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G. Aad, S. Albrand, J. Brown, J. Collot, S. Crépé-Renaudin, B. Dechenaux, P.A. Delsart, C. Gabaldon, M.H. Genest, J.Y. Hostachy, et al.

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G. Aad, S. Albrand, J. Brown, J. Collot, S. Crépé-Renaudin, et al.. Measurement of Spin Correlation in Top-Antitop Quark Events and Search for Top Squark Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV Using the ATLAS Detector. Physical Review Letters, 2015, 114 (14), pp.142001. 10.1103/PhysRevLett.114.142001 . in2p3-01095656

HAL Id: in2p3-01095656

<https://in2p3.hal.science/in2p3-01095656v1>

Submitted on 7 Sep 2023

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CERN-PH-EP-2014-257

Submitted to: PRL

arXiv:1412.4742v2 [hep-ex] 20 Apr 2015

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The ATLAS Collaboration

Abstract

A measurement of spin correlation in $t\bar{t}$ production is presented using data collected with the ATLAS detector at the Large Hadron Collider in proton–proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 20.3 fb^{-1} . The correlation between the top and antitop quark spins is extracted from dilepton $t\bar{t}$ events by using the difference in azimuthal angle between the two charged leptons in the laboratory frame. In the helicity basis the measured degree of correlation corresponds to $A_{\text{helicity}} = 0.38 \pm 0.04$, in agreement with the Standard Model prediction. A search is performed for pair production of top squarks with masses close to the top quark mass decaying to predominantly right-handed top quarks and a light neutralino, the lightest supersymmetric particle. Top squarks with masses between the top quark mass and 191 GeV are excluded at the 95% confidence level.

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PACS numbers: 14.65.Ha, 14.80.Ly, 12.38.Qk, 13.85.Qk, 11.30.Pb, 12.60.Jv

Detailed studies of the correlation of the spin of top and antitop quarks in $t\bar{t}$ events produced at hadron colliders are of great interest; they provide important precision tests of the predictions of the Standard Model (SM) and are sensitive to many new physics scenarios [1–16]. The orientations of the top and antitop quark spins are transferred to the decay products and can be measured directly via their angular distributions [3, 17–36]. The strength of their correlation has been studied previously by the CDF and D0 collaborations in proton–antiproton scattering at 1.98 TeV [37–40] and by the ATLAS and CMS collaborations in proton–proton scattering at 7 TeV [41–43].

In this Letter the first measurement of $t\bar{t}$ spin correlation in proton–proton collisions at a center-of-mass energy of 8 TeV is presented. Because the polarization-analyzing power of the angular distributions of charged leptons from top and antitop quark decays is effectively 100% [44, 45], dilepton final states of ee , $\mu\mu$ and $e\mu$ are analyzed. An observable very sensitive to $t\bar{t}$ spin correlation is the azimuthal angle $\Delta\phi$ between the charged leptons [34], which is also well measured by the ATLAS detector.

First, the measurement of $\Delta\phi$ is used to extract the spin correlation strength $A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}}$, where N_{like} (N_{unlike}) is the number of events where the top quark and top antiquark spins are parallel (anti-parallel) with respect to the spin quantization axis. This axis is chosen to be that of the helicity basis, using the direction of flight of the top quark in the center-of-mass frame of the $t\bar{t}$ system. Second, to study a specific model that predicts zero spin correlation, a search for supersymmetric (SUSY) top squark pair production is performed.

At the Large Hadron Collider (LHC), the SUSY partners of the top quark, the top squarks, could be produced in pairs. Models with light top squarks are particularly attractive since they provide a solution to the hierarchy problem [46–49]. In such models, the mass $m_{\tilde{t}_1}$ of the lighter top squark mass eigenstate \tilde{t}_1 could be close to the mass of the top quark m_t [50, 51]. If the lightest SUSY particle, the neutralino $\tilde{\chi}_1^0$ (or alternatively the gravitino), is light and the

top squark mass is only slightly larger than the top quark mass, two-body decays $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ in which the momentum of $\tilde{\chi}_1^0$ is very small can predominate [16]. The masses of all other SUSY particles are assumed to be large. In SUSY models where R -parity is conserved, such as the Minimal Supersymmetric Standard Model (MSSM) [52–56], this could lead to $t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$ intermediate states, appearing like SM $t\bar{t}$ production with additional missing transverse momentum carried away by the escaping neutralinos, making traditional searches exploiting kinematic differences as presented in Refs. [57–63] very difficult. $\tilde{t}_1\tilde{t}_1$ events can be distinguished from SM $t\bar{t}$ events through an increase of the measured $t\bar{t}$ cross section as analyzed in Ref. [64], and since top squarks have zero spin, through measuring angular correlations sensitive to spin correlation, as analyzed in this Letter.

A description of the ATLAS detector can be found elsewhere [65]. This analysis uses proton–proton collision data with a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb^{-1} .

Monte Carlo (MC) simulation samples are used to evaluate the contributions, and shapes of distributions of kinematic variables, for signal $t\bar{t}$ events and for background processes not evaluated from complementary data samples. All MC samples are processed with the GEANT4 [66] simulation of the ATLAS detector [67] and are passed through the same analysis chain as data. The simulation includes multiple proton–proton interactions per bunch crossing (pile-up). Events are weighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data.

Samples of $t\bar{t}$ events with SM spin correlation and without spin correlation are generated using MC@NLO v4.06 [68, 69] interfaced to HERWIG v6.520 [70] for shower simulation and hadronization. Both samples are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71, 72]. The CT10 parton distribution function (PDF) set [73] is used. For the sample with no spin correlation, the parton shower simu-

lation performs isotropic decays of the top quarks whereas the full matrix element is used for the generation of the SM spin-correlation sample. The top quark mass is set to 172.5 GeV [74]. The production of a $t\bar{t}$ pair in association with a Z or W boson is simulated using MADGRAPH 5 [75] interfaced to PYTHIA v6.426 [76] and is normalized to the next-to-leading-order (NLO) quantum chromodynamics (QCD) cross sections [77].

Backgrounds to $t\bar{t}$ events with same-flavor dilepton final states arise from the Drell–Yan Z/γ^* +jets production process with the Z/γ^* boson decaying into e^+e^- , $\mu^+\mu^-$ and $\tau^+\tau^-$, followed by leptonic decays of the τ leptons. They are generated using the ALPGEN v2.13 [77] generator including leading-order (LO) matrix elements with up to five additional partons. The CTEQ6L1 PDF set [78] is used, and the cross section is normalized to the next-to-next-to-leading-order (NNLO) QCD prediction [79]. Parton showering and fragmentation are modeled by HERWIG, and multiparton interactions are simulated by JIMMY [80]. The ‘‘MLM’’ parton–jet matching scheme [81] is employed. Correction factors are derived from data in Z/γ^* +jets-dominated control regions and applied to the predicted yields in the signal region, to account for the difference between the simulation prediction and data.

Single top quark background from associated Wt production is modeled with POWHEG-BOX r2129 [82–85] interfaced with PYTHIA using the CT10 PDF set [73] and normalized to the approximate NNLO QCD theoretical cross section [86]. Single-top Zt and WZt production is generated by MADGRAPH 5 interfaced with PYTHIA.

The diboson (WW , WZ , ZZ) backgrounds are modeled using SHERPA v1.4.1 [87] and are normalized to the theoretical calculation at NLO QCD [88].

The background arising from the misidentified and non-prompt leptons (collectively referred to as ‘‘fake leptons’’) is determined from a combination of MC simulation of W +jets events using SHERPA, single-top events via t -channel exchange using MC@NLO+HERWIG, $t\bar{t}$ events with single-lepton final states using MC@NLO+HERWIG, and data using a technique known as the matrix method [89, 90].

Top squark pair-production samples are simulated using the HERWIG++ v2.6.1 [91] generator with the CTEQ6L1 PDFs [78]. The top squarks are assumed to decay exclusively via $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. The corresponding mixing matrices for the top squarks and for the neutralinos are chosen such that the top quark has a right-handed polarization in 95% of the decays.

Candidate events are selected in the dilepton topology. The analysis requires events selected online by inclusive single-lepton triggers (e or μ). Electron candidates are reconstructed from an isolated electromagnetic calorimeter energy deposit matched to a charged-particle track in the inner detector and must pass ‘medium identification requirements’ [92]. Muon candidates were reconstructed by combining tracks reconstructed in both the inner de-

tor and muon spectrometer [93]. Jets are reconstructed from clusters of adjacent calorimeter cells [65, 94] using the anti- k_t algorithm [95–97] with a radius parameter $R = 0.4$. Jets originating from b -quarks were identified (‘tagged’) using a multivariate discriminant employing the long lifetime, high decay multiplicity, hard fragmentation and high mass of B hadrons [98, 99]. The missing transverse momentum (E_T^{miss}) is reconstructed as the magnitude of a vector sum of all calorimeter cell energies associated with topological clusters [100]. The following kinematic requirements are made:

- Electron candidates are required to have transverse momentum of $p_T > 25$ GeV and pseudorapidity¹ of $|\eta| < 2.47$, excluding electrons from the transition region between the barrel and end-cap calorimeters defined by $1.37 < |\eta| < 1.52$. Muon candidates are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. Events must have exactly two oppositely charged lepton candidates (e^+e^- , $\mu^+\mu^-$, $e^\pm\mu^\mp$).
- Events must have at least two jets (after having removed the jet closest to the electron, if there are jets within a cone of $\Delta R = 0.2$ around a selected electron) with $p_T > 25$ GeV and $|\eta| < 2.5$. At least one jet must be identified as a b -jet using a requirement in the multivariate discriminant corresponding to a 70% b -tagging efficiency.
- Events in the e^+e^- and $\mu^+\mu^-$ channels must satisfy $E_T^{\text{miss}} > 30$ GeV to suppress backgrounds from Drell–Yan Z/γ^* +jets and W +jets events.
- Events in the e^+e^- and $\mu^+\mu^-$ channels are required to have $m_{\ell\ell} > 15$ GeV (where ℓ indicates e or μ) to ensure compatibility with the simulated backgrounds and to remove contributions from Υ and J/ψ production. In addition, $m_{\ell\ell}$ must differ by at least 10 GeV from the Z boson mass ($m_Z = 91$ GeV) to further suppress the Z/γ^* +jets background.
- For the $e^\pm\mu^\mp$ channel, no E_T^{miss} or $m_{\ell\ell}$ requirements are applied. In this case, the remaining background from $Z/\gamma^*(\rightarrow \tau\tau)$ +jets production is further suppressed by requiring that the scalar sum of the p_T of all selected jets and leptons is greater than 130 GeV.

The expected numbers of $t\bar{t}$ signal and background events are compared to data in Table I. The expected yield for top squark pair production with a top squark mass of 180 GeV and a neutralino mass of 1 GeV is also shown.

Figure 1 shows the reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels. A binned log-

¹The pseudorapidity η is defined via the polar angle θ as $\eta = -\ln \tan(\theta/2)$ [65].

Process	Yield
$t\bar{t}$	$54000 \pm^{3400}_{-3600}$
$Z/\gamma^* + \text{jets}$	2800 ± 300
tV (single top)	2600 ± 180
$t\bar{t}V$	80 ± 11
WW, WZ, ZZ	180 ± 65
Fake leptons	780 ± 780
Total non- $t\bar{t}$	6400 ± 860
Expected	$60000 \pm^{3500}_{-3700}$
Observed	60424
$\tilde{t}_1\tilde{t}_1$	7100 ± 1100

$(m_{\tilde{t}_1} = 180 \text{ GeV}, m_{\tilde{\chi}_1^0} = 1 \text{ GeV})$

TABLE I. Observed dilepton yield in data and the expected SUSY and $t\bar{t}$ signals and background contributions. Systematic uncertainties due to theoretical cross sections and systematic uncertainties evaluated for data-driven backgrounds are included in the uncertainties.

likelihood fit is used to extract the spin correlation from the $\Delta\phi$ distribution in data. This is done by defining a coefficient f_{SM} that measures the degree of spin correlation relative to the SM prediction. The fit includes a linear superposition of the $\Delta\phi$ distribution from SM $t\bar{t}$ MC simulation with coefficient f_{SM} , and from the $t\bar{t}$ simulation without spin correlation with coefficient $(1 - f_{\text{SM}})$. The e^+e^- , $\mu^+\mu^-$ and $e^\pm\mu^\mp$ channels are fitted simultaneously with a common value of f_{SM} , leaving the $t\bar{t}$ normalization free with a fixed background normalization. The $t\bar{t}$ normalization obtained by the fit agrees with the theoretical prediction of the production cross section [71] within the uncertainties. Negative values of f_{SM} correspond to an anti-correlation of the top and antitop quark spins. A value of $f_{\text{SM}} = 0$ implies that the spins are uncorrelated and values of $f_{\text{SM}} > 1$ indicate a degree of $t\bar{t}$ spin correlation larger than predicted by the SM.

