



Search for supersymmetry in events with three leptons and missing transverse momentum in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector

G. Aad, S. Albrand, Q. Buat, B. Clement, J. Collot, S. Crépé-Renaudin, B. Dechenaux, T. Delemontex, P.A. Delsart, M.H. Genest, et al.

► To cite this version:

G. Aad, S. Albrand, Q. Buat, B. Clement, J. Collot, et al.. Search for supersymmetry in events with three leptons and missing transverse momentum in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector. Physical Review Letters, 2012, 108, pp.261804. 10.1103/PhysRevLett.108.261804 . in2p3-00691346

HAL Id: in2p3-00691346

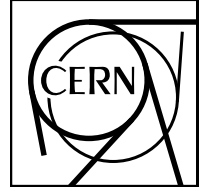
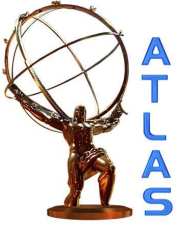
<https://hal.in2p3.fr/in2p3-00691346>

Submitted on 12 Sep 2023

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EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



CERN-PH-EP-2012-098

Submitted to: Physical Review Letters

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The ATLAS Collaboration

Abstract

A search for the weak production of charginos and neutralinos decaying to a final state with three leptons (electrons or muons) and missing transverse momentum is presented. The analysis uses 2.06 fb^{-1} of $\sqrt{s} = 7$ TeV proton-proton collision data delivered by the Large Hadron Collider and recorded with the ATLAS detector. Observations are consistent with standard model expectations in two signal regions that are either depleted or enriched in Z -boson decays. Upper limits at 95% confidence level are set in R-parity conserving phenomenological minimal supersymmetric and simplified models. For the simplified models, degenerate lightest chargino and next-to-lightest neutralino masses up to 300 GeV are excluded for mass differences from the lightest neutralino up to 300 GeV.

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PACS numbers: 14.80.Ly, 14.80.Nb, 12.60.Jv

Supersymmetric (SUSY) extensions [1–9] of the standard model (SM) naturally address the gauge hierarchy problem [10–12] by postulating the existence of SUSY particles, or “sparticles”, with spin differing by one-half unit with respect to that of their SM partner. If R-parity [13–17] is conserved, sparticles can only be pair-produced and will eventually decay into SM particles and the lightest SUSY particle (LSP) which is stable. Charginos ($\tilde{\chi}_i^\pm$, $i = 1, 2$) and neutralinos ($\tilde{\chi}_j^0$, $j = 1, 2, 3, 4$) are the mass eigenstates formed from the linear superposition of the SUSY partners of the Higgs and electroweak gauge bosons. These are the higgsinos, and the winos, zino, and bino, collectively known as gauginos. Naturalness requires $\tilde{\chi}_i^\pm$ and $\tilde{\chi}_j^0$ (and third generation sparticles) to have masses in the hundreds of GeV range [18]. In scenarios where first and second generation sfermion masses are larger than few TeVs, the direct production of weak gauginos may be the dominant SUSY process at the Large Hadron Collider (LHC).

Leptonic decays of charginos include sneutrinos ($\tilde{\nu}\ell^\pm$), sleptons ($\tilde{\ell}^\pm\nu$) or W bosons ($W^\pm(*)\tilde{\chi}_1^0$), while those of unstable neutralinos include sleptons ($\ell\tilde{\ell}^\pm$) or Z bosons ($Z(*)\tilde{\chi}_1^0$). When both gauginos decay leptonically, a distinctive signature with three leptons and significant missing transverse momentum can be observed, the latter originating from the two undetected LSPs and the neutrinos.

This letter presents the first search with the ATLAS detector for the weak production of charginos and neutralinos decaying to a final state with three leptons (electrons or muons) and missing transverse momentum. The analysis is based on 2.06 fb^{-1} of proton-proton collision data delivered by the LHC at a center-of-mass energy $\sqrt{s} = 7$ TeV between March and August 2011. The search significantly extends the current mass limits on charginos and neutralinos [19–22] and yields sensitivity in the mass region preferred by naturalness.

In this analysis, observations are interpreted in the phenomenological minimal supersymmetric SM (pMSSM)

[23]) and in simplified models [24]. In the pMSSM the masses of the $\tilde{\chi}_i^\pm$ and $\tilde{\chi}_j^0$ depend on the gaugino masses M_1 and M_2 , the Higgs mass parameter $|\mu|$, and $\tan\beta$, the ratio of the expectation values of the two Higgs doublets. The masses of the gluinos, squarks and left-handed sleptons are chosen to be larger than 1 TeV, while the right-handed sleptons (including third-generation ones) are assumed to be degenerate with $m_{\tilde{\ell}_R} = (m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0})/2$. In these scenarios, decays to sleptons are favored. In the simplified models, the masses of the relevant particles (mass degenerate wino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$; bino-like $\tilde{\chi}_1^0$; $\tilde{\nu}$; $\tilde{\ell}_L$) are the only free parameters of the theory. The $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are produced via the s -channel exchange of a virtual gauge boson and decay via left-handed sleptons, including staus, and sneutrinos of mass $m_{\tilde{\nu}} = m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm})/2$ with a branching ratio of 50% each.

ATLAS [25] is a multipurpose particle detector with forward-backward symmetric cylindrical geometry. It includes an inner tracker (ID) immersed in a 2 T magnetic field providing precision tracking of charged particles for pseudorapidities $|\eta| < 2.5$ [26]. Calorimeter systems with either liquid argon or scintillating tiles as the active media provide energy measurements over the range $|\eta| < 4.9$. The muon detectors outside the calorimeters are contained in a toroidal magnetic field produced by air-core superconducting magnets with field integrals varying from 1 to 8 T·m. They provide trigger and high-precision tracking capabilities for $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively. Electrons must satisfy tight identification criteria and fulfil $|\eta| < 2.47$ and $E_T > 10$ GeV, where $|\eta|$ and E_T are determined from the calibrated clustered energy deposits in the electromagnetic calorimeter matched to an ID track. Muons are reconstructed by combining tracks in the ID and tracks in the muon spectrometer [27]. Reconstructed muons are considered as candidates if they have transverse momentum $p_T > 10$ GeV, $|\eta| < 2.4$, and transverse impact parameter with respect to the primary vertex $|d_0| < 0.2$ mm. “Tagged” leptons are electrons and

muons, well separated from each other and from candidate jets. “Signal” leptons are tagged leptons for which the scalar sum of the tracks’ transverse momenta within $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.2$ around the lepton candidate is less than 10% of the E_T for electrons, and less than 1.8 GeV for muons. Jets are reconstructed from clustered energy deposits calibrated at the electromagnetic scale using the anti- k_t algorithm [28] with a radius parameter of 0.4. The jet energy is corrected to account for the non-compensating nature of the calorimeter using correction factors obtained from Monte Carlo (MC) simulation and parameterized as a function of the jet E_T and η [29]. Jets considered in this analysis have $E_T > 20$ GeV and $|\eta| < 2.8$. Jets are identified as containing a b -quark, and thus called “ b -tagged”, using a multivariate technique based on quantities such as the impact parameter of the tracks associated to the secondary vertex, tracks in jet and other jet shape information, consistent with the expected topology of b -quark decays. The b -tagging algorithm [30] correctly identifies b -quark jets in top decays with an efficiency of 60% and misidentifies jets containing light flavor quarks and gluons with a rate of $< 1\%$, for jets with $|\eta| < 2.5$ and jet $E_T > 20$ GeV. The missing transverse momentum, E_T^{miss} , is the magnitude of the vector sum of the transverse momentum or transverse energy of all $p_T > 10$ GeV muons, $E_T > 10$ GeV electrons, $E_T > 20$ GeV jets, and calibrated calorimeter clusters with $|\eta| < 4.5$ not associated to these objects [31].

