



Aad, G. et al. (2012) Search for $t\bar{t}$ Resonances in Proton-Proton Collisions at $\sqrt{s}=7$ TeV with the ATLAS Detector. Physical Review Letters, 109 (8). ISSN 0031-9007

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Deposited on: 25th February 2013

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Search for tb Resonances in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad *et al.**

(ATLAS Collaboration)

(Received 4 May 2012; published 21 August 2012)

This Letter presents a search for tb resonances in 1.04 fb^{-1} of LHC proton-proton collision data collected by the ATLAS detector at a center-of-mass energy of 7 TeV. Events with a lepton, missing transverse momentum, and two jets are selected and the invariant mass of the corresponding final state is reconstructed. The search exploits the shape of the tb invariant mass distribution compared to the expected standard model backgrounds. The model of a right-handed W'_R with standard model-like couplings is chosen as the benchmark model for this search. No statistically significant excess of events is observed in the data, and upper limits on the cross section times the branching ratio of W'_R resonances at 95% C.L. lie in the range of $6.1\text{--}1.0 \text{ pb}$ for W'_R masses ranging from 0.5 to 2.0 TeV. These limits are translated into a lower bound on the allowed right-handed W'_R mass, giving $m_{W'_R} > 1.13 \text{ TeV}$ at 95% C.L.

DOI: [10.1103/PhysRevLett.109.081801](https://doi.org/10.1103/PhysRevLett.109.081801)

PACS numbers: 14.70.Pw, 12.60.Cn, 13.85.Rm, 14.65.Ha

This Letter presents a search for tb ($t\bar{b}$ or $\bar{t}b$) resonances using data collected in 2011 by the ATLAS detector [1] at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of $1.04 \pm 0.04 \text{ fb}^{-1}$ [2,3] from pp collisions at a center-of-mass energy of 7 TeV. These resonances include new heavy gauge bosons such as the W' boson. The W' boson is a charged heavy gauge boson that is predicted in many extensions of the standard model (SM) such as universal extra dimensions [4] and little Higgs models [5]. If the W' boson is assumed to have similar coupling strengths to those of the SM W boson, searches in the $W' \rightarrow \ell\nu$ decay channel, where ℓ is a charged lepton, are the most sensitive. However, the $W' \rightarrow tb$ channel is competitive if $W' \rightarrow \ell\nu$ decay is suppressed. For example, for a right-handed W'_R this can happen if the right-handed neutrino ν_R is heavy enough to prevent $W'_R \rightarrow \ell\nu_R$ decay [6]. The model of a right-handed W'_R with SM-like couplings is chosen as the benchmark model for the analysis presented in this Letter. The $W'_R \rightarrow tb$ decay channel has been searched for at the Tevatron [7,8]. The best previous limit on a W'_R with standard model-like couplings of the W' to quarks was set by the D0 experiment and excludes a W'_R mass below 890 GeV at 95% confidence level.

The innermost part of the ATLAS detector [9], a tracking system in a 2 T axial magnetic field, measures the momentum of the charged particles produced in the collisions. Outside of the solenoid are the calorimeter subsystems, which measure the electron, photon, and hadronic particle energies, and the muon spectrometer, which is

used to identify and measure the momentum of muons in a toroidal magnetic field. A three-level trigger system [10] reduces the event rate and selects the events for analysis.

The tb resonances are searched for in the $tb \rightarrow \ell\nu b\bar{b}$ decay channel, where the lepton ℓ is either an electron or a muon. W'_R signal events are simulated to leading order (LO) with the PYTHIA v6.421[11] Monte Carlo (MC) generator, using the MRST2007 LO* parton distribution functions (PDFs) [12]. Seven signal samples are simulated, with different W'_R mass assumptions, ranging from 500 GeV to 2.0 TeV, as reported in Table I. The respective signal cross section times the branching ratio values are computed at next-to-leading-order (NLO) [13], using CTEQ6.6 PDFs [14].

Data-driven methods and MC simulated samples are used to estimate and model backgrounds. The $t\bar{t}$ process is simulated with the MC@NLO v3.41[15,16] MC generator, assuming a top quark mass of 172.5 GeV, and using the CTEQ6.6 PDFs. The parton shower is added using the HERWIG [17] and JIMMY [18] MC generators. The $t\bar{t}$ cross

TABLE I. NLO branching ratios, $\mathcal{B}(W'_R \rightarrow tb)$, and W'_R production cross section times the branching ratio value, $\sigma(pp \rightarrow W'_R) \times \mathcal{B}(W'_R \rightarrow tb)$, in pp collisions at 7 TeV center-of-mass energy [13]. The uncertainties on the branching ratios are due to the top quark mass uncertainty. The uncertainties on the cross sections include statistical, α_s , NLO renormalization and factorization scales, and PDF uncertainties.

$m_{W'_R}$ [GeV]	$\mathcal{B}(W'_R \rightarrow tb)$	$\sigma \times \mathcal{B}$ [pb]
500	0.298 ± 0.002	54.6 ± 2.1
750	0.319 ± 0.001	10.9 ± 0.6
1000	0.326 ± 0.001	2.92 ± 0.18
1250	$0.328 < 0.001$	0.91 ± 0.07
1500	$0.330 < 0.001$	0.31 ± 0.03
1750	$0.331 < 0.001$	0.11 ± 0.01
2000	$0.332 < 0.001$	0.044 ± 0.005

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

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section is obtained from the approximate next-to-next-to-leading order (NNLO) prediction calculated with the HATHOR program [19] using the MSTW2008 NNLO PDF sets [20]. The single top quark processes are simulated using the ACERMC v3.7[21] MC generator and hadronization is performed with the PYTHIA MC generator; the cross section is calculated to approximate NNLO [22–24] using the CTEQ6.6 PDFs. Diboson processes are simulated using the HERWIG v6.5 MC generator and their cross sections are obtained at NLO using the MCFM [25] program with the MSTW2008 PDFs. The MC samples simulated with the ACERMC and HERWIG MC generators use the MRST2007 LO* PDFs. Vector boson production in association with jets (W + light jets, $Wb\bar{b}$, $Wc\bar{c}$, Wc , and Z + jets with up to five additional partons) is simulated using the ALPGEN v2.13 [26] MC generator, coupled with the CTEQ6L1 PDFs [14] and hadronization is performed with the HERWIG and JIMMY MC generators. In these samples, additional jets can be created from the parton shower. In order to avoid double counting between the inclusive W + n parton samples and the parton shower, overlaps are removed following the MLM matching prescription [27]. A cross section correction factor is applied to the LO W/Z + jet cross sections computed by comparing the LO and NLO predictions from the FEWZ [28] program. The Wc cross section correction factor is obtained using the MCFM [29] program with the CTEQ6.6 PDFs. All samples are passed through the full simulation of the ATLAS detector [30] based on GEANT4 [31] and are then reconstructed using the same procedure as collision data. The simulated samples include the effect of multiple pp collisions per bunch crossing (pileup) which on average is six events per bunch crossing. In order to ensure a good description of the energy scale and resolution, the trigger, the reconstruction and identification efficiency, corrections based on comparisons between data and MC events are applied to the simulated signal and background samples. The corresponding scale factors are obtained as a function of the object kinematics, resulting in final corrections of the order of a few percent.

Candidate events are identified using single high transverse momentum electron and muon triggers and stringent detector and data quality requirements. For each candidate, two jets, one isolated charged lepton, and the missing transverse momentum E_T^{miss} are required. The definition of the objects and details of a similar event selection, including lepton isolation requirements, are given in Ref. [32]. The reconstructed charged lepton is required to have a transverse momentum $p_T > 25$ GeV to ensure a constant trigger efficiency, $|\eta| < 2.5$ for a muon [33–35] and $|\eta| < 2.47$ for an electron [36] (the calorimeter transition region $1.37 < |\eta| < 1.52$ is excluded), and to lie within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.15$ of the corresponding triggered lepton. Jets are reconstructed from energy clusters in the calorimeters with the anti- k_t algorithm [37]

with a radius parameter $R = 0.4$ and calibrated to the hadronic energy scale [38]. Exactly two jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are required in the event, and at least one of them must be tagged as a b jet. The b -tagging algorithm uses measurements of the impact parameters of tracks and the properties of reconstructed vertices; these are combined in a neural network to extract a tagging decision for each jet [39]. Based on a $t\bar{t}$ MC sample, the working point is chosen at a b -tagging efficiency of 57%, leading to a light-quark tagging probability of 0.2% derived from the same sample. To account for the differences between observed and simulated jet, p_T and η , distributions, the b -tagging efficiency and the corresponding scaling factors to be applied to MC simulations are derived from data [40]. Events before applying any b tagging are referred to as *pretagged* events. Events where one or both jets are b tagged are referred to as *single-* or *double-tagged* events, respectively.

The E_T^{miss} is calculated using calorimeter energy clusters [41] calibrated according to the reconstructed physics object to which they are associated [42]; events are required to satisfy $E_T^{\text{miss}} > 25$ GeV. The background contribution from multiple hadron jets (multijet background) is reduced by imposing a requirement on the sum of the W boson transverse mass $m_T(W)$ [43] and E_T^{miss} : $m_T(W) + E_T^{\text{miss}} > 60$ GeV [32]. After applying all selection criteria, the acceptance times efficiency for W'_R signal events with $m_{W'_R} = 1.0$ TeV is 1.38% for single-tagged events and 0.49% for double-tagged events.

One of the most important backgrounds for the tb resonance search comes from W production in association with either heavy-flavor jets, or light-flavor jets misidentified as b jets. Multijet production is another source of background, when either a hadronic jet is misidentified as a lepton, or when a real high- p_T lepton from semileptonic decay of a heavy hadron within a jet fulfills the selection requirements. Another important background comes from $t\bar{t}$ pair production in the case that one W boson decays leptonically and the decay products of the other W boson are lost due to the detector acceptance. Other smaller backgrounds come from single top production, diboson production, and Z + jet events.

Kinematic variable distributions for the W + jet background are taken from MC samples, while the overall normalization and flavor composition are derived from data; this is done after rejecting signal-like events with the tb invariant mass m_{tb} , which is described later, satisfying $m_{tb} > 500$ GeV. In each jet multiplicity bin, the number of W + jet events in the data is assumed to be the difference between the number of observed data events and the number of events estimated for SM non- W + jet processes including the multijet process estimated from a data-driven method. The overall W + jet normalization factor is the ratio of the number of W + jet events in the data to the number of W + jet events in simulation. The

TABLE II. Predicted signal event yields derived using the theoretical cross section times the branching ratio values for $W'_R \rightarrow tb$, for single- and double-tagged two-jet events in 1.04 fb^{-1} of data. The uncertainties correspond to the NLO cross section uncertainties [13].

$m_{W'_R}$ [GeV]	Single-tagged	Double-tagged
500	973 ± 37	455 ± 17
750	174 ± 9	77 ± 4
1000	42 ± 3	15 ± 1
1250	11 ± 1	3.9 ± 0.3
1500	3.2 ± 0.3	1.0 ± 0.1
1750	1.0 ± 0.1	0.26 ± 0.03
2000	0.36 ± 0.04	0.09 ± 0.01

flavor composition of the $W + \text{jet}$ background is estimated by comparing the MC prediction to data while its dependence on jet and b -tagging multiplicity is modeled using MC simulations. The fractions of $Wb\bar{b}$, $Wc\bar{c}$, Wc , and $W + \text{light jet}$ components of the total $W + \text{jet}$ MC simulations are scaled such that the background sum equals the observed data in three separate samples: a single-tagged one-jet sample and the pretagged and single-tagged two-jet samples. The same scale factor is used for $Wb\bar{b}$ and $Wc\bar{c}$.

The multijet background normalization and the shape of each distribution are obtained from data. The shape of each multijet background distribution is taken from a data sample which requires a jet instead of an isolated lepton. This jet is required to have a detector signature similar to an electron: it must have $p_T > 25 \text{ GeV}$ and between 80% and 95% of its energy deposited in the electromagnetic section of the calorimeter. The jet must also be associated with at least four tracks. The normalization is estimated using a binned likelihood fit to the E_T^{miss} distribution in data in which the normalization of the $W + \text{jet}$ and the multijet components is allowed to vary. The fit is performed separately in the pretagged, single-, and double-tagged samples, after applying all selection criteria except the E_T^{miss} cut. The uncertainty on the multijet rate is 50% for pretagged and single-tagged events, while it amounts to 100% for double-tagged events. The uncertainty is estimated by using the $m_T(W)$ distribution instead of the E_T^{miss} distribution in the binned likelihood fit, and by using multijet background models built from data samples with low and high numbers of pp collisions per event.

The $t\bar{t}$, single top, $Z + \text{jet}$, and diboson events are normalized to the theoretical cross sections and the shape of each distribution is taken from the MC simulation.

Based on the theoretical predictions shown in Table I, the numbers of single- and double-tagged W'_R signal events expected in 1.04 fb^{-1} are listed in Table II, as a function of $m_{W'_R}$. Table III lists the expected background yields.

The tb invariant mass is used as the observable to discriminate signal from background. The neutrino momentum in the decay $tb \rightarrow \ell \nu b\bar{b}$ is computed assuming the

TABLE III. Predicted background event yields compared to the total observed event yields for single- and double-tagged two-jet events in 1.04 fb^{-1} of data. All $W + \text{jet}$ samples are scaled by the factors determined from data, with the uncertainties also derived from data. The multijet estimation is from the fitting method with a 50% (100%) uncertainty for single- (double-) tagged events. All the other predictions are derived using the theoretical cross sections and uncertainties.

Samples	Single-tagged	Double-tagged
$W + \text{jets}$	5970 ± 1000	290 ± 180
Multijets	1120 ± 560	47 ± 47
$t\bar{t}$	1560 ± 130	360 ± 30
Single top	1240 ± 90	120 ± 10
Diboson, $Z + \text{jets}$	320 ± 120	14 ± 2
Total prediction	10200 ± 1200	830 ± 190
Data	10428	844

transverse component to be equal to E_T^{miss} , and extracting the longitudinal component (p_z) by constraining the $\ell - \nu$ invariant mass to $m_W = 80.42 \text{ GeV}$. This gives a quadratic equation in p_z and the solution with the smaller $|p_z|$ is used. If the solution is complex, only the real part is taken and the imaginary part is neglected.

Figure 1 shows the data and expected background distributions of m_{tb} for single- and double-tagged two-jet events. The data event with the highest m_{tb} value corresponds to a single-tagged event with $m_{tb} \simeq 2.0 \text{ TeV}$. The BUMPHUNTER tool [44] is used to search for a local excess in the data due to the production of a tb resonance. This tool is used to test the consistency of the data with the SM background only hypothesis, comparing the data to the SM prediction over the spectrum of the tb invariant mass, scanning over sliding mass windows from 0.5 to 2.0 TeV. The width of the mass windows is chosen to be constant in $\log(m_{tb})$ as shown in Fig. 1 to deal with low background MC statistics in the higher mass bins. This comparison has been performed for single- and double-tagged events separately. The region with the highest data-background difference is 1024–1129 (764–842) GeV for single (double)-tagged events. The probability of observing the SM background fluctuating up to or above the number of observed data events in these regions is 0.66 for single-tagged events and 0.72 for double-tagged events. These values, which are based on the statistical error only, indicate that there is no significant evidence for tb resonances in the observed data.

Systematic uncertainties from various sources affecting the background and the signal acceptance (rate uncertainty), as well as shape changes in the invariant mass distribution (shape uncertainty) are considered.