Systematic uncertainties are evaluated by applying the fit procedure to pseudo-experiments created from simulated samples modified to reflect the systematic variations. The fit of f_{SM} is repeated to determine the effect of each systematic uncertainty using the nominal templates. The difference between the means of Gaussian fits to the results from many pseudo-experiments using nominal and modified pseudo-data is taken as the systematic uncertainty on f_{SM} [102].

The various systematic uncertainties are estimated in the same way as in Ref. [42] with the following exceptions: since this analysis employs b -tagging, the associated uncertainty is estimated by varying the relative normalizations of simulated b -jet, c -jet and light-jet samples. The uncertainty due the choice of generator is determined by comparing the default to an alternative $t\bar{t}$ sample generated with the POWHEG-BOX generator interfaced with PYTHIA.

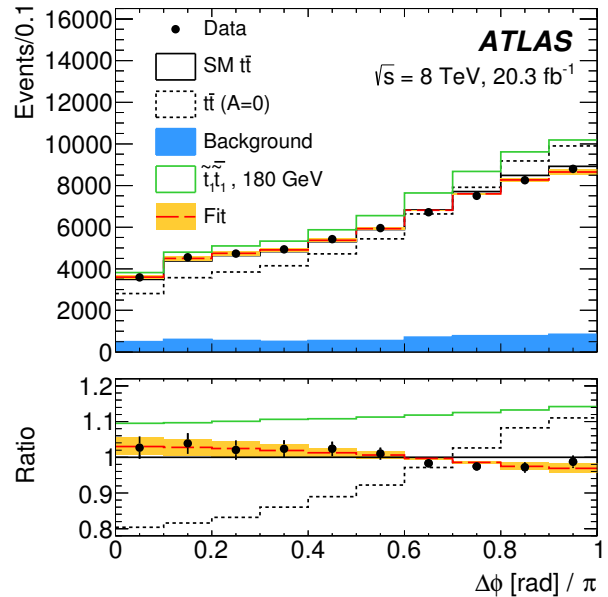


FIG. 1. Reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels. The prediction for background (blue histogram) plus SM $t\bar{t}$ production (solid black histogram) and background plus $t\bar{t}$ prediction with no spin correlation (dashed black histogram) is compared to the data and to the result of the fit to the data (red dashed histogram) with the orange band representing the total systematic uncertainty on f_{SM} . Both the SM $t\bar{t}$ and the no spin correlation $t\bar{t}$ predictions are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71, 72] (the theory uncertainty of 7% on this cross section is not displayed). The prediction for $\tilde{t}_1\tilde{t}_1$ production ($m_{\tilde{t}_1} = 180 \text{ GeV}$ and $m_{\tilde{\chi}_1^0} = 1 \text{ GeV}$) normalized to the NLO cross section including next-to-leading-logarithm corrections [101] plus SM $t\bar{t}$ production plus background is also shown (solid green histogram). The lower plot shows those distributions (except for background only) divided by the SM $t\bar{t}$ plus background prediction.

The uncertainty due to the parton shower and hadronization model is determined by comparing two $t\bar{t}$ samples generated by ALPGEN, one interfaced with PYTHIA and the other one interfaced with HERWIG. The uncertainty on the amount of initial- and final-state radiation (ISR/FSR) in the simulated $t\bar{t}$ sample is assessed by comparing ALPGEN events, showered with PYTHIA, with varied amounts of ISR and FSR. As in Ref. [42], the size of the variation is compatible with the recent measurements of additional jet activity in $t\bar{t}$ events [103]. The Wt normalization is varied within the theoretical uncertainties of the cross-section calculation [86], and the sensitivity to the interference between Wt production and $t\bar{t}$ production at NLO is studied by comparing the predictions of POWHEG-BOX with the diagram-removal (baseline) and diagram-subtraction schemes [85, 104]. As in Ref. [42], the uncertainty due to the top quark mass is evaluated but not included in the systematic uncertainties, since it would have no significant

Source of uncertainty	Δf_{SM}
Detector modeling	
Lepton reconstruction	± 0.01
Jet energy scale	± 0.02
Jet reconstruction	± 0.01
$E_{\text{T}}^{\text{miss}}$	< 0.01
Fake leptons	< 0.01
b -tagging	< 0.01
Signal and background modeling	
Renormalization/factorization scale	± 0.05
MC generator	± 0.03
Parton shower and fragmentation	± 0.06
ISR/FSR	± 0.06
Underlying event	± 0.04
Color reconnection	± 0.01
PDF uncertainty	± 0.05
Background	± 0.01
MC statistics	± 0.04
Total systematic uncertainty	± 0.13
Data statistics	± 0.05

TABLE II. Summary of systematic uncertainties on f_{SM} in the combined dilepton final state.

impact on the results.

The sizes of the systematic uncertainties in terms of Δf_{SM} are listed in Table II. The total systematic uncertainty is calculated by combining all systematic uncertainties in quadrature.

The measured value of f_{SM} for the combined fit is 1.20 ± 0.05 (stat) ± 0.13 (syst). This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41, 42], and compares to the best previous measurement using $\Delta\phi$ of $f_{\text{SM}} = 1.19 \pm 0.09$ (stat) ± 0.18 (syst) [42]. It also agrees with the SM prediction to within two standard deviations.

This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41, 42] and agrees with the SM prediction to within two standard deviations. An indirect extraction of A_{helicity} can be achieved by assuming that the $t\bar{t}$ sample is composed of top quark pairs as predicted by the SM, but with varying spin correlation. In that case, a change in the fraction f_{SM} leads to a linear change of A_{helicity} (see also Ref. [42]), and a value of the spin correlation strength in the helicity basis A_{helicity} at a center-of-mass energy of 8 TeV is obtained by applying the measured value of f_{SM} as a multiplicative factor to the SM prediction of $A_{\text{helicity}}^{\text{SM}} = 0.318 \pm 0.005$ [36]. This yields a measured value of $A_{\text{helicity}} = 0.38 \pm 0.04$.

The measurement of the variable $\Delta\phi$ is also used to search for top squark pair production with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ de-

cays. The present analysis is sensitive both to changes in the yield and to changes in the shape of the $\Delta\phi$ distribution caused by a potential admixture of $\tilde{t}_1\tilde{t}_1$ with the SM $t\bar{t}$ sample. An example is shown in Fig. 1, where the effect of $\tilde{t}_1\tilde{t}_1$ production in addition to SM $t\bar{t}$ production and backgrounds is compared to data. No evidence for $\tilde{t}_1\tilde{t}_1$ production was found.

Limits are set on the top squark pair-production cross section by fitting each bin of the $\Delta\phi$ distribution to the difference between the data and the SM prediction, varying the top squark signal strength μ . In contrast to the measurement of f_{SM} where the $t\bar{t}$ cross section is varied in the fit, here the $t\bar{t}$ cross section is fixed to its SM value [71]. In addition, a systematic uncertainty of 7% is introduced, composed of factorization and renormalization scale variation, top quark mass uncertainty, PDF uncertainty and uncertainty in the measurement of the beam energy. All other sources of systematic uncertainty are identical to ones in the measurement of f_{SM} . All shape-dependent modeling uncertainties on the SUSY signal are found to be negligible. The limits are determined using a profile likelihood ratio in the asymptotic limit [105], using nuisance parameters to account for the theoretical and experimental uncertainties.

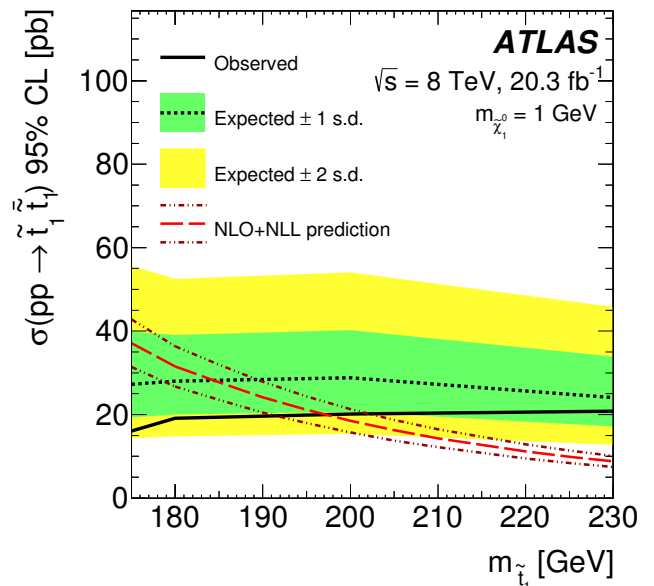


FIG. 2. Expected and observed limits at 95% CL on the top squark pair-production cross section as a function of $m_{\tilde{t}_1}$, for pair-produced top squarks \tilde{t}_1 decaying with 100% branching ratio via $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ to predominantly right-handed top quarks, assuming $m_{\tilde{\chi}_1^0} = 1$ GeV. The black dotted line shows the expected limit with ± 1 (green) and ± 2 (green+yellow) standard deviation contours, taking into account all uncertainties. The red dashed line shows the theoretical cross section with uncertainties. The solid black line gives the observed limit.

The observed and expected limits on the top squark

pair-production cross section at the 95% confidence level (CL) are extracted using the CLs prescription [106] and are shown in Fig. 2. Adopting the convention of reducing the estimated SUSY production cross section by one standard deviation of its theoretical uncertainty (15%, coming from PDFs and QCD scale uncertainties [107]), top squark masses between the top quark mass and 191 GeV are excluded, assuming a 100% branching ratio for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and $m_{\tilde{\chi}_1^0} = 1$ GeV. The expected limit is 178 GeV. In the presented range of $m_{\tilde{t}_1}$, within the allowed phase space, varying the neutralino mass does not affect the cross-section limits by more than a few percent. If the top quarks are produced with full left-handed polarization, the expected limits change by less than 10% compared to the predominantly right-handed case.

If the $t\bar{t}$ cross-section normalization were arbitrary and not fixed to its theory prediction, the expected cross-section limit would increase by approximately 30%. If, on the other hand, the shape information of $\Delta\phi$ were not used in the fit, the expected cross-section limit would increase by 30-40%.

The constraints on the top squark mass presented here improve previous limits in a region not explored before, to top squark masses larger than limits from Ref. [64] and to top squark masses lower than limits from analyses exploring kinematic distributions as presented in Ref. [61].

