarangi,[173] E. Sarkisyan-Grinbaum,[8] F. Sarri,[122a,122b] G. Sartisohn,[175] O. Sasaki,[65] Y. Sasaki,[155] N. Sasao,[67] I. Satsounkevitch,[90] G. Sauvage,[5,a] E. Sauvan,[5] J. B. Sauvan,[115] P. Savard,[158,e] V. Savinov,[123] D. O. Savu,[30] L. Sawyer,[25,n] D. H. Saxon,[53] J. Saxon,[120] C. Sbarra,[20a] A. Sbrizzi,[20a,20b] D. A. Scannicchio,[163] M. Scarcella,[150] J. Schaarschmidt,[115] P. Schacht,[99] D. Schaefer,[120] U. Schäfer,[81] S. Schaepe,[21] 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. Schernau,[163] M. I. Scherzer,[35] C. Schiavi,[50a,50b] J. Schieck,[98] M. Schioppa,[37a,37b] S. Schlenker,[30] E. Schmidt,[48] K. Schmieden,[21] C. Schmitt,[81] S. Schmitt,[58b] M. Schmitz,[21] B. Schneider,[17] U. Schnoor,[44] A. Schoening,[58b] A. L. S. Schorlemmer,[54] M. Schott,[30] D. Schouten,[159a] J. Schovancova,[125] M. Schram,[85] C. Schroeder,[81] N. Schroer,[58c] M. J. Schultens,[21] J. Schultes,[175] H.-C. Schultz-Coulon,[58a] H. Schulz,[16] M. Schumacher,[48] B. A. Schumm,[137] Ph. Schune,[136] C. Schwanenberger,[82] A. Schwartzman,[143] Ph. Schwegler,[99] Ph. Schwemling,[78] R. Schwienhorst,[88] R. Schwierz,[44] J. Schwindling,[136] T. Schwindt,[21] M. Schwoerer,[5] G. Sciolla,[23] W. G. Scott,[129] J. Searcy,[114] G. Sedov,[42] E. Sedykh,[121] S. C. Seidel,[103] A. Seiden,[137] F. Seifert,[44] J. M. Seixas,[24a] G. Sekhniaidze,[102a] S. J. Sekula,[40] K. E. Selbach,[46] D. M. Seliverstov,[121] B. Sellden,[146a] G. Sellers,[73] M. Seman,[144b] N. Semprini-Cesari,[20a,20b] C. Serfon,[98] L. Serin,[115] L. Serkin,[54] R. Seuster,[99] H. Severini,[111] A. Sfyrla,[30] E. Shabalina,[54] M. Shamim,[114] L. Y. Shan,[33a] J. T. Shank,[22] Q. T. Shao,[86] M. Shapiro,[15] P. B. Shatalov,[95] K. Shaw,[164a,164c] D. Sherman,[176] P. Sherwood,[77] A. Shibata,[108] S. Shimizu,[101] M. Shimojima,[100] T. Shin,[56] M. Shiyakova,[64] A. Shmeleva,[94] M. J. Shochet,[31] D. Short,[118] S. Shrestha,[63] E. Shulga,[96] M. A. Shupe,[7] P. Sicho,[125] A. Sidoti,[132a] F. Siegert,[48] Dj. Sijacki,[13a] O. Silbert,[172] J. Silva,[124a] Y. Silver,[153] D. Silverstein,[143] S. B. Silverstein,[146a] V. Simak,[127] O. Simard,[136] Lj. Simic,[13a] S. Simion,[115] E. Simioni,[81] B. Simmons,[77] R. Simoniello,[89a,89b] M. Simonyan,[36] P. Sinervo,[158] N. B. Sinev,[114] V. Sipica,[141] G. Siragusa,[174] A. Sircar,[25] A. N. Sisakyan,[64,a] S. Yu. Sivoklokov,[97] J. Sjölin,[146a,146b] T. B. Sjursen,[14] L. A. Skinnari,[15] H. P. Skottowe,[57] K. Skovpen,[107] P. Skubic,[111] M. Slater,[18] T. Slavicek,[127] K. Sliwa,[161] V. Smakhtin,[172] B. H. Smart,[46] S. L. Smestad,[117] S. Yu. Smirnov,[96] Y. 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] S. Snyder,[25] R. Sobie,[169,l] J. Sodomka,[127] A. Soffer,[153] C. A. Solans,[167] M. Solar,[127] J. Solc,[127] E. Yu. Soldatov,[96] U. Soldevila,[167] E. Solfaroli Camillocci,[132a,132b] A. A. Solodkov,[128] O. V. Solovyanov,[128] V. Solovyev,[121] N. Soni,[1] V. Sopko,[127] B. Sopko,[127] M. Sosebee,[8] R. Soualah,[164a,164c] A. Soukharev,[107] S. Spagnolo,[72a,72b] F. Spanò,[76] R. Spighi,[20a] G. Spigo,[30] R. Spiwoks,[30] M. Spousta,[126,ii] T. Spreitzer,[158] B. Spurlock,[8] R. D. St. Denis,[53] J. Stahlman,[120]

R. Stamen,[58a] E. Stanecka,[39] R. W. Stanek,[6] C. Stanescu,[134a] M. Stanescu-Bellu,[42] M. M. Stanitzki,[42] S. Stapnes,[117] E. A. Starchenko,[128] J. Stark,[55] P. Staroba,[125] P. Starovoitov,[42] R. Staszewski,[39] A. Staude,[98] P. Stavina,[144a,a] G. Steele,[53] P. Steinbach,[44] P. Steinberg,[25] I. Stekl,[127] B. Stelzer,[142] H. J. Stelzer,[88] O. Stelzer-Chilton,[159a] H. Stenzel,[52] S. Stern,[99] G. A. Stewart,[30] J. A. Stillings,[21] M. C. Stockton,[85] K. Stoerig,[48] G. Stoicea,[26a] S. Stonjek,[99] P. Strachota,[126] A. R. Stradling,[8] A. Straessner,[44] J. Strandberg,[147] S. Strandberg,[146a,146b] A. Strandlie,[117] M. Strang,[109] E. Strauss,[143] M. Strauss,[111] P. Strizenec,[144b] R. Ströhmer,[174] D. M. Strom,[114] J. A. Strong,[76,a] R. Stroynowski,[40] J. Strube,[129] B. Stugu,[14] I. Stumer,[25,a] J. Stupak,[148] P. Sturm,[175] N. A. Styles,[42] D. A. Soh,[151,x] D. Su,[143] HS. Subramania,[3] A. Succurro,[12] Y. Sugaya,[116] C. Suhr,[106] M. 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