Measurement of Top Quark Polarization in Top-Antitop Events from Proton-Proton Collisions at $\sqrt{s} = 7$ TeV Using the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)
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This Letter presents measurements of the polarization of the top quark in top-antitop quark pair events, using 4.7 fb^{-1} of proton-proton collision data recorded with the ATLAS detector at the Large Hadron Collider at $\sqrt{s} = 7$ TeV. Final states containing one or two isolated leptons (electrons or muons) and jets are considered. Two measurements of $\alpha_\ell P$, the product of the leptonic spin-analyzing power and the top quark polarization, are performed assuming that the polarization is introduced by either a CP conserving or a maximally CP violating production process. The measurements obtained, $\alpha_\ell P_{\mathrm{CPC}} = -0.035 \pm 0.014(\mathrm{stat}) \pm 0.037(\mathrm{syst})$ and $\alpha_\ell P_{\mathrm{CPV}} = 0.020 \pm 0.016(\mathrm{stat})^{+0.013}_{-0.017}(\mathrm{syst})$, are in good agreement with the standard model prediction of negligible top quark polarization.

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The short lifetime of the top quark [1–5] implies that it decays before hadronization takes place, allowing its spin state to be studied using the angular distributions of its decay products. In the standard model (SM), parity conservation in the strong production of top-antitop quark pairs ($t\bar{t}$) in proton-proton (pp) collisions implies zero longitudinal polarization of the quarks. A negligible polarization (0.003) is generated by the weak interaction [6]. Physics beyond the SM can induce top quark polarization. For example, models that predict the top quark forward-backward production asymmetry to be larger than the SM prediction, as seen by the Tevatron experiments D0 [7,8] and CDF [9], can generate nonzero polarization of top quarks [10–12]. A first study of polarization in $t\bar{t}$ events has been performed by the D0 Collaboration [8], showing good agreement between the SM prediction and data.

In this Letter, measurements are presented of the polarization of the top quark in inclusive $t\bar{t}$ production in single charged lepton ($t\bar{t} \to \ell\nu q\bar{q}b\bar{b}$) and dilepton ($t\bar{t} \to \ell^+\nu\ell^-\bar{\nu}b\bar{b}$) events. The double differential distribution in polar angles, θ, of two of the final-state decay products, with respect to a given quantization axis, is given by [13]

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + \alpha_1 P_1 \cos\theta_1 + \alpha_2 P_2 \cos\theta_2 - C\cos\theta_1\cos\theta_2), \quad (1)$$

where θ_1 (θ_2) is the angular distribution of the decay daughter particle of the top (antitop) quark. Here, C represents the $t\bar{t}$ spin correlation, P_1 (P_2) represents the degree of polarization of the top (antitop) quark along the chosen quantization axis, and α_i is the spin-analyzing power of the final-state object [14,15], which is a measure of the sensitivity of the daughter particle to the spin state of the parent. At leading order, charged leptons and down-type quarks from W-boson decays are predicted to have the largest sensitivity to the spin state of the top quark with a spin-analyzing power of $\alpha = 1$. The helicity basis is used, in which the momentum direction of the top quark in the $t\bar{t}$ center-of-mass frame is chosen as the quantization axis. The $\cos\theta_\ell$ distributions of the charged leptons are used as observables to extract a measurement of $\alpha_\ell P$.

The analysis is based on the full 2011 data set of pp collision events, collected at a center-of-mass energy of 7 TeV by the ATLAS detector [16], corresponding to an integrated luminosity of $4.66 \pm 0.08\ \mathrm{fb}^{-1}$ [17] after data quality requirements.