In conclusion, the first measurement of $t\bar{t}$ spin correlation in proton-proton scattering at a center-of-mass energy of 8 TeV at the LHC has been presented using 20.3 fb⁻¹ of ATLAS data in the dilepton decay topology. A template fit is performed to the $\Delta\phi$ distribution and the measured value of $f_{SM} = 1.20 \pm 0.05$ (stat) ± 0.13 (syst) is consistent with the SM prediction. This represents the most precise measurement to date. The results have been used to search for pair-produced supersymmetric top squarks decaying to top quarks and light neutralinos. Assuming 100% branching ratio for the decay $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, and the production of predominantly right-handed top quarks, top squark masses between the top quark mass and 191 GeV are excluded at 95% CL, which is an improvement over previous constraints.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions with whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, 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, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan;

CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, 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

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Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso⁴⁸, N. Amram¹⁵⁴, G. Amundsen²³, C. Anastopoulos¹⁴⁰, L.S. Ancu⁴⁹, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders³⁰, K.J. Anderson³¹, A. Andreazza^{91a,91b}, V. Andrei^{58a}, X.S. Anduaga⁷¹, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov^{109,c}, N. Anjos¹², A. Annovi⁴⁷, M. Antonelli⁴⁷, A. Antonov⁹⁸, J. Antos^{145b}, F. Anulli^{133a}, M. Aoki⁶⁶, L. Aperio Bella¹⁸, G. Arabidze⁹⁰, Y. Arai⁶⁶, J.P. Araque^{126a}, A.T.H. Arce⁴⁵, F.A. Arduh⁷¹, J-F. Arguin⁹⁵, S. Argyropoulos⁴², M. Arik^{19a}, A.J. Armbruster³⁰, O. Arnaez³⁰, V. Arnal⁸², H. Arnold⁴⁸, M. Arratia²⁸, O. Arslan²¹, A. Artamonov⁹⁷, G. Artoni²³, S. Asai¹⁵⁶, N. Asbah⁴², A. Ashkenazi¹⁵⁴, B. Åsman^{147a,147b}, L. Asquith¹⁵⁰, K. Assamagan²⁵, R. Astalos^{145a}, M. Atkinson¹⁶⁶, N.B. Atlay¹⁴², B. Auerbach⁶, K. Augsten¹²⁸, M. Auresseau^{146b}, G. Avolio³⁰, B. Axen¹⁵, G. Azuelos^{95,d}, Y. Azuma¹⁵⁶, M.A. Baak³⁰, A.E. 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Brandt^{58a}, U. Bratzler¹⁵⁷, B. Brau⁸⁶, J.E. Brau¹¹⁶, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelier¹⁵⁹, K. Brendlinger¹²², A.J. Brennan⁸⁸, R. Brenner¹⁶⁷, S. Bressler¹⁷³, K. Bristow^{146c}, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹, R. Brock⁹⁰, J. Bronner¹⁰¹, G. Brooijmans³⁵, T. Brooks⁷⁷, W.K. Brooks^{32b}, J. Brosamer¹⁵, E. Brost¹¹⁶, J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{145b}, R. Brunelieire⁴⁸, S. Brunet⁶¹, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸¹, T. Buanes¹⁴, Q. Buat¹⁴³, F. Bucci⁴⁹, P. Buchholz¹⁴², A.G. Buckley⁵³, S.I. Buda^{26a}, I.A. Budagov⁶⁵, F. Buehrer⁴⁸, L. Bugge¹¹⁹, M.K. Bugge¹¹⁹, O. Bulekov⁹⁸, A.C. Bundock⁷⁴, H. Burckhart³⁰, S. Burdin⁷⁴, B. Burghgrave¹⁰⁸, S. Burke¹³¹, I. Burmeister⁴³, E. Busato³⁴, D. Büscher⁴⁸, V. Büscher⁸³, P. Bussey⁵³, C.P. Buszello¹⁶⁷, B. Butler⁵⁷, J.M. Butler²², A.I. Butt³, C.M. Buttar⁵³, J.M. Butterworth⁷⁸, P. Butti¹⁰⁷, W. Buttinger²⁸, A. Buzatu⁵³, M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁸, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, A. Calandri¹³⁷, G. Calderini⁸⁰, P. Calfayan¹⁰⁰, L.P. Caloba^{24a}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹, S. Camarda⁴², D. Cameron¹¹⁹, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰, M. Campanelli⁷⁸, A. Campoverde¹⁴⁹, V. Canale^{104a,104b},

A. Canepa^{160a}, M. Cano Bret⁷⁶, J. Cantero⁸², R. Cantrill^{126a}, T. Cao⁴⁰, M.D.M. Capeans Garrido³⁰, I. Caprini^{26a},
 M. Caprini^{26a}, M. Capua^{37a,37b}, R. Caputo⁸³, R. Cardarelli^{134a}, T. Carli³⁰, G. Carlino^{104a}, L. Carminati^{91a,91b},
 S. Caron¹⁰⁶, E. Carquin^{32a}, G.D. Carrillo-Montoya^{146c}, J.R. Carter²⁸, J. Carvalho^{126a,126c}, D. Casadei⁷⁸, M.P. Casado¹²,
 M. Casolino¹², E. Castaneda-Miranda^{146b}, A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁸, N.F. Castro^{126a}, P. Catastini⁵⁷,
 A. Catinaccio³⁰, J.R. Catmore¹¹⁹, A. Cattai³⁰, G. Cattani^{134a,134b}, J. Caudron⁸³, V. Cavaliere¹⁶⁶, D. Cavalli^{91a},
 M. Cavalli-Sforza¹², V. Cavasinni^{124a,124b}, F. Ceradini^{135a,135b}, B.C. Cerio⁴⁵, K. Cerny¹²⁹, A.S. Cerqueira^{24b},
 A. Cerri¹⁵⁰, L. Cerrito⁷⁶, F. Cerutti¹⁵, M. Cervy³⁰, A. Cervelli¹⁷, S.A. Cetin^{19b}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁸,
 I. Chalupkova¹²⁹, P. Chang¹⁶⁶, B. Chapleau⁸⁷, J.D. Chapman²⁸, D. Charfeddine¹¹⁷, D.G. Charlton¹⁸, C.C. Chau¹⁵⁹,
 C.A. Chavez Barajas¹⁵⁰, S. Cheatham¹⁵³, A. Chegwiddden⁹⁰, S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov^{65,g},
 M.A. Chelstowska⁸⁹, C. Chen⁶⁴, H. Chen²⁵, K. Chen¹⁴⁹, L. Chen^{33d,h}, S. Chen^{33c}, X. Chen^{33f}, Y. Chen⁶⁷, H.C. Cheng⁸⁹,
 Y. Cheng³¹, A. Cheplakov⁶⁵, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{25,*}, E. Cheu⁷,
 L. Chevalier¹³⁷, V. Chiarella⁴⁷, G. Chiefari^{104a,104b}, J.T. Childers⁶, A. Chilingarov⁷², G. Chiodini^{73a}, A.S. Chisholm¹⁸,
 R.T. Chislett⁷⁸, A. Chitan^{26a}, M.V. Chizhov⁶⁵, S. Chouridou⁹, B.K.B. Chow¹⁰⁰, D. Chromek-Burckhart³⁰, M.L. Chu¹⁵²,
 J. Chudoba¹²⁷, J.J. Chwastowski³⁹, L. Chytka¹¹⁵, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁵³, V. Cindro⁷⁵,
 A. Ciocio¹⁵, Z.H. Citron¹⁷³, M. Citterio^{91a}, M. Ciubancan^{26a}, A. Clark⁴⁹, P.J. Clark⁴⁶, R.N. Clarke¹⁵, W. Cleland¹²⁵,
 J.C. Clemens⁸⁵, C. Clement^{147a,147b}, Y. Coadou⁸⁵, M. Cobal^{165a,165c}, A. Cocco¹³⁹, J. Cochran⁶⁴, L. Coffey²³,
 J.G. Cogan¹⁴⁴, B. Cole³⁵, S. Cole¹⁰⁸, A.P. Colijn¹⁰⁷, J. Collot⁵⁵, T. Colombo^{58c}, G. Compostella¹⁰¹,
 P. Conde Muiño^{126a,126b}, E. Coniavitis⁴⁸, S.H. Connell^{146b}, I.A. Connelly⁷⁷, S.M. Consonni^{91a,91b}, V. Consorti⁴⁸,
 S. Constantinescu^{26a}, C. Conta^{121a,121b}, G. Conti⁵⁷, F. Conventi^{104a,i}, M. Cooke¹⁵, B.D. Cooper⁷⁸,
 A.M. Cooper-Sarkar¹²⁰, N.J. Cooper-Smith⁷⁷, K. Copic¹⁵, T. Cornelissen¹⁷⁶, M. Corradi^{20a}, F. Corriveau^{87,j},
 A. Corso-Radu¹⁶⁴, A. Cortes-Gonzalez¹², G. Cortiana¹⁰¹, G. Costa^{91a}, M.J. Costa¹⁶⁸, D. Costanzo¹⁴⁰, D. Côté⁸,
 G. Cottin²⁸, G. Cowan⁷⁷, B.E. Cox⁸⁴, K. Cranmer¹¹⁰, G. Cree²⁹, S. Crépe-Renaudin⁵⁵, F. Crescioli⁸⁰,
 W.A. Cribbs^{147a,147b}, M. Crispin Ortuzar¹²⁰, M. Cristinziani²¹, V. Croft¹⁰⁶, G. Crosetti^{37a,37b},
 T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁷, M. Curatolo⁴⁷, C. Cuthbert¹⁵¹, H. Czirr¹⁴², P. Czodrowski³, S. D'Auria⁵³,
 M. D'Onofrio⁷⁴, M.J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁴, W. Dabrowski^{38a}, A. Dafinca¹²⁰, T. Dai⁸⁹,
 O. Dale¹⁴, F. Dallaire⁹⁵, C. Dallapiccola⁸⁶, M. Dam³⁶, A.C. Daniells¹⁸, M. Danninger¹⁶⁹, M. Dano Hoffmann¹³⁷,
 V. Dao⁴⁸, G. Darbo^{50a}, S. Darmora⁸, J. Dassoulas⁷⁴, A. Dattagupta⁶¹, W. Davey²¹, C. David¹⁷⁰, T. Davidek¹²⁹,
 E. Davies^{120,k}, M. Davies¹⁵⁴, O. Davignon⁸⁰, A.R. Davison⁷⁸, P. Davison⁷⁸, Y. Davygora^{58a}, E. Dawe¹⁴³, I. Dawson¹⁴⁰,
 R.K. Daya-Ishmukhametova⁸⁶, K. De⁸, R. de Asmundis^{104a}, S. De Castro^{20a,20b}, S. De Cecco⁸⁰, N. De Groot¹⁰⁶,
 P. de Jong¹⁰⁷, H. De la Torre⁸², F. De Lorenzi⁶⁴, L. De Nooij¹⁰⁷, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis¹⁵⁰,
 A. De Santo¹⁵⁰, J.B. De Vivie De Regie¹¹⁷, W.J. Dearnaley⁷², R. Debbes²⁵, C. Debenedetti¹³⁸, B. Dechenaux⁵⁵,
 D.V. Dedovich⁶⁵, I. Deigaard¹⁰⁷, J. Del Peso⁸², T. Del Prete^{124a,124b}, F. Deliot¹³⁷, C.M. Delitzsch⁴⁹, M. Deliyergiyev⁷⁵,
 A. Dell'Acqua³⁰, L. Dell'Asta²², M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,i}, D. della Volpe⁴⁹, M. Delmastro⁵,
 P.A. Delsart⁵⁵, C. Deluca¹⁰⁷, D.A. DeMarco¹⁵⁹, S. Demers¹⁷⁷, M. Demichev⁶⁵, A. Demilly⁸⁰, S.P. Denisov¹³⁰,
 D. Derendarz³⁹, J.E. Derkaoui^{136d}, F. Derue⁸⁰, P. Dervan⁷⁴, K. Desch²¹, C. Deterre⁴², P.O. Deviveiros³⁰,
 A. Dewhurst¹³¹, S. Dhaliwal¹⁰⁷, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, A. Di Domenico^{133a,133b}, C. Di Donato^{104a,104b},
 A. Di Girolamo³⁰, B. Di Girolamo³⁰, A. Di Mattia¹⁵³, B. Di Micco^{135a,135b}, R. Di Nardo⁴⁷, A. Di Simone⁴⁸,
 R. Di Sipio^{20a,20b}, D. Di Valentino²⁹, F.A. Dias⁴⁶, M.A. Diaz^{32a}, E.B. Diehl⁸⁹, J. Dietrich¹⁶, T.A. Dietzsch^{58a},
 S. Diglio⁸⁵, A. Dimitrievska^{13a}, J. Dingfelder²¹, P. Dita^{26a}, S. Dita^{26a}, F. Dittus³⁰, F. Djama⁸⁵, T. Djobava^{51b},
 J.I. Djuvsland^{58a}, M.A.B. do Vale^{24c}, D. Dobos³⁰, C. Doglioni⁴⁹, T. Doherty⁵³, T. Dohmae¹⁵⁶, J. Dolejsi¹²⁹,
 Z. Dolezal¹²⁹, B.A. Dolgoshein^{98,*}, M. Donadelli^{24d}, S. Donati^{124a,124b}, P. Dondero^{121a,121b}, J. Donini³⁴, J. Dopke¹³¹,
 A. Doria^{104a}, M.T. Dova⁷¹, A.T. Doyle⁵³, M. Dris¹⁰, J. Dubbert⁸⁹, S. Dube¹⁵, E. Dubreuil³⁴, E. Duchovni¹⁷³,
 G. Duckeck¹⁰⁰, O.A. Ducu^{26a}, D. Duda¹⁷⁶, A. Dudarev³⁰, F. Dudziak⁶⁴, L. Dufloc¹¹⁷, L. Duguid⁷⁷, M. Dührssen³⁰,
 M. Dunford^{58a}, H. Duran Yildiz^{4a}, M. Düren⁵², A. Durglishvili^{51b}, D. Duschinger⁴⁴, M. Dwuznik^{38a}, M. Dyndal^{38a},
 W. Edson², N.C. Edwards⁴⁶, W. Ehrenfeld²¹, T. Eifert³⁰, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁷, M. El Kacimi^{136c},
 M. Ellert¹⁶⁷, S. Elles⁵, F. Ellinghaus⁸³, A.A. Elliot¹⁷⁰, N. Ellis³⁰, J. Elmsheuser¹⁰⁰, M. Elsing³⁰, D. Emelianov¹³¹,
 Y. Enari¹⁵⁶, O.C. Endner⁸³, M. Endo¹¹⁸, R. Engelmann¹⁴⁹, J. Erdmann⁴³, A. Ereditato¹⁷, D. Eriksson^{147a}, G. Ernis¹⁷⁶,
 J. Ernst², M. Ernst²⁵, J. Erwein¹³⁷, S. Errede¹⁶⁶, E. Ertel⁸³, M. Escalier¹¹⁷, H. Esch⁴³, C. Escobar¹²⁵, B. Esposito⁴⁷,
 A.I. Etienvre¹³⁷, E. Etzion¹⁵⁴, H. Evans⁶¹, A. Ezhilov¹²³, L. Fabbri^{20a,20b}, G. Facini³¹, R.M. Fakhruddinov¹³⁰,
 S. Falciano^{133a}, R.J. Falla⁷⁸, J. Faltova¹²⁹, Y. Fang^{33a}, M. Fanti^{91a,91b}, A. Farbin⁸, A. Farilla^{135a}, T. Faroque¹²,
 S. Farrell¹⁵, S.M. Farrington¹⁷¹, P. Farthouat³⁰, F. Fassi^{136e}, P. Fassnacht³⁰, D. Fassouliotis⁹, A. Favareto^{50a,50b},
 L. Fayard¹¹⁷, P. Federic^{145a}, O.L. Fedin^{123,l}, W. Fedorko¹⁶⁹, S. Feigl³⁰, L. Feligioni⁸⁵, C. Feng^{33d}, E.J. Feng⁶,
 H. Feng⁸⁹, A.B. Fenyuk¹³⁰, P. Fernandez Martinez¹⁶⁸, S. Fernandez Perez³⁰, S. Ferrag⁵³, J. Ferrando⁵³, A. Ferrari¹⁶⁷,
 P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁸, D. Ferrere⁴⁹, C. Ferretti⁸⁹, A. Ferretto Parodi^{50a,50b},
 M. Fiascaris³¹, F. Fiedler⁸³, A. Filipčić⁷⁵, M. Filipuzzi⁴², F. Filthaut¹⁰⁶, M. Fincke-Keeler¹⁷⁰, K.D. Finelli¹⁵¹,
 M.C.N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁸, A. Firan⁴⁰, A. Fischer², J. Fischer¹⁷⁶, W.C. Fisher⁹⁰, E.A. Fitzgerald²³,