The jet energy scale and the uncertainty on the b -tagging scale factors are the dominant systematic uncertainties for the signal. The background normalization yields are the dominant systematic uncertainty for the background

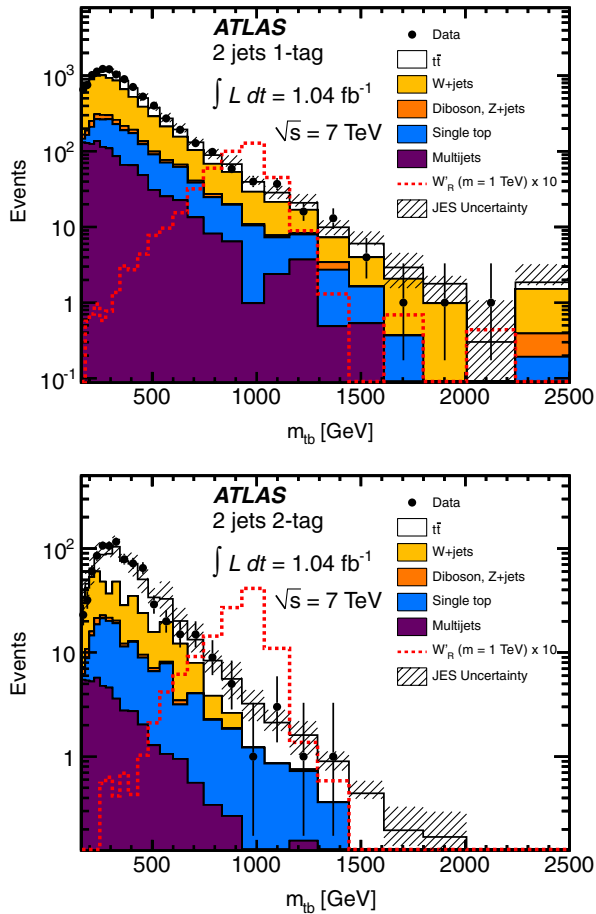


FIG. 1 (color online). The distribution of m_{tb} for single-tagged (top) and double-tagged (bottom) two-jet events in data compared to standard model expectations. The expected W'_R signal, normalized to the theoretical cross section times the $\mathcal{B}(W'_R \rightarrow tb)$ values from Table I, has been scaled by a factor of 10. The effect of the jet energy scale (JES) uncertainty on the predicted background is shown, as are the data statistical uncertainties. The bin width is constant in $\log(m_{tb})$. The highest bin in each plot includes overflows.

contribution. The jet energy scale uncertainty is evaluated by scaling 1σ up or down the energy of each jet. The b -tagging scale factors are p_T dependent and have an uncertainty between 8% and 20%. The multijet background uncertainty has already been described. The uncertainty on the normalization of the W + jets background and its flavor composition include both systematic contributions and a statistical contribution from the limited size of the sample. The W + jet flavor uncertainties are treated as fully correlated between $Wb\bar{b}$ and $Wc\bar{c}$ and uncorrelated otherwise. Theoretical cross section uncertainties for the top ($t\bar{t}$ and single top), diboson and Z + jet backgrounds of 10%, 5%, and 60% are assigned, respectively. The Z + jet theoretical cross section uncertainty is estimated based on the variation of ALPGEN parameters, and a relative uncertainty of 50% on the heavy-quark contributions, but it has a very small impact on the result

due to the small contribution of Z + jet events. Systematic uncertainties due to the residual differences between data and MC simulation for the reconstruction and energy calibration of jets, electrons, and muons are estimated to have a small impact on the result. The uncertainty on the integrated luminosity is 3.7% [3]. The uncertainty on the background modeling in the m_{tb} distribution is evaluated using pretagged data and found to be negligible.

An uncertainty due to the MC event generator is estimated by comparing MC@NLO and POWHEG [45,46] for $t\bar{t}$ and ACERMC and MC@NLO for single top events. The uncertainty in parton shower modeling is estimated by comparing two POWHEG $t\bar{t}$ samples for which the hadronization is performed by PYTHIA or HERWIG. Uncertainties from modeling the amount of initial and final-state QCD radiation are also taken into account. The uncertainty due to the specific choice of PDFs in the simulated events is determined by reweighting the MC events using the NNPDF20, MSTW2008, and CTEQ6.6 [20] eigenvector PDF sets. Finally, an uncertainty to account for the limited MC sample sizes is also included.

No significant data excess is identified for any value of m_{tb} , and an upper limit on the $W'_R \rightarrow tb$ production cross section (σ) times the $\mathcal{B}(W'_R \rightarrow tb)$ at 95% credibility-level (C.L.) is determined using a Bayesian approach assuming flat priors [47]. The likelihood function used is the product of the Poisson probabilities over all mass bins [48] per channel. The combination of single- and double-tagged events is done by extending the likelihood function; the joint likelihood is the product of Poisson probabilities for each individual bin in each channel. Systematic and statistical uncertainties are incorporated and treated as nuisance parameters with a Gaussian probability density function. Figure 2 shows the observed and the expected limits from single- and double-tagged events combined. Observed (expected) upper limits obtained on $\sigma(pp \rightarrow W'_R) \times \mathcal{B}(W'_R \rightarrow tb)$ at 95% C.L. lie in the range

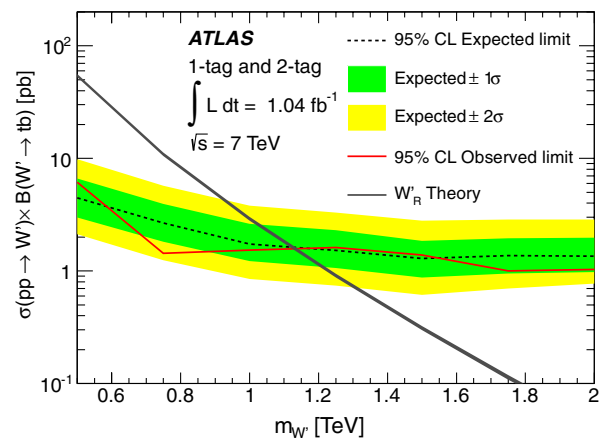


FIG. 2 (color online). 95% C.L. limit on the cross section, $\sigma(pp \rightarrow W'_R)$, times branching ratio for $W'_R \rightarrow tb$ as a function of the W' boson mass. The theory curve is also shown.

6.1–1.0 (4.5–1.4) pb for W'_R masses ranging from 0.5 to 2.0 TeV. These $\sigma \times \mathcal{B}$ limits are also applicable to a left-handed W' . The $\sigma \times \mathcal{B}$ limits are converted into mass limits using the intersection between the theoretical $\sigma \times \mathcal{B}$ curve as a function of $m_{W'_R}$ and the expected and observed $\sigma \times \mathcal{B}$ limit curves. The corresponding observed (expected) 95% C.L. lower limit is $m_{W'_R} > 1.13(1.13)$ TeV. These are currently the most stringent direct limits on production of $W'_R \rightarrow tb$.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We thank Z. Sullivan for discussions on the W' model and for providing NLO signal cross section calculations. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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- N. Boelaert,³⁵ J. A. Bogaerts,²⁹ A. Bogdanchikov,¹⁰⁶ A. Bogouch,^{89,a} C. Bohm,^{145a} J. Bohm,¹²⁴ V. Boisvert,⁷⁵ T. Bold,³⁷ V. Boldea,^{25a} N. M. Bolnet,¹³⁵ M. Bomben,⁷⁷ M. Bona,⁷⁴ V. G. Bondarenko,⁹⁵ M. Bondioli,¹⁶² M. Boonekamp,¹³⁵ C. N. Booth,¹³⁸ S. Bordoni,⁷⁷ C. Borer,¹⁶ A. Borisov,¹²⁷ G. Borissov,⁷⁰ I. Borjanovic,^{12a} M. Borri,⁸¹ S. Borroni,⁸⁶ V. Bortolotto,^{133a,133b} K. Bos,¹⁰⁴ D. Boscherini,^{19a} M. Bosman,¹¹ H. Boterenbrood,¹⁰⁴ D. Botterill,¹²⁸ J. Bouchami,⁹² J. Boudreau,¹²² E. V. Bouhova-Thacker,⁷⁰ D. Boumediene,³³ C. Bourdarios,¹¹⁴ N. Bousson,⁸² A. Boveia,³⁰ J. Boyd,²⁹ I. R. Boyko,⁶³ N. I. Bozhko,¹²⁷ I. Bozovic-Jelisavcic,^{12b} J. Bracinik,¹⁷ A. Braem,²⁹ P. Branchini,^{133a} G. W. Brandenburg,⁵⁶ A. Brandt,⁷ G. Brandt,¹¹⁷ O. Brandt,⁵³ U. Bratzler,¹⁵⁵ B. Brau,⁸³ J. E. Brau,¹¹³ H. M. Braun,¹⁷³ B. Brelier,¹⁵⁷ J. Bremer,²⁹ K. Brendlinger,¹¹⁹ R. Brenner,¹⁶⁵ S. Bressler,¹⁷⁰ D. Britton,⁵² F. M. Brochu,²⁷ I. Brock,²⁰ R. Brock,⁸⁷ T. J. Brodbeck,⁷⁰ E. Brodet,¹⁵² F. Broggi,^{88a} C. Bromberg,⁸⁷ J. Bronner,⁹⁸ G. Brooijmans,³⁴ W. K. Brooks,^{31b} G. Brown,⁸¹ H. Brown,⁷ P. A. Bruckman de Renstrom,³⁸ D. Bruncko,^{143b} R. Bruneliere,⁴⁷ S. Brunet,⁵⁹ A. Bruni,^{19a} G. Bruni,^{19a} M. Bruschi,^{19a} T. Buanes,¹³ Q. Buat,⁵⁴ F. Bucci,⁴⁸ J. Buchanan,¹¹⁷ P. Buchholz,¹⁴⁰ R. M. Buckingham,¹¹⁷ A. G. Buckley,⁴⁵ S. I. Buda,^{25a} I. A. Budagov,⁶³ B. Budick,¹⁰⁷ V. Büscher,⁸⁰ L. Bugge,¹¹⁶ O. Bulekov,⁹⁵ A. C. Bundock,⁷² M. Bunse,⁴² T. Buran,¹¹⁶ H. Burckhart,²⁹ S. Burdin,⁷² T. Burgess,¹³ S. Burke,¹²⁸ E. Busato,³³ P. Bussey,⁵² C. P. Buszello,¹⁶⁵ F. Butin,²⁹ B. Butler,¹⁴² J. M. Butler,²¹ C. M. Buttar,⁵² J. M. Butterworth,⁷⁶ W. Buttinger,²⁷ S. Cabrera Urbán,¹⁶⁶ D. Caforio,^{19a,19b} O. Cakir,^{3a} P. Calafiura,¹⁴ G. Calderini,⁷⁷ P. Calfayan,⁹⁷ R. Calkins,¹⁰⁵ L. P. Caloba,^{23a} R. Caloi,^{131a,131b} D. Calvet,³³ S. Calvet,³³ R. Camacho Toro,³³ P. Camarri,^{132a,132b} M. Cambiaghi,^{118a,118b} D. Cameron,¹¹⁶ L. M. Caminada,¹⁴ S. Campana,²⁹ M. Campanelli,⁷⁶ V. Canale,^{101a,101b} F. Canelli,^{30,h} A. Canepa,^{158a} J. Cantero,⁷⁹ L. Capasso,^{101a,101b} M. D. M. Capeans Garrido,²⁹ I. Caprini,^{25a} M. Caprini,^{25a} D. Capriotti,⁹⁸ M. Capua,^{36a,36b} R. Caputo,⁸⁰ R. Cardarelli,^{132a} T. Carli,²⁹ G. Carlino,^{101a} L. Carminati,^{88a,88b} B. Caron,⁸⁴ S. Caron,¹⁰³ E. Carquin,^{31b} G. D. Carrillo Montoya,¹⁷¹ A. A. Carter,⁷⁴ J. R. Carter,²⁷ J. Carvalho,^{123a,i} D. Casadei,¹⁰⁷ M. P. Casado,¹¹ M. Cascella,^{121a,121b} C. Caso,^{49a,49b,a} A. M. Castaneda Hernandez,¹⁷¹ E. Castaneda-Miranda,¹⁷¹ V. Castillo Gimenez,¹⁶⁶ N. F. Castro,^{123a} G. Cataldi,^{71a} P. Catastini,⁵⁶ A. Catinaccio,²⁹ J. R. Catmore,²⁹ A. Cattai,²⁹ G. Cattani,^{132a,132b} S. Caughron,⁸⁷ D. Cauz,^{163a,163c} P. Cavalleri,⁷⁷ D. Cavalli,^{88a} M. Cavalli-Sforza,¹¹ V. Cavasinni,^{121a,121b} F. Ceradini,^{133a,133b} A. S. Cerqueira,^{23b} A. Cerri,²⁹ L. Cerrito,⁷⁴ F. Cerutti,⁴⁶ S. A. Cetin,^{18b} F. Cevenini,^{101a,101b} A. Chafaq,^{134a} D. Chakraborty,¹⁰⁵ I. Chalupkova,¹²⁵ K. Chan,² B. Chapleau,⁸⁴ J. D. Chapman,²⁷ J. W. Chapman,⁸⁶ E. Chareyre,⁷⁷ D. G. Charlton,¹⁷ V. Chavda,⁸¹ C. A. Chavez Barajas,²⁹ S. Cheatham,⁸⁴ S. Chekanov,⁵ S. V. Chekulaev,^{158a} G. A. Chelkov,⁶³ M. A. Chelstowska,¹⁰³ C. Chen,⁶² H. Chen,²⁴ S. Chen,^{32c} T. Chen,^{32c} X. Chen,¹⁷¹ S. Cheng,^{32a} A. Cheplakov,⁶³ V. F. Chepurinov,⁶³ R. Cherkaoui El Moursli,^{134e} V. Chernyatin,²⁴ E. Cheu,⁶ S. L. Cheung,¹⁵⁷ L. Chevalier,¹³⁵ G. Chiefari,^{101a,101b} L. Chikovani,^{50a} J. T. Childers,²⁹ A. Chilingarov,⁷⁰ G. Chiodini,^{71a} A. S. Chisholm,¹⁷ R. T. Chislett,⁷⁶ M. V. Chizhov,⁶³ G. Choudalakis,³⁰ S. Chouridou,¹³⁶ I. A. Christidi,⁷⁶ A. Christov,⁴⁷ D. Chromek-Burckhart,²⁹ M. L. Chu,¹⁵⁰ J. Chudoba,¹²⁴ G. Ciapetti,^{131a,131b} A. K. Ciftci,^{3a} R. Ciftci,^{3a} D. Cinca,³³ V. Cindro,⁷³ C. Ciocca,^{19a} A. Ciocio,¹⁴ M. Cirilli,⁸⁶ M. Citterio,^{88a} M. Ciubancan,^{25a} A. Clark,⁴⁸ P. J. Clark,⁴⁵ W. Cleland,¹²² J. C. Clemens,⁸² B. Clement,⁵⁴ C. Clement,^{145a,145b} Y. Coadou,⁸² M. Cobal,^{163a,163c} A. Cocco,¹³⁷ J. Cochran,⁶² P. Coe,¹¹⁷ J. G. Cogan,¹⁴² J. Coggeshall,¹⁶⁴ E. Cogneras,¹⁷⁶ J. Colas,⁴ A. P. Colijn,¹⁰⁴ N. J. Collins,¹⁷ C. Collins-Tooth,⁵² J. Collot,⁵⁴ G. Colon,⁸³ P. Conde Muiño,^{123a} E. Coniavitis,¹¹⁷ M. C. Conidi,¹¹ M. Consonni,¹⁰³ S. M. Consonni,^{88a,88b} V. Consorti,⁴⁷ S. Constantinescu,^{25a} C. Conta,^{118a,118b} G. Conti,⁵⁶ F. Conventi,^{101a,j} J. Cook,²⁹ M. Cooke,¹⁴ B. D. Cooper,⁷⁶ A. M. Cooper-Sarkar,¹¹⁷ K. Copic,¹⁴ T. Cornelissen,¹⁷³ M. Corradi,^{19a} F. Corriveau,^{84,k} A. Cortes-Gonzalez,¹⁶⁴ G. Cortiana,⁹⁸ G. Costa,^{88a} M. J. Costa,¹⁶⁶ D. Costanzo,¹³⁸ T. Costin,³⁰ D. Côté,²⁹ L. Courneyea,¹⁶⁸ G. Cowan,⁷⁵ C. Cowden,²⁷ B. E. Cox,⁸¹ K. Cranmer,¹⁰⁷ F. Crescioli,^{121a,121b} M. Cristinziani,²⁰ G. Crosetti,^{36a,36b} R. Crupi,^{71a,71b} S. Crépe-Renaudin,⁵⁴ C.-M. Cuciuc,^{25a} C. Cuenca Almenar,¹⁷⁴ T. Cuhadar Donszelmann,¹³⁸ M. Curatolo,⁴⁶ C. J. Curtis,¹⁷ C. Cuthbert,¹⁴⁹ P. Cwetanski,⁵⁹ H. Czirr,¹⁴⁰ P. Czodrowski,⁴³ Z. Czyczula,¹⁷⁴ S. D'Auria,⁵² M. D'Onofrio,⁷² A. D'Orazio,^{131a,131b} P. V. M. Da Silva,^{23a} C. Da Via,⁸¹ W. Dabrowski,³⁷ A. Dafinca,¹¹⁷ T. Dai,⁸⁶ C. Dallapiccola,⁸³ M. Dam,³⁵ M. Dameri,^{49a,49b} D. S. Damiani,¹³⁶ H. O. Danielsson,²⁹ D. Dannheim,⁹⁸ V. Dao,⁴⁸ G. Darbo,^{49a} G. L. Darlea,^{25b} W. Davey,²⁰ T. Davidek,¹²⁵ N. Davidson,⁸⁵ R. Davidson,⁷⁰ E. Davies,^{117,d} M. Davies,⁹² A. R. Davison,⁷⁶ Y. Davygora,^{57a} E. Dawe,¹⁴¹ I. Dawson,¹³⁸ J. W. Dawson,^{5a} R. K. Daya-Ishmukhametova,²² K. De,⁷ R. de Asmundis,^{101a} S. De Castro,^{19a,19b} P. E. De Castro Faria Salgado,²⁴ S. De Cecco,⁷⁷ J. de Graat,⁹⁷ N. De Groot,¹⁰³ P. de Jong,¹⁰⁴ C. De La Taille,¹¹⁴ H. De la Torre,⁷⁹ F. De Lorenzi,⁶² B. De Lotto,^{163a,163c} L. de Mora,⁷⁰ L. De Nooij,¹⁰⁴ D. De Pedis,^{131a} A. De Salvo,^{131a} U. De Sanctis,^{163a,163c} A. De Santo,¹⁴⁸ J. B. De Vivie De Regie,¹¹⁴