ATLAS includes an inner tracking detector, covering a pseudorapidity [18] range $|\eta| < 2.5$, surrounded by a superconducting solenoid providing a 2 T magnetic field. A liquid argon (LAr) electromagnetic sampling calorimeter ($|\eta| < 3.2$), an iron-scintillator tile hadronic calorimeter ($|\eta| < 1.7$), a LAr hadronic calorimeter ($1.4 < |\eta| < 3.2$), and a LAr forward calorimeter ($3.1 < |\eta| < 4.9$) provide the energy measurements. The muon spectrometer consists of tracking chambers covering $|\eta| < 2.7$, and trigger chambers covering $|\eta| < 2.4$, in a toroidal magnetic field. Events considered in this analysis are required to have one high-transverse-momentum (p_{T}) electron or muon that passes requirements of the three-level trigger system.

Both data-driven techniques and Monte Carlo (MC) simulations are used to estimate the sample composition of the data. For each MC sample, generated events are

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

processed through a GEANT4 [19] simulation of the full ATLAS detector [20], and the same reconstruction and analysis software is used for both the data and the MC events. Signal $t\bar{t}$ events are simulated by the next-to-leading-order (NLO) generator MC@NLO 3.41 [21] with the NLO parton distribution function (PDF) set CT10 [22], assuming a top quark mass of 172.5 GeV. Parton showering is modeled with HERWIG 6.510 [23], and JIMMY 4.31 [24] is used for the underlying event. A $t\bar{t}$ production cross section of 167^{+17}_{-18} pb is used, calculated at approximate next-to-next-to-leading order (NNLO) in QCD using HATHOR 1.2 [25]. Backgrounds are simulated using the MC@NLO, ACERMC [26], ALPGEN [27], and HERWIG generators, as detailed in Ref. [28]. Each simulated signal or background event is overlaid with additional pp collisions. The events are given a weight such that the distribution of the average number of events per beam crossing agrees with data. For each sample the cross section is rescaled to the most up-to-date theoretical expectations, as described in Ref. [29].

The data sample is enriched in $t\bar{t}$ events by applying several selection criteria based on the $t\bar{t}$ event topology. The selected $t\bar{t}$ events consist of jets, isolated leptons, and missing transverse momentum from the undetected neutrinos. Jets are reconstructed from clustered energy deposits in the calorimeters using the anti-k_t algorithm [30] with a radius parameter $R = 0.4$. Their energies are corrected to correspond on average to the total energy of the stable particles emitted towards the jet using energy- and η-dependent correction factors derived from simulation, and a residual correction derived from *in situ* measurements [31,32]. They are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. Furthermore, at least 75% of the scalar sum of the p_T of all the tracks associated with each jet must belong to tracks originating from the primary vertex, which is defined as the vertex with the highest sum of the squared p_T values of the associated tracks in the event. Jets originating from b quarks are selected using a neural network algorithm that combines information about the impact parameter significance of tracks with information about explicitly reconstructed secondary vertices and other variables. At the chosen working point, the algorithm identifies ("b tags") simulated b jets from top quark decays with 70% efficiency and a rejection factor of about 140 for light partons [33–35]. Reconstructed electrons must have $p_T >$ 25 GeV and be associated with a calorimeter cluster in the range $|\eta_{cl}| < 2.47$, excluding the transition between calorimeter sections, $1.37 < |\eta_{cl}| < 1.52$. Selected muons are required to fulfill $|\eta| < 2.5$ and $p_T > 20$ GeV. Each lepton is required to pass quality criteria, to be compatible with being produced at the primary vertex by having a longitudinal impact parameter smaller than 2 mm, and to be isolated from other calorimeter energy deposits and tracks [36]. The E_T^{miss} is calculated [37] as the magnitude of the negative of the vectorial sum of all energy deposits in the calorimeters, and then corrected for the momenta of the reconstructed muons.