M. Flechl⁴⁸, I. Fleck¹⁴², P. Fleischmann⁸⁹, S. Fleischmann¹⁷⁶, G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁶, T. Flick¹⁷⁶, A. Floderus⁸¹, L.R. Flores Castillo^{60a}, M.J. Flowerdew¹⁰¹, A. Formica¹³⁷, A. Forti⁸⁴, D. Fournier¹¹⁷, H. Fox⁷², S. Fracchia¹², P. Francavilla⁸⁰, M. Franchini^{20a,20b}, S. Franchino³⁰, D. Francis³⁰, L. Franconi¹¹⁹, M. Franklin⁵⁷, M. Fraternali^{121a,121b}, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost¹²⁰, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸³, B.G. Fulsom¹⁴⁴, J. Fuster¹⁶⁸, C. Gabaldon⁵⁵, O. Gabizon¹⁷⁶, A. Gabrielli^{20a,20b}, A. Gabrielli^{133a,133b}, S. Gadatsch¹⁰⁷, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶¹, C. Galea¹⁰⁶, B. Galhardo^{126a,126c}, E.J. Gallas¹²⁰, B.J. Gallop¹³¹, P. Gallus¹²⁸, G. Galster³⁶, K.K. Gan¹¹¹, J. Gao^{33b,h}, Y.S. Gao^{144,e}, F.M. Garay Walls⁴⁶, F. Garberson¹⁷⁷, C. García¹⁶⁸, J.E. García Navarro¹⁶⁸, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴⁴, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{121a}, B. Gaur¹⁴², L. Gauthier⁹⁵, P. Gauzzi^{133a,133b}, I.L. Gavrilenko⁹⁶, C. Gay¹⁶⁹, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gece¹⁶⁹, C.N.P. Gee¹³¹, D.A.A. Geerts¹⁰⁷, Ch. Geich-Gimbel²¹, K. Gellerstedt^{147a,147b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{133a,133b}, M. George⁵⁴, S. George⁷⁷, D. Gerbaudo¹⁶⁴, A. Gershon¹⁵⁴, H. Ghazlane^{136b}, N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{133a,133b}, V. Giangiobbe¹², P. Giannetti^{124a,124b}, F. Gianotti³⁰, B. Gibbard²⁵, S.M. Gibson⁷⁷, M. Gilchriese¹⁵, T.P.S. Gillam²⁸, D. Gillberg³⁰, G. Gilles³⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{165a,165c}, R. Giordano^{104a,104b}, F.M. Giorgi^{20a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁷, D. Giugni^{91a}, C. Giuliani⁴⁸, M. Giulini^{58b}, B.K. Gjølsten¹¹⁹, S. Gkaitatzis¹⁵⁵, I. Gkialas¹⁵⁵, E.L. Gkougkousis¹¹⁷, L.K. Gladilin⁹⁹, C. Glasman⁸², J. Glatzer³⁰, P.C.F. Glaysheer⁴⁶, A. Glazov⁴², G.L. Glonti⁶², M. Goblirsch-Kolb¹⁰¹, J.R. Goddard⁷⁶, J. Godlewski³⁰, S. Goldfarb⁸⁹, T. Golling⁴⁹, D. Golubkov¹³⁰, A. Gomes^{126a,126b,126d}, L.S. Gomez Fajardo⁴², R. Gonçalves^{126a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, L. Gonella²¹, S. González de la Hoz¹⁶⁸, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁷, H.A. Gordon²⁵, I. Gorelov¹⁰⁵, B. Gorini³⁰, E. Gorini^{73a,73b}, A. Gorišek⁷⁵, E. Gornicki³⁹, A.T. Goshaw⁴⁵, C. Gössling⁴³, M.I. Gostkin⁶⁵, M. Gouighri^{136a}, D. Goujdami^{136c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁹, C. Goy⁵, H.M.X. Grabas¹³⁸, L. Graber⁵⁴, I. Grabowska-Bold^{38a}, P. Grafström^{20a,20b}, K.-J. Grahn⁴², J. Gramling⁴⁹, E. Gramstad¹¹⁹, S. Grancagnolo¹⁶, V. Grassi¹⁴⁹, V. Gratchev¹²³, H.M. Gray³⁰, E. Graziani^{135a}, O.G. Grebenyuk¹²³, Z.D. Greenwood^{79,m}, K. Gregersen⁷⁸, I.M. Gregor⁴², P. Grenier¹⁴⁴, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷², S. Grinstein^{12,n}, Ph. Gris³⁴, Y.V. Grishkevich⁹⁹, J.-F. Grivaz¹¹⁷, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷³, J. Grosse-Knetter⁵⁴, G.C. Grossi^{134a,134b}, Z.J. Grout¹⁵⁰, L. Guan^{33b}, J. Guenther¹²⁸, F. Guescini⁴⁹, D. Guest¹⁷⁷, O. Gueta¹⁵⁴, C. Guicheney³⁴, E. Guido^{50a,50b}, T. Guillemin¹¹⁷, S. Guindon², U. Gul⁵³, C. Gumpert⁴⁴, J. Guo³⁵, S. Gupta¹²⁰, P. Gutierrez¹¹³, N.G. Gutierrez Ortiz⁵³, C. Gutsche⁷⁸, N. Guttman¹⁵⁴, C. Guyot¹³⁷, C. Gwenlan²¹, C.B. Gwilliam⁷⁴, A. Haas¹¹⁰, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{136e}, P. Haefner²¹, S. Hageböck²¹, Z. Hajduk³⁹, H. Hakobyan¹⁷⁸, M. Haleem⁴², J. Haley¹¹⁴, D. Hall¹²⁰, G. Halladjian⁹⁰, G.D. Hallewell⁸⁵, K. Hamacher¹⁷⁶, P. Hamal¹¹⁵, K. Hamano¹⁷⁰, M. Hamer⁵⁴, A. Hamilton^{146a}, S. Hamilton¹⁶², G.N. Hamity^{146c}, P.G. Hamnett⁴², L. Han^{33b}, K. Hanagaki¹¹⁸, K. Hanawa¹⁵⁶, M. Hance¹⁵, P. Hanke^{58a}, R. Hanna¹³⁷, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, K. Hara¹⁶¹, A.S. Hard¹⁷⁴, T. Harenberg¹⁷⁶, F. Hariri¹¹⁷, S. Harkusha⁹², R.D. Harrington⁴⁶, P.F. Harrison¹⁷¹, F. Hartjes¹⁰⁷, M. Hasegawa⁶⁷, S. Hasegawa¹⁰³, Y. Hasegawa¹⁴¹, A. Hasib¹¹³, S. Hassani¹³⁷, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁹⁰, M. Havranek¹²⁷, C.M. Hawkes¹⁸, R.J. Hawkins³⁰, A.D. Hawkins⁸¹, T. Hayashi¹⁶¹, D. Hayden⁹⁰, C.P. Hays¹²⁰, J.M. Hays⁷⁶, H.S. Hayward⁷⁴, S.J. Hayward¹³¹, S.J. Head¹⁸, T. Heck⁸³, V. Hedberg⁸¹, L. Heelan⁸, S. Heim¹²², T. Heim¹⁷⁶, B. Heinemann¹⁵, L. Heinrich¹¹⁰, J. Hejbal¹²⁷, L. Helary²², M. Heller³⁰, S. Hellman^{147a,147b}, D. Hellmich²¹, C. Helsen³⁰, J. Henderson¹²⁰, R.C.W. Henderson⁷², Y. Heng¹⁷⁴, C. Hengler⁴², A. Henrichs¹⁷⁷, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁷, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁸, R. Herrberg-Schubert¹⁶, G. Herten⁴⁸, R. Hertenberger¹⁰⁰, L. Hervas³⁰, G.G. Hesketh⁷⁸, N.P. Hessey¹⁰⁷, R. Hickling⁷⁶, E. Higón-Rodríguez¹⁶⁸, E. Hill¹⁷⁰, J.C. Hill²⁸, K.H. Hiller⁴², S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²², R.R. Hinman¹⁵, M. Hirose¹⁵⁸, D. Hirschbuehl¹⁷⁶, J. Hobbs¹⁴⁹, N. Hod¹⁰⁷, M.C. Hodgkinson¹⁴⁰, P. Hodgson¹⁴⁰, A. Hoecker³⁰, M.R. Hoferkamp¹⁰⁵, F. Hoenig¹⁰⁰, D. Hoffmann⁸⁵, M. Hohlfeld⁸³, T.R. Holmes¹⁵, T.M. Hong¹²², L. Hooft van Huysduynen¹¹⁰, W.H. Hopkins¹¹⁶, Y. Horii¹⁰³, A.J. Horton¹⁴³, J.-Y. Hostachy⁵⁵, S. Hou¹⁵², A. Hoummada^{136a}, J. Howard¹²⁰, J. Howarth⁴², M. Hrabovsky¹¹⁵, I. Hristova¹⁶, J. Hrivnac¹¹⁷, T. Hryn'ova⁵, A. Hrynevich⁹³, C. Hsu^{146c}, P.J. Hsu¹⁵², S.-C. Hsu¹³⁹, D. Hu³⁵, X. Hu⁸⁹, Y. Huang⁴², Z. Hubacek³⁰, F. Hubaut⁸⁵, F. Huegging²¹, T.B. Huffman¹²⁰, E.W. Hughes³⁵, G. Hughes⁷², M. Huhtinen³⁰, T.A. Hülsing⁸³, M. Hurwitz¹⁵, N. Huseynov^{65,b}, J. Huston⁹⁰, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, I. Ibragimov¹⁴², L. Iconomidou-Fayard¹¹⁷, E. Ideal¹⁷⁷, Z. Idrissi^{136e}, P. Inengo^{104a}, O. Igonkina¹⁰⁷, T. Iizawa¹⁷², Y. Ikegami⁶⁶, K. Ikematsu¹⁴², M. Ikeno⁶⁶, Y. Ilchenko^{31,o}, D. Iliadis¹⁵⁵, N. Ilic¹⁵⁹, Y. Inamaru⁶⁷, T. Ince¹⁰¹, P. Ioannou⁹, M. Iodice^{135a}, K. Iordanidou⁹, V. Ippolito⁵⁷, A. Irls Quiles¹⁶⁸, C. Isaksson¹⁶⁷, M. Ishino⁶⁸, M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹¹, C. Issever¹²⁰, S. Istin^{19a}, J.M. Iturbe Ponce⁸⁴, R. Iuppa^{134a,134b}, J. Ivarsson⁸¹, W. Iwanski³⁹, H. Iwasaki⁶⁶, J.M. Izen⁴¹, V. Izzo^{104a}, B. Jackson¹²², M. Jackson⁷⁴, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁰, T. Jakoubek¹²⁷, J. Jakubek¹²⁸, D.O. Jamin¹⁵², D.K. Jana⁷⁹, E. Jansen⁷⁸, J. Janssen²¹, M. Janus¹⁷¹, G. Jarlskog⁸¹, N. Javadov^{65,b}, T. Javůrek⁴⁸, L. Jeanty¹⁵, J. Jejelava^{51a,p}, G.-Y. Jeng¹⁵¹, D. Jennens⁸⁸, P. Jenni^{48,q}, J. Jentsch⁴³, C. Jeske¹⁷¹, S. Jézéquel⁵, H. Ji¹⁷⁴, J. Jia¹⁴⁹, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, A. Jinaru^{26a}, O. Jinnouchi¹⁵⁸, M.D. Joergensen³⁶, P. Johansson¹⁴⁰, K.A. Johns⁷, K. Jon-And^{147a,147b}, G. Jones¹⁷¹, R.W.L. Jones⁷², T.J. Jones⁷⁴,