- G. De Zorzi,^{131a,131b} S. Dean,⁷⁶ W. J. Dearnaley,⁷⁰ R. Debbe,²⁴ C. Debenedetti,⁴⁵ B. Dechenaux,⁵⁴ D. V. Dedovich,⁶³ J. Degenhardt,¹¹⁹ C. Del Papa,^{163a,163c} J. Del Peso,⁷⁹ T. Del Prete,^{121a,121b} T. Delemontex,⁵⁴ M. Deliyergiyev,⁷³ A. Dell'Acqua,²⁹ L. Dell'Asta,²¹ M. Della Pietra,^{101a,j} D. della Volpe,^{101a,101b} M. Delmastro,⁴ N. Delruelle,²⁹ P. A. Delsart,⁵⁴ C. Deluca,¹⁴⁷ S. Demers,¹⁷⁴ M. Demichev,⁶³ B. Demirköz,^{11,l} J. Deng,¹⁶² S. P. Denisov,¹²⁷ D. Derendarz,³⁸ J. E. Derkaoui,^{134d} F. Derue,⁷⁷ P. Dervan,⁷² K. Desch,²⁰ E. Devetak,¹⁴⁷ P. O. Deviveiros,¹⁰⁴ A. Dewhurst,¹²⁸ B. DeWilde,¹⁴⁷ S. Dhaliwal,¹⁵⁷ R. Dhullipudi,^{24,m} A. Di Ciaccio,^{132a,132b} L. Di Ciaccio,⁴ A. Di Girolamo,²⁹ B. Di Girolamo,²⁹ S. Di Luise,^{133a,133b} A. Di Mattia,¹⁷¹ B. Di Micco,²⁹ R. Di Nardo,⁴⁶ A. Di Simone,^{132a,132b} R. Di Sipio,^{19a,19b} M. A. Diaz,^{31a} F. Diblen,^{18c} E. B. Diehl,⁸⁶ J. Dietrich,⁴¹ T. A. Dietzsch,^{57a} S. Diglio,⁸⁵ K. Dindar Yagci,³⁹ J. Dingfelder,²⁰ C. Dionisi,^{131a,131b} P. Dita,^{25a} S. Dita,^{25a} F. Dittus,²⁹ F. Djama,⁸² T. Djobava,^{50b} M. A. B. do Vale,^{23c} A. Do Valle Wemans,^{123a} T. K. O. Doan,⁴ M. Dobbs,⁸⁴ R. Dobinson,^{29,a} D. Dobos,²⁹ E. Dobson,^{29,n} J. Dodd,³⁴ C. Doglioni,⁴⁸ T. Doherty,⁵² Y. Doi,^{64,a} J. Dolejsi,¹²⁵ I. Dolenc,⁷³ Z. Dolezal,¹²⁵ B. A. Dolgoshein,^{95,a} T. Dohmae,¹⁵⁴ M. Donadelli,^{23d} M. Donega,¹¹⁹ J. Donini,³³ J. Dopke,²⁹ A. Doria,^{101a} A. Dos Anjos,¹⁷¹ M. Dosil,¹¹ A. Dotti,^{121a,121b} M. T. Dova,⁶⁹ A. D. Doxiadis,¹⁰⁴ A. T. Doyle,⁵² Z. Drasal,¹²⁵ N. Dressnandt,¹¹⁹ C. Driouichi,³⁵ M. Dris,⁹ J. Dubbert,⁹⁸ S. Dube,¹⁴ E. Duchovni,¹⁷⁰ G. Duckeck,⁹⁷ A. Dudarev,²⁹ F. Dudziak,⁶² M. Dührssen,²⁹ I. P. Duerdoth,⁸¹ L. Duflot,¹¹⁴ M-A. Dufour,⁸⁴ M. Dunford,²⁹ H. Duran Yildiz,^{3a} R. Duxfield,¹³⁸ M. Dwuznik,³⁷ F. Dydak,²⁹ M. Düren,⁵¹ W. L. Ebenstein,⁴⁴ J. Ebke,⁹⁷ S. Eckweiler,⁸⁰ K. Edmonds,⁸⁰ C. A. Edwards,⁷⁵ N. C. Edwards,⁵² W. Ehrenfeld,⁴¹ T. Ehrich,⁹⁸ T. Eifert,¹⁴² G. Eigen,¹³ K. Einsweiler,¹⁴ E. Eisenhandler,⁷⁴ T. Ekelof,¹⁶⁵ M. El Kacimi,^{134c} M. Ellert,¹⁶⁵ S. Elles,⁴ F. Ellinghaus,⁸⁰ K. Ellis,⁷⁴ N. Ellis,²⁹ J. Elmsheuser,⁹⁷ M. Elsing,²⁹ D. Emelianov,¹²⁸ R. Engelmann,¹⁴⁷ A. Engl,⁹⁷ B. Epp,⁶⁰ A. Eppig,⁸⁶ J. Erdmann,⁵³ A. Ereditato,¹⁶ D. Eriksson,^{145a} J. Ernst,¹ M. Ernst,²⁴ J. Ernwein,¹³⁵ D. Errede,¹⁶⁴ S. Errede,¹⁶⁴ E. Ertel,⁸⁰ M. Escalier,¹¹⁴ C. Escobar,¹²² X. Espinal Curull,¹¹ B. Esposito,⁴⁶ F. Etienne,⁸² A. I. Etienvre,¹³⁵ E. Etzion,¹⁵² D. Evangelakou,⁵³ H. Evans,⁵⁹ L. Fabbri,^{19a,19b} C. Fabre,²⁹ R. M. Fakhruddinov,¹²⁷ S. Falciano,^{131a} Y. Fang,¹⁷¹ M. Fanti,^{88a,88b} A. Farbin,⁷ A. Farilla,^{133a} J. Farley,¹⁴⁷ T. Farooque,¹⁵⁷ S. Farrell,¹⁶² S. M. Farrington,¹¹⁷ P. Farthouat,²⁹ P. Fassnacht,²⁹ D. Fassouliotis,⁸ B. Fatholahzadeh,¹⁵⁷ A. Favareto,^{88a,88b} L. Fayard,¹¹⁴ S. Fazio,^{36a,36b} R. Febbraro,³³ P. Federic,^{143a} O. L. Fedin,¹²⁰ W. Fedorko,⁸⁷ M. Fehling-Kaschek,⁴⁷ L. Felgioni,⁸² D. Fellmann,⁵ C. Feng,^{32d} E. J. Feng,³⁰ A. B. Fenyuk,¹²⁷ J. Ferencei,^{143b} J. Ferland,⁹² W. Fernando,⁵ S. Ferrag,⁵² J. Ferrando,⁵² V. Ferrara,⁴¹ A. Ferrari,¹⁶⁵ P. Ferrari,¹⁰⁴ R. Ferrari,^{118a} D. E. Ferreira de Lima,⁵² A. Ferrer,¹⁶⁶ M. L. Ferrer,⁴⁶ D. Ferrere,⁴⁸ C. Ferretti,⁸⁶ A. Ferretto Parodi,^{49a,49b} M. Fiassaric,³⁰ F. Fiedler,⁸⁰ A. Filipčič,⁷³ A. Filippas,⁹ F. Filthaut,¹⁰³ M. Fincke-Keeler,¹⁶⁸ M. C. N. Fiolhais,^{123a,i} L. Fiorini,¹⁶⁶ A. Firan,³⁹ G. Fischer,⁴¹ M. J. Fisher,¹⁰⁸ M. Flechl,⁴⁷ I. Fleck,¹⁴⁰ J. Fleckner,⁸⁰ P. Fleischmann,¹⁷² S. Fleischmann,¹⁷³ T. Flick,¹⁷³ A. Floderus,⁷⁸ L. R. Flores Castillo,¹⁷¹ M. J. Flowerdew,⁹⁸ M. Fokitis,⁹ T. Fonseca Martin,¹⁶ D. A. Forbush,¹³⁷ A. Formica,¹³⁵ A. Forti,⁸¹ D. Fortin,^{158a} J. M. Foster,⁸¹ D. Fournier,¹¹⁴ A. Foussat,²⁹ A. J. Fowler,⁴⁴ K. Fowler,¹³⁶ H. Fox,⁷⁰ P. Francavilla,¹¹ S. Franchino,^{118a,118b} D. Francis,²⁹ T. Frank,¹⁷⁰ M. Franklin,⁵⁶ S. Franz,²⁹ M. Fraternali,^{118a,118b} S. Fratina,¹¹⁹ S. T. French,²⁷ C. Friedrich,⁴¹ F. Friedrich,⁴³ R. Froeschl,²⁹ D. Froidevaux,²⁹ J. A. Frost,²⁷ C. Fukunaga,¹⁵⁵ E. Fullana Torregrosa,²⁹ B. G. Fulsom,¹⁴² J. Fuster,¹⁶⁶ C. Gabaldon,²⁹ O. Gabizon,¹⁷⁰ T. Gadfort,²⁴ S. Gadomski,⁴⁸ G. Gagliardi,^{49a,49b} P. Gagnon,⁵⁹ C. Galea,⁹⁷ E. J. Gallas,¹¹⁷ V. Gallo,¹⁶ B. J. Gallop,¹²⁸ P. Gallus,¹²⁴ K. K. Gan,¹⁰⁸ Y. S. Gao,^{142,f} V. A. Gapienko,¹²⁷ A. Gaponenko,¹⁴ F. Garberson,¹⁷⁴ M. Garcia-Sciveres,¹⁴ C. García,¹⁶⁶ J. E. García Navarro,¹⁶⁶ R. W. Gardner,³⁰ N. Garelli,²⁹ H. Garitaonandia,¹⁰⁴ V. Garonne,²⁹ J. Garvey,¹⁷ C. Gatti,⁴⁶ G. Gaudio,^{118a} B. Gaur,¹⁴⁰ L. Gauthier,¹³⁵ P. Gauzzi,^{131a,131b} I. L. Gavrilenko,⁹³ C. Gay,¹⁶⁷ G. Gaycken,²⁰ J-C. Gayde,²⁹ E. N. Gazis,⁹ P. Ge,^{32d} Z. Gecse,¹⁶⁷ C. N. P. Gee,¹²⁸ D. A. A. Geerts,¹⁰⁴ Ch. Geich-Gimbel,²⁰ K. Gellerstedt,^{145a,145b} C. Gemme,^{49a} A. Gemmell,⁵² M. H. Genest,⁵⁴ S. Gentile,^{131a,131b} M. George,⁵³ S. George,⁷⁵ P. Gerlach,¹⁷³ A. Gershon,¹⁵² C. Geweniger,^{57a} H. Ghazlane,^{134b} N. Ghodbane,³³ B. Giacobbe,^{19a} S. Giagu,^{131a,131b} V. Giakoumopoulou,⁸ V. Giangiobbe,¹¹ F. Gianotti,²⁹ B. Gibbard,²⁴ A. Gibson,¹⁵⁷ S. M. Gibson,²⁹ L. M. Gilbert,¹¹⁷ V. Gilevsky,⁹⁰ D. Gillberg,²⁸ A. R. Gillman,¹²⁸ D. M. Gingrich,^{2,e} J. Ginzburg,¹⁵² N. Giokaris,⁸ M. P. Giordani,^{163c} R. Giordano,^{101a,101b} F. M. Giorgi,¹⁵ P. Giovannini,⁹⁸ P. F. Giraud,¹³⁵ D. Giugni,^{88a} M. Giunta,⁹² P. Giusti,^{19a} B. K. Gjelsten,¹¹⁶ L. K. Gladilin,⁹⁶ C. Glasman,⁷⁹ J. Glatzer,⁴⁷ A. Glazov,⁴¹ K. W. Glitza,¹⁷³ G. L. Glonti,⁶³ J. R. Goddard,⁷⁴ J. Godfrey,¹⁴¹ J. Godlewski,²⁹ M. Goebel,⁴¹ T. Göpfert,⁴³ C. Goeringer,⁸⁰ C. Gössling,⁴² T. Göttfert,⁹⁸ S. Goldfarb,⁸⁶ T. Golling,¹⁷⁴ A. Gomes,^{123a,c} L. S. Gomez Fajardo,⁴¹ R. Gonçalves,⁷⁵ J. Goncalves Pinto Firmino Da Costa,⁴¹ L. Gonella,²⁰ A. Gonidec,²⁹ S. Gonzalez,¹⁷¹ S. González de la Hoz,¹⁶⁶ G. Gonzalez Parra,¹¹ M. L. Gonzalez Silva,²⁶ S. Gonzalez-Sevilla,⁴⁸ J. J. Goodson,¹⁴⁷ L. Goossens,²⁹ P. A. Gorbounov,⁹⁴ H. A. Gordon,²⁴ I. Gorelov,¹⁰² G. Gorfine,¹⁷³ B. Gorini,²⁹ E. Gorini,^{71a,71b} A. Gorišek,⁷³