The details of the final event selection depend on the W decay channels. This measurement uses five different channels, containing either one or two electrons or muons in the final state, including the ones coming from τ decays. The requirements for the single-lepton channels (ℓ + jets) include (i) exactly one electron or muon; (ii) at least four jets, at least one of which is b tagged; (iii) $E_T^{miss} > 30$ GeV for the electron channel and $E_T^{miss} >$ 20 GeV for the muon channel; and (iv) the transverse mass of the W boson to be greater than 30 GeV for the electron channel, while $m_T + E_T^{miss} > 60$ GeV is required for the muon channel. The transverse mass is computed from the lepton p_T and ϕ angle (p_T^ℓ, ϕ^ℓ) and the direction of the E_T^{miss} as $m_T = \sqrt{2p_T^\ell E_T^{miss}[1 - \cos(\phi^\ell - \phi(E_T^{miss}))]}$.

The selection of the dilepton channels (ee, $e\mu$, $\mu\mu$) requires (i) exactly two oppositely charged electrons or muons; (ii) at least two jets; (iii) a dilepton invariant mass larger than 15 GeV for all the channels, and more than 10 GeV away from the Z boson mass for the ee and $\mu\mu$ channels; (iv) $E_T^{miss} > 60$ GeV for the ee and $\mu\mu$ channels; and (v) the scalar sum of the p_T of all selected leptons and jets to be larger than 130 GeV for the $e\mu$ channel.

The major backgrounds are due to vector boson production with additional jets, single top quark production, and to misidentified leptons. Their contributions are estimated using data-driven methods and MC simulation. In particular, the normalization of the dominant background in the ℓ + jets channels, W + jets production, is estimated using a measurement of the lepton charge asymmetry in data [38], while the shape of the distribution of $\cos\theta_\ell$ is taken from simulation. In the ee ($\mu\mu$) channel, the normalization of the Z/γ^* + jets background with Z/γ^* decaying into ee ($\mu\mu$) is determined from data. A Z/γ^* + jets enriched control region is defined, where a correction factor for the simulation normalization is derived as a function of the E_T^{miss} in the event, and applied to the signal region in order to account for possible E_T^{miss} mismodeling.

The contributions of nonprompt leptons from semileptonic hadron decays and of jets misidentified as leptons (fakes) are determined from data using matrix methods [29,39]. For ℓ + jets channels this contribution comes primarily from multijet events, while for dilepton channels it originates primarily from W + jets events where one charged lepton comes from W decay and the other lepton is a nonprompt or fake lepton.

After selection, the expected yields for signal and background compared to data are shown in Table I.

The selected events are reconstructed under the $t\bar{t}$ event hypothesis: jets are associated with particular quarks, and the longitudinal momenta of the neutrinos in the event are determined. From the fully reconstructed decay chain we calculate the momentum of the top quark in the $t\bar{t}$ frame and from it $\cos\theta_\ell$.

TABLE I. Expected signal and background rounded yields compared to data for each of the five lepton flavor channels considered. The approximate NNLO SM prediction [25] is assumed for $t\bar{t}$ production, and the total systematic and statistical uncertainties are reported.

Source	e + jets	μ + jets	ee	$e\mu$	$\mu\mu$
$t\bar{t}$	16 200	26 500	570	4400	1660
Background	5100	9400	110	700	320
Total	21 300	35 900	690	5000	1980
Uncertainty	±1300	±1700	±80	±500	±180
Data	21 956	37 919	740	5328	2057

In the ℓ + jets channels, a kinematic likelihood fit is performed. The likelihood for the event to correspond to a $t\bar{t}$ decay topology is calculated for each possible assignment of four jets selected from the up to five jets of highest p_T in the event, to the two b quark jets and the two jets from the W boson decay [40]. The energies of the jets and the charged lepton, as well as the E_T^{miss}, are allowed to vary within their respective resolutions to best meet the W boson and top quark mass constraints to form the kinematic likelihood. For each assignment, the combined probability is calculated as the product of the maximum kinematic likelihood, the b tagging efficiencies and light-parton rejection probabilities. The highest probability assignment is chosen as the best reconstruction and used to calculate the charged lepton $\cos\theta_\ell$.