J. Jongmanns^{58a}, P.M. Jorge^{126a,126b}, K.D. Joshi⁸⁴, J. Jovicevic¹⁴⁸, X. Ju¹⁷⁴, C.A. Jung⁴³, P. Jussel⁶², A. Juste Rozas^{12,n}, M. Kaci¹⁶⁸, A. Kaczmarek³⁹, M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴⁴, E. Kajomovitz⁴⁵, C.W. Kalderon¹²⁰, S. Kama⁴⁰, A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁶, M. Kaneda³⁰, S. Kaneti²⁸, V.A. Kantserov⁹⁸, J. Kanzaki⁶⁶, B. Kaplan¹¹⁰, A. Kapliy³¹, D. Kar⁵³, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M.J. Kareem⁵⁴, M. Karnevskiy⁸³, S.N. Karpov⁶⁵, Z.M. Karpova⁶⁵, K. Karthik¹¹⁰, V. Kartvelishvili⁷², A.N. Karyukhin¹³⁰, L. Kashif¹⁷⁴, G. Kasieczka^{58b}, R.D. Kass¹¹¹, A. Kastanas¹⁴, Y. Kataoka¹⁵⁶, A. Katre⁴⁹, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁷⁰, T. Kawamoto¹⁵⁶, G. Kawamura⁵⁴, S. Kazama¹⁵⁶, V.F. Kazanin¹⁰⁹, M.Y. Kazarinov⁶⁵, R. Keeler¹⁷⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, J.S. Keller⁴², J.J. Kempster⁷⁷, H. Keoshkerian⁵, O. Kepka¹²⁷, B.P. Kerševan⁷⁵, S. Kersten¹⁷⁶, K. Kessoku¹⁵⁶, J. Keung¹⁵⁹, R.A. Keyes⁸⁷, F. Khalil-zada¹¹, H. Khandanyan^{147a,147b}, A. Khanov¹¹⁴, A. Kharlamov¹⁰⁹, A. Khodinov⁹⁸, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khorauli²¹, V. Khovanskiy⁹⁷, E. Khramov⁶⁵, J. Khubua^{51b}, H.Y. Kim⁸, H. Kim^{147a,147b}, S.H. Kim¹⁶¹, N. Kimura¹⁵⁵, O. Kind¹⁶, B.T. King⁷⁴, M. King¹⁶⁸, R.S.B. King¹²⁰, S.B. King¹⁶⁹, J. Kirk¹³¹, A.E. Kiryunin¹⁰¹, T. Kishimoto⁶⁷, D. Kisielewska^{38a}, F. Kiss⁴⁸, K. Kiuchi¹⁶¹, E. Kladiiva^{145b}, M. Klein⁷⁴, U. Klein⁷⁴, K. Kleinknecht⁸³, P. Klimek^{147a,147b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸⁴, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁶, E.-E. Kluge^{58a}, P. Kluit¹⁰⁷, S. Kluth¹⁰¹, E. Kneringer⁶², E.B.F.G. Knoop⁸⁵, A. Knue⁵³, D. Kobayashi¹⁵⁸, T. Kobayashi¹⁵⁶, M. Kobel⁴⁴, M. Kocian¹⁴⁴, P. Kodys¹²⁹, T. Koffas²⁹, E. Koffeman¹⁰⁷, L.A. Kogan¹²⁰, S. Kohlmann¹⁷⁶, Z. Kohout¹²⁸, T. Kohriki⁶⁶, T. Koi¹⁴⁴, H. Kolanoski¹⁶, I. Koletsou⁵, J. Koll⁹⁰, A.A. Komar^{96,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁶, N. Kondrashova⁴², K. Köneke⁴⁸, A.C. König¹⁰⁶, S. König⁸³, T. Kono^{66,r}, R. Konoplich^{110,s}, N. Konstantinidis⁷⁸, R. Kopeliansky¹⁵³, S. Koperny^{38a}, L. Köpke⁸³, A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁵, A. Korn⁷⁸, A.A. Korol^{109,c}, I. Korolkov¹², E.V. Korolkova¹⁴⁰, V.A. Korotkov¹³⁰, O. Kortner¹⁰¹, S. Kortner¹⁰¹, V.V. Kostyukhin²¹, V.M. Kotov⁶⁵, A. Kotwal⁴⁵, A. Kourkoumeli-Charalampidi¹⁵⁵, C. Kourkoumelis⁹, V. Kouskoura²⁵, A. Koutsman^{160a}, R. Kowalewski¹⁷⁰, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁷, A.S. Kozhin¹³⁰, V.A. Kramarenko⁹⁹, G. Kramberger⁷⁵, D. Krasnopevtsev⁹⁸, M.W. Krasny⁸⁰, A. Krasznahorkay³⁰, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹¹⁰, M. Kretz^{58c}, J. Kretzschmar⁷⁴, K. Kreuzfeldt⁵², P. Krieger¹⁵⁹, K. Krizka³¹, K. Kroeninger⁴³, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁵, H. Krüger²¹, N. Krumnack⁶⁴, Z.V. Krumshyteyn⁶⁵, A. Kruse¹⁷⁴, M.C. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁸, H. Kucuk⁷⁸, S. Kuday^{4c}, S. Kuehn⁴⁸, A. Kugel^{58c}, F. Kuger¹⁷⁵, A. Kuhl¹³⁸, T. Kuhl⁴², V. Kukhtin⁶⁵, Y. Kulchitsky⁹², S. Kuleshov^{32b}, M. Kuna^{133a,133b}, T. Kunigo⁶⁸, A. Kupco¹²⁷, H. Kurashige⁶⁷, Y.A. Kurochkin⁹², R. Kurumida⁶⁷, V. Kus¹²⁷, E.S. Kuwertz¹⁴⁸, M. Kuze¹⁵⁸, J. Kvita¹¹⁵, D. Kyriazopoulos¹⁴⁰, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, C. Lacasta¹⁶⁸, F. Lacava^{133a,133b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁸⁰, V.R. Lacuesta¹⁶⁸, E. Ladygin⁶⁵, R. Lafaye⁵, B. Laforge⁸⁰, T. Lagouri¹⁷⁷, S. Lai⁴⁸, H. Laier^{58a}, L. Lambourne⁷⁸, S. Lammers⁶¹, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁴⁸, M.P.J. Landon⁷⁶, V.S. Lang^{58a}, A.J. Lankford¹⁶⁴, F. Lanni²⁵, K. Lantzsck³⁰, S. Laplace⁸⁰, C. Lapoire²¹, J.F. Laporte¹³⁷, T. Lari^{91a}, F. Lasagni Manghi^{20a,20b}, M. Lassnig³⁰, P. Laurelli⁴⁷, W. Lavrijsen¹⁵, A.T. Law¹³⁸, P. Laycock⁷⁴, O. Le Dortz⁸⁰, E. Le Guirriec⁸⁵, E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee^{146b}, H. Lee¹⁰⁷, S.C. Lee¹⁵², L. Lee¹, G. Lefebvre⁸⁰, M. Lefebvre¹⁷⁰, F. Legger¹⁰⁰, C. Leggett¹⁵, A. Lehan⁷⁴, G. Lehmann Miotto³⁰, X. Lei⁷, W.A. Leight²⁹, A. Leisos¹⁵⁵, A.G. Leister¹⁷⁷, M.A.L. Leite^{24d}, R. Leitner¹²⁹, D. Lellouch¹⁷³, B. Lemmer⁵⁴, K.J.C. Leney⁷⁸, T. Lenz²¹, G. Lenzen¹⁷⁶, B. Lenzi³⁰, R. Leone⁷, S. Leone^{124a,124b}, C. Leonidopoulos⁴⁶, S. Leontsinis¹⁰, C. Leroy⁹⁵, C.G. Lester²⁸, C.M. Lester¹²², M. Levchenko¹²³, J. Levêque⁵, D. Levin⁸⁹, L.J. Levinson¹⁷³, M. Levy¹⁸, A. Lewis¹²⁰, A.M. Leyko²¹, M. Leyton⁴¹, B. Li^{33b,t}, B. Li⁸⁵, H. Li¹⁴⁹, H.L. Li³¹, L. Li⁴⁵, L. Li^{33e}, S. Li⁴⁵, Y. Li^{33c,u}, Z. Liang¹³⁸, H. Liao³⁴, B. Liberti^{134a}, P. Lichard³⁰, K. Lie¹⁶⁶, J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani¹⁵¹, S.C. Lin^{152,v}, T.H. Lin⁸³, F. Linde¹⁰⁷, B.E. Lindquist¹⁴⁹, J.T. Linnemann⁹⁰, E. Lipeles¹²², A. Lipniacka¹⁴, M. Lisovyi⁴², T.M. Liss¹⁶⁶, D. Lissauer²⁵, A. Lister¹⁶⁹, A.M. Litke¹³⁸, B. Liu¹⁵², D. Liu¹⁵², J. Liu⁸⁵, J.B. Liu^{33b}, K. Liu^{33b,w}, L. Liu⁸⁹, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{121a,121b}, A. Lleres⁵⁵, J. Llorente Merino⁸², S.L. Lloyd⁷⁶, F. Lo Sterzo¹⁵², E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸⁴, A.E. Loevschall-Jensen³⁶, A. Loginov¹⁷⁷, T. Lohse¹⁶, K. Lohwasser⁴², M. Lokajicek¹²⁷, B.A. Long²², J.D. Long⁸⁹, R.E. Long⁷², K.A. Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁷, B. Lopez Paredes¹⁴⁰, I. Lopez Paz¹², J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶¹, M. Losada¹⁶³, P. Loscutoff¹⁵, X. Lou^{33a}, A. Lounis¹¹⁷, J. Love⁶, P.A. Love⁷², A.J. Lowe^{144,e}, F. Lu^{33a}, N. Lu⁸⁹, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵, F. Luehring⁶¹, W. Lukas⁶², L. Luminari^{133a}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, M. Lungwitz⁸³, D. Lynn²⁵, R. Lysak¹²⁷, E. Lytken⁸¹, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰¹, J. Machado Miguens^{126a,126b}, D. Macina³⁰, D. Madaffari⁸⁵, R. Madar⁴⁸, H.J. Maddocks⁷², W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁸, T. Maeno²⁵, A. Maevskiy⁹⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁷, S. Mahmoud⁷⁴, C. Maiani¹³⁷, C. Maidantchik^{24a}, A.A. Maier¹⁰¹, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁶, N. Makovec¹¹⁷, P. Mal^{137,x}, B. Malaescu⁸⁰, Pa. Malecki³⁹, V.P. Maleev¹²³, F. Malek⁵⁵, U. Mallik⁶³, D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁹, S. Malyukov³⁰, J. Mamuzic^{13b}, B. Mandelli³⁰, L. Mandelli^{91a}, I. Mandić⁷⁵, R. Mandrysch⁶³, J. Maneira^{126a,126b}, A. Manfredini¹⁰¹, L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos^{160b}, A. Mann¹⁰⁰, P.M. Manning¹³⁸, A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁷, M. Mantoani⁵⁴, L. Mapelli³⁰, L. March^{146c}, J.F. Marchand²⁹, G. Marchiori⁸⁰, M. Marcisovsky¹²⁷, C.P. Marino¹⁷⁰, M. Marjanovic^{13a}, F. Marroquim^{24a},