Several MC generators are used to simulate SM processes and SUSY signals relevant for this analysis. HERWIG [32] is used to simulate diboson processes ($WW^{(*)}$, $ZZ^{(*)}$, $WZ^{(*)}$), while MadGraph [33] is used for the $t\bar{t}W^{(*)}/Z^{(*)}$ processes. MC@NLO [34] is chosen for the simulation of single and pair production of top quarks, while ALPGEN [35] is used to simulate $W^{(*)}/Z^{(*)} + \text{jets}$. Expected diboson yields are normalized using next-to-leading order (NLO) QCD predictions obtained with MCFM [36, 37]. The top-quark pair-production contribution is normalized to approximate next-to-next-to-leading (NNLO) order calculations [38] and the $t\bar{t}W^{(*)}/Z^{(*)}$ contributions are normalized to NLO results [39]. The QCD NNLO FEWZ [40, 41] and MCFM cross-sections are used for NNLO normalization of the Z +light-flavor jets and Z +heavy-flavor jets processes, respectively. The choice of the parton distribution functions (PDFs) depends on the generator. MRST 2007 LO* [42] sets are used for HERWIG, CTEQ6L1 [43] with MadGraph and ALPGEN, and CTEQ6.6 [44] with MC@NLO. The pMSSM and simplified model samples are produced with HERWIG and HERWIG++ [45], respectively, and the yields are normalized to the NLO cross-sections obtained from PROSPINO [46] using the PDF set CTEQ6.6 with the renormalization/factorization scales set to the average of the relevant gaugino masses. Fragmentation and hadronization for the ALPGEN and MC@NLO (MadGraph)

samples are performed with HERWIG (PYTHIA [47]). For all MC samples, the propagation of particles through the ATLAS detector is modeled using GEANT4 [48, 49]. The effect of multiple proton-proton collisions from the same or different bunch crossings is incorporated into the simulation by overlaying additional minimum bias events onto hard scatter events using JIMMY [50]. Simulated events are weighted to match the distribution of the mean number of interactions per bunch crossing observed in data.

The data sample was collected with a single-muon trigger ($p_T > 18$ GeV) or a single-electron trigger ($E_T > 20$ or 22 GeV, depending on the instantaneous luminosity). At least one signal lepton is required to have triggered the event and have p_T (E_T) above 20 GeV (25 GeV) for muons (electrons). Events recorded during normal running conditions are analyzed if at least one of the reconstructed primary vertices has more than four tracks associated to it. Events containing jets with $|\eta| < 4.9$ and failing the quality criteria described in Ref. [29] are rejected to suppress both collisional and non-collisional background. Selected events must contain exactly three signal leptons. As leptonic decays of $\tilde{\chi}_j^0$ yield same-flavor opposite-sign (SFOS) lepton pairs, the presence of at least one such pair is required. The invariant mass of any SFOS lepton pair must be above 20 GeV to suppress background from low mass resonances and the missing transverse momentum must satisfy $E_T^{\text{miss}} > 50$ GeV.

Two signal regions are then defined: a “ Z -depleted” region (SR1), with no SFOS pairs having invariant mass within 10 GeV of the nominal Z -boson mass; and a “ Z -enriched” one (SR2), where at least one SFOS pair has an invariant mass within 10 GeV of the Z -boson mass. Events in SR1 are further required to contain no b -tagged jets to suppress contributions from b -jet-rich backgrounds, where a fake lepton could originate from a heavy-flavor decay. The SR1 and SR2 selections target SUSY events with intermediate slepton or on-mass-shell Z -boson decays, respectively.

Several SM processes contribute to the background in SR1 and SR2. A background process is considered “irreducible” if it leads to events with three real and isolated leptons, referred to as “real” leptons below. These include diboson ($WZ^{(*)}$ and $ZZ^{(*)}$) and $t\bar{t}W/Z^{(*)}$ production, where the gauge boson may be produced off-mass-shell. Their contribution is determined using the corresponding MC samples, for which lepton and jet selection efficiencies are corrected to account for differences with respect to data. A “reducible” process has at least one “fake” object, that is either a lepton from a semileptonic decay of a heavy-flavor quark or an electron from an isolated photon conversion. The contribution from misidentified light-flavor quarks is negligible. The reducible background includes single- and pair-production of top-quark and $WW^{(*)}$ or $W^{(*)}/Z^{(*)}$ produced in association with jets or photons. The dominant component is the production of top quarks, with a contribution of 1%

or less from $Z^{(*)} + \text{jets}$ production. The reducible background is estimated using a “matrix method” similar to that described in Ref. [51].

In this implementation of the matrix method, the signal lepton with the highest p_T or E_T is taken to be real, which is a valid assumption in 99% of the cases, based on MC studies. The number of observed events with one or two fakes is then extracted from a system of linear equations linking the number of events with two additional signal or tagged candidates to the number of events with two additional candidates that are either real or fake. The coefficients of the linear equations are functions of the real lepton identification efficiencies and of the fake object misidentification probabilities. The identification efficiency is measured in data using lepton candidates from $Z \rightarrow \ell\ell$ decays.

Misidentification probabilities for each fake type (heavy flavor, conversion) and for each reducible background process are obtained using simulated events with one signal and two tagged leptons. These misidentification probabilities are then corrected using the ratio (fake scale factor) of the misidentification probability in data and that in MC simulation obtained in dedicated control samples. For heavy flavor fakes, the correction factor is measured in $b\bar{b}$ events, while for conversion fakes it is determined in a sample of photons radiated from a muon in $Z \rightarrow \mu\mu$ decays. A weighted average misidentification probability is then calculated by weighting the corrected type- and process-dependent misidentification probabilities according to the process cross-section.

An additional source of background is due to events with two signal leptons and one virtual photon converting into two muons, one with p_T above 10 GeV. The contribution from events in which both muons from the virtual photons have p_T above 10 GeV is negligible due to the requirement on the dilepton pair invariant mass. For events with only one muon above threshold, an upper limit of 0.5 ± 0.5 in SR1 and of 0.7 ± 0.7 in SR2 is obtained from data as follows. The number of observed events with exactly two signal leptons and $E_T^{\text{miss}} > 50$ GeV is rescaled by the probability that any of the signal leptons could have radiated the converted photon. This probability is measured in events with $E_T^{\text{miss}} < 50$ GeV as the ratio of number of events with three signal muons with trilepton invariant mass within 10 GeV of the nominal Z boson mass to the number of events with two signal muons having the dilepton mass in the same mass window.

The matrix method has been tested using MC events and shown to be accurate within 2%. The background predictions have been validated in a region dominated by $Z^{(*)} + \text{jets}$ production (VR1: three signal leptons, $30 < E_T^{\text{miss}} < 50$ GeV) and in one dominated by top pair-production (VR2: three signal leptons, SFOS lepton pairs vetoed, $E_T^{\text{miss}} > 50$ GeV). The data and predictions are in agreement within the quoted statistical and systematic uncertainties as shown in Table I.

Several sources of systematic uncertainty are considered in the signal regions. The systematic uncertainties affecting the MC based estimates (irreducible background yield, misidentification probabilities, signal yield) include the theoretical cross section uncertainty due to scale and PDFs, the acceptance uncertainty due to PDFs, jet energy scale, jet energy resolution, lepton energy scale, lepton energy resolution, lepton efficiency, b -tagging efficiency, event quality selection, and the uncertainty on the luminosity. In SR1, the total uncertainty on the irreducible background is 17%. This includes the uncertainty on the acceptance due to PDFs (14%), that on the theoretical cross section due to scale and PDFs (7%), and that from the limited number of simulated events (10%), while all the remaining uncertainties on the irreducible background in this signal region range between 0.5-5%. The total uncertainty on the reducible background is 29%. This includes an uncertainty on the object misidentification probability of 10-30% from the sources listed above. The uncertainty from the dependence of the misidentification probability on E_T^{miss} (0.4–17%) and the uncertainty on the fake scale factors (10–50%) are also included in the total, together with the uncertainty from the limited number of data events with three tagged leptons, of which at least one is a signal lepton. The total uncertainties on the signal cross-section range between 10-15%. These include uncertainties due to the renormalization and factorization scale, α_S , and PDFs. The maximum uncertainty obtained from either the CTEQ6.6 or the MSTW [52] PDF set is used. In SR2, the values of systematic uncertainties are similar to those obtained in SR1. The only exceptions are the uncertainty from the limited number of simulated events (4%) and the uncertainty on the reducible background (52%). In all of the above, the value used for the uncertainty on the luminosity is 3.7%.

The numbers of observed events and the prediction for SM backgrounds in SR1 and SR2 are reported in Table I. The probability that the background fluctuates to the observed number of events or higher is calculated in the frequentist approach and found to be 19% in SR1 and 6% in SR2. The distributions of the E_T^{miss} in the two signal regions are presented in Fig. 1. The yield in SR1 for one of the simplified model scenarios ($m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_L}, m_{\tilde{\chi}_1^0} = 250, 250, 175, 100$ GeV) is also shown for illustration purposes.