In the dilepton channels, the neutrino weighting method is used [41]. Because of the presence of two neutrinos from W boson decays, the final system is underconstrained and assumptions must be made to calculate all particle momenta. Making a hypothesis for the pseudorapidities of the two neutrinos (η_1, η_2), a weight is assigned for each permutation of jets, based on the compatibility of the total neutrino transverse momentum vector and the measured E_T^{miss}, accounting for E_T^{miss} resolution [37]. For each event, 10 000 different hypotheses for (η_1, η_2) are scanned, drawn from the observed probability distribution in the signal MC sample. The configuration with the maximal weight is selected and used to reconstruct the values of $\cos\theta_\ell$ for both charged leptons. Events for which no physical solution can be found with this method are discarded, corresponding to 15% of the selected events in the simulated dilepton $t\bar{t}$ sample. The assumed η distributions of the neutrinos are insensitive to top quark polarization.

To extract the value of $\alpha_\ell P$ from the data, a fit using templates for partially polarized top quarks is performed. The signal templates are obtained by reweighting the top and antitop quark decay products in the simulated $t\bar{t}$ sample according to Eq. (1) using the helicity basis and setting C to the SM value of $t\bar{t}$ spin correlation, $C = 0.31$ [6]. Two different assumptions about the top quark polarization are made to produce two template fits. In one case, the polarization is assumed to be induced by a charge-parity (CP) conserving process, labeled CPC, which leads to top and antitop quarks having equal values of $\alpha_\ell P$ and therefore the same angular distribution for the daughter particles. In the other, maximal CP violation, labeled CPV, is assumed, leading to opposite values of $\alpha_\ell P$ for the top and antitop quarks. In this case, when a value of $\alpha_\ell P$ is quoted its sign refers to the sign of the coefficient for positively charged leptons. The positive and negative templates used in the fit are built assuming a value of $\alpha_\ell P = \pm 0.3$, to guarantee that the differential decay distribution is positive for all values of $\cos\theta_\ell$ given the degree of spin correlation. The fraction, f, of the positive template component and the $t\bar{t}$ production cross section are fitted simultaneously, in order to reduce the influence of normalization uncertainties on the measured polarization. The polarization is computed as $\alpha_\ell P = 0.6f - 0.3$.

For all the considered channels, a template fit is performed with a binned maximum likelihood method on the positive lepton and on the negative lepton distributions. Channels are combined by multiplying their respective likelihood functions. The fitting method is unbiased, which was shown using pseudoexperiments.

For each source of systematic uncertainty, new templates corresponding to the respective 1 standard deviation up and down variation are considered. When an uncertainty is evaluated as the difference between two points, it is symmetrized around the central value. The mean of the distribution of the respective differences between the central fit values and the up and down results from 1000 pseudodata sets is taken as the systematic uncertainty on that source. Systematic uncertainties arising from the same source are treated as being correlated between the different lepton charge and flavor samples.

Detector systematic uncertainties, related to the determination of the energy or momentum scales, resolutions, and efficiencies for jets, electrons, and muons, as well as the E_T^{miss}, are considered [32,37,42–46]. Simulated samples are corrected in order to match the reconstructed object properties observed in data, and the correction factors are varied depending on the uncertainties of their values, in order to estimate the uncertainty on the final measurement. The largest uncertainty in this measurement comes from the jet energy scale.

Systematic uncertainties from the modeling of $t\bar{t}$ production are accounted for using alternative signal templates. These templates are produced by varying the MC event generator, initial- and final- state radiation, color reconnection, fragmentation modeling, and the PDF sets, as detailed in Ref. [47]. The estimation of the uncertainty due to the top quark mass is performed by repeating the fitting procedure using seven samples with different mass settings in the simulation, and interpolating the change in the parameter f corresponding to a variation of the top quark mass of ±1.4 GeV [48] around the nominal value. Because an assumption on the degree of spin correlation is

TABLE II. Summary of the systematic uncertainties on $\alpha_\ell P$ for the CP conserving and CP violating fits in the combined channels. The systematic uncertainties have been added in quadrature to obtain the total uncertainty.