S.P. Marsden⁸⁴, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰, B. Martin⁹⁰, T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, H. Martinez¹³⁷, M. Martinez^{12,n}, S. Martin-Haugh¹³¹, A.C. Martyniuk⁷⁸, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin³⁰, L. Masetti⁸³, T. Mashimo¹⁵⁶, R. Mashinistov⁹⁶, J. Masik⁸⁴, A.L. Maslennikov^{109,c}, I. Massa^{20a,20b}, L. Massa^{20a,20b}, N. Massol⁵, P. Mastrandrea¹⁴⁹, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁶, J. Mattmann⁸³, J. Maurer^{26a}, S.J. Maxfield⁷⁴, D.A. Maximov^{109,c}, R. Mazini¹⁵², S.M. Mazza^{91a,91b}, L. Mazzaferro^{134a,134b}, G. Mc Goldrick¹⁵⁹, S.P. Mc Kee⁸⁹, A. McCarn⁸⁹, R.L. McCarthy¹⁴⁹, T.G. McCarthy²⁹, N.A. McCubbin¹³¹, K.W. McFarlane^{56,*}, J.A. Mcfayden⁷⁸, G. Mchedlidze⁵⁴, S.J. McMahon¹³¹, R.A. McPherson^{170,j}, J. Mechnich¹⁰⁷, M. Medinnis⁴², S. Meehan³¹, S. Mehlhase¹⁰⁰, A. Mehta⁷⁴, K. Meier^{58a}, C. Meineck¹⁰⁰, B. Meirose⁴¹, C. Melachrinou³¹, B.R. Mellado Garcia^{146c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰¹, E. Meoni¹⁶², K.M. Mercurio⁵⁷, S. Mergelmeyer²¹, N. Meric¹³⁷, P. Mermod⁴⁹, L. Merola^{104a,104b}, C. Meroni^{91a}, F.S. Merritt³¹, H. Merritt¹¹¹, A. Messina^{30,y}, J. Metcalfe²⁵, A.S. Mete¹⁶⁴, C. Meyer⁸³, C. Meyer¹²², J-P. Meyer¹³⁷, J. Meyer³⁰, R.P. Middleton¹³¹, S. Migas⁷⁴, S. Miglioranzì^{165a,165c}, L. Mijović²¹, G. Mikenberg¹⁷³, M. Mikestikova¹²⁷, M. Mikuz⁷⁵, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷³, D.A. Milstead^{147a,147b}, A.A. Minaenko¹³⁰, Y. Minami¹⁵⁶, I.A. Minashvili⁶⁵, A.I. Mincer¹¹⁰, B. Mindur^{38a}, M. Mineev⁶⁵, Y. Ming¹⁷⁴, L.M. Mir¹², G. Mirabelli^{133a}, T. Mitani¹⁷², J. Mitrevski¹⁰⁰, V.A. Mitsou¹⁶⁸, A. Miucci⁴⁹, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸¹, T. Moa^{147a,147b}, K. Mochizuki⁸⁵, S. Mohapatra³⁵, W. Mohr⁴⁸, S. Molander^{147a,147b}, R. Moles-Valls¹⁶⁸, K. Mönig⁴², C. Monini⁵⁵, J. Monk³⁶, E. Monnier⁸⁵, J. Montejo Berlingen¹², F. Monticelli⁷¹, S. Monzani^{133a,133b}, R.W. Moore³, N. Morange⁶³, D. Moreno¹⁶³, M. Moreno Llácer⁵⁴, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷, V. Morisbak¹¹⁹, S. Moritz⁸³, A.K. Morley¹⁴⁸, G. Mornacchi³⁰, J.D. Morris⁷⁶, A. Morton⁴², L. Morvaj¹⁰³, H.G. Moser¹⁰¹, M. Mosidze^{51b}, J. Moss¹¹¹, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁵, S.V. Mouraviev^{96,*}, E.J.W. Moyse⁸⁶, S. Muanza⁸⁵, R.D. Mudd¹⁸, F. Mueller^{58a}, J. Mueller¹²⁵, K. Mueller²¹, T. Mueller²⁸, D. Muenstermann⁴⁹, P. Mullen⁵³, Y. Munwes¹⁵⁴, J.A. Murillo Quijada¹⁸, W.J. Murray^{171,131}, H. Musheghyan⁵⁴, E. Musto¹⁵³, A.G. Myagkov^{130,z}, M. Myska¹²⁸, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai¹²⁰, R. Nagai¹⁵⁸, Y. Nagai⁸⁵, K. Nagano⁶⁶, A. Nagarkar¹¹¹, Y. Nagasaka⁵⁹, K. Nagata¹⁶¹, M. Nagel¹⁰¹, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁶, T. Nakamura¹⁵⁶, I. Nakano¹¹², H. Namasivayam⁴¹, G. Nanava²¹, R.F. Naranjo Garcia⁴², R. Narayan^{58b}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶³, R. Nayyar⁷, H.A. Neal⁸⁹, P.Yu. Nechaeva⁹⁶, T.J. Neep⁸⁴, P.D. Nef¹⁴⁴, A. Negri^{121a,121b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, C. Nellist¹¹⁷, A. Nelson¹⁶⁴, T.K. Nelson¹⁴⁴, S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A.A. Nepomuceno^{24a}, M. Nessi^{30,aa}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁶, R.M. Neves¹¹⁰, P. Nevski²⁵, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹²⁰, R. Nicolaidou¹³⁷, B. Nicquevert³⁰, J. Nielsen¹³⁸, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{130,z}, I. Nikolic-Audit⁸⁰, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson²⁵, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁸, M. Nomachi¹¹⁸, I. Nomidis²⁹, S. Norberg¹¹³, M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰¹, M. Nozaki⁶⁶, L. Nozka¹¹⁵, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁸, T. Nunnemann¹⁰⁰, E. Nurse⁷⁸, F. Nuti⁸⁸, B.J. O'Brien⁴⁶, F. O'grady⁷, D.C. O'Neil¹⁴³, V. O'Shea⁵³, F.G. Oakham^{29,d}, H. Oberlack¹⁰¹, T. Obermann²¹, J. Ocariz⁸⁰, A. Ochi⁶⁷, I. Ochoa⁷⁸, S. Oda⁷⁰, S. Odaka⁶⁶, H. Ogren⁶¹, A. Oh⁸⁴, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁷, H. Oide³⁰, W. Okamura¹¹⁸, H. Okawa¹⁶¹, Y. Okumura³¹, T. Okuyama¹⁵⁶, A. Olariu^{26a}, A.G. Olchevski⁶⁵, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁸, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{126a,126e}, P.U.E. Onyisi^{31,o}, C.J. Oram^{160a}, M.J. Oreglia³¹, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{73a,73b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁹, B. Osculati^{50a,50b}, R. Ospanov¹²², G. Otero y Garzon²⁷, H. Otono⁷⁰, M. Ouchrif^{136d}, E.A. Ouellette¹⁷⁰, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁷, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸⁴, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹²⁰, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹⁴⁰, C. Pahl¹⁰¹, F. Paige²⁵, P. Pais⁸⁶, K. Pajchel¹¹⁹, G. Palacino^{160b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{126a,126b}, J.D. Palmer¹⁸, Y.B. Pan¹⁷⁴, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁷, P. Pani¹⁰⁷, N. Panikashvili⁸⁹, S. Panitkin²⁵, D. Pantea^{26a}, L. Paolozzi^{134a,134b}, Th.D. Papadopolou¹⁰, K. Papageorgiou¹⁵⁵, A. Paramonov⁶, D. Paredes Hernandez¹⁵⁵, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{133a}, S. Passaggio^{50a}, A. Passeri^{135a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁷, G. Pásztor²⁹, S. Pataria¹⁷⁶, N.D. Patel¹⁵¹, J.R. Pater⁸⁴, S. Patricelli^{104a,104b}, T. Pauly³⁰, J. Pearce¹⁷⁰, L.E. Pedersen³⁶, M. Pedersen¹¹⁹, S. Pedraza Lopez¹⁶⁸, R. Pedro^{126a,126b}, S.V. Peleganchuk¹⁰⁹, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶¹, D.V. Perepelitsa²⁵, E. Perez Codina^{160a}, M.T. Pérez García-Estañ¹⁶⁸, L. Perini^{91a,91b}, H. Pernegger³⁰, S. Perrella^{104a,104b}, R. Peschke⁴², V.D. Peshekhonov⁶⁵, K. Peters³⁰, R.F.Y. Peters⁸⁴, B.A. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁴², A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, N.E. Pettersson¹⁵⁸, R. Pezoa^{32b}, P.W. Phillips¹³¹, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁶, M. Piccinini^{20a,20b}, M.A. Pickering¹²⁰, R. Piegaia²⁷, D.T. Pignotti¹¹¹, J.E. Pilcher³¹, A.D. Pilkington⁷⁸, J. Pina^{126a,126b,126d}, M. Pinamonti^{165a,165c,ab}, A. Pinder¹²⁰, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{126a}, S. Pires⁸⁰, M. Pitt¹⁷³, C. Pizio^{91a,91b}, L. Plazak^{145a}, M.-A. Pleier²⁵, V. Pleskot¹²⁹, E. Plotnikova⁶⁵, P. Plucinski^{147a,147b}, D. Pluth⁶⁴, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸³, L. Poggioli¹¹⁷, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{121a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, C.S. Pollard⁵³, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁹⁰, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, S. Pospisil¹²⁸, K. Potamianos¹⁵, I.N. Potrap⁶⁵,