No significant excess of events is found in either signal region. Upper limits on the visible production cross-section of 9.9 fb in SR1 and 23.8 fb in SR2 are placed at 95% confidence level (CL) with the modified frequentist CL_s prescription [53]. No corrections for the effects of experimental resolution, acceptance and efficiency are applied. All systematic uncertainties and their correlations are taken into account via nuisance parameters. The corresponding expected limits are 7.1 fb and 14.1 fb, respectively. In SR2, the observed limit on the visible

TABLE I. Expected numbers of events from SM backgrounds (Bkg.) and observed numbers of events in data, for 2.06 fb^{-1} , in control regions VR1 and VR2, and in signal regions SR1 and SR2. Both statistical and systematic uncertainties are included.

Selection	VR1	VR2	SR1	SR2
$t\bar{t}W^{(*)}/Z^{(*)}$	1.4 ± 1.1	0.7 ± 0.6	0.4 ± 0.3	2.7 ± 2.1
$ZZ^{(*)}$	6.7 ± 1.5	0.03 ± 0.04	0.7 ± 0.2	3.4 ± 0.8
$WZ^{(*)}$	61 ± 11	0.4 ± 0.2	11 ± 2	58 ± 11
Reducible Bkg.	56 ± 35	14 ± 9	14 ± 4	7.5 ± 3.9
Total Bkg.	125 ± 37	15 ± 9	26 ± 5	72 ± 12
Data	122	12	32	95

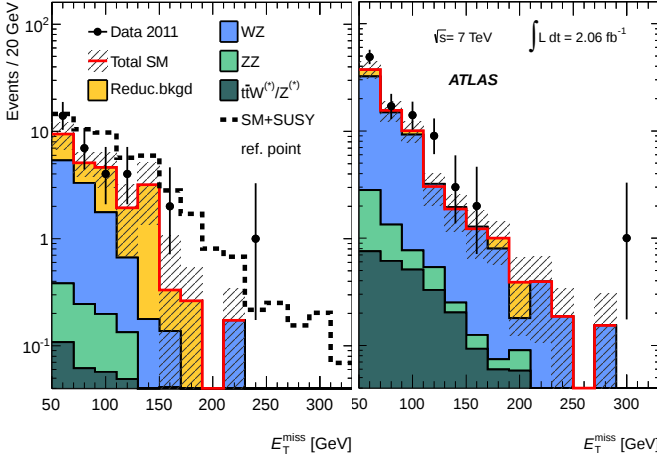


FIG. 1. E_T^{miss} distributions for events in signal regions SR1 (left) and SR2 (right). The error band includes both statistical and systematic uncertainty, while the errors on the data points are statistical only. The SUSY reference point used in SR1 is described in the text.

cross-section is less stringent than the expected limit because of the upwards fluctuation in the number of events in data with respect to the expected background. SR1 provides better sensitivity in the parameter space considered and the limits are interpreted in simplified models and pMSSM scenarios with $M_1 = 100 \text{ GeV}$ and $\tan \beta = 6$ (Fig. 2). The chosen M_1 value leads to a sizable mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ and therefore to a large acceptance. The value of $\tan \beta$ does not have a significant impact on $\sigma(pp \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^0) \times BR(\tilde{\chi}_i^\pm \tilde{\chi}_j^0 \rightarrow \ell\ell\ell\tilde{\chi}_1^0)$, which varies by $\sim 10\%$ if $\tan \beta$ is raised to 10.

In the simplified models, degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses up to 300 GeV are excluded for large mass differences from the $\tilde{\chi}_1^0$. Care has to be taken when interpreting the simplified model limit in the context of a pMSSM scenario, where the mass of the sneutrino is lighter than the mass of the left-handed slepton, leading to higher lepton momenta from chargino decays and to a change

in the branching ratios of the $\tilde{\chi}_2^0$.

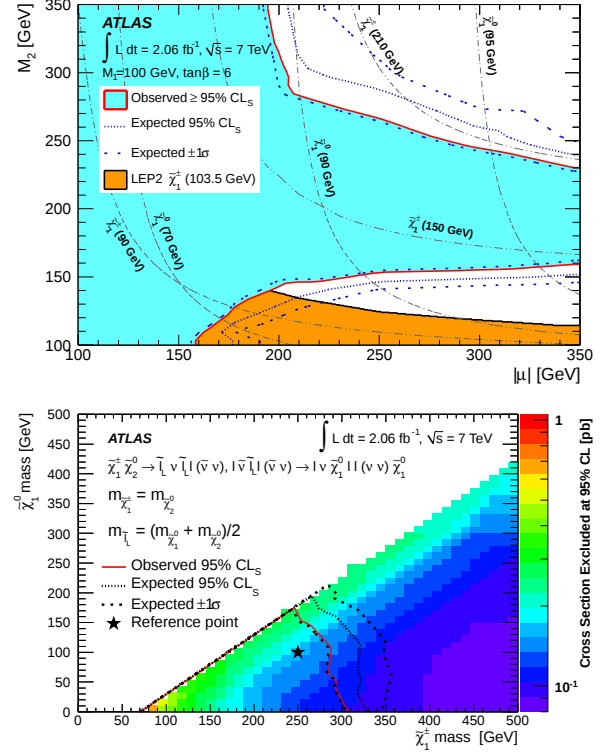


FIG. 2. Observed and expected 95% CL limit contours for chargino and neutralino production in the pMSSM (upper) and simplified model (lower) scenarios. For the simplified models, the 95% CL upper limit on the production cross-section is also shown. Interpolation is used to account for the discreteness of the signal grids.

In summary, results from the first ATLAS search for the weak production of charginos and neutralinos decaying to a final state with three leptons (electrons or muons) and missing transverse momentum are reported. The analysis is based on 2.06 fb^{-1} of proton-proton collision data delivered by the LHC at $\sqrt{s} = 7 \text{ TeV}$. No significant excess of events is found in data, where upwards fluctuations of less than 2-sigma are observed. The null result is interpreted in pMSSM and in simplified models. For the simplified models with intermediate sleptons considered in this paper, degenerate lightest chargino and next-to-lightest neutralino masses are excluded up to 300 GeV for mass differences to the lightest neutralino up to 300 GeV .

ACKNOWLEDGEMENTS

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 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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The ATLAS Collaboration