- E. Gornicki,³⁸ V. N. Goryachev,¹²⁷ B. Gosdzik,⁴¹ A. T. Goshaw,⁵ M. Gosselink,¹⁰⁴ M. I. Gostkin,⁶³
 I. Gough Eschrich,¹⁶² M. Gouighri,^{134a} D. Goujdami,^{134c} M. P. Goulette,⁴⁸ A. G. Goussiou,¹³⁷ C. Goy,⁴
 S. Gozpinar,²² I. Grabowska-Bold,³⁷ P. Grafström,²⁹ K.-J. Grahm,⁴¹ F. Grancagnolo,^{71a} S. Grancagnolo,¹⁵
 V. Grassi,¹⁴⁷ V. Gratchev,¹²⁰ N. Grau,³⁴ H. M. Gray,²⁹ J. A. Gray,¹⁴⁷ E. Graziani,^{133a} O. G. Grebenyuk,¹²⁰
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 S. Guindon,⁵³ H. Guler,^{84,o} J. Gunther,¹²⁴ B. Guo,¹⁵⁷ J. Guo,³⁴ A. Gupta,³⁰ Y. Gusakov,⁶³ V. N. Gushchin,¹²⁷
 P. Gutierrez,¹¹⁰ N. Guttman,¹⁵² O. Gutzwiller,¹⁷¹ C. Guyot,¹³⁵ C. Gwenlan,¹¹⁷ C. B. Gwilliam,⁷² A. Haas,¹⁴²
 S. Haas,²⁹ C. Haber,¹⁴ H. K. Hadavand,³⁹ D. R. Hadley,¹⁷ P. Haefner,⁹⁸ F. Hahn,²⁹ S. Haider,²⁹ Z. Hajduk,³⁸
 H. Hakobyan,¹⁷⁵ D. Hall,¹¹⁷ J. Haller,⁵³ K. Hamacher,¹⁷³ P. Hamal,¹¹² M. Hamer,⁵³ A. Hamilton,^{144b,p}
 S. Hamilton,¹⁶⁰ H. Han,^{32a} L. Han,^{32b} K. Hanagaki,¹¹⁵ K. Hanawa,¹⁵⁹ M. Hance,¹⁴ C. Handel,⁸⁰ P. Hanke,^{57a}
 J. R. Hansen,³⁵ J. B. Hansen,³⁵ J. D. Hansen,³⁵ P. H. Hansen,³⁵ P. Hansson,¹⁴² K. Hara,¹⁵⁹ G. A. Hare,¹³⁶
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 F. Hartjes,¹⁰⁴ T. Haruyama,⁶⁴ A. Harvey,⁵⁵ S. Hasegawa,¹⁰⁰ Y. Hasegawa,¹³⁹ S. Hassani,¹³⁵ M. Hatch,²⁹ D. Hauff,⁹⁸
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 C. Heller,⁹⁷ M. Heller,²⁹ S. Hellman,^{145a,145b} D. Hellmich,²⁰ C. Helsens,¹¹ R. C. W. Henderson,⁷⁰ M. Henke,^{57a}
 A. Henrichs,⁵³ A. M. Henriques Correia,²⁹ S. Henrot-Versille,¹¹⁴ F. Henry-Couannier,⁸² C. Hensel,⁵³ T. Henß,¹⁷³
 C. M. Hernandez,⁷ Y. Hernández Jiménez,¹⁶⁶ R. Herrberg,¹⁵ G. Herten,⁴⁷ R. Hertenberger,⁹⁷ L. Hervas,²⁹
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 S. J. Hillier,¹⁷ I. Hinchliffe,¹⁴ E. Hines,¹¹⁹ M. Hirose,¹¹⁵ F. Hirsch,⁴² D. Hirschbuehl,¹⁷³ J. Hobbs,¹⁴⁷ N. Hod,¹⁵²
 M. C. Hodgkinson,¹³⁸ P. Hodgson,¹³⁸ A. Hoecker,²⁹ M. R. Hoferkamp,¹⁰² J. Hoffman,³⁹ D. Hoffmann,⁸²
 M. Hohlfeld,⁸⁰ M. Holder,¹⁴⁰ S. O. Holmgren,^{145a} T. Holy,¹²⁶ J. L. Holzbauer,⁸⁷ Y. Homma,⁶⁵ T. M. Hong,¹¹⁹
 L. Hoof van Huysduynen,¹⁰⁷ T. Horazdovsky,¹²⁶ C. Horn,¹⁴² S. Horner,⁴⁷ J.-Y. Hostachy,⁵⁴ S. Hou,¹⁵⁰
 M. A. Houlden,⁷² A. Hoummada,^{134a} J. Howarth,⁸¹ D. F. Howell,¹¹⁷ I. Hristova,¹⁵ J. Hrivnac,¹¹⁴ I. Hruska,¹²⁴
 T. Hryn'ova,⁴ P. J. Hsu,⁸⁰ S.-C. Hsu,¹⁴ G. S. Huang,¹¹⁰ Z. Hubacek,¹²⁶ F. Hubaut,⁸² F. Huegging,²⁰ A. Huettmann,⁴¹
 T. B. Huffman,¹¹⁷ E. W. Hughes,³⁴ G. Hughes,⁷⁰ R. E. Hughes-Jones,⁸¹ M. Huhtinen,²⁹ P. Hurst,⁵⁶ M. Hurwitz,¹⁴
 U. Husemann,⁴¹ N. Huseynov,^{63,q} J. Huston,⁸⁷ J. Huth,⁵⁶ G. Iacobucci,⁴⁸ G. Iakovidis,⁹ M. Ibbotson,⁸¹
 I. Ibragimov,¹⁴⁰ L. Iconomidou-Fayard,¹¹⁴ J. Idarraga,¹¹⁴ P. Iengo,^{101a} O. Igonkina,¹⁰⁴ Y. Ikegami,⁶⁴ M. Ikeno,⁶⁴
 D. Iliadis,¹⁵³ N. Ilic,¹⁵⁷ M. Imori,¹⁵⁴ T. Ince,²⁰ J. Inigo-Golfin,²⁹ P. Ioannou,⁸ M. Iodice,^{133a} K. Iordanidou,⁸
 V. Ippolito,^{131a,131b} A. Irls Quiles,¹⁶⁶ C. Isaksson,¹⁶⁵ A. Ishikawa,⁶⁵ M. Ishino,⁶⁶ R. Ishmukhametov,³⁹ C. Issever,¹¹⁷
 S. Istin,^{18a} A. V. Ivashin,¹²⁷ W. Iwanski,³⁸ H. Iwasaki,⁶⁴ J. M. Izen,⁴⁰ V. Izzo,^{101a} B. Jackson,¹¹⁹ J. N. Jackson,⁷²
 P. Jackson,¹⁴² M. R. Jaekel,²⁹ V. Jain,⁵⁹ K. Jakobs,⁴⁷ S. Jakobsen,³⁵ J. Jakubek,¹²⁶ D. K. Jana,¹¹⁰ E. Jansen,⁷⁶
 H. Jansen,²⁹ A. Jantsch,⁹⁸ M. Janus,⁴⁷ G. Jarlskog,⁷⁸ L. Jeanty,⁵⁶ K. Jelen,³⁷ I. Jen-La Plante,³⁰ P. Jenni,²⁹
 A. Jeremie,⁴ P. Jež,³⁵ S. Jézéquel,⁴ M. K. Jha,^{19a} H. Ji,¹⁷¹ W. Ji,⁸⁰ J. Jia,¹⁴⁷ Y. Jiang,^{32b} M. Jimenez Belenguer,⁴¹
 G. Jin,^{32b} S. Jin,^{32a} O. Jinnouchi,¹⁵⁶ M. D. Joergensen,³⁵ D. Joffe,³⁹ L. G. Johansen,¹³ M. Johansen,^{145a,145b}
 K. E. Johansson,^{145a} P. Johansson,¹³⁸ S. Johnert,⁴¹ K. A. Johns,⁶ K. Jon-And,^{145a,145b} G. Jones,¹¹⁷ R. W. L. Jones,⁷⁰
 T. W. Jones,⁷⁶ T. J. Jones,⁷² O. Jonsson,²⁹ C. Joram,²⁹ P. M. Jorge,^{123a} J. Joseph,¹⁴ K. D. Joshi,⁸¹ J. Jovicevic,¹⁴⁶
 T. Jovin,^{12b} X. Ju,¹⁷¹ C. A. Jung,⁴² R. M. Jungst,²⁹ V. Juranek,¹²⁴ P. Jussel,⁶⁰ A. Juste Rozas,¹¹ V. V. Kabachenko,¹²⁷
 S. Kabana,¹⁶ M. Kaci,¹⁶⁶ A. Kaczmarek,³⁸ P. Kadlecik,³⁵ M. Kado,¹¹⁴ H. Kagan,¹⁰⁸ M. Kagan,⁵⁶ S. Kaiser,⁹⁸
 E. Kajomovitz,¹⁵¹ S. Kalinin,¹⁷³ L. V. Kalinovskaya,⁶³ S. Kama,³⁹ N. Kanaya,¹⁵⁴ M. Kaneda,²⁹ S. Kaneti,²⁷
 T. Kanno,¹⁵⁶ V. A. Kantserov,⁹⁵ J. Kanzaki,⁶⁴ B. Kaplan,¹⁷⁴ A. Kapliy,³⁰ J. Kaplon,²⁹ D. Kar,⁵² M. Karagounis,²⁰
 M. Karagoz,¹¹⁷ M. Karnevskiy,⁴¹ V. Kartvelishvili,⁷⁰ A. N. Karyukhin,¹²⁷ L. Kashif,¹⁷¹ G. Kasieczka,^{57b}
 R. D. Kass,¹⁰⁸ A. Kastanas,¹³ M. Kataoka,⁴ Y. Kataoka,¹⁵⁴ E. Katsoufis,⁹ J. Katzy,⁴¹ V. Kaushik,⁶ K. Kawagoe,⁶⁸
 T. Kawamoto,¹⁵⁴ G. Kawamura,⁸⁰ M. S. Kayl,¹⁰⁴ V. A. Kazanin,¹⁰⁶ M. Y. Kazarinov,⁶³ R. Keeler,¹⁶⁸ R. Kehoe,³⁹
 M. Keil,⁵³ G. D. Kekelidze,⁶³ J. S. Keller,¹³⁷ J. Kennedy,⁹⁷ M. Kenyon,⁵² O. Kepka,¹²⁴ N. Kerschen,²⁹
 B. P. Kerševan,⁷³ S. Kersten,¹⁷³ K. Kessoku,¹⁵⁴ J. Keung,¹⁵⁷ F. Khalil-zada,¹⁰ H. Khandanyan,¹⁶⁴ A. Khanov,¹¹¹
 D. Kharchenko,⁶³ A. Khodinov,⁹⁵ A. G. Kholodenko,¹²⁷ A. Khomich,^{57a} T. J. Khoo,²⁷ G. Khoraiuli,²⁰
 A. Khoroshilov,¹⁷³ N. Khovanskiy,⁶³ V. Khovanskiy,⁹⁴ E. Khramov,⁶³ J. Khubua,^{50b} H. Kim,^{145a,145b} M. S. Kim,²