C.J. Potter¹⁵⁰, C.T. Potter¹¹⁶, G. Poulard³⁰, J. Poveda³⁰, V. Pozdnyakov⁶⁵, P. Pralavorio⁸⁵, A. Pranko¹⁵, S. Prasad³⁰, S. Prell⁶⁴, D. Price⁸⁴, J. Price⁷⁴, L.E. Price⁶, D. Prieur¹²⁵, M. Primavera^{73a}, S. Prince⁸⁷, M. Proissl⁴⁶, K. Prokofiev^{60c}, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, H. Przysieszniak⁵, E. Ptacek¹¹⁶, D. Puddu^{135a,135b}, E. Pueschel⁸⁶, D. Puldon¹⁴⁹, M. Purohit^{25,ac}, P. Puzo¹¹⁷, J. Qian⁸⁹, G. Qin⁵³, Y. Qin⁸⁴, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{165a,165b}, M. Queitsch-Maitland⁸⁴, D. Quilty⁵³, A. Qureshi^{160b}, V. Radeka²⁵, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁶, P. Rados⁸⁸, F. Ragusa^{91a,91b}, G. Rahal¹⁷⁹, S. Rajagopalan²⁵, M. Rammensee³⁰, C. Rangel-Smith¹⁶⁷, K. Rao¹⁶⁴, F. Rauscher¹⁰⁰, S. Rave⁸³, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁹, N.P. Readioff⁷⁴, D.M. Rebutzi^{121a,121b}, A. Redelbach¹⁷⁵, G. Redlinger²⁵, R. Reece¹³⁸, K. Reeves⁴¹, L. Rehnisch¹⁶, H. Reisin²⁷, M. Relich¹⁶⁴, C. Rembser³⁰, H. Ren^{33a}, Z.L. Ren¹⁵², A. Renaud¹¹⁷, M. Rescigno^{133a}, S. Resconi^{91a}, O.L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹, M. Ridel⁸⁰, P. Rieck¹⁶, J. Rieger⁵⁴, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{121a,121b}, L. Rinaldi^{20a}, E. Ritsch⁶², I. Riu¹², F. Rizatdinova¹¹⁴, E. Rizvi⁷⁶, S.H. Robertson^{87,j}, A. Robichaud-Veronneau⁸⁷, D. Robinson²⁸, J.E.M. Robinson⁸⁴, A. Robson⁵³, C. Roda^{124a,124b}, L. Rodrigues³⁰, S. Roe³⁰, O. Røhne¹¹⁹, S. Rolli¹⁶², A. Romaniouk⁹⁸, M. Romano^{20a,20b}, E. Romero Adam¹⁶⁸, N. Rompotis¹³⁹, M. Ronzani⁴⁸, L. Roos⁸⁰, E. Ros¹⁶⁸, S. Rosati^{133a}, K. Rosbach⁴⁹, M. Rose⁷⁷, P. Rose¹³⁸, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴², V. Rossetti^{147a,147b}, E. Rossi^{104a,104b}, L.P. Rossi^{50a}, R. Rosten¹³⁹, M. Rotaru^{26a}, I. Roth¹⁷³, J. Rothberg¹³⁹, D. Rousseau¹¹⁷, C.R. Royon¹³⁷, A. Rozanov⁸⁵, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹², I. Rubinskiy⁴², V.I. Rud⁹⁹, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁴⁸, A. Ruiz-Martinez³⁰, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁵, A. Ruschke¹⁰⁰, H.L. Russell¹³⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸, Y.F. Ryabov¹²³, M. Rybar¹²⁹, G. Rybkin¹¹⁷, N.C. Ryder¹²⁰, A.F. Saavedra¹⁵¹, G. Sabato¹⁰⁷, S. Sacerdoti²⁷, A. Saddique³, H.F.W. Sadrozinski¹³⁸, R. Sadykov⁶⁵, F. Safai Tehrani^{133a}, H. Sakamoto¹⁵⁶, Y. Sakurai¹⁷², G. Salamanna^{135a,135b}, A. Salamon^{134a}, M. Saleem¹¹³, D. Salek¹⁰⁷, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰¹, A. Salnikov¹⁴⁴, J. Salt¹⁶⁸, D. Salvatore^{37a,37b}, F. Salvatore¹⁵⁰, A. Salvucci¹⁰⁶, A. Salzburger³⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{104a,104b}, J. Sánchez¹⁶⁸, V. Sanchez Martinez¹⁶⁸, H. Sandaker¹⁴, R.L. Sandbach⁷⁶, H.G. Sander⁸³, M.P. Sanders¹⁰⁰, M. Sandhoff¹⁷⁶, T. Sandoval²⁸, C. Sandoval¹⁶³, R. Sandstroem¹⁰¹, D.P.C. Sankey¹³¹, A. Sansoni⁴⁷, C. Santoni³⁴, R. Santonico^{134a,134b}, H. Santos^{126a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁵, A. Sapronov⁶⁵, J.G. Saraiva^{126a,126d}, B. Sarrazin²¹, G. Sartiso¹⁷⁶, O. Sasaki⁶⁶, Y. Sasaki¹⁵⁶, K. Sato¹⁶¹, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁷, P. Savard^{159,d}, C. Sawyer¹²⁰, L. Sawyer^{79,m}, D.H. Saxon⁵³, J. Saxon³¹, C. Sbarra^{20a}, A. Sbrizzi^{20a,20b}, T. Scanlon⁷⁸, D.A. Scannicchio¹⁶⁴, M. Scarcella¹⁵¹, V. Scarfone^{37a,37b}, J. Schaarschmidt¹⁷³, P. Schacht¹⁰¹, D. Schaefer³⁰, R. Schaefer⁴², S. Schaepe²¹, S. Schaetzel^{58b}, U. Schäfer⁸³, A.C. Schaffer¹¹⁷, D. Schaile¹⁰⁰, R.D. Schamberger¹⁴⁹, V. Scharf^{58a}, V.A. Schegelsky¹²³, D. Scheirich¹²⁹, M. Schernau¹⁶⁴, C. Schiavi^{50a,50b}, J. Schieck¹⁰⁰, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden³⁰, C. Schmitt⁸³, S. Schmitt^{58b}, B. Schneider¹⁷, Y.J. Schnellbach⁷⁴, U. Schnoor⁴⁴, L. Schoeffel¹³⁷, A. Schoening^{58b}, B.D. Schoenrock⁹⁰, A.L.S. Schorlemmer⁵⁴, M. Schott⁸³, D. Schouten^{160a}, J. Schovancova²⁵, S. Schramm¹⁵⁹, M. Schreyer¹⁷⁵, C. Schroeder⁸³, N. Schuh⁸³, M.J. Schultens²¹, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, C. Schwanenberger⁸⁴, A. Schwartzman¹⁴⁴, T.A. Schwarz⁸⁹, Ph. Schwegler¹⁰¹, Ph. Schwemling¹³⁷, R. Schwiendler⁹⁰, J. Schwindling¹³⁷, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, E. Scifo¹¹⁷, G. Sciolla²³, F. Scuri^{124a,124b}, F. Scutti²¹, J. Searcy⁸⁹, G. Sedov⁴², E. Sedykh¹²³, P. Seema²¹, S.C. Seidel¹⁰⁵, A. Seiden¹³⁸, F. Seifert¹²⁸, J.M. Seixas^{24a}, G. Sekhniaidze^{104a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov^{123,*}, G. Sellers⁷⁴, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁷, L. Serkin⁵⁴, T. Serre⁸⁵, R. Seuster^{160a}, H. Severini¹¹³, T. Sfiligoi⁷⁵, F. Sforza¹⁰¹, A. Sfyrly³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁶, L.Y. Shan^{33a}, R. Shang¹⁶⁶, J.T. Shank²², M. Shapiro¹⁵, P.B. Shatalov⁹⁷, K. Shaw^{165a,165b}, A. Shcherbakova^{147a,147b}, C.Y. Shehu¹⁵⁰, P. Sherwood⁷⁸, L. Shi^{152,ad}, S. Shimizu⁶⁷, C.O. Shimmin¹⁶⁴, M. Shimojima¹⁰², M. Shiyakova⁶⁵, A. Shmeleva⁹⁶, D. Shoaleh Saadi⁹⁵, M.J. Shochet³¹, S. Shojaii^{91a,91b}, D. Short¹²⁰, S. Shrestha¹¹¹, E. Shulga⁹⁸, M.A. Shupe⁷, S. Shushkevich⁴², P. Sicho¹²⁷, O. Sidiropoulou¹⁵⁵, D. Sidorov¹¹⁴, A. Sidoti^{133a}, F. Siegert⁴⁴, Dj. Sijacki^{13a}, J. Silva^{126a,126d}, Y. Silver¹⁵⁴, D. Silverstein¹⁴⁴, S.B. Silverstein^{147a}, V. Simak¹²⁸, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁷, E. Simioni⁸³, B. Simmons⁷⁸, D. Simon³⁴, R. Simoniello^{91a,91b}, P. Sinervo¹⁵⁹, N.B. Sinev¹¹⁶, G. Siragusa¹⁷⁵, A. Sircar⁷⁹, A.N. Sisakyan^{65,*}, S.Yu. Sivoklov⁹⁹, J. Sjölin^{147a,147b}, T.B. Sjurson¹⁴, H.P. Skottowe⁵⁷, P. Skubic¹¹³, M. Slater¹⁸, T. Slavicek¹²⁸, M. Slawinska¹⁰⁷, K. Sliwa¹⁶², V. Smakhtin¹⁷³, B.H. Smart⁴⁶, L. Smestad¹⁴, S.Yu. Smirnov⁹⁸, Y. Smirnov⁹⁸, L.N. Smirnova^{99,ae}, O. Smirnova⁸¹, K.M. Smith⁵³, M. Smith³⁵, M. Smizanska⁷², K. Smolek¹²⁸, A.A. Snesarev⁹⁶, G. Snidero⁷⁶, S. Snyder²⁵, R. Sobie^{170,j}, F. Socher⁴⁴, A. Soffer¹⁵⁴, D.A. Soh^{152,ad}, C.A. Solans³⁰, M. Solar¹²⁸, J. Solc¹²⁸, E.Yu. Soldatov⁹⁸, U. Soldevila¹⁶⁸, A.A. Solodkov¹³⁰, A. Soloshenko⁶⁵, O.V. Solovyanov¹³⁰, V. Solovyevev¹²³, P. Sommer⁴⁸, H.Y. Song^{33b}, N. Soni¹, A. Sood¹⁵, A. Sopczak¹²⁸, B. Sopko¹²⁸, V. Sopko¹²⁸, V. Sorin¹², M. Sosebee⁸, R. Soualah^{165a,165c}, P. Soueid⁹⁵, A.M. Soukharev^{109,c}, D. South⁴², S. Spagnolo^{73a,73b}, F. Spanò⁷⁷, W.R. Spearman⁵⁷, F. Spettel¹⁰¹, R. Spighi^{20a}, G. Spigo³⁰, L.A. Spiller¹²⁹, M. Spousta¹²⁹, T. Spreitzer¹⁵⁹, R.D. St. Denis^{53,*}, S. Staerz⁴⁴, J. Stahlman¹²², R. Stamen^{58a}, S. Stamm¹⁶, E. Stanecka³⁹, C. Stanescu^{135a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁹, E.A. Starchenko¹³⁰, J. Stark⁵⁵, P. Staroba¹²⁷, P. Starovoitov⁴², R. Staszewski³⁹, P. Stavina^{145a,*}, P. Steinberg²⁵, B. Stelzer¹⁴³, H.J. Stelzer³⁰,