G. Aad⁴⁸, B. Abbott¹¹¹, J. Abdallah¹¹, S. Abdel Khalek¹¹⁵, A.A. Abdelalim⁴⁹, O. Abidinov¹⁰, B. Abi¹¹², M. Abolins⁸⁸, O.S. AbouZeid¹⁵⁸, H. Abramowicz¹⁵³, H. Abreu¹³⁶, E. Acerbi^{89a,89b}, B.S. Acharya^{164a,164b}, L. Adamczyk³⁷, D.L. Adams²⁴, T.N. Addy⁵⁶, J. Adelman¹⁷⁶, S. Adomeit⁹⁸, P. Adragna⁷⁵, T. Adye¹²⁹, S. Aefsky²², J.A. Aguilar-Saavedra^{124b,a}, M. Aharrouche⁸¹, S.P. Ahlen²¹, F. Ahles⁴⁸, A. Ahmad¹⁴⁸, M. Ahsan⁴⁰, G. Aielli^{133a,133b}, T. Akdogan^{18a}, T.P.A. Åkesson⁷⁹, G. Akimoto¹⁵⁵, A.V. Akimov⁹⁴, A. Akiyama⁶⁶, M.S. Alam¹, M.A. Alam⁷⁶, J. Albert¹⁶⁹, S. Albrand⁵⁵, M. Aleksa²⁹, I.N. Aleksandrov⁶⁴, F. Alessandria^{89a}, C. Alexa^{25a}, G. Alexander¹⁵³, G. Alexandre⁴⁹, T. Alexopoulos⁹, M. Alhroob^{164a,164c}, M. Aliev¹⁵, G. Alimonti^{102a,102b}, J. Alison¹²⁰, B.M.M. Allbrooke¹⁷, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸², A. Aloisio^{102a,102b}, R. Alon¹⁷², A. Alonso⁷⁹, B. Alvarez Gonzalez⁸⁸, M.G. Alviggi^{102a,102b}, K. Amako⁶⁵, C. Amelung²², V.V. Ammosov¹²⁸, A. Amorim^{124a,b}, G. Amorós¹⁶⁷, N. Amram¹⁵³, C. Anastopoulos²⁹, L.S. Ancu¹⁶, N. Andari¹¹⁵, T. Andeen³⁴, C.F. Anders²⁰, G. Anders^{58a}, K.J. Anderson³⁰, A. Andreazza^{89a,89b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰, A. Angerami³⁴, F. Anghinolfi²⁹, A. Anisenkov¹⁰⁷, N. Anjos^{124a}, A. Annovi⁴⁷, A. Antonaki⁸, M. Antonelli⁴⁷, A. Antonov⁹⁶, J. Antos^{144b}, F. Anulli^{132a}, S. Aoun⁸³, L. Aperio Bella⁴, R. Apolle^{118,c}, G. Arabidze⁸⁸, I. Aracena¹⁴³, Y. Arai⁶⁵, A.T.H. Arce⁴⁴, S. Arfaoui¹⁴⁸, J-F. Arguin¹⁴, E. Arik^{18a,*}, M. Arik^{18a}, A.J. Armbruster⁸⁷, O. Arnaez⁸¹, V. Arnal⁸⁰, C. Arnault¹¹⁵, A. Artamonov⁹⁵, G. Artoni^{132a,132b}, D. Arutinov²⁰, S. Asai¹⁵⁵, R. Asfandiyarov¹⁷³, S. Ask²⁷, B. Åsman^{146a,146b}, L. Asquith⁵, K. Assamagan²⁴, A. Astbury¹⁶⁹, B. Aubert⁴, E. Auge¹¹⁵, K. Augsten¹²⁷, M. Auresseu^{145a}, G. Avolio¹⁶³, R. Avramidou⁹, D. Axen¹⁶⁸, G. Azuelos^{93,d}, Y. Azuma¹⁵⁵, M.A. Baak²⁹, G. Baccaglioni^{89a}, C. Bacci^{134a,134b}, A.M. Bach¹⁴, H. Bachacou¹³⁶, K. Bachas²⁹, M. Backes⁴⁹, M. Backhaus²⁰, E. Badescu^{25a}, P. Bagnaia^{132a,132b}, S. Bahinipati², Y. Bai^{32a}, D.C. Bailey¹⁵⁸, T. Bain¹⁵⁸, J.T. Baines¹²⁹, O.K. Baker¹⁷⁶, M.D. Baker²⁴, S. Baker⁷⁷, E. Banas³⁸, P. Banerjee⁹³, Sw. Banerjee¹⁷³, D. Banfi²⁹, A. Bangert¹⁵⁰, V. Bansal¹⁶⁹, H.S. Bansil¹⁷, L. Barak¹⁷², S.P. Baranov⁹⁴, A. Barbaro Galtieri¹⁴, T. Barber⁴⁸, E.L. Barberio⁸⁶, D. Barberis^{50a,50b}, M. Barbero²⁰, D.Y. Bardin⁶⁴, T. Barillari⁹⁹, M. Barisonzi¹⁷⁵, T. Barklow¹⁴³, N. Barlow²⁷, B.M. Barnett¹²⁹, R.M. Barnett¹⁴, A. Baroncelli^{134a}, G. Barone⁴⁹, A.J. Barr¹¹⁸, F. Barreiro⁸⁰, J. Barreiro Guimarães da Costa⁵⁷, P. Barrillon¹¹⁵, R. Bartoldus¹⁴³, A.E. Barton⁷¹, V. Bartsch¹⁴⁹, R.L. Bates⁵³, L. Batkova^{144a}, J.R. Batley²⁷, A. Battaglia¹⁶, M. Battistin²⁹, F. Bauer¹³⁶, H.S. Bawa^{143,e}, S. Beale⁹⁸, T. Beau⁷⁸, P.H. Beauchemin¹⁶¹, R. Beccherle^{50a}, P. Bechtel²⁰, H.P. Beck¹⁶, S. Becker⁹⁸, M. Beckingham¹³⁸, K.H. Becks¹⁷⁵, A.J. Beddall^{18c}, A. Beddall^{18c}, S. Bedikian¹⁷⁶, V.A. Bednyakov⁶⁴, C.P. Bee⁸³, M. Beger²⁴, S. Behar Harpaz¹⁵², P.K. Behara⁶², M. Beimforde⁹⁹, C. Belanger-Champagne⁸⁵, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵³, L. Bellagamba^{19a}, F. Bellina²⁹, M. Bellomo²⁹, A. Belloni⁵⁷, O. Beloborodova^{107,f}, K. Belotskiy⁹⁶, O. Beltramello²⁹, O. Benary¹⁵³, D. Bencheikroun^{135a}, K. Bendtz^{146a,146b}, N. Benekos¹⁶⁵, Y. Benhammou¹⁵³, E. Benhar Nocchioli⁴⁹, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁴, M. Benoit¹¹⁵, J.R. Bensinger²², K. Benslama¹³⁰, S. Bentvelsen¹⁰⁵, D. Berge²⁹, E. Bergeas Kuutmann⁴¹, N. Berger⁴, F. Berghaus¹⁶⁹, E. Berglund¹⁰⁵, J. Beringer¹⁴, P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius²⁴, T. Berry⁷⁶, C. Bertella⁸³, A. Bertin^{19a,19b}, F. Bertolucci^{122a,122b}, M.I. Besana^{89a,89b}, N. Besson¹³⁶, S. Bethke⁹⁹, W. Bhimji⁴⁵, R.M. Bianchi²⁹, M. Bianco^{72a,72b}, O. Biebel⁹⁸, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁴, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁵, A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵, J.-B. Blanchard¹³⁶, G. Blanchot²⁹, T. Blazek^{144a}, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁴, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁵, N. Boelaert³⁵, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Bohm^{146a}, J. Bohm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁷, V. Boldea^{25a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Bondioli¹⁶³, M. Boonekamp¹³⁶, C.N. Booth¹³⁹, S. Bordon⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{12a}, M. Borri⁸², S. Borroni⁸⁷, V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, D. Boumediene³³, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁴, N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, P. Branchini^{134a}, A. Brandt⁷, G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun¹⁷⁵, B. Bräuer¹⁵⁸, J. Bremer²⁹, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶, S. Bressler¹⁷², D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, E. Brodet¹⁵³, F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², H. Brown⁷, P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³, T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁷, S. Cabrera Urbán¹⁶⁷, D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, S. Calvet³³, R. Camacho Toro³³, P. Camarri^{133a,133b}, D. Cameron¹¹⁷,