S. H. Kim,¹⁵⁹ N. Kimura,¹⁶⁹ O. Kind,¹⁵ B. T. King,⁷² M. King,⁶⁵ R. S. B. King,¹¹⁷ J. Kirk,¹²⁸ L. E. Kirsch,²² A. E. Kiryunin,⁹⁸ T. Kishimoto,⁶⁵ D. Kisielewska,³⁷ T. Kittelmann,¹²² A. M. Kiver,¹²⁷ E. Kladiva,^{143b} M. Klein,⁷² U. Klein,⁷² K. Kleinknecht,⁸⁰ M. Klemetti,⁸⁴ A. Klier,¹⁷⁰ P. Klimek,^{145a,145b} A. Klimentov,²⁴ R. Klingenberg,⁴² J. A. Klinger,⁸¹ E. B. Klinkby,³⁵ T. Klioutchnikova,²⁹ P. F. Klok,¹⁰³ S. Klous,¹⁰⁴ E.-E. Kluge,^{57a} T. Kluge,⁷² P. Kluit,¹⁰⁴ S. Kluth,⁹⁸ N. S. Knecht,¹⁵⁷ E. Kneringer,⁶⁰ J. Knobloch,²⁹ E. B. F. G. Knoops,⁸² A. Knue,⁵³ B. R. Ko,⁴⁴ T. Kobayashi,¹⁵⁴ M. Kobel,⁴³ M. Kocian,¹⁴² P. Kodys,¹²⁵ K. Köneke,²⁹ A. C. König,¹⁰³ S. Koenig,⁸⁰ L. Köpke,⁸⁰ F. Koetsveld,¹⁰³ P. Koevesarki,²⁰ T. Koffas,²⁸ E. Koffeman,¹⁰⁴ L. A. Kogan,¹¹⁷ S. Kohlmann,¹⁷³ F. Kohn,⁵³ Z. Kohout,¹²⁶ T. Kohriki,⁶⁴ T. Koi,¹⁴² T. Kokott,²⁰ G. M. Kolachev,¹⁰⁶ H. Kolanoski,¹⁵ V. Kolesnikov,⁶³ I. Koletsou,^{88a} J. Koll,⁸⁷ M. Kollefrath,⁴⁷ S. D. Kolya,⁸¹ A. A. Komar,⁹³ Y. Komori,¹⁵⁴ T. Kondo,⁶⁴ T. Kono,^{41,r} A. I. Kononov,⁴⁷ R. Konoplich,^{107,s} N. Konstantinidis,⁷⁶ A. Kootz,¹⁷³ S. Koperny,³⁷ K. Korcyl,³⁸ K. Kordas,¹⁵³ V. Koreshev,¹²⁷ A. Korn,¹¹⁷ A. Korol,¹⁰⁶ I. Korolkov,¹¹ E. V. Korolkova,¹³⁸ V. A. Korotkov,¹²⁷ O. Kortner,⁹⁸ S. Kortner,⁹⁸ V. V. Kostyukhin,²⁰ M. J. Kotamäki,²⁹ S. Kotov,⁹⁸ V. M. Kotov,⁶³ A. Kotwal,⁴⁴ C. Kourkoumelis,⁸ V. Kouskoura,¹⁵³ A. Koutsman,^{158a} R. Kowalewski,¹⁶⁸ T. Z. Kowalski,³⁷ W. Kozanecki,¹³⁵ A. S. Kozhin,¹²⁷ V. Kral,¹²⁶ V. A. Kramarenko,⁹⁶ G. Kramberger,⁷³ M. W. Krasny,⁷⁷ A. Krasznahorkay,¹⁰⁷ J. Kraus,⁸⁷ J. K. Kraus,²⁰ F. Krejci,¹²⁶ J. Kretschmar,⁷² N. Krieger,⁵³ P. Krieger,¹⁵⁷ K. Kroeninger,⁵³ H. Kroha,⁹⁸ J. Kroll,¹¹⁹ J. Kroseberg,²⁰ J. Krstic,^{12a} U. Kruchonak,⁶³ H. Krüger,²⁰ T. Kruker,¹⁶ N. Krumnack,⁶² Z. V. Krumshteyn,⁶³ A. Kruth,²⁰ T. Kubota,⁸⁵ S. Kuday,^{3a} S. Kuehn,⁴⁷ A. Kugel,^{57c} T. Kuhl,⁴¹ D. Kuhn,⁶⁰ V. Kukhtin,⁶³ Y. Kulchitsky,⁸⁹ S. Kuleshov,^{31b} C. Kummer,⁹⁷ M. Kuna,⁷⁷ J. Kunkle,¹¹⁹ A. Kupco,¹²⁴ H. Kurashige,⁶⁵ M. Kurata,¹⁵⁹ Y. A. Kurochkin,⁸⁹ V. Kus,¹²⁴ E. S. Kuwertz,¹⁴⁶ M. Kuze,¹⁵⁶ J. Kvita,¹⁴¹ R. Kwee,¹⁵ A. La Rosa,⁴⁸ L. La Rotonda,^{36a,36b} L. Labarga,⁷⁹ J. Labbe,⁴ S. Lablak,^{134a} C. Lacasta,¹⁶⁶ F. Lacava,^{131a,131b} H. Lacker,¹⁵ D. Lacour,⁷⁷ V. R. Lacuesta,¹⁶⁶ E. Ladygin,⁶³ R. Lafaye,⁴ B. Laforge,⁷⁷ T. Lagouri,⁷⁹ S. Lai,⁴⁷ E. Laisne,⁵⁴ M. Lamanna,²⁹ L. Lambourne,⁷⁶ C. L. Lampen,⁶ W. Lampl,⁶ E. Lancon,¹³⁵ U. Landgraf,⁴⁷ M. P. J. Landon,⁷⁴ J. L. Lane,⁸¹ C. Lange,⁴¹ A. J. Lankford,¹⁶² F. Lanni,²⁴ K. Lantzsch,¹⁷³ S. Laplace,⁷⁷ C. Lapoire,²⁰ J. F. Laporte,¹³⁵ T. Lari,^{88a} A. V. Larionov,¹²⁷ A. Larner,¹¹⁷ C. Lasseur,²⁹ M. Lassnig,²⁹ P. Laurelli,⁴⁶ V. Lavorini,^{36a,36b} W. Lavrijsen,¹⁴ P. Laycock,⁷² A. B. Lazarev,⁶³ O. Le Dortz,⁷⁷ E. Le Guirriec,⁸² C. Le Maner,¹⁵⁷ E. Le Menedeu,¹¹ C. Lebel,⁹² T. LeCompte,⁵ F. Ledroit-Guillon,⁵⁴ H. Lee,¹⁰⁴ J. S. H. Lee,¹¹⁵ S. C. Lee,¹⁵⁰ L. Lee,¹⁷⁴ M. Lefebvre,¹⁶⁸ M. Legendre,¹³⁵ A. Leger,⁴⁸ B. C. LeGeyt,¹¹⁹ F. Legger,⁹⁷ C. Leggett,¹⁴ M. Lehmacher,²⁰ G. Lehmann Miotto,²⁹ X. Lei,⁶ M. A. L. Leite,^{23d} R. Leitner,¹²⁵ D. Lellouch,¹⁷⁰ M. Leltchouk,³⁴ B. Lemmer,⁵³ V. Lendermann,^{57a} K. J. C. Leney,^{144b} T. Lenz,¹⁰⁴ G. Lenzen,¹⁷³ B. Lenzi,²⁹ K. Leonhardt,⁴³ S. Leontsinis,⁹ F. Lepold,^{57a} C. Leroy,⁹² J.-R. Lessard,¹⁶⁸ C. G. Lester,²⁷ C. M. Lester,¹¹⁹ J. Levêque,⁴ D. Levin,⁸⁶ L. J. Levinson,¹⁷⁰ M. S. Levitski,¹²⁷ A. Lewis,¹¹⁷ G. H. Lewis,¹⁰⁷ A. M. Leyko,²⁰ M. Leyton,¹⁵ B. Li,⁸² H. Li,^{171,t} S. Li,^{32b,u} X. Li,⁸⁶ Z. Liang,^{117,v} H. Liao,³³ B. Liberti,^{132a} P. Lichard,²⁹ M. Lichtnecker,⁹⁷ K. Lie,¹⁶⁴ W. Liebig,¹³ C. Limbach,²⁰ A. Limosani,⁸⁵ M. Limper,⁶¹ S. C. Lin,^{150,w} F. Linde,¹⁰⁴ J. T. Linnemann,⁸⁷ E. Lipeles,¹¹⁹ L. Lipinsky,¹²⁴ A. Lipniacka,¹³ T. M. Liss,¹⁶⁴ D. Lissauer,²⁴ A. Lister,⁴⁸ A. M. Litke,¹³⁶ C. Liu,²⁸ D. Liu,¹⁵⁰ H. Liu,⁸⁶ J. B. Liu,⁸⁶ M. Liu,^{32b} Y. Liu,^{32b} M. Livan,^{118a,118b} S. S. A. Livermore,¹¹⁷ A. Lleres,⁵⁴ J. Llorente Merino,⁷⁹ S. L. Lloyd,⁷⁴ E. Lobodzinska,⁴¹ P. Loch,⁶ W. S. Lockman,¹³⁶ T. Loddenkoetter,²⁰ F. K. Loebinger,⁸¹ A. Loginov,¹⁷⁴ C. W. Loh,¹⁶⁷ T. Lohse,¹⁵ K. Lohwasser,⁴⁷ M. Lokajicek,¹²⁴ J. Loken,¹¹⁷ V. P. Lombardo,⁴ R. E. Long,⁷⁰ L. Lopes,^{123a} D. Lopez Mateos,⁵⁶ J. Lorenz,⁹⁷ N. Lorenzo Martinez,¹¹⁴ M. Losada,¹⁶¹ P. Loscutoff,¹⁴ F. Lo Sterzo,^{131a,131b} M. J. Losty,^{158a} X. Lou,⁴⁰ A. Lounis,¹¹⁴ K. F. Loureiro,¹⁶¹ J. Love,²¹ P. A. Love,⁷⁰ A. J. Lowe,^{142,f} F. Lu,^{32a} H. J. Lubatti,¹³⁷ C. Luci,^{131a,131b} A. Lucotte,⁵⁴ A. Ludwig,⁴³ D. Ludwig,⁴¹ I. Ludwig,⁴⁷ J. Ludwig,⁴⁷ F. Luehring,⁵⁹ G. Luijckx,¹⁰⁴ W. Lukas,⁶⁰ D. Lumb,⁴⁷ L. Luminari,^{131a} E. Lund,¹¹⁶ B. Lund-Jensen,¹⁴⁶ B. Lundberg,⁷⁸ J. Lundberg,^{145a,145b} J. Lundquist,³⁵ M. Lungwitz,⁸⁰ G. Lutz,⁹⁸ D. Lynn,²⁴ J. Lys,¹⁴ E. Lytken,⁷⁸ H. Ma,²⁴ L. L. Ma,¹⁷¹ J. A. Macana Goia,⁹² G. Maccarrone,⁴⁶ A. Macchiolo,⁹⁸ B. Maček,⁷³ J. Machado Miguens,^{123a} R. Mackeprang,³⁵ R. J. Madaras,¹⁴ W. F. Mader,⁴³ R. Maenner,^{57c} T. Maeno,²⁴ P. Mättig,¹⁷³ S. Mättig,⁴¹ L. Magnoni,²⁹ E. Magradze,⁵³ Y. Mahalalel,¹⁵² K. Mahboubi,⁴⁷ S. Mahmoud,⁷² G. Mahout,¹⁷ C. Maiani,^{131a,131b} C. Maidantchik,^{23a} A. Maio,^{123a,c} S. Majewski,²⁴ Y. Makida,⁶⁴ N. Makovec,¹¹⁴ P. Mal,¹³⁵ B. Malaescu,²⁹ Pa. Malecki,³⁸ P. Malecki,³⁸ V. P. Maleev,¹²⁰ F. Malek,⁵⁴ U. Mallik,⁶¹ D. Malon,⁵ C. Malone,¹⁴² S. Maltezos,⁹ V. Malyshev,¹⁰⁶ S. Malyukov,²⁹ R. Mameghani,⁹⁷ J. Mamuzic,^{12b} A. Manabe,⁶⁴ L. Mandelli,^{88a} I. Mandić,⁷³ R. Mandrysch,¹⁵ J. Maneira,^{123a} P. S. Mangedard,⁸⁷ L. Manhaes de Andrade Filho,^{23a} I. D. Manjavidze,⁶³ A. Mann,⁵³ P. M. Manning,¹³⁶ A. Manousakis-Katsikakis,⁸ B. Mansoulie,¹³⁵ A. Manz,⁹⁸ A. Mapelli,²⁹ L. Mapelli,²⁹ L. March,⁷⁹ J. F. Marchand,²⁸ F. Marchese,^{132a,132b} G. Marchiori,⁷⁷ M. Marcisovsky,¹²⁴ C. P. Marino,¹⁶⁸ F. Marroquim,^{23a} R. Marshall,⁸¹ Z. Marshall,²⁹ F. K. Martens,¹⁵⁷ S. Marti-Garcia,¹⁶⁶ B. Martin,²⁹ B. Martin,⁸⁷ F. F. Martin,¹¹⁹

J. P. Martin,⁹² Ph. Martin,⁵⁴ T. A. Martin,¹⁷ V. J. Martin,⁴⁵ B. Martin dit Latour,⁴⁸ S. Martin-Haugh,¹⁴⁸ M. Martinez,¹¹ V. Martinez Outschoorn,⁵⁶ A. C. Martyniuk,¹⁶⁸ M. Marx,⁸¹ F. Marzano,^{131a} A. Marzin,¹¹⁰ L. Masetti,⁸⁰ T. Mashimo,¹⁵⁴ R. Mashinistov,⁹³ J. Masik,⁸¹ A. L. Maslennikov,¹⁰⁶ I. Massa,^{19a,19b} G. Massaro,¹⁰⁴ N. Massol,⁴ P. Mastrandrea,^{131a,131b} A. Mastroberardino,^{36a,36b} T. Masubuchi,¹⁵⁴ P. Matricon,¹¹⁴ H. Matsunaga,¹⁵⁴ T. Matsushita,⁶⁵ C. Mattravers,^{117,d} J. M. Maugain,²⁹ J. Maurer,⁸² S. J. Maxfield,⁷² E. N. May,⁵ A. Mayne,¹³⁸ R. Mazini,¹⁵⁰ M. Mazur,²⁰ L. Mazzaferro,^{132a,132b} M. Mazzanti,^{88a} S. P. Mc Kee,⁸⁶ A. McCarn,¹⁶⁴ R. L. McCarthy,¹⁴⁷ T. G. McCarthy,²⁸ N. A. McCubbin,¹²⁸ K. W. McFarlane,⁵⁵ J. A. McFayden,¹³⁸ H. McGlone,⁵² G. Mchedlidze,^{50b} R. A. McLaren,²⁹ T. McLaughlan,¹⁷ S. J. McMahon,¹²⁸ R. A. McPherson,^{168,k} A. Meade,⁸³ J. Mechnich,¹⁰⁴ M. Mechtel,¹⁷³ M. Medinnis,⁴¹ R. Meera-Lebbai,¹¹⁰ T. Meguro,¹¹⁵ R. Mehdiyev,⁹² S. Mehlhase,³⁵ A. Mehta,⁷² K. Meier,^{57a} B. Meirose,⁷⁸ C. Melachrinou,³⁰ B. R. Mellado Garcia,¹⁷¹ F. Meloni,^{88a,88b} L. Mendoza Navas,¹⁶¹ Z. Meng,^{150,t} A. Mengarelli,^{19a,19b} S. Menke,⁹⁸ C. Menot,²⁹ E. Meoni,¹¹ K. M. Mercurio,⁵⁶ P. Mermod,⁴⁸ L. Merola,^{101a,101b} C. Meroni,^{88a} F. S. Merritt,³⁰ H. Merritt,¹⁰⁸ A. Messina,²⁹ J. Metcalfe,¹⁰² A. S. Mete,⁶² C. Meyer,⁸⁰ C. Meyer,³⁰ J-P. Meyer,¹³⁵ J. Meyer,¹⁷² J. Meyer,⁵³ T. C. Meyer,²⁹ W. T. Meyer,⁶² J. Miao,^{32d} S. Michal,²⁹ L. Micu,^{25a} R. P. Middleton,¹²⁸ S. Migas,⁷² L. Mijović,⁴¹ G. Mikenberg,¹⁷⁰ M. Mikesikova,¹²⁴ M. Mikuž,⁷³ D. W. Miller,³⁰ R. J. Miller,⁸⁷ W. J. Mills,¹⁶⁷ C. Mills,⁵⁶ A. Milov,¹⁷⁰ D. A. Milstead,^{145a,145b} D. Milstein,¹⁷⁰ A. A. Minaenko,¹²⁷ M. Miñano Moya,¹⁶⁶ I. A. Minashvili,⁶³ A. I. Mincer,¹⁰⁷ B. Mindur,³⁷ M. Mineev,⁶³ Y. Ming,¹⁷¹ L. M. Mir,¹¹ G. Mirabelli,^{131a} L. Miralles Verge,¹¹ A. Misiejuk,⁷⁵ J. Mitrevski,¹³⁶ G. Y. Mitrofanov,¹²⁷ V. A. Mitsou,¹⁶⁶ S. Mitsui,⁶⁴ P. S. Miyagawa,¹³⁸ K. Miyazaki,⁶⁵ J. U. Mjörnmark,⁷⁸ T. Moa,^{145a,145b} P. Mockett,¹³⁷ S. Moed,⁵⁶ V. Moeller,²⁷ K. Mönig,⁴¹ N. Möser,²⁰ S. Mohapatra,¹⁴⁷ W. Mohr,⁴⁷ S. Mohrdieck-Möck,⁹⁸ R. Moles-Valls,¹⁶⁶ J. Molina-Perez,²⁹ J. Monk,⁷⁶ E. Monnier,⁸² S. Montesano,^{88a,88b} F. Monticelli,⁶⁹ S. Monzani,^{19a,19b} R. W. Moore,² G. F. Moorhead,⁸⁵ C. Mora Herrera,⁴⁸ A. Moraes,⁵² N. Morange,¹³⁵ J. Morel,⁵³ G. Morello,^{36a,36b} D. Moreno,⁸⁰ M. Moreno Llácer,¹⁶⁶ P. Morettini,^{49a} M. Morgenstern,⁴³ M. Morii,⁵⁶ J. Morin,⁷⁴ A. K. Morley,²⁹ G. Mornacchi,²⁹ S. V. Morozov,⁹⁵ J. D. Morris,⁷⁴ L. Morvaj,¹⁰⁰ H. G. Moser,⁹⁸ M. Mosidze,^{50b} J. Moss,¹⁰⁸ R. Mount,¹⁴² E. Mountricha,^{9,x} S. V. Mouraviev,⁹³ E. J. W. Moyses,⁸³ M. Mudrinic,^{12b} F. Mueller,^{57a} J. Mueller,¹²² K. Mueller,²⁰ T. A. Müller,⁹⁷ T. Mueller,⁸⁰ D. Muenstermann,²⁹ Y. Munwes,¹⁵² W. J. Murray,¹²⁸ I. Mussche,¹⁰⁴ E. Musto,^{101a,101b} A. G. Myagkov,¹²⁷ M. Myska,¹²⁴ J. Nadal,¹¹ K. Nagai,¹⁵⁹ K. Nagano,⁶⁴ A. Nagarkar,¹⁰⁸ Y. Nagasaka,⁵⁸ M. Nagel,⁹⁸ A. M. Nairz,²⁹ Y. Nakahama,²⁹ K. Nakamura,¹⁵⁴ T. Nakamura,¹⁵⁴ I. Nakano,¹⁰⁹ G. Nanava,²⁰ A. Napier,¹⁶⁰ R. Narayan,^{57b} M. Nash,^{76,d} N. R. Nation,²¹ T. Nattermann,²⁰ T. Naumann,⁴¹ G. Navarro,¹⁶¹ H. A. Neal,⁸⁶ E. Nebot,⁷⁹ P. Yu. Nechaeva,⁹³ T. J. Neep,⁸¹ A. Negri,^{118a,118b} G. Negri,²⁹ S. Nektarijevic,⁴⁸ A. Nelson,¹⁶² T. K. Nelson,¹⁴² S. Nemecek,¹²⁴ P. Nemethy,¹⁰⁷ A. A. Nepomuceno,^{23a} M. Nessi,^{29,y} M. S. Neubauer,¹⁶⁴ A. Neusiedl,⁸⁰ R. M. Neves,¹⁰⁷ P. Nevski,²⁴ P. R. Newman,¹⁷ V. Nguyen Thi Hong,¹³⁵ R. B. Nickerson,¹¹⁷ R. Nicolaidou,¹³⁵ L. Nicolas,¹³⁸ B. Nicquevert,²⁹ F. Niedercorn,¹¹⁴ J. Nielsen,¹³⁶ T. Niinikoski,²⁹ N. Nikiforou,³⁴ A. Nikiforov,¹⁵ V. Nikolaenko,¹²⁷ K. Nikolaev,⁶³ I. Nikolic-Audit,⁷⁷ K. Nikolics,⁴⁸ K. Nikolopoulos,²⁴ H. Nilsen,⁴⁷ P. Nilsson,⁷ Y. Ninomiya,¹⁵⁴ A. Nisati,^{131a} T. Nishiyama,⁶⁵ R. Nisius,⁹⁸ L. Nodulman,⁵ M. Nomachi,¹¹⁵ I. Nomidis,¹⁵³ M. Nordberg,²⁹ P. R. Norton,¹²⁸ J. Novakova,¹²⁵ M. Nozaki,⁶⁴ L. Nozka,¹¹² I. M. Nugent,^{158a} A.-E. Nuncio-Quiroz,²⁰ G. Nunes Hanninger,⁸⁵ T. Nunnemann,⁹⁷ E. Nurse,⁷⁶ B. J. O'Brien,⁴⁵ S. W. O'Neale,^{17,a} D. C. O'Neil,¹⁴¹ V. O'Shea,⁵² L. B. Oakes,⁹⁷ F. G. Oakham,^{28,e} H. Oberlack,⁹⁸ J. Ocariz,⁷⁷ A. Ochi,⁶⁵ S. Oda,¹⁵⁴ S. Odaka,⁶⁴ J. Odier,⁸² H. Ogren,⁵⁹ A. Oh,⁸¹ S. H. Oh,⁴⁴ C. C. Ohm,^{145a,145b} T. Ohshima,¹⁰⁰ H. Ohshita,¹³⁹ S. Okada,⁶⁵ H. Okawa,¹⁶² Y. Okumura,¹⁰⁰ T. Okuyama,¹⁵⁴ A. Olariu,^{25a} M. Olcese,^{49a} A. G. Olchevski,⁶³ S. A. Olivares Pino,^{31a} M. Oliveira,^{123a,i} D. Oliveira Damazio,²⁴ E. Oliver Garcia,¹⁶⁶ D. Olivito,¹¹⁹ A. Olszewski,³⁸ J. Olszowska,³⁸ C. Omachi,⁶⁵ A. Onofre,^{123a,z} P. U. E. Onyisi,³⁰ C. J. Oram,^{158a} M. J. Oreglia,³⁰ Y. Oren,¹⁵² D. Orestano,^{133a,133b} N. Orlando,^{71a,71b} I. Orlov,¹⁰⁶ C. Oropeza Barrera,⁵² R. S. Orr,¹⁵⁷ B. Osculati,^{49a,49b} R. Ospanov,¹¹⁹ C. Osuna,¹¹ G. Otero y Garzon,²⁶ J. P. Ottersbach,¹⁰⁴ M. Ouchrif,^{134d} E. A. Ouellette,¹⁶⁸ F. Ould-Saada,¹¹⁶ A. Ouraou,¹³⁵ Q. Ouyang,^{32a} A. Ovcharova,¹⁴ M. Owen,⁸¹ S. Owen,¹³⁸ V. E. Ozcan,^{18a} N. Ozturk,⁷ A. Pacheco Pages,¹¹ C. Padilla Aranda,¹¹ S. Pagan Griso,¹⁴ E. Paganis,¹³⁸ F. Paige,²⁴ P. Pais,⁸³ K. Pajchel,¹¹⁶ G. Palacino,^{158b} C. P. Paleari,⁶ S. Palestini,²⁹ D. Pallin,³³ A. Palma,^{123a} J. D. Palmer,¹⁷ Y. B. Pan,¹⁷¹ E. Panagiotopoulou,⁹ N. Panikashvili,⁸⁶ S. Panitkin,²⁴ D. Pantea,^{25a} M. Panuskova,¹²⁴ V. Paolone,¹²² A. Papadelis,^{145a} Th. D. Papadopoulou,⁹ A. Paramonov,⁵ D. Paredes Hernandez,³³ W. Park,^{24,aa} M. A. Parker,²⁷ F. Parodi,^{49a,49b} J. A. Parsons,³⁴ U. Parzefall,⁴⁷ S. Pashapour,⁵³ E. Pasqualucci,^{131a} S. Passaggio,^{49a} A. Passeri,^{133a} F. Pastore,^{133a,133b} Fr. Pastore,⁷⁵ G. Pásztor,^{48,bb} S. Pataria,¹⁷³ N. Patel,¹⁴⁹ J. R. Pater,⁸¹ S. Patricelli,^{101a,101b} T. Pauly,²⁹ M. Pecsý,^{143a} M. I. Pedraza Morales,¹⁷¹ S. V. Peleganchuk,¹⁰⁶ D. Pelikan,¹⁶⁵ H. Peng,^{32b} B. Penning,³⁰