O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰¹, G.A. Stewart⁵³, J.A. Stillings²¹, M.C. Stockton⁸⁷, M. Stoebe⁸⁷, G. Stoicea^{26a}, P. Stolte⁵⁴, S. Stonjek¹⁰¹, A.R. Stradling⁸, A. Straessner⁴⁴, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b}, A. Strandlie¹¹⁹, E. Strauss¹⁴⁴, M. Strauss¹¹³, P. Strizenc^{145b}, R. Ströhrer¹⁷⁵, D.M. Strom¹¹⁶, R. Stroynowski⁴⁰, A. Strubig¹⁰⁶, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴², D. Su¹⁴⁴, J. Su¹²⁵, R. Subramaniam⁷⁹, A. Succurro¹², Y. Sugaya¹¹⁸, C. Suhr¹⁰⁸, M. Suk¹²⁸, V.V. Sulin⁹⁶, S. Sultansoy^{4d}, T. Sumida⁶⁸, S. Sun⁵⁷, X. Sun^{33a}, J.E. Sundermann⁴⁸, K. Suruliz¹⁵⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁶, M. Svatos¹²⁷, S. Swedish¹⁶⁹, M. Swiatlowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁹, D. Ta⁹⁰, C. Taccini^{135a,135b}, K. Tackmann⁴², J. Taenzer¹⁵⁹, A. Taffard¹⁶⁴, R. Tafirout^{160a}, N. Taiblum¹⁵⁴, H. Takai²⁵, R. Takashima⁶⁹, H. Takeda⁶⁷, T. Takeshita¹⁴¹, Y. Takubo⁶⁶, M. Talby⁸⁵, A.A. Talyshev^{109,c}, J.Y.C. Tam¹⁷⁵, K.G. Tan⁸⁸, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁷, S. Tanaka¹³², S. Tanaka⁶⁶, A.J. Tanasijczuk¹⁴³, B.B. Tannenwald¹¹¹, N. Tannoury²¹, S. Tapprogge⁸³, S. Tarem¹⁵³, F. Tarrade²⁹, G.F. Tartarelli^{91a}, P. Tas¹²⁹, M. Tasevsky¹²⁷, T. Tashiro⁶⁸, E. Tassi^{37a,37b}, A. Tavares Delgado^{126a,126b}, Y. Tayalati^{136d}, F.E. Taylor⁹⁴, G.N. Taylor⁸⁸, W. Taylor^{160b}, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁶, P. Teixeira-Dias⁷⁷, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵², J.J. Teoh¹¹⁸, F. Tepel¹⁷⁶, S. Terada⁶⁶, K. Terashi¹⁵⁶, J. Terron⁸², S. Terzo¹⁰¹, M. Testa⁴⁷, R.J. Teuscher^{159,j}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁷, E.N. Thompson³⁵, P.D. Thompson¹⁸, R.J. Thompson⁸⁴, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²², M. Thomson²⁸, W.M. Thong⁸⁸, R.P. Thun^{89,*}, F. Tian³⁵, M.J. Tibbetts¹⁵, V.O. Tikhomirov^{96,af}, Yu.A. Tikhonov^{109,c}, S. Timoshenko⁹⁸, E. Tiouchichine⁸⁵, P. Tipton¹⁷⁷, S. Tisserant⁸⁵, T. Todorov⁵, S. Todorova-Nova¹²⁹, J. Tojo⁷⁰, S. Tokár^{145a}, K. Tokushuku⁶⁶, K. Tollefson⁹⁰, E. Tolley⁵⁷, L. Tomlinson⁸⁴, M. Tomoto¹⁰³, L. Tompkins³¹, K. Toms¹⁰⁵, N.D. Topilin⁶⁵, E. Torrence¹¹⁶, H. Torres¹⁴³, E. Torró Pastor¹⁶⁸, J. Toth^{85,ag}, F. Touchard⁸⁵, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁷, T. Trefzger¹⁷⁵, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincaz-Duvoid⁸⁰, M.F. Tripiana¹², W. Trischuk¹⁵⁹, B. Trocme⁵⁵, C. Troncon^{91a}, M. Trotter-McDonald¹⁵, M. Trovatelli^{135a,135b}, P. True⁹⁰, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C.-L. Tseng¹²⁰, P.V. Tsiareshka⁹², D. Tsionou¹³⁷, G. Tsiopolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁷, V. Tsulaia¹⁵, S. Tsuno⁶⁶, D. Tsybychev¹⁴⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, A.N. Tuna¹²², S.A. Tuppuri^{20a,20b}, S. Turchikhin^{99,ae}, D. Turecek¹²⁸, I. Turk Cakir^{4c}, R. Turra^{91a,91b}, A.J. Turvey⁴⁰, P.M. Tuts³⁵, A. Tykhonov⁴⁹, M. Tylmad^{147a,147b}, M. Tyndel¹³¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁵, M. Ugland¹⁴, M. Uhlenbrock²¹, F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁶, C. Unverdorben¹⁰⁰, J. Urban^{145b}, D. Urbaniec³⁵, P. Urquijo⁸⁸, G. Usai⁸, A. Usanova⁶², L. Vacavant⁸⁵, V. Vacek¹²⁸, B. Vachon⁸⁷, N. Valencic¹⁰⁷, S. Valentineti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁹, E. Valladolid Gallego¹⁶⁸, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁸, W. Van Den Wollenberg¹⁰⁷, P.C. Van Der Deijl¹⁰⁷, R. van der Geer¹⁰⁷, H. van der Graaf¹⁰⁷, R. Van Der Leeuw¹⁰⁷, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁷, M.C. van Woerden³⁰, M. Vanadia^{133a,133b}, W. Vandelli³⁰, R. Vanguri¹²², A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁸⁰, G. Vardanyan¹⁷⁸, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁶, D. Varouchas⁸⁰, A. Vartapetian⁸, K.E. Varvell¹⁵¹, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{126a,126c}, T. Velz²¹, S. Veneziano^{133a}, A. Ventura^{73a,73b}, D. Ventura⁸⁶, M. Venturi¹⁷⁰, N. Venturi¹⁵⁹, A. Venturini²³, V. Vercesi^{121a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁷, J.C. Vermeulen¹⁰⁷, A. Vest⁴⁴, M.C. Vetterli^{143,d}, O. Viazlo⁸¹, I. Vichou¹⁶⁶, T. Vickey^{146c,ah}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹²⁰, S. Viel¹⁶⁹, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez^{91a,91b}, E. Vilucchi⁴⁷, M.G. Vincker²⁹, V.B. Vinogradov⁶⁵, J. Virzi¹⁵, I. Vivarelli¹⁵⁰, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladioiu¹⁰⁰, M. Vlasak¹²⁸, A. Vogel²¹, M. Vogel^{32a}, P. Vokac¹²⁸, G. Volpi^{124a,124b}, M. Volpi⁸⁸, H. von der Schmitt¹⁰¹, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁹, K. Vorobev⁹⁸, M. Vos¹⁶⁸, R. Voss³⁰, J.H. Vosseveld⁷⁴, N. Vranjes¹³⁷, M. Vranjes Milosavljevic^{13a}, V. Vrba¹²⁷, M. Vreeswijk¹⁰⁷, T. Vu Anh⁴⁸, R. Vuillemet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁸, P. Wagner²¹, W. Wagner¹⁷⁶, H. Wahlberg⁷¹, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰³, J. Walder⁷², R. Walker¹⁰⁰, W. Walkowiak¹⁴², R. Wall¹⁷⁷, P. Waller⁷⁴, B. Walsh¹⁷⁷, C. Wang^{33c}, C. Wang⁴⁵, F. Wang¹⁷⁴, H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang^{33a}, K. Wang⁸⁷, R. Wang¹⁰⁵, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, C. Wanotayaroj¹¹⁶, A. Warburton⁸⁷, C.P. Ward²⁸, D.R. Wardrope⁷⁸, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸⁴, B.M. Waugh⁷⁸, S. Webb⁸⁴, M.S. Weber¹⁷, S.W. Weber¹⁷⁵, J.S. Webster³¹, A.R. Weidberg¹²⁰, B. Weinert⁶¹, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁷, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152,ad}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{58a}, J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White¹, R. White^{32b}, S. White^{124a,124b}, D. Whiteson¹⁶⁴, D. Wicke¹⁷⁶, F.J. Wickens¹³¹, W. Wiedenmann¹⁷⁴, M. Wielers¹³¹, P. Wienemann²¹, C. Wigglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁸, A. Wildauer¹⁰¹, M.A. Wildt^{42,ai}, H.G. Wilkens³⁰, H.H. Williams¹²², S. Williams²⁸, C. Willis⁹⁰, S. Willocq⁸⁶, A. Wilson⁸⁹, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁶, B.T. Winter²¹, M. Wittgen¹⁴⁴, J. Wittkowski¹⁰⁰, S.J. Wollstadt⁸³, M.W. Wolter³⁹, H. Wolters^{126a,126c}, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸⁴, K.W. Wozniak³⁹, M. Wright⁵³, M. Wu⁵⁵, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁹, T.R. Wyatt⁸⁴, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷, D. Xu^{33a}, L. Xu^{33b,aj}, B. Yabsley¹⁵¹, S. Yacoob^{146b,ak}, R. Yakabe⁶⁷, M. Yamada⁶⁶, H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹¹⁸, A. Yamamoto⁶⁶, S. Yamamoto¹⁵⁶, T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰³, Y. Yamazaki⁶⁷, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷⁴, Y. Yang¹¹¹, S. Yanush⁹³, L. Yao^{33a}, W.-M. Yao¹⁵, Y. Yasu⁶⁶, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵,

I. Yeletsikh⁶⁵, A.L. Yen⁵⁷, E. Yildirim⁴², M. Yilmaz^{4b}, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴, C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁸⁹, J. Yu¹¹⁴, L. Yuan⁶⁷, A. Yurkewicz¹⁰⁸, I. Yusuf^{28,al}, B. Zabinski³⁹, R. Zaidan⁶³, A.M. Zaitsev^{130,z}, A. Zaman¹⁴⁹, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi⁸⁸, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁸, A. Zemla^{38a}, K. Zengel²³, O. Zenin¹³⁰, T. Ženiš^{145a}, D. Zerwas¹¹⁷, G. Zevi della Porta⁵⁷, D. Zhang⁸⁹, F. Zhang¹⁷⁴, H. Zhang⁹⁰, J. Zhang⁶, L. Zhang¹⁵², R. Zhang^{33b}, X. Zhang^{33d}, Z. Zhang¹¹⁷, X. Zhao⁴⁰, Y. Zhao^{33d}, Z. Zhao^{33b}, A. Zhemchugov⁶⁵, J. Zhong¹²⁰, B. Zhou⁸⁹, C. Zhou⁴⁵, L. Zhou³⁵, L. Zhou⁴⁰, N. Zhou¹⁶⁴, C.G. Zhu^{33d}, H. Zhu^{33a}, J. Zhu⁸⁹, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁶, A. Zibell¹⁷⁵, D. Zieminska⁶¹, N.I. Zimine⁶⁵, C. Zimmermann⁸³, R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Ziolkowski¹⁴², G. Zobernig¹⁷⁴, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{104a,104b}, L. Zwalinski³⁰.

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany NY, United States of America

³ Department of Physics, University of Alberta, Edmonton AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Istanbul Aydin University, Istanbul; (d) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

⁷ Department of Physics, University of Arizona, Tucson AZ, United States of America

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

¹³ (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

²⁰ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²¹ Physikalisches Institut, University of Bonn, Bonn, Germany

²² Department of Physics, Boston University, Boston MA, United States of America

²³ Department of Physics, Brandeis University, Waltham MA, United States of America

²⁴ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, 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 Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁵ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

²⁶ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁹ Department of Physics, Carleton University, Ottawa ON, Canada

³⁰ CERN, Geneva, Switzerland

³¹ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

³² (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³³ (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; (e) Physics Department, Shanghai Jiao Tong University, Shanghai;

- (f) Physics Department, Tsinghua University, Beijing 100084, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham NC, United States of America
- ⁴⁶ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, 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, Iv. Javakishvili 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 Grenoble-Alpes, CNRS/IN2P3, 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 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶¹ Department of Physics, Indiana University, Bloomington IN, United States of America
- ⁶² Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶³ University of Iowa, Iowa City IA, United States of America
- ⁶⁴ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- ⁶⁵ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁶ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁷ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁸ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁹ Kyoto University of Education, Kyoto, Japan
- ⁷⁰ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷¹ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷² Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷³ (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁴ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁵ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁶ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁷ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁸ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁹ Louisiana Tech University, Ruston LA, United States of America
- ⁸⁰ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3,

Paris, France

- ⁸¹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸² Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- ⁸³ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁴ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁵ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁶ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁸⁷ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁸ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁹ Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁹⁰ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁹¹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹² B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹³ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹⁴ Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- ⁹⁵ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁶ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁷ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁸ National Research Nuclear University MEPhI, Moscow, Russia
- ⁹⁹ D.V.Skobel'syn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ¹⁰⁰ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰¹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰² Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰³ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁴ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁵ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁶ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁷ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁸ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹⁰⁹ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹⁰ Department of Physics, New York University, New York NY, United States of America
- ¹¹¹ Ohio State University, Columbus OH, United States of America
- ¹¹² Faculty of Science, Okayama University, Okayama, Japan
- ¹¹³ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹⁴ Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹⁵ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁶ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁷ LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ¹¹⁸ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁹ Department of Physics, University of Oslo, Oslo, Norway
- ¹²⁰ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²¹ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²² Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²³ Petersburg Nuclear Physics Institute, Gatchina, Russia
- ¹²⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁵ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- ¹²⁶ ^(a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Fisica, Universidade do Minho, Braga; ^(f) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁷ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁸ Czech Technical University in Prague, Praha, Czech Republic
- ¹²⁹ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

- 130 State Research Center Institute for High Energy Physics, Protvino, Russia
- 131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 132 Ritsumeikan University, Kusatsu, Shiga, Japan
- 133 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 134 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 135 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 136 ^(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) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- 139 Department of Physics, University of Washington, Seattle WA, United States of America
- 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 141 Department of Physics, Shinshu University, Nagano, Japan
- 142 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
- 145 ^(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
- 146 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 147 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 151 School of Physics, University of Sydney, Sydney, Australia
- 152 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 159 Department of Physics, University of Toronto, Toronto ON, Canada
- 160 ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- 161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- 162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- 163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- 165 ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 166 Department of Physics, University of Illinois, Urbana IL, United States of America
- 167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 168 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
- 169 Department of Physics, University of British Columbia, Vancouver BC, Canada
- 170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- 171 Department of Physics, University of Warwick, Coventry, United Kingdom
- 172 Waseda University, Tokyo, Japan
- 173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

- ¹⁷⁴ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁶ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁷ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁷⁸ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, United Kingdom
- ^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^c Also at Novosibirsk State University, Novosibirsk, Russia
- ^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 Department of Physics, University of Fribourg, Fribourg, Switzerland
- ^g Also at Tomsk State University, Tomsk, Russia
- ^h Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy
- ^j Also at Institute of Particle Physics (IPP), Canada
- ^k Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ^l Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- ^m Also at Louisiana Tech University, Ruston LA, United States of America
- ⁿ Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^o Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ^p Also at Institute of Theoretical Physics, Iliia State University, Tbilisi, Georgia
- ^q Also at CERN, Geneva, Switzerland
- ^r Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- ^s Also at Manhattan College, New York NY, United States of America
- ^t Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^u Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- ^v Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^w Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ^x Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
- ^y Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ^z Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ^{ab} Also at International School for Advanced Studies (SISSA), Trieste, Italy
- ^{ac} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- ^{ad} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- ^{ae} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ^{af} Also at National Research Nuclear University MEPhI, Moscow, Russia
- ^{ag} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{ah} Also at Department of Physics, Oxford University, Oxford, United Kingdom
- ^{ai} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- ^{aj} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ^{ak} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- ^{al} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- * Deceased