L.M. Caminada¹⁴, S. Campana²⁹, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli^{30,g}, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b}, M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo⁸¹, R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{31b}, G.D. Carrillo Montoya¹⁷³, A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,h}, D. Casadei¹⁰⁸, M.P. Casado¹¹, M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez¹⁷³, E. Castaneda-Miranda¹⁷³, V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio²⁹, J.R. Catmore²⁹, A. Cattai²⁹, G. Cattani^{133a,133b}, S. Caughron⁸⁸, D. Cauz^{164a,164c}, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹, V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b}, A.S. Cerqueira^{23b}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷, S.A. Cetin^{18b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁶, K. Chan², B. Champleau⁸⁵, J.D. Chapman²⁷, J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸², C.A. Chavez Barajas²⁹, S. Cheatham⁸⁵, S. Chekanov⁵, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³, H. Chen²⁴, S. Chen^{32c}, X. Chen¹⁷³, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁴, E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani^{51a}, J.T. Childers²⁹, A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁷, R.T. Chislett⁷⁷, M.V. Chizhov⁶⁴, G. Choudalakis³⁰, S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, C. Ciocca^{19a}, A. Ciocio¹⁴, M. Cirilli⁸⁷, M. Citterio^{89a}, M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³, B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Cocco¹³⁸, J. Cochran⁶³, P. Coe¹¹⁸, J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁸, J. Colas⁴, A.P. Colijn¹⁰⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³, J. Collot⁵⁵, G. Colon⁸⁴, P. Conde Muiño^{124a}, E. Coniavitis¹¹⁸, M.C. Conidi¹¹, S.M. Consonni^{89a,89b}, V. Consorti⁴⁸, S. Constantinescu^{25a}, C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,i}, M. Cooke¹⁴, B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁴, T. Cornelissen¹⁷⁵, M. Corradi^{19a}, F. Corriveau^{85,j}, A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹, L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli^{122a,122b}, M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b}, S. Crépé-Renaudin⁵⁵, C.-M. Cuciuc^{25a}, C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, M. Curatolo⁴⁷, C.J. Curtis¹⁷, C. Cuthbert¹⁵⁰, P. Cwetanski⁶⁰, H. Cziri¹⁴¹, P. Czodrowski⁴³, Z. Czyzula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{132a,132b}, C. Da Via⁸², W. Dabrowski³⁷, A. Dafinca¹¹⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴, M. Dam³⁵, M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson²⁹, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b}, W. Davey²⁰, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, E. Davies^{118,c}, M. Davies⁹³, A.R. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴², I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²², K. De⁷, R. de Asmundis^{102a}, S. De Castro^{19a,19b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵, H. De la Torre⁸⁰, F. De Lorenzi⁶³, B. De Lotto^{164a,164c}, L. de Mora⁷¹, L. De Nooij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b}, W.J. Dearnaley⁷¹, R. Debbé²⁴, C. Debenedetti⁴⁵, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²⁰, C. Del Papa^{164a,164c}, J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴, A. Dell'Acqua²⁹, L. Dell'Asta²¹, M. Della Pietra^{102a,i}, D. della Volpe^{102a,102b}, M. Delmastro⁴, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸, S. Demers¹⁷⁶, M. Demichev⁶⁴, B. Demirköz^{11,k}, J. Deng¹⁶³, S.P. Denisov¹²⁸, D. Derendarz³⁸, J.E. Derkaoui^{135d}, F. Derue⁷⁸, P. Dervan⁷³, K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸, S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,l}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹, B. Di Girolamo²⁹, S. Di Luise^{134a,134b}, A. Di Mattia¹⁷³, B. Di Micco²⁹, R. Di Nardo⁴⁷, A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c}, E.B. Diehl⁸⁷, J. Dietrich⁴¹, T.A. Dietzsch^{58a}, S. Diglio⁸⁶, K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a}, F. Dittus²⁹, F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{23c}, A. Do Valle Wemans^{124a}, T.K.O. Doan⁴, M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos²⁹, E. Dobson^{29,m}, J. Dodd³⁴, C. Doglioni⁴⁹, T. Doherty⁵³, Y. Doi^{65,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{23d}, M. Donega¹²⁰, J. Donini³³, J. Dopke²⁹, A. Doria^{102a}, A. Dos Anjos¹⁷³, A. Dotti^{122a,122b}, M.T. Dova⁷⁰, A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, M. Dris⁹, J. Dubbert⁹⁹, S. Dube¹⁴, E. Duchovni¹⁷², G. Duckeck⁹⁸, A. Dudarev²⁹, F. Dudziak⁶³, M. Dührssen²⁹, I.P. Duerdoth⁸², L. Duflot¹¹⁵, M.-A. Dufour⁸⁵, M. Dunford²⁹, H. Duran Yildiz^{3a}, R. Duxfield¹³⁹, M. Dwuznik³⁷, F. Dydak²⁹, M. Düren⁵², J. Ebke⁹⁸, S. Eckweiler⁸¹, K. Edmonds⁸¹, C.A. Edwards⁷⁶, N.C. Edwards⁵³, W. Ehrenfeld⁴¹, T. Eifert¹⁴³, G. Eigen¹³, K. Einsweiler¹⁴, E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁴, F. Ellinghaus⁸¹, K. Ellis⁷⁵, N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹, D. Emelianov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹, A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, D. Eriksson^{146a}, J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁶, D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, C. Escobar¹²³, X. Espinal Curull¹¹, B. Esposito⁴⁷, F. Etienne⁸³, A.I. Etienve¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{19a,19b}, C. Fabre²⁹, R.M. Fakhruddinov¹²⁸, S. Falciano^{132a}, Y. Fang¹⁷³, M. Fanti^{89a,89b}, A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸, T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹¹⁸, P. Farthouat²⁹, P. Fassnacht²⁹, D. Fassouliotis⁸, B. Fathollahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a}, O.L. Fedin¹²¹,

W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, D. Fellmann⁵, C. Feng^{32d}, E.J. Feng³⁰, A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁵, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴¹, A. Ferrari¹⁶⁶, P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³⁰, F. Fiedler⁸¹, A. Filipčić⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹, M.C.N. Fiolhais^{124a,h}, L. Fiorini¹⁶⁷, A. Firan³⁹, G. Fischer⁴¹, M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹, J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³, M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁶, D.A. Forbush¹³⁸, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, D. Fournier¹¹⁵, H. Fox⁷¹, P. Francavilla¹¹, S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷², M. Franklin⁵⁷, S. Franz²⁹, M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁷, C. Friedrich⁴¹, F. Friedrich⁴³, R. Froeschl²⁹, D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa²⁹, B.G. Fulsom¹⁴³, J. Fuster¹⁶⁷, C. Gabaldon²⁹, O. Gabizon¹⁷², T. Gadfort²⁴, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸, E.J. Gallas¹¹⁸, V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,e}, A. Gaponenko¹⁴, F. Garberson¹⁷⁶, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, R.W. Gardner³⁰, N. Garelli²⁹, H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶, P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, E.N. Gazis⁹, P. Ge^{32d}, Z. Gecse¹⁶⁸, C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, P. Gerlach¹⁷⁵, A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b}, V. Giakoumopoulou⁸, V. Giangiobbe¹¹, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson²⁹, D. Gillberg²⁸, A.R. Gillman¹²⁹, D.M. Gingrich^{2,d}, J. Ginzburg¹⁵³, N. Giokaris⁸, M.P. Giordani^{164c}, R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³, P. Giusti^{19a}, B.K. Gjølsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁵, G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹, C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷, T. Golling¹⁷⁶, A. Gomes^{124a,b}, L.S. Gomez Fajardo⁴¹, R. Gonçalves⁷⁶, J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰, S. Gonzalez¹⁷³, S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹¹, M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹, J.J. Goodson¹⁴⁸, L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵, B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸, B. Gosdzik⁴¹, A.T. Goshaw⁵, M. Gosselink¹⁰⁵, M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶³, M. Goughri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁸, C. Goy⁴, S. Gozpinar²², I. Grabowska-Bold³⁷, P. Grafström²⁹, K.-J. Grahn⁴¹, F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray²⁹, J.A. Gray¹⁴⁸, E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³, Z.D. Greenwood^{24,l}, K. Gregersen³⁵, I.M. Gregor⁴¹, P. Grenier¹⁴³, J. Griffiths¹³⁸, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁷, S. Grinstein¹¹, Y.V. Grishkevich⁹⁷, J.-F. Grivaz¹¹⁵, E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶, C. Guicheney³³, A. Guida^{72a,72b}, S. Guindon⁵⁴, H. Guler^{85,n}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁴, V.N. Gushchin¹²⁸, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸, C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner⁹⁹, F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁷, D. Hall¹¹⁸, J. Haller⁵⁴, K. Hamacher¹⁷⁵, P. Hamal¹¹³, M. Hamer⁵⁴, A. Hamilton^{145b,o}, S. Hamilton¹⁶¹, L. Han^{32b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰, M. Hance¹⁴, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵, P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷, R.D. Harrington⁴⁵, O.M. Harris¹³⁸, K. Harrison¹⁷, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶, S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁸, M. Havranek²⁰, C.M. Hawkes¹⁷, R.J. Hawkings²⁹, A.D. Hawkins⁷⁹, D. Hawkins¹⁶³, T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰, D. Hayden⁷⁶, H.S. Hayward⁷³, S.J. Haywood¹²⁹, M. He^{32d}, S.J. Head¹⁷, V. Hedberg⁷⁹, L. Heelan⁷, S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵, L. Helary⁴, C. Heller⁹⁸, M. Heller²⁹, S. Hellman^{146a,146b}, D. Hellmich²⁰, C. Helsens¹¹, R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴, A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³, C. Hensel⁵⁴, T. Henß¹⁷⁵, C.M. Hernandez⁷, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, G. Herten⁴⁸, R. Hertenberger⁹⁸, L. Hervas²⁹, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁷, K.H. Hiller⁴¹, S. Hillert²⁰, S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴², D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸, N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹, M.R. Hoferkamp¹⁰³, J. Hoffman³⁹, D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸, T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, C. Horn¹⁴³, S. Horner⁴⁸, J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howarth⁸², I. Hristova¹⁵, J. Hrivnac¹¹⁵, I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu⁸¹, S.-C. Hsu¹⁴, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰, A. Huettmann⁴¹, T.B. Huffman¹¹⁸, E.W. Hughes³⁴, G. Hughes⁷¹, M. Huhtinen²⁹, M. Hurwitz¹⁴, U. Husemann⁴¹, N. Huseynov^{64,p}, J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹, M. Ibbotson⁸², I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵, D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, M. Imori¹⁵⁵, T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{134a}, K. Iordanidou⁸, V. Ippolito^{132a,132b}, A. Irles Quiles¹⁶⁷, C. Isaksson¹⁶⁶, A. Ishikawa⁶⁶, M. Ishino⁶⁷,