A. Penson,³⁴ J. Penwell,⁵⁹ M. Perantoni,^{23a} K. Perez,^{34,cc} T. Perez Cavalcanti,⁴¹ E. Perez Codina,^{158a}
M. T. Pérez García-Estañ,¹⁶⁶ V. Perez Reale,³⁴ L. Perini,^{88a,88b} H. Pernegger,²⁹ R. Perrino,^{71a} P. Perrodo,⁴
S. Perseme,^{3a} V. D. Peshekhonov,⁶³ K. Peters,²⁹ B. A. Petersen,²⁹ J. Petersen,²⁹ T. C. Petersen,³⁵ E. Petit,⁴
A. Petridis,¹⁵³ C. Petridou,¹⁵³ E. Petrolo,^{131a} F. Petrucci,^{133a,133b} D. Petschull,⁴¹ M. Petteni,¹⁴¹ R. Pezoa,^{31b}
A. Phan,⁸⁵ P. W. Phillips,¹²⁸ G. Piacquadio,²⁹ A. Picazio,⁴⁸ E. Piccaro,⁷⁴ M. Piccinini,^{19a,19b} S. M. Piec,⁴¹
R. Piegai,²⁶ D. T. Pignotti,¹⁰⁸ J. E. Pilcher,³⁰ A. D. Pilkington,⁸¹ J. Pina,^{123a,c} M. Pinamonti,^{163a,163c} A. Pinder,¹¹⁷
J. L. Pinfeld,² J. Ping,^{32c} B. Pinto,^{123a} C. Pizio,^{88a,88b} R. Placakyte,⁴¹ M. Plamondon,¹⁶⁸ M.-A. Pleier,²⁴
A. V. Pleskach,¹²⁷ E. Plotnikova,⁶³ A. Poblaguev,²⁴ S. Poddar,^{57a} F. Podlyski,³³ L. Poggioli,¹¹⁴ T. Poghosyan,²⁰
M. Pohl,⁴⁸ F. Polci,⁵⁴ G. Polesello,^{118a} A. Policicchio,^{36a,36b} A. Polini,^{19a} J. Poll,⁷⁴ V. Polychronakos,²⁴
D. M. Pomarede,¹³⁵ D. Pomeroy,²² K. Pommès,²⁹ L. Pontecorvo,^{131a} B. G. Pope,⁸⁷ G. A. Popeneciu,^{25a}
D. S. Popovic,^{12a} A. Poppleton,²⁹ X. Portell Bueso,²⁹ C. Posch,²¹ G. E. Pospelov,⁹⁸ S. Pospisil,¹²⁶ I. N. Potrap,⁹⁸
C. J. Potter,¹⁴⁸ C. T. Potter,¹¹³ G. Poulard,²⁹ J. Poveda,¹⁷¹ V. Pozdnyakov,⁶³ R. Prabhu,⁷⁶ P. Pralavorio,⁸² A. Pranko,¹⁴
S. Prasad,²⁹ R. Pravahan,²⁴ S. Prell,⁶² K. Pretzl,¹⁶ L. Pribyl,²⁹ D. Price,⁵⁹ J. Price,⁷² L. E. Price,⁵ M. J. Price,²⁹
D. Prieur,¹²² M. Primavera,^{71a} K. Prokofiev,¹⁰⁷ F. Prokoshin,^{31b} S. Protopopescu,²⁴ J. Proudfoot,⁵ X. Prudent,⁴³
M. Przybycien,³⁷ H. Przysiezniak,⁴ S. Psoroulas,²⁰ E. Ptacek,¹¹³ E. Pueschel,⁸³ J. Purdham,⁸⁶ M. Purohit,^{24,aa}
P. Puzo,¹¹⁴ Y. Pylypchenko,⁶¹ J. Qian,⁸⁶ Z. Qian,⁸² Z. Qin,⁴¹ A. Quadt,⁵³ D. R. Quarrie,¹⁴ W. B. Quayle,¹⁷¹
F. Quinonez,^{31a} M. Raas,¹⁰³ V. Radescu,⁴¹ B. Radics,²⁰ P. Radloff,¹¹³ T. Rador,^{18a} F. Ragusa,^{88a,88b} G. Rahal,¹⁷⁶
A. M. Rahimi,¹⁰⁸ D. Rahm,²⁴ S. Rajagopalan,²⁴ M. Rammensee,⁴⁷ M. Rammes,¹⁴⁰ A. S. Randle-Conde,³⁹
K. Randrianarivony,²⁸ P. N. Ratoff,⁷⁰ F. Rauscher,⁹⁷ T. C. Rave,⁴⁷ M. Raymond,²⁹ A. L. Read,¹¹⁶
D. M. Rebutzi,^{118a,118b} A. Redelbach,¹⁷² G. Redlinger,²⁴ R. Reece,¹¹⁹ K. Reeves,⁴⁰ A. Reichold,¹⁰⁴
E. Reinherz-Aronis,¹⁵² A. Reinsch,¹¹³ I. Reisinger,⁴² C. Rembser,²⁹ Z. L. Ren,¹⁵⁰ A. Renaud,¹¹⁴ M. Rescigno,^{131a}
S. Resconi,^{88a} B. Resende,¹³⁵ P. Reznicke,⁹⁷ R. Rezvani,¹⁵⁷ A. Richards,⁷⁶ R. Richter,⁹⁸ E. Richter-Was,^{4,dd}
M. Ridel,⁷⁷ M. Rijpstra,¹⁰⁴ M. Rijssenbeek,¹⁴⁷ A. Rimoldi,^{118a,118b} L. Rinaldi,^{19a} R. R. Rios,³⁹ I. Riu,¹¹
G. Rivoltella,^{88a,88b} F. Rizatdinova,¹¹¹ E. Rizvi,⁷⁴ S. H. Robertson,^{84,k} A. Robichaud-Veronneau,¹¹⁷ D. Robinson,²⁷
J. E. M. Robinson,⁷⁶ A. Robson,⁵² J. G. Rocha de Lima,¹⁰⁵ C. Roda,^{121a,121b} D. Roda Dos Santos,²⁹ D. Rodriguez,¹⁶¹
A. Roe,⁵³ S. Roe,²⁹ O. Røhne,¹¹⁶ V. Rojo,¹ S. Rolli,¹⁶⁰ A. Romaniouk,⁹⁵ M. Romano,^{19a,19b} V. M. Romanov,⁶³
G. Romeo,²⁶ E. Romero Adam,¹⁶⁶ L. Roos,⁷⁷ E. Ros,¹⁶⁶ S. Rosati,^{131a} K. Rosbach,⁴⁸ A. Rose,¹⁴⁸ M. Rose,⁷⁵
G. A. Rosenbaum,¹⁵⁷ E. I. Rosenberg,⁶² P. L. Rosendahl,¹³ O. Rosenthal,¹⁴⁰ L. Rosselet,⁴⁸ V. Rossetti,¹¹
E. Rossi,^{131a,131b} L. P. Rossi,^{49a} M. Rotaru,^{25a} I. Roth,¹⁷⁰ J. Rothberg,¹³⁷ D. Rousseau,¹¹⁴ C. R. Royon,¹³⁵
A. Rozanov,⁸² Y. Rozen,¹⁵¹ X. Ruan,^{32a,ee} F. Rubbo,¹¹ I. Rubinskiy,⁴¹ B. Ruckert,⁹⁷ N. Ruckstuhl,¹⁰⁴ V. I. Rud,⁹⁶
C. Rudolph,⁴³ G. Rudolph,⁶⁰ F. Rühr,⁶ F. Ruggieri,^{133a,133b} A. Ruiz-Martinez,⁶² L. Rumyantsev,⁶³ K. Runge,⁴⁷
Z. Rurikova,⁴⁷ N. A. Rusakovich,⁶³ J. P. Rutherford,⁶ C. Ruwiedel,¹⁴ P. Ruzicka,¹²⁴ Y. F. Ryabov,¹²⁰
V. Ryadovikov,¹²⁷ P. Ryan,⁸⁷ M. Rybar,¹²⁵ G. Rybkin,¹¹⁴ N. C. Ryder,¹¹⁷ S. Rzaeva,¹⁰ A. F. Saavedra,¹⁴⁹ I. Sadeh,¹⁵²
H. F. W. Sadrozinski,¹³⁶ R. Sadykov,⁶³ F. Safai Tehrani,^{131a} H. Sakamoto,¹⁵⁴ G. Salamanna,⁷⁴ A. Salamon,^{132a}
M. Saleem,¹¹⁰ D. Salek,²⁹ D. Salihagic,⁹⁸ A. Salnikov,¹⁴² J. Salt,¹⁶⁶ B. M. Salvachua Ferrando,⁵ D. Salvatore,^{36a,36b}
F. Salvatore,¹⁴⁸ A. Salvucci,¹⁰³ A. Salzburger,²⁹ D. Sampsonidis,¹⁵³ B. H. Samset,¹¹⁶ A. Sanchez,^{101a,101b}
V. Sanchez Martinez,¹⁶⁶ H. Sandaker,¹³ H. G. Sander,⁸⁰ M. P. Sanders,⁹⁷ M. Sandhoff,¹⁷³ T. Sandoval,²⁷
C. Sandoval,¹⁶¹ R. Sandstroem,⁹⁸ S. Sandvoss,¹⁷³ D. P. C. Sankey,¹²⁸ A. Sansoni,⁴⁶ C. Santamarina Rios,⁸⁴
C. Santoni,³³ R. Santonico,^{132a,132b} H. Santos,^{123a} J. G. Saraiva,^{123a} T. Sarangi,¹⁷¹ E. Sarkisyan-Grinbaum,⁷
F. Sarri,^{121a,121b} G. Sartisoehn,¹⁷³ O. Sasaki,⁶⁴ N. Sasao,⁶⁶ I. Satsounkevitch,⁸⁹ G. Sauvage,⁴ E. Sauvan,⁴
J. B. Sauvan,¹¹⁴ P. Savard,^{157,e} V. Savinov,¹²² D. O. Savu,²⁹ L. Sawyer,^{24,m} D. H. Saxon,⁵² J. Saxon,¹¹⁹ L. P. SAYS,³³
C. Sbarra,^{19a} A. Sbrizzi,^{19a,19b} O. Scallan,⁹² D. A. Scannicchio,¹⁶² M. Scarcella,¹⁴⁹ J. Schaarschmidt,¹¹⁴ P. Schacht,⁹⁸
D. Schaefer,¹¹⁹ U. Schäfer,⁸⁰ S. Schaepe,²⁰ S. Schaezel,^{57b} A. C. Schaffer,¹¹⁴ D. Schaile,⁹⁷ R. D. Schamberger,¹⁴⁷
A. G. Schamov,¹⁰⁶ V. Scharf,^{57a} V. A. Schegelsky,¹²⁰ D. Scheirich,⁸⁶ M. Schernau,¹⁶² M. I. Scherzer,³⁴
C. Schiavi,^{49a,49b} J. Schieck,⁹⁷ M. Schioppa,^{36a,36b} S. Schlenker,²⁹ J. L. Schlereth,⁵ E. Schmidt,⁴⁷ K. Schmieden,²⁰
C. Schmitt,⁸⁰ S. Schmitt,^{57b} M. Schmitz,²⁰ A. Schöning,^{57b} M. Schott,²⁹ D. Schouten,^{158a} J. Schovancova,¹²⁴
M. Schram,⁸⁴ C. Schroeder,⁸⁰ N. Schroer,^{57c} G. Schuler,²⁹ M. J. Schultens,²⁰ J. Schultes,¹⁷³ H.-C. Schultz-Coulon,^{57a}
H. Schulz,¹⁵ J. W. Schumacher,²⁰ M. Schumacher,⁴⁷ B. A. Schumm,¹³⁶ Ph. Schune,¹³⁵ C. Schwanenberger,⁸¹
A. Schwartzman,¹⁴² Ph. Schwemling,⁷⁷ R. Schwienhorst,⁸⁷ R. Schwier,⁴³ J. Schwindling,¹³⁵ T. Schwindt,²⁰
M. Schwoerer,⁴ G. Sciolla,²² W. G. Scott,¹²⁸ J. Searcy,¹¹³ G. Sedov,⁴¹ E. Sedykh,¹²⁰ E. Segura,¹¹ S. C. Seidel,¹⁰²
A. Seiden,¹³⁶ F. Seifert,⁴³ J. M. Seixas,^{23a} G. Sekhniaidze,^{101a} S. J. Sekula,³⁹ K. E. Selbach,⁴⁵ D. M. Seliverstov,¹²⁰