R. Ishmukhametov³⁹, C. Issever¹¹⁸, S. Istin^{18a}, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁵, J.M. Izen⁴⁰, V. Izzo^{102a}, B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹, V. Jain⁶⁰, K. Jakobs⁴⁸, S. Jakobsen³⁵, J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen²⁹, A. Jantsch⁹⁹, M. Janus⁴⁸, G. Jarlskog⁷⁹, L. Jeanty⁵⁷, I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jez³⁵, S. Jézéquel⁴, M.K. Jha^{19a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸, Y. Jiang^{32b}, M. Jimenez Belenguer⁴¹, S. Jin^{32a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁵, D. Joffe³⁹, L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶, K. Jon-And^{146a,146b}, G. Jones¹¹⁸, R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram²⁹, P.M. Jorge^{124a}, K.D. Joshi⁸², J. Jovicevic¹⁴⁷, T. Jovin^{12b}, X. Ju¹⁷³, C.A. Jung⁴², R.M. Jungst²⁹, V. Juranek¹²⁵, P. Jussel⁶¹, A. Juste Rozas¹¹, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarzka³⁸, P. Kadlecik³⁵, M. Kado¹¹⁵, H. Kagan¹⁰⁹, M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴, S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda²⁹, S. Kaneti²⁷, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵, B. Kaplan¹⁷⁶, A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁵³, M. Karagounis²⁰, M. Karnevskiy⁴¹, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³, G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹, V. Kaushik⁶, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷, M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kelidze⁶⁴, J.S. Keller¹³⁸, J. Kennedy⁹⁸, M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵, K. Kessoku¹⁵⁵, J. Keung¹⁵⁸, F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁴, A. Khodinov⁹⁶, A. Khomich^{58a}, T.J. Khoo²⁷, G. Khorauli²⁰, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁴, J. Khubua^{51b}, H. Kim^{146a,146b}, M.S. Kim², S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸, J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielska³⁷, T. Kittelmann¹²³, A.M. Kiver¹²⁸, E. Kladiva^{144b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b}, A. Klimentov²⁴, R. Klingenberg⁴², J.A. Klinger⁸², E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴, S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, N.S. Knecht¹⁵⁸, E. Kneringer⁶¹, E.B.F.G. Knoops⁸³, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, M. Kocian¹⁴³, P. Kodys¹²⁶, K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁸, E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴³, G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸, M. Kollefth⁴⁸, A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{41,q}, A.I. Kononov⁴⁸, R. Konoplich^{108,r}, N. Konstantinidis⁷⁷, A. Kootz¹⁷⁵, S. Koperny³⁷, K. Korcyl³⁸, K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷, I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰, S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁴, C. Kourkoulis⁸, V. Kouskoura¹⁵⁴, A. Koutsman^{159a}, R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷, G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, J.K. Kraus²⁰, F. Krejci¹²⁷, J. Kretschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰, J. Krstic^{12a}, U. Kruchonak⁶⁴, H. Krüger²⁰, T. Kruker¹⁶, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruth²⁰, T. Kubota⁸⁶, S. Kuday^{3a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹, D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰, S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁷⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶, M. Kurata¹⁶⁰, Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁵, A. La Rosa⁴⁹, L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵, D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵, M. Lamanna²⁹, L. Lambourne⁷⁷, C.L. Lampen⁶, W. Lamp¹⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzsch¹⁷⁵, S. Laplace⁷⁸, C. Lapoire²⁰, J.F. Laporte¹³⁶, T. Lari^{89a}, A. Larnier¹¹⁸, M. Lassnig²⁹, P. Laurelli⁴⁷, V. Lavorini^{36a,36b}, W. Lavrijsen¹⁴, P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirrec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹¹, T. LeCompte⁵, F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶, B.C. LeGeyt¹²⁰, F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, X. Lei⁶, M.A.L. Leite^{23d}, R. Leitner¹²⁶, D. Lellouch¹⁷², B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b}, T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi²⁹, K. Leonhardt⁴³, S. Leontsinis⁹, F. Lepold^{58a}, C. Leroy⁹³, J.-R. Lessard¹⁶⁹, C.G. Lester²⁷, C.M. Lester¹²⁰, J. Levêque⁴, D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸, G.H. Lewis¹⁰⁸, A.M. Leyko²⁰, M. Leyton¹⁵, B. Li⁸³, H. Li^{173,s}, S. Li^{32b,t}, X. Li⁸⁷, Z. Liang^{118,u}, H. Liao³³, B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, C. Limbach²⁰, A. Limosani⁸⁶, M. Limper⁶², S.C. Lin^{151,v}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, A. Lipniacka¹³, T.M. Liss¹⁶⁵, D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu¹⁵¹, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, Y. Liu^{32b}, M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹, P. Loch⁶, W.S. Lockman¹³⁷, T. Loddienkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁵, K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁴, R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷, J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a}, X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe^{143,e}, F. Lu^{32a}, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, G. Luijckx¹⁰⁵, W. Lukas⁶¹, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹,

J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷³, J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a}, R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁵, S. Mättig⁴¹, L. Magnoni²⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸, S. Mahmoud⁷³, G. Mahout¹⁷, C. Maiani^{132a,132b}, C. Maidantchik^{23a}, A. Maio^{124a,b}, S. Majewski²⁴, Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶, B. Malaescu²⁹, Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁵, C. Malone¹⁴³, S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov²⁹, R. Mameghani⁹⁸, J. Mamuzic^{12b}, A. Manabe⁶⁵, L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangeard⁸⁸, L. Manhaes de Andrade Filho^{23a}, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸, B. Mansoulie¹³⁶, A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁸, F. Marchese^{133a,133b}, G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquin^{23a}, Z. Marshall²⁹, F.K. Martens¹⁵⁸, S. Marti-Garcia¹⁶⁷, B. Martin²⁹, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁷, V.J. Martin⁴⁵, B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷, A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴, P. Mastrandrea^{132a,132b}, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, P. Matricon¹¹⁵, H. Matsunaga¹⁵⁵, T. Matsushita⁶⁶, C. Mattravers^{118,c}, J. Maurer⁸³, S.J. Maxfield⁷³, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰, L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸, N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶, J.A. Mcfayden¹³⁹, H. McGlone⁵³, G. Mchedlidze^{51b}, T. McLaughlan¹⁷, S.J. McMahon¹²⁹, R.A. McPherson^{169,j}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁵, M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, S. Mehlhase³⁵, A. Mehta⁷³, K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b}, L. Mendoza Navas¹⁶², Z. Meng^{151,s}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹, E. Meoni¹¹, K.M. Mercurio⁵⁷, P. Mermoud⁴⁹, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰, H. Merritt¹⁰⁹, A. Messina^{29,w}, J. Metcalfe¹⁰³, A.S. Mete⁶³, C. Meyer⁸¹, C. Meyer³⁰, J-P. Meyer¹³⁶, J. Meyer¹⁷⁴, J. Meyer⁵⁴, T.C. Meyer²⁹, W.T. Meyer⁶³, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹, S. Migas⁷³, L. Mijović⁴¹, G. Mikenberg¹⁷², M. Mikestikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller³⁰, R.J. Miller⁸⁸, W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷², A.A. Minaenko¹²⁸, M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁴, Y. Ming¹⁷³, L.M. Mir¹¹, G. Mirabelli^{132a}, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹, K. Miyazaki⁶⁶, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, P. Mockett¹³⁸, S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰, S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, J. Monk⁷⁷, E. Monnier⁸³, S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶, C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹, M. Moreno Llaser¹⁶⁷, P. Morettini^{50a}, M. Morgenstern⁴³, M. Morii⁵⁷, J. Morin⁷⁵, A.K. Morley²⁹, G. Mornacchi²⁹, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³, E. Mountricha^{9,x}, S.V. Mouraviev⁹⁴, E.J.W. Moyse⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰, T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann²⁹, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵, E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁵, A. Nagarkar¹⁰⁹, Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz²⁹, Y. Nakahama²⁹, K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵, I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,c}, T. Nattermann²⁰, T. Naumann⁴¹, G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹, A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi^{29,y}, M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁶, R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷, N. Nikiforou³⁴, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos²⁴, H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁶, R. Nisius⁹⁹, L. Nodulman⁵, M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, M. Nordberg²⁹, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁵, L. Nozka¹¹³, I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷, B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{28,d}, H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda¹⁵⁵, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁴, C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, S. Okada⁶⁶, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵, A. Olariu^{25a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{31a}, M. Oliveira^{124a,h}, D. Oliveira Damazio²⁴, E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, A. Onofre^{124a,z}, P.U.E. Onyisi³⁰, C.J. Oram^{159a}, M.J. Oreglia³⁰, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{72a,72b}, I. Orlov¹⁰⁷, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶, J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a}, A. Ovcharova¹⁴, M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{18a}, N. Ozturk⁷, A. Pacheco Pages¹¹, C. Padilla Aranda¹¹, S. Pagan Griso¹⁴, E. Paganis¹³⁹, F. Paige²⁴, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b}, C.P. Paleari⁶, S. Palestini²⁹, D. Pallin³³, A. Palma^{124a}, J.D. Palmer¹⁷, Y.B. Pan¹⁷³, E. Panagiotopoulou⁹, N. Panikashvili⁸⁷, S. Panitkin²⁴, D. Pantea^{25a}, A. Papadelis^{146a}, Th.D. Papadopoulos⁹, A. Paramonov⁵, D. Paredes Hernandez³³, W. Park^{24,aa}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸, S. Pashapour⁵⁴, E. Pasqualucci^{132a}, S. Passaggio^{50a},