B. Sellden,^{145a} G. Sellers,⁷² M. Seman,^{143b} N. Semprini-Cesari,^{19a,19b} C. Serfon,⁹⁷ L. Serin,¹¹⁴ L. Serkin,⁵³
R. Seuster,⁹⁸ H. Severini,¹¹⁰ M. E. Sevir,⁸⁵ A. Sfyrla,²⁹ E. Shabalina,⁵³ M. Shamim,¹¹³ L. Y. Shan,^{32a} J. T. Shank,²¹
Q. T. Shao,⁸⁵ M. Shapiro,¹⁴ P. B. Shatalov,⁹⁴ L. Shaver,⁶ K. Shaw,^{163a,163c} D. Sherman,¹⁷⁴ P. Sherwood,⁷⁶
A. Shibata,¹⁰⁷ H. Shichi,¹⁰⁰ S. Shimizu,²⁹ M. Shimojima,⁹⁹ T. Shin,⁵⁵ M. Shiyakova,⁶³ A. Shmeleva,⁹³
M. J. Shochet,³⁰ D. Short,¹¹⁷ S. Shrestha,⁶² E. Shulga,⁹⁵ M. A. Shupe,⁶ P. Sicho,¹²⁴ A. Sidoti,^{131a} F. Siegert,⁴⁷
Dj. Sijacki,^{12a} O. Silbert,¹⁷⁰ J. Silva,^{123a} Y. Silver,¹⁵² D. Silverstein,¹⁴² S. B. Silverstein,^{145a} V. Simak,¹²⁶
O. Simard,¹³⁵ Lj. Simic,^{12a} S. Simion,¹¹⁴ B. Simmons,⁷⁶ R. Simoniello,^{88a,88b} M. Simonyan,³⁵ P. Sinervo,¹⁵⁷
N. B. Sinev,¹¹³ V. Sipica,¹⁴⁰ G. Siragusa,¹⁷² A. Sircar,²⁴ A. N. Sisakyan,⁶³ S. Yu. Sivoklov,⁹⁶ J. Sjölin,^{145a,145b}
T. B. Sjursen,¹³ L. A. Skinnari,¹⁴ H. P. Skottowe,⁵⁶ K. Skovpen,¹⁰⁶ P. Skubic,¹¹⁰ N. Skvorodnev,²² M. Slater,¹⁷
T. Slavicek,¹²⁶ K. Sliwa,¹⁶⁰ J. Sloper,²⁹ V. Smakhtin,¹⁷⁰ B. H. Smart,⁴⁵ S. Yu. Smirnov,⁹⁵ Y. Smirnov,⁹⁵
L. N. Smirnova,⁹⁶ O. Smirnova,⁷⁸ B. C. Smith,⁵⁶ D. Smith,¹⁴² K. M. Smith,⁵² M. Smizanska,⁷⁰ K. Smolek,¹²⁶
A. A. Snesarev,⁹³ S. W. Snow,⁸¹ J. Snow,¹¹⁰ S. Snyder,²⁴ R. Sobie,^{168,k} J. Sodomka,¹²⁶ A. Soffer,¹⁵² C. A. Solans,¹⁶⁶
M. Solar,¹²⁶ J. Solc,¹²⁶ E. Soldatov,⁹⁵ U. Soldevila,¹⁶⁶ E. Solfaroli Camillocci,^{131a,131b} A. A. Solodkov,¹²⁷
O. V. Solovyanov,¹²⁷ N. Soni,² V. Sopko,¹²⁶ B. Sopko,¹²⁶ M. Sosebee,⁷ R. Soualah,^{163a,163c} A. Soukharev,¹⁰⁶
S. Spagnolo,^{71a,71b} F. Spanò,⁷⁵ R. Spighi,^{19a} G. Spigo,²⁹ F. Spila,^{131a,131b} R. Spiwoks,²⁹ M. Spousta,¹²⁵
T. Spreitzer,¹⁵⁷ B. Spurlock,⁷ R. D. St. Denis,⁵² J. Stahlman,¹¹⁹ R. Stamen,^{57a} E. Stanecka,³⁸ R. W. Stanek,⁵
C. Stanescu,^{133a} M. Stanescu-Bellu,⁴¹ S. Stapnes,¹¹⁶ E. A. Starchenko,¹²⁷ J. Stark,⁵⁴ P. Staroba,¹²⁴ P. Starovoitov,⁴¹
A. Staude,⁹⁷ P. Stavina,^{143a} G. Steele,⁵² P. Steinbach,⁴³ P. Steinberg,²⁴ I. Stekl,¹²⁶ B. Stelzer,¹⁴¹ H. J. Stelzer,⁸⁷
O. Stelzer-Chilton,^{158a} H. Stenzel,⁵¹ S. Stern,⁹⁸ K. Stevenson,⁷⁴ G. A. Stewart,²⁹ J. A. Stillings,²⁰ M. C. Stockton,⁸⁴
K. Stoerig,⁴⁷ G. Stoicea,^{25a} S. Stonjek,⁹⁸ P. Strachota,¹²⁵ A. R. Stradling,⁷ A. Straessner,⁴³ J. Strandberg,¹⁴⁶
S. Strandberg,^{145a,145b} A. Strandlie,¹¹⁶ M. Strang,¹⁰⁸ E. Strauss,¹⁴² M. Strauss,¹¹⁰ P. Strizenec,^{143b} R. Ströhmer,¹⁷²
D. M. Strom,¹¹³ J. A. Strong,^{75,a} R. Stroynowski,³⁹ J. Strube,¹²⁸ B. Stugu,¹³ I. Stumer,^{24,a} J. Stupak,¹⁴⁷ P. Sturm,¹⁷³
N. A. Styles,⁴¹ D. A. Soh,^{150,v} D. Su,¹⁴² H. S. Subramania,² A. Succurro,¹¹ Y. Sugaya,¹¹⁵ T. Sugimoto,¹⁰⁰ C. Suhr,¹⁰⁵
K. Suita,⁶⁵ M. Suk,¹²⁵ V. V. Sulin,⁹³ S. Sultansoy,^{3d} T. Sumida,⁶⁶ X. Sun,⁵⁴ J. E. Sundermann,⁴⁷ K. Suruliz,¹³⁸
S. Sushkov,¹¹ G. Susinno,^{36a,36b} M. R. Sutton,¹⁴⁸ Y. Suzuki,⁶⁴ Y. Suzuki,⁶⁵ M. Svatos,¹²⁴ Yu. M. Sviridov,¹²⁷
S. Swedish,¹⁶⁷ I. Sykora,^{143a} T. Sykora,¹²⁵ B. Szeless,²⁹ J. Sánchez,¹⁶⁶ D. Ta,¹⁰⁴ K. Tackmann,⁴¹ A. Taffard,¹⁶²
R. Tafirout,^{158a} N. Taiblum,¹⁵² Y. Takahashi,¹⁰⁰ H. Takai,²⁴ R. Takashima,⁶⁷ H. Takeda,⁶⁵ T. Takeshita,¹³⁹
Y. Takubo,⁶⁴ M. Talby,⁸² A. Talyshev,^{106,g} M. C. Tamssett,²⁴ J. Tanaka,¹⁵⁴ R. Tanaka,¹¹⁴ S. Tanaka,¹³⁰ S. Tanaka,⁶⁴
Y. Tanaka,⁹⁹ A. J. Tanasijczuk,¹⁴¹ K. Tani,⁶⁵ N. Tannoury,⁸² G. P. Tappern,²⁹ S. Tapprogge,⁸⁰ D. Tardif,¹⁵⁷
S. Tarem,¹⁵¹ F. Tarrade,²⁸ G. F. Tartarelli,^{88a} P. Tas,¹²⁵ M. Tasevsky,¹²⁴ E. Tassi,^{36a,36b} M. Tatarkhanov,¹⁴
Y. Tayalati,^{134d} C. Taylor,⁷⁶ F. E. Taylor,⁹¹ G. N. Taylor,⁸⁵ W. Taylor,^{158b} M. Teinturier,¹¹⁴
M. Teixeira Dias Castanheira,⁷⁴ P. Teixeira-Dias,⁷⁵ K. K. Temming,⁴⁷ H. Ten Kate,²⁹ P. K. Teng,¹⁵⁰ S. Terada,⁶⁴
K. Terashi,¹⁵⁴ J. Terron,⁷⁹ M. Testa,⁴⁶ R. J. Teuscher,^{157,k} J. Thadome,¹⁷³ J. Therhaag,²⁰ T. Theveneaux-Pelzer,⁷⁷
M. Thioye,¹⁷⁴ S. Thoma,⁴⁷ J. P. Thomas,¹⁷ E. N. Thompson,³⁴ P. D. Thompson,¹⁷ P. D. Thompson,¹⁵⁷
A. S. Thompson,⁵² L. A. Thomsen,³⁵ E. Thomson,¹¹⁹ M. Thomson,²⁷ R. P. Thun,⁸⁶ F. Tian,³⁴ M. J. Tibbetts,¹⁴
T. Tic,¹²⁴ V. O. Tikhomirov,⁹³ Y. A. Tikhonov,^{106,g} S. Timoshenko,⁹⁵ P. Tipton,¹⁷⁴ F. J. Tique Aires Viegas,²⁹
S. Tisserant,⁸² B. Toczek,³⁷ T. Todorov,⁴ S. Todorova-Nova,¹⁶⁰ B. Toggerson,¹⁶² J. Tojo,⁶⁸ S. Tokár,^{143a}
K. Tokunaga,⁶⁵ K. Tokushuku,⁶⁴ K. Tollefson,⁸⁷ M. Tomoto,¹⁰⁰ L. Tompkins,³⁰ K. Toms,¹⁰² G. Tong,^{32a}
A. Tonoyan,¹³ C. Topfel,¹⁶ N. D. Topilin,⁶³ I. Torchiani,²⁹ E. Torrence,¹¹³ H. Torres,⁷⁷ E. Torró Pastor,¹⁶⁶ J. Toth,^{82,bb}
F. Touchard,⁸² D. R. Tovey,¹³⁸ T. Trefzger,¹⁷² L. Tremblet,²⁹ A. Tricoli,²⁹ I. M. Trigger,^{158a} S. Trincaz-Duvoid,⁷⁷
M. F. Tripiana,⁶⁹ W. Trischuk,¹⁵⁷ A. Trivedi,^{24,aa} B. Trocmé,⁵⁴ C. Troncon,^{88a} M. Trotter-McDonald,¹⁴¹
M. Trzebinski,³⁸ A. Trzupek,³⁸ C. Tsarouchas,²⁹ J. C-L. Tseng,¹¹⁷ M. Tsiakiris,¹⁰⁴ P. V. Tsiarshka,⁸⁹ D. Tsiouou,^{4,ff}
G. Tsipolitis,⁹ V. Tsiskaridze,⁴⁷ E. G. Tskhadadze,^{50a} I. I. Tsukerman,⁹⁴ V. Tsulaia,¹⁴ J.-W. Tsung,²⁰ S. Tsuno,⁶⁴
D. Tsybychev,¹⁴⁷ A. Tua,¹³⁸ A. Tudorache,^{25a} V. Tudorache,^{25a} J. M. Tuggle,³⁰ M. Turala,³⁸ D. Turecek,¹²⁶
I. Turk Cakir,^{3e} E. Turlay,¹⁰⁴ R. Turra,^{88a,88b} P. M. Tuts,³⁴ A. Tykhonov,⁷³ M. Tylmad,^{145a,145b} M. Tyndel,¹²⁸
G. Tzanakos,⁸ K. Uchida,²⁰ I. Ueda,¹⁵⁴ R. Ueno,²⁸ M. Uglund,¹³ M. Uhlenbrock,²⁰ M. Uhrmacher,⁵³ F. Ukegawa,¹⁵⁹
G. Unal,²⁹ D. G. Underwood,⁵ A. Undrus,²⁴ G. Unel,¹⁶² Y. Unno,⁶⁴ D. Urbaniec,³⁴ G. Usai,⁷ M. Uslenghi,^{118a,118b}
L. Vacavant,⁸² V. Vacek,¹²⁶ B. Vachon,⁸⁴ S. Vahsen,¹⁴ J. Valenta,¹²⁴ P. Valente,^{131a} S. Valentineti,^{19a,19b} S. Valkar,¹²⁵
E. Valladolid Gallego,¹⁶⁶ S. Vallecorsa,¹⁵¹ J. A. Valls Ferrer,¹⁶⁶ H. van der Graaf,¹⁰⁴ E. van der Kraaij,¹⁰⁴
R. Van Der Leeuw,¹⁰⁴ E. van der Poel,¹⁰⁴ D. van der Ster,²⁹ N. van Eldik,⁸³ P. van Gemmeren,⁵ Z. van Kesteren,¹⁰⁴
I. van Vulpen,¹⁰⁴ M. Vanadia,⁹⁸ W. Vandelli,²⁹ G. Vandoni,²⁹ A. Vaniachine,⁵ P. Vankov,⁴¹ F. Vannucci,⁷⁷