A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore⁷⁶, G. Pásztor^{49,ab}, S. Patariaia¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsý^{144a}, M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶, H. Peng^{32b}, B. Penning³⁰, A. Penson³⁴, J. Penwell⁶⁰, M. Perantoni^{23a}, K. Perez^{34,ac}, T. Perez Cavalcanti⁴¹, E. Perez Codina^{159a}, M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴, S. Persembe^{3a}, V.D. Peshekhonov⁶⁴, K. Peters²⁹, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁴, A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolo^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteni¹⁴², R. Pezoa^{31b}, A. Phan⁸⁶, P.W. Phillips¹²⁹, G. Piacquadio²⁹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b}, S.M. Piec⁴¹, R. Piegaia²⁶, D.T. Pignotti¹⁰⁹, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,b}, M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold², B. Pinto^{124a}, C. Pizio^{89a,89b}, M. Plamondon¹⁶⁹, M.-A. Pleier²⁴, E. Plotnikova⁶⁴, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³, L. Poggioli¹¹⁵, T. Poghossyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio^{36a,36b}, A. Polini^{19a}, J. Poll⁷⁵, V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸, G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso²⁹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷, I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard²⁹, J. Poveda¹⁷³, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸³, A. Pranko¹⁴, S. Prasad²⁹, R. Pravahan²⁴, S. Prell⁶³, K. Pretzl¹⁶, D. Price⁶⁰, J. Price⁷³, L.E. Price⁵, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{31b}, S. Protopopescu²⁴, J. Proudfoot⁵, X. Prudent⁴³, M. Przybycien³⁷, H. Przysiechniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴, E. Pueschel⁸⁴, J. Purdham⁸⁷, M. Purohit^{24,aa}, P. Puzo¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, Z. Qin⁴¹, A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷³, F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radescu⁴¹, P. Radloff¹¹⁴, T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁴, S. Rajagopalan²⁴, M. Rammensee⁴⁸, M. Rammes¹⁴¹, A.S. Randle-Conde³⁹, K. Randrianarivony²⁸, F. Rauscher⁹⁸, T.C. Rave⁴⁸, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuzzi^{119a,119b}, A. Redelbach¹⁷⁴, G. Redlinger²⁴, R. Reece¹²⁰, K. Reeves⁴⁰, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², C. Rembser²⁹, Z.L. Ren¹⁵¹, A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹, E. Richter-Was^{4,ad}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a}, R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,j}, A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁷, J.E.M. Robinson⁷⁷, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶, C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, D. Rodriguez¹⁶², A. Roe⁵⁴, S. Roe²⁹, O. Røhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶, M. Romano^{19a,19b}, G. Romeo²⁶, E. Romero Adam¹⁶⁷, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹, A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶³, P.L. Rosendahl¹³, O. Rosenthal¹⁴¹, L. Rosselet⁴⁹, V. Rossetti¹¹, E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{25a}, I. Roth¹⁷², J. Rothberg¹³⁸, D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{32a,ae}, F. Rubbo¹¹, I. Rubinskiy⁴¹, B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴³, G. Rudolph⁶¹, F. Rühr⁶, F. Ruggieri^{134a,134b}, A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴, K. Runge⁴⁸, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, J.P. Rutherford⁶, C. Ruwiedel¹⁴, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸, A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵, G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salek²⁹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷, B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger²⁹, D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹³, H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵, T. Sandoval²⁷, C. Sandoval¹⁶², R. Sandstroem⁹⁹, D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a}, J.G. Saraiva^{124a}, T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵, N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage⁴, E. Sauvan⁴, J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³, D.O. Savu²⁹, L. Sawyer^{24,l}, D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{19a}, A. Sbrizzi^{19a,19b}, O. Scallan⁹³, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹, S. Schaepe²⁰, S. Schaetzel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷, V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer³⁴, C. Schiavi^{50a,50b}, J. Schieck⁹⁸, M. Schioppa^{36a,36b}, S. Schlenker²⁹, E. Schmidt⁴⁸, K. Schmieden²⁰, C. Schmitt⁸¹, S. Schmitt^{58b}, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹, D. Schouten^{159a}, J. Schovancova¹²⁵, M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²⁰, J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³, J. Schwindling¹³⁶, T. Schwindt²⁰, M. Schwoerer⁴, G. Sciolla²², W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴¹, E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, S.J. Sekula³⁹, K.E. Selbach⁴⁵, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b}, N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴, R. Seuster⁹⁹, H. Severini¹¹¹, A. Sfyrta²⁹, E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵, K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, A. Shibata¹⁰⁸, H. Shichi¹⁰¹, S. Shimizu²⁹, M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³⁰, D. Short¹¹⁸, S. Shrestha⁶³, E. Shulga⁹⁶, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{12a}, O. Silbert¹⁷², J. Silva^{124a}, Y. Silver¹⁵³, D. Silverstein¹⁴³,

S.B. Silverstein^{146a}, V. Simak¹²⁷, O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵, B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁵, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹, G. Siragusa¹⁷⁴, A. Sircar²⁴, A.N. Sisakyan⁶⁴, S.Yu. Sivoklokov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sijursen¹³, L.A. Skinnari¹⁴, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹, V. Smakhtin¹⁷², B.H. Smart⁴⁵, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹, B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁴, S.W. Snow⁸², J. Snow¹¹¹, S. Snyder²⁴, R. Sobie^{169,j}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷, E. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸, N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁷, R. Soualah^{164a,164c}, A. Soukharev¹⁰⁷, S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, R. Spiwoks²⁹, M. Spousta¹²⁶, T. Spreitzer¹⁵⁸, B. Spurlock⁷, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka³⁸, R.W. Stanek⁵, C. Stanescu^{134a}, M. Stanescu-Bellu⁴¹, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵, P. Starovoitov⁴¹, A. Staude⁹⁸, P. Stavina^{144a}, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷, B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart²⁹, J.A. Stillings²⁰, M.C. Stockton⁸⁵, K. Stoerig⁴⁸, G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷, A. Straessner⁴³, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³, M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroyanowski³⁹, J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵, N.A. Styles⁴¹, D.A. Soh^{151,u}, D. Su¹⁴³, H.S. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, K. Suita⁶⁶, M. Suk¹²⁶, V.V. Sulin⁹⁴, S. Sultansoy^{3d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{36a,36b}, M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶, J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴¹, A. Taffard¹⁶³, R. Tafirout^{159a}, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹, H. Takai²⁴, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵, M. Talby⁸³, A. Talyshev^{107,f}, M.C. Tamssett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶, N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁸, G.F. Tartarelli^{89a}, P. Tas¹²⁶, M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹², G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Testa⁴⁷, R.J. Teuscher^{158,j}, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸, M. Thioye¹⁷⁶, S. Thoma⁴⁸, J.P. Thomas¹⁷, E.N. Thompson³⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁵, E. Thomson¹²⁰, M. Thomson²⁷, R.P. Thun⁸⁷, F. Tian³⁴, M.J. Tibbets¹⁴, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴, Y.A. Tikhonov^{107,f}, S. Timoshenko⁹⁶, P. Tipton¹⁷⁶, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, T. Todorov⁴, S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokunaga⁶⁶, K. Tokushuku⁶⁵, K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³⁰, K. Toms¹⁰³, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁴, I. Torchiani²⁹, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torró Pastor¹⁶⁷, J. Toth^{83,ab}, F. Touchard⁸³, D.R. Tovey¹³⁹, T. Trefzger¹⁷⁴, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvold⁷⁸, M.F. Tripana⁷⁰, W. Trischuk¹⁵⁸, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trotter-McDonald¹⁴², M. Trzebinski³⁸, A. Trzupek³⁸, C. Tsarouchas²⁹, J.C-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiareshka⁹⁰, D. Tsionou^{4,af}, G. Tsipolitis⁹, V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁴, J.-W. Tsung²⁰, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{25a}, V. Tudorache^{25a}, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷, I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁴, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b}, M. Tyndel¹²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰, M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁵, D. Urbaniec³⁴, G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, J. Valenta¹²⁵, P. Valente^{132a}, S. Valentini^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵², J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵, D. van der Ster²⁹, N. van Eldik⁸⁴, P. van Gemmeren⁵, I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli²⁹, A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, R. Vari^{132a}, T. Varol⁸⁴, D. Varouchas¹⁴, A. Vartapetian⁷, K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b}, J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴, M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵, A. Vest⁴³, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵, T. Vickey^{145b,ag}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸, S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincet²⁸, E. Vinek²⁹, V.B. Vinogradov⁶⁴, M. Virchaux^{136,*}, J. Virzi¹⁴, O. Vitells¹⁷², M. Viti⁴¹, I. Vivarelli⁴⁸, F. Vives Vaque², S. Vlachos⁹, D. Vladoiu⁹⁸, M. Vlasak¹²⁷, A. Vogel²⁰, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a}, H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶, V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁵, J.H. Vosseveld⁷³, N. Vranjes¹³⁶, M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet²⁹, I. Vukotic¹¹⁵, W. Wagner¹⁷⁵, P. Wagner¹²⁰, H. Wahlen¹⁷⁵, S. Währmund⁴³, J. Wakabayashi¹⁰¹, S. Walch⁸⁷, J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷³, H. Wang^{32b,ah}, J. Wang¹⁵¹, J. Wang⁵⁵, J.C. Wang¹³⁸, R. Wang¹⁰³,

S.M. Wang¹⁵¹, T. Wang²⁰, A. Warburton⁸⁵, C.P. Ward²⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁵, C. Wasicki⁴¹, P.M. Watkins¹⁷, A.T. Watson¹⁷, I.J. Watson¹⁵⁰, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²², P.S. Wells²⁹, T. Wenaus²⁴, D. Wendland¹⁵, Z. Weng^{151,u}, T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, A. White⁷, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, F. Wicek¹¹⁵, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wieler¹²⁹, P. Wienemann²⁰, C. Wigglesworth⁷⁵, L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁷, A. Wildauer¹⁶⁷, M.A. Wildt^{41,q}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸, H. Wolters^{124a,h}, W.C. Wong⁴⁰, G. Wooden⁸⁷, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸⁴, K.W. Wozniak³⁸, K. Wraight⁵³, C. Wright⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{32b,ai}, E. Wulf³⁴, B.M. Wynne⁴⁵, S. Xella³⁵, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{32b,x}, D. Xu¹³⁹, B. Yabsley¹⁵⁰, S. Yacoub^{145b}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶⁰, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{32a}, Y. Yao¹⁴, Y. Yasu⁶⁵, G.V. Ybeles Smit¹³⁰, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹, R. Yoshida⁵, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, B. Zabinski³⁸, R. Zaidan⁶², A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, L. Zanello^{132a,132b}, A. Zaytsev¹⁰⁷, C. Zeitnitz¹⁷⁵, M. Zeller¹⁷⁶, M. Zeman¹²⁵, A. Zemla³⁸, C. Zendler²⁰, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zinonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b,ah}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹, J. Zhu⁸⁷, Y. Zhu^{32b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶⁰, R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{19a,19b}, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalinski²⁹.

¹ University at Albany, Albany NY, United States of America

² Department of Physics, University of Alberta, Edmonton AB, Canada

³ ^(a)Department of Physics, Ankara University, Ankara; ^(b)Department of Physics, Dumlupinar University, Kutahya;

^(c)Department of Physics, Gazi University, Ankara; ^(d)Division of Physics, TOBB University of Economics and Technology, Ankara; ^(e)Turkish Atomic Energy Authority, Ankara, Turkey

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

⁵ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

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

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

⁸ Physics Department, University of Athens, Athens, Greece

⁹ Physics 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

¹² ^(a)Institute of Physics, University of Belgrade, Belgrade; ^(b)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 CA, United States of America

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

¹⁸ ^(a)Department of Physics, Bogazici University, Istanbul; ^(b)Division of Physics, Dogus University, Istanbul;

^(c)Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d)Department of Physics, Istanbul Technical University, Istanbul, Turkey

¹⁹ ^(a)INFN Sezione di Bologna; ^(b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy

²⁰ Physikalisches Institut, University of Bonn, Bonn, Germany

²¹ Department of Physics, Boston University, Boston MA, United States of America

²² Department of Physics, Brandeis University, Waltham MA, United States of America

²³ ^(a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b)Federal University of Juiz de Fora

- (UFJF), Juiz de Fora; ^(c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d)Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁴ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ²⁵ ^(a)National Institute of Physics and Nuclear Engineering, Bucharest; ^(b)University Politehnica Bucharest, Bucharest; ^(c)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 ON, Canada
- ²⁹ CERN, Geneva, Switzerland
- ³⁰ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³¹ ^(a)Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; ^(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³² ^(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b)Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c)Department of Physics, Nanjing University, Jiangsu; ^(d)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 NY, United States of America
- ³⁵ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁶ ^(a)INFN Gruppo Collegato di Cosenza; ^(b)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 TX, United States of America
- ⁴⁰ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- 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 NC, United States of America
- ⁴⁵ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a)INFN Sezione di Genova; ^(b)Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a)E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; ^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton VA, United States of America
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- ⁵⁸ ^(a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City IA, United States of America
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan

- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a)INFN Sezione di Lecce; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁰ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸¹ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸² School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁵ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁶ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁸⁹ ^(a)INFN Sezione di Milano; ^(b)Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹³ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a)INFN Sezione di Napoli; ^(b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁷ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York NY, United States of America
- ¹⁰⁹ Ohio State University, Columbus OH, United States of America
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹² Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹³ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁵ LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁶ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁷ Department of Physics, University of Oslo, Oslo, Norway
- ¹¹⁸ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹¹⁹ ^(a)INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²⁰ Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

- 121 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 122 ^(a)INFN Sezione di Pisa; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- 124 ^(a)Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; ^(b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 127 Czech Technical University in Prague, Praha, Czech Republic
- 128 State Research Center Institute for High Energy Physics, Protvino, Russia
- 129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 130 Physics Department, University of Regina, Regina SK, Canada
- 131 Ritsumeikan University, Kusatsu, Shiga, Japan
- 132 ^(a)INFN Sezione di Roma I; ^(b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 133 ^(a)INFN Sezione di Roma Tor Vergata; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 134 ^(a)INFN Sezione di Roma Tre; ^(b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy
- 135 ^(a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b)Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e)Faculty of sciences, Mohammed V-Agdal University, Rabat, Morocco
- 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
- 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- 138 Department of Physics, University of Washington, Seattle WA, United States of America
- 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 140 Department of Physics, Shinshu University, Nagano, Japan
- 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
- 144 ^(a)Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 145 ^(a)Department of Physics, University of Johannesburg, Johannesburg; ^(b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 146 ^(a)Department of Physics, Stockholm University; ^(b)The Oskar Klein Centre, Stockholm, Sweden
- 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 150 School of Physics, University of Sydney, Sydney, Australia
- 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 152 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
- 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 158 Department of Physics, University of Toronto, Toronto ON, Canada
- 159 ^(a)TRIUMF, Vancouver BC; ^(b)Department of Physics and Astronomy, York University, Toronto ON, Canada
- 160 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
- 161 Science and Technology Center, Tufts University, Medford MA, United States of America
- 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- 164 ^(a)INFN Gruppo Collegato di Udine; ^(b)ICTP, Trieste; ^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 165 Department of Physics, University of Illinois, Urbana IL, United States of America

- ¹⁶⁶ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁷ 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
- ¹⁶⁸ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷¹ Waseda University, Tokyo, Japan
- ¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷³ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁵ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁶ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁸ Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
- ^a Also at Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ^b Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal
- ^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^d Also at TRIUMF, Vancouver BC, Canada
- ^e Also at Department of Physics, California State University, Fresno CA, United States of America
- ^f Also at Novosibirsk State University, Novosibirsk, Russia
- ^g Also at Fermilab, Batavia IL, United States of America
- ^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy
- ^j Also at Institute of Particle Physics (IPP), Canada
- ^k Also at Department of Physics, Middle East Technical University, Ankara, Turkey
- ^l Also at Louisiana Tech University, Ruston LA, United States of America
- ^m Also at Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁿ Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ^o Also at Department of Physics, University of Cape Town, Cape Town, South Africa
- ^p Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^q Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^r Also at Manhattan College, New York NY, United States of America
- ^s Also at School of Physics, Shandong University, Shandong, China
- ^t Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^u Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
- ^v Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^w Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- ^x Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
- ^y Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ^z Also at Departamento de Física, Universidade de Minho, Braga, Portugal
- ^{aa} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ^{ab} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{ac} Also at California Institute of Technology, Pasadena CA, United States of America
- ^{ad} Also at Institute of Physics, Jagiellonian University, Krakow, Poland
- ^{ae} Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
- ^{af} Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ^{ag} Also at Department of Physics, Oxford University, Oxford, United Kingdom
- ^{ah} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{ai} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- * Deceased