F. Varela Rodriguez,²⁹ R. Vari,^{131a} T. Varol,⁸³ D. Varouchas,¹⁴ A. Vartapetian,⁷ K. E. Varvell,¹⁴⁹
V. I. Vassilikopoulos,⁵⁵ F. Vazeille,³³ T. Vazquez Schroeder,⁵³ G. Vegni,^{88a,88b} J. J. Veillet,¹¹⁴ C. Vellidis,⁸
F. Veloso,^{123a} R. Veness,²⁹ S. Veneziano,^{131a} A. Ventura,^{71a,71b} D. Ventura,¹³⁷ M. Venturi,⁴⁷ N. Venturi,¹⁵⁷
V. Vercesi,^{118a} M. Verducci,¹³⁷ W. Verkerke,¹⁰⁴ J. C. Vermeulen,¹⁰⁴ A. Vest,⁴³ M. C. Vetterli,^{141,e} I. Vichou,¹⁶⁴
T. Vickey,^{144b,gg} O. E. Vickey Boeriu,^{144b} G. H. A. Viehhauser,¹¹⁷ S. Viel,¹⁶⁷ M. Villa,^{19a,19b} M. Villaplana Perez,¹⁶⁶
E. Vilucchi,⁴⁶ M. G. Vincker,²⁸ E. Vinek,²⁹ V. B. Vinogradov,⁶³ M. Virchaux,^{135,a} J. Virzi,¹⁴ O. Vitells,¹⁷⁰ M. Viti,⁴¹
I. Vivarelli,⁴⁷ F. Vives Vaque,² S. Vlachos,⁹ D. Vladoiu,⁹⁷ M. Vlasak,¹²⁶ N. Vlasov,²⁰ A. Vogel,²⁰ P. Vokac,¹²⁶
G. Volpi,⁴⁶ M. Volpi,⁸⁵ G. Volpini,^{88a} H. von der Schmitt,⁹⁸ J. von Loeben,⁹⁸ H. von Radziewski,⁴⁷ E. von Toerne,²⁰
V. Vorobel,¹²⁵ A. P. Vorobiev,¹²⁷ V. Vorwerk,¹¹ M. Vos,¹⁶⁶ R. Voss,²⁹ T. T. Voss,¹⁷³ J. H. Vosseveld,⁷² N. Vranjes,¹³⁵
M. Vranjes Milosavljevic,¹⁰⁴ V. Vrba,¹²⁴ M. Vreeswijk,¹⁰⁴ T. Vu Anh,⁴⁷ R. Vuillermet,²⁹ I. Vukotic,¹¹⁴
W. Wagner,¹⁷³ P. Wagner,¹¹⁹ H. Wahlen,¹⁷³ J. Wakabayashi,¹⁰⁰ S. Walch,⁸⁶ J. Walder,⁷⁰ R. Walker,⁹⁷
W. Walkowiak,¹⁴⁰ R. Wall,¹⁷⁴ P. Waller,⁷² C. Wang,⁴⁴ H. Wang,¹⁷¹ H. Wang,^{32b,hh} J. Wang,¹⁵⁰ J. Wang,⁵⁴
J. C. Wang,¹³⁷ R. Wang,¹⁰² S. M. Wang,¹⁵⁰ T. Wang,²⁰ A. Warburton,⁸⁴ C. P. Ward,²⁷ M. Warsinsky,⁴⁷
A. Washbrook,⁴⁵ C. Wasicki,⁴¹ P. M. Watkins,¹⁷ A. T. Watson,¹⁷ I. J. Watson,¹⁴⁹ M. F. Watson,¹⁷ G. Watts,¹³⁷
S. Watts,⁸¹ A. T. Waugh,¹⁴⁹ B. M. Waugh,⁷⁶ M. Weber,¹²⁸ M. S. Weber,¹⁶ P. Weber,⁵³ A. R. Weidberg,¹¹⁷ P. Weigell,⁹⁸
J. Weingarten,⁵³ C. Weiser,⁴⁷ H. Wellenstein,²² P. S. Wells,²⁹ T. Wenaus,²⁴ D. Wendland,¹⁵ S. Wendler,¹²²
Z. Weng,^{150,v} T. Wengler,²⁹ S. Wenig,²⁹ N. Wermes,²⁰ M. Werner,⁴⁷ P. Werner,²⁹ M. Werth,¹⁶² M. Wessels,^{57a}
J. Wetter,¹⁶⁰ C. Weydert,⁵⁴ K. Whalen,²⁸ S. J. Wheeler-Ellis,¹⁶² S. P. Whitaker,²¹ A. White,⁷ M. J. White,⁸⁵
S. White,^{121a,121b} S. R. Whitehead,¹¹⁷ D. Whiteson,¹⁶² D. Whittington,⁵⁹ F. Wicek,¹¹⁴ D. Wicke,¹⁷³ F. J. Wickens,¹²⁸
W. Wiedenmann,¹⁷¹ M. Wielers,¹²⁸ P. Wienemann,²⁰ C. Wiglesworth,⁷⁴ L. A. M. Wiik-Fuchs,⁴⁷ P. A. Wijeratne,⁷⁶
A. Wildauer,¹⁶⁶ M. A. Wildt,^{41,r} I. Wilhelm,¹²⁵ H. G. Wilkens,²⁹ J. Z. Will,⁹⁷ E. Williams,³⁴ H. H. Williams,¹¹⁹
W. Willis,³⁴ S. Willocq,⁸³ J. A. Wilson,¹⁷ M. G. Wilson,¹⁴² A. Wilson,⁸⁶ I. Wingerter-Seez,⁴ S. Winkelmann,⁴⁷
F. Winklmeier,²⁹ M. Wittgen,¹⁴² M. W. Wolter,³⁸ H. Wolters,^{123a,i} W. C. Wong,⁴⁰ G. Wooden,⁸⁶ B. K. Wosiek,³⁸
J. Wotschack,²⁹ M. J. Woudstra,⁸³ K. W. Wozniak,³⁸ K. Wraight,⁵² C. Wright,⁵² M. Wright,⁵² B. Wrona,⁷²
S. L. Wu,¹⁷¹ X. Wu,⁴⁸ Y. Wu,^{32b,ii} E. Wulf,³⁴ R. Wunstorf,⁴² B. M. Wynne,⁴⁵ S. Xella,³⁵ M. Xiao,¹³⁵ S. Xie,⁴⁷
Y. Xie,^{32a} C. Xu,^{32b,x} D. Xu,¹³⁸ G. Xu,^{32a} B. Yabsley,¹⁴⁹ S. Yacoub,^{144b} M. Yamada,⁶⁴ H. Yamaguchi,¹⁵⁴
A. Yamamoto,⁶⁴ K. Yamamoto,⁶² S. Yamamoto,¹⁵⁴ T. Yamamura,¹⁵⁴ T. Yamanaka,¹⁵⁴ J. Yamaoka,⁴⁴ T. Yamazaki,¹⁵⁴
Y. Yamazaki,⁶⁵ Z. Yan,²¹ H. Yang,⁸⁶ U. K. Yang,⁸¹ Y. Yang,⁵⁹ Y. Yang,^{32a} Z. Yang,^{145a,145b} S. Yanush,⁹⁰ Y. Yao,¹⁴
Y. Yasu,⁶⁴ G. V. Ybeles Smit,¹²⁹ J. Ye,³⁹ S. Ye,²⁴ M. Yilmaz,^{3c} R. Yoosoofmiya,¹²² K. Yorita,¹⁶⁹ R. Yoshida,⁵
C. Young,¹⁴² C. J. Young,¹¹⁷ S. Youssef,²¹ D. Yu,²⁴ J. Yu,⁷ J. Yu,¹¹¹ L. Yuan,⁶⁵ A. Yurkewicz,¹⁰⁵ B. Zabinski,³⁸
V. G. Zaets,¹²⁷ R. Zaidan,⁶¹ A. M. Zaitsev,¹²⁷ Z. Zajacova,²⁹ L. Zanello,^{131a,131b} A. Zaytsev,¹⁰⁶ C. Zeitnitz,¹⁷³
M. Zeller,¹⁷⁴ M. Zeman,¹²⁴ A. Zemla,³⁸ C. Zender,²⁰ O. Zenin,¹²⁷ T. Ženiš,^{143a} Z. Zinonos,^{121a,121b} S. Zenz,¹⁴
D. Zerwas,¹¹⁴ G. Zevi della Porta,⁵⁶ Z. Zhan,^{32d} D. Zhang,^{32b,hh} H. Zhang,⁸⁷ J. Zhang,⁵ X. Zhang,^{32d} Z. Zhang,¹¹⁴
L. Zhao,¹⁰⁷ T. Zhao,¹³⁷ Z. Zhao,^{32b} A. Zhemchugov,⁶³ S. Zheng,^{32a} J. Zhong,¹¹⁷ B. Zhou,⁸⁶ N. Zhou,¹⁶² Y. Zhou,¹⁵⁰
C. G. Zhu,^{32d} H. Zhu,⁴¹ J. Zhu,⁸⁶ Y. Zhu,^{32b} X. Zhuang,⁹⁷ V. Zhuravlov,⁹⁸ D. Zieminska,⁵⁹ R. Zimmermann,²⁰
S. Zimmermann,²⁰ S. Zimmermann,⁴⁷ M. Ziolkowski,¹⁴⁰ R. Zitoun,⁴ L. Živković,³⁴ V. V. Zmouchko,^{127,a}
G. Zobernig,¹⁷¹ A. Zoccoli,^{19a,19b} M. zur Nedden,¹⁵ V. Zutshi,¹⁰⁵ and L. Zwalinski²⁹

(ATLAS Collaboration)

¹University at Albany, Albany New York, USA²Department of Physics, University of Alberta, Edmonton Alberta, Canada^{3a}Department of Physics, Ankara University, Ankara, Turkey^{3b}Department of Physics, Dumlupinar University, Kutahya, Turkey^{3c}Department of Physics, Gazi University, Ankara, Turkey^{3d}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey^{3e}Turkish Atomic Energy Authority, Ankara, Turkey⁴LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France⁵High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA⁶Department of Physics, University of Arizona, Tucson Arizona, USA⁷Department of Physics, The University of Texas at Arlington, Arlington Texas, USA⁸Physics Department, University of Athens, Athens, Greece⁹Physics Department, National Technical University of Athens, Zografou, Greece

- ¹⁰*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- ¹¹*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
- ^{12a}*Institute of Physics, University of Belgrade, Belgrade, Serbia*
- ^{12b}*Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
- ¹³*Department for Physics and Technology, University of Bergen, Bergen, Norway*
- ¹⁴*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA*
- ¹⁵*Department of Physics, Humboldt University, Berlin, Germany*
- ¹⁶*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- ¹⁷*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ^{18a}*Department of Physics, Bogazici University, Istanbul, Turkey*
- ^{18b}*Division of Physics, Dogus University, Istanbul, Turkey*
- ^{18c}*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
- ^{18d}*Department of Physics, Istanbul Technical University, Istanbul, Turkey*
- ^{19a}*INFN Sezione di Bologna, Italy*
- ^{19b}*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
- ²⁰*Physikalisches Institut, University of Bonn, Bonn, Germany*
- ²¹*Department of Physics, Boston University, Boston Massachusetts, USA*
- ²²*Department of Physics, Brandeis University, Waltham Massachusetts, USA*
- ^{23a}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- ^{23b}*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
- ^{23c}*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
- ^{23d}*Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil*
- ²⁴*Physics Department, Brookhaven National Laboratory, Upton New York, USA*
- ^{25a}*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- ^{25b}*University Politehnica Bucharest, Bucharest, Romania*
- ^{25c}*West University in Timisoara, Timisoara, Romania*
- ²⁶*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ²⁷*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ²⁸*Department of Physics, Carleton University, Ottawa Ontario, Canada*
- ²⁹*CERN, Geneva, Switzerland*
- ³⁰*Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA*
- ^{31a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{31b}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ^{32a}*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
- ^{32b}*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
- ^{32c}*Department of Physics, Nanjing University, Jiangsu, China*
- ^{32d}*School of Physics, Shandong University, Shandong, China*
- ³³*Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France*
- ³⁴*Nevis Laboratory, Columbia University, Irvington New York, USA*
- ³⁵*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
- ^{36a}*INFN Gruppo Collegato di Cosenza, Italy*
- ^{36b}*Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy*
- ³⁷*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- ³⁸*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
- ³⁹*Physics Department, Southern Methodist University, Dallas Texas, USA*
- ⁴⁰*Physics Department, University of Texas at Dallas, Richardson Texas, USA*
- ⁴¹*DESY, Hamburg and Zeuthen, Germany*
- ⁴²*Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴³*Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
- ⁴⁴*Department of Physics, Duke University, Durham North Carolina, USA*
- ⁴⁵*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁴⁶*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁴⁷*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany*
- ⁴⁸*Section de Physique, Université de Genève, Geneva, Switzerland*
- ^{49a}*INFN Sezione di Genova, Italy*
- ^{49b}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{50a}*E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi, Georgia*
- ^{50b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ⁵¹*II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*

- ⁵²SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵³II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁴Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁵Department of Physics, Hampton University, Hampton Virginia, USA
- ⁵⁶Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
- ^{57a}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{57b}Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{57c}ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁸Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁵⁹Department of Physics, Indiana University, Bloomington Indiana, USA
- ⁶⁰Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶¹University of Iowa, Iowa City Iowa, USA
- ⁶²Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA
- ⁶³Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁴KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁵Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁶Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁷Kyoto University of Education, Kyoto, Japan
- ⁶⁸Department of Physics, Kyushu University, Fukuoka, Japan
- ⁶⁹Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁰Physics Department, Lancaster University, Lancaster, United Kingdom
- ^{71a}INFN Sezione di Lecce, Italy
- ^{71b}Dipartimento di Fisica, Università del Salento, Lecce, Italy
- ⁷²Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷³Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁴School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁵Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁶Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁷Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁸Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁷⁹Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁰Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸¹School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸²CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸³Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
- ⁸⁴Department of Physics, McGill University, Montreal Quebec, Canada
- ⁸⁵School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁶Department of Physics, The University of Michigan, Ann Arbor Michigan, United States of America, USA
- ⁸⁷Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, United States of America, USA
- ^{88a}INFN Sezione di Milano, Italy
- ^{88b}Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁸⁹B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹⁰National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹¹Department of Physics, Massachusetts Institute of Technology, Cambridge Massachusetts, USA
- ⁹²Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹³P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁴Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁵Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁶Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁷Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁸Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ⁹⁹Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁰Graduate School of Science, Nagoya University, Nagoya, Japan
- ^{101a}INFN Sezione di Napoli, Italy
- ^{101b}Dipartimento di Scienze Fische, Università di Napoli, Napoli, Italy
- ¹⁰²Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA
- ¹⁰³Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁴Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁵Department of Physics, Northern Illinois University, DeKalb Illinois, USA

- ¹⁰⁶*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ¹⁰⁷*Department of Physics, New York University, New York New York, USA*
- ¹⁰⁸*The Ohio State University, Columbus Ohio, USA*
- ¹⁰⁹*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹⁰*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA*
- ¹¹¹*Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA*
- ¹¹²*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹³*Center for High Energy Physics, University of Oregon, Eugene Oregon, USA*
- ¹¹⁴*LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France*
- ¹¹⁵*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹¹⁶*Department of Physics, University of Oslo, Oslo, Norway*
- ¹¹⁷*Department of Physics, Oxford University, Oxford, United Kingdom*
- ^{118a}*INFN Sezione di Pavia, Italy*
- ^{118b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ¹¹⁹*Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA*
- ¹²⁰*Petersburg Nuclear Physics Institute, Gatchina, Russia*
- ^{121a}*INFN Sezione di Pisa, Italy*
- ^{121b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ¹²²*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA*
- ^{123a}*Laboratorio de Instrumentacao e Fisica Experimental de Particulas—LIP, Lisboa, Portugal*
- ^{123b}*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
- ¹²⁴*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
- ¹²⁵*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
- ¹²⁶*Czech Technical University in Prague, Praha, Czech Republic*
- ¹²⁷*State Research Center Institute for High Energy Physics, Protvino, Russia*
- ¹²⁸*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹²⁹*Physics Department, University of Regina, Regina Saskatchewan, Canada*
- ¹³⁰*Ritsumeikan University, Kusatsu, Shiga, Japan*
- ^{131a}*INFN Sezione di Roma I, Italy*
- ^{131b}*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
- ^{132a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{132b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{133a}*INFN Sezione di Roma Tre, Italy*
- ^{133b}*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
- ^{134a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- ^{134b}*Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
- ^{134c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{134d}*Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda, Morocco*
- ^{134e}*Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco*
- ¹³⁵*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France*
- ¹³⁶*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz California, USA*
- ¹³⁷*Department of Physics, University of Washington, Seattle Washington, USA*
- ¹³⁸*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹³⁹*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁰*Fachbereich Physik, Universität Siegen, Siegen, Germany*
- ¹⁴¹*Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada*
- ¹⁴²*SLAC National Accelerator Laboratory, Stanford California, USA*
- ^{143a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{143b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ^{144a}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- ^{144b}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{145a}*Department of Physics, Stockholm University, Sweden*
- ^{145b}*The Oskar Klein Centre, Stockholm, Sweden*
- ¹⁴⁶*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁷*Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA*
- ¹⁴⁸*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁴⁹*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵⁰*Institute of Physics, Academia Sinica, Taipei, Taiwan*

- ¹⁵¹*Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel*
- ¹⁵²*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵³*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁴*International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
- ¹⁵⁵*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁶*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
- ¹⁵⁷*Department of Physics, University of Toronto, Toronto Ontario, Canada*
- ^{158a}*TRIUMF, Vancouver BC, Canada*
- ^{158b}*Department of Physics and Astronomy, York University, Toronto Ontario, Canada*
- ¹⁵⁹*Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan*
- ¹⁶⁰*Science and Technology Center, Tufts University, Medford Massachusetts, USA*
- ¹⁶¹*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
- ¹⁶²*Department of Physics and Astronomy, University of California Irvine, Irvine California, USA*
- ^{163a}*INFN Gruppo Collegato di Udine, Italy*
- ^{163b}*ICTP, Trieste, Italy*
- ^{163c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
- ¹⁶⁴*Department of Physics, University of Illinois, Urbana Illinois, USA*
- ¹⁶⁵*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁶*Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
- ¹⁶⁷*Department of Physics, University of British Columbia, Vancouver British Columbia, Canada*
- ¹⁶⁸*Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada*
- ¹⁶⁹*Waseda University, Tokyo, Japan*
- ¹⁷⁰*Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷¹*Department of Physics, University of Wisconsin, Madison Wisconsin, USA*
- ¹⁷²*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
- ¹⁷³*Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷⁴*Department of Physics, Yale University, New Haven Connecticut, USA*
- ¹⁷⁵*Yerevan Physics Institute, Yerevan, Armenia*
- ¹⁷⁶*Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France*

^aDeceased.

^bAlso at Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal.

^cAlso at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal

^dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

^eAlso at TRIUMF, Vancouver BC, Canada.

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

^gAlso at Novosibirsk State University, Novosibirsk, Russia.

^hAlso at Fermilab, Batavia IL, USA.

ⁱAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.

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

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

^lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.

^mAlso at LA Tech University, Ruston LA, USA.

ⁿAlso at Department of Physics and Astronomy, University College London, London, United Kingdom.

^oAlso at Group of Particle Physics, University of Montreal, Montreal QC, Canada.

^pAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.

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

^rAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

^sAlso at Manhattan College, New York NY, USA.

^tAlso at School of Physics, Shandong University, Shandong, China.

^uAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^vAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

^wAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^xAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique), Gif-sur-Yvette, France.

^yAlso at Section de Physique, Université de Genève, Geneva, Switzerland.

^zAlso at Departamento de Física, Universidade de Minho, Braga, Portugal.

^{aa}Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

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

^{cc}Also at California Institute of Technology, Pasadena CA, United States of America, USA.

^{dd}Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

^{ee}Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.

^{ff}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

^{gg}Also at Department of Physics, Oxford University, Oxford, United Kingdom.

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

ⁱⁱAlso at Department of Physics, The University of Michigan, Ann Arbor MI, USA.