Source	$\Delta\alpha_\ell P_{\rm CPC}$	$\Delta\alpha_\ell P_{\rm CPV}$
Jet reconstruction	+0.031 − 0.031	+0.009 − 0.005
Lepton reconstruction	+0.006 − 0.007	+0.002 − 0.001
$E_{\rm T}^{\rm miss}$ reconstruction	+0.008 − 0.007	+0.004 − 0.001
$t\bar{t}$ modeling	+0.015 − 0.016	+0.005 − 0.013
Background modeling	+0.011 − 0.010	+0.005 − 0.007
Template statistics	+0.005 − 0.005	+0.006 − 0.006
Total systematic uncertainty	+0.037 − 0.037	+0.013 − 0.017

made when constructing the template, an additional uncertainty is applied based on the difference in the parton-level spin correlation in simulated $t\bar{t}$ events between the MC@NLO and POWHEG [49] generators.

For the W + jets background in the ℓ + jets final state, the overall normalization is varied according to the residual uncertainty after the rescaling based on the measured charge asymmetry [38]. In addition, the W + jets template is varied in shape and normalization by reweighting events according to both the uncertainty in the associated heavy quark production flavor fractions and the parameters of the simulation of extra jets [39]. For the estimate of the systematic uncertainty due to events with nonprompt or fake leptons, the templates are varied according to the uncertainties in the matrix method inputs [29,39]. The MC statistical uncertainty is taken into account by performing pseudoexperiments, where the bin content of each template is varied independently according to the uncertainty. Table II summarizes the sources of systematic uncertainty and their effect on $\alpha_\ell P$ for the combined fit. The two largest uncertainties come from jet reconstruction and MC modeling, both affecting the shape of the $\cos\theta_\ell$ distribution. For sources of systematic uncertainty that do not depend on the lepton charge in the event, the uncertainty in the CP violating scenario is greatly reduced. These uncertainties push the fit parameters in opposite directions for the samples with different lepton charge, leading to a smaller total uncertainty in the combination.

The results of the fit to the data in the single-lepton and dilepton channels are summarized in Table III. Figure 1 shows the fitted observable in the single-lepton and dilepton final states with the CP conserving hypothesis, and Fig. 2 shows the same observable in the CP violating hypothesis. The deviation from the expected linear behavior of the $\cos\theta_\ell$ distributions is primarily a result of the detector acceptance.

The combined results are

$$\alpha_\ell P_{\rm CPC} = -0.035 \pm 0.014({\rm stat}) \pm 0.037({\rm syst}) \quad (2)$$

in the CP conserving scenario, and

$$\alpha_\ell P_{\rm CPV} = 0.020 \pm 0.016({\rm stat})^{+0.013}_{-0.017}({\rm syst}) \quad (3)$$

TABLE III. Summary of fitted $\alpha_\ell P$ in the individual channels for the CP conserving and CP violating fits. The uncertainties quoted are first statistical and then systematic.

Channel	$\alpha_\ell P_{\rm CPC}$	$\alpha_\ell P_{\rm CPV}$
ee	$0.12 \pm 0.10^{+0.09}_{-0.12}$	$-0.04 \pm 0.12^{+0.18}_{-0.12}$
$e\mu$	$-0.07 \pm 0.04^{+0.05}_{-0.06}$	$0.00 \pm 0.04^{+0.05}_{-0.04}$
$\mu\mu$	$-0.04 \pm 0.06^{+0.07}_{-0.07}$	$0.04 \pm 0.07^{+0.06}_{-0.06}$
Dilepton	$-0.04 \pm 0.03^{+0.05}_{-0.05}$	$0.01 \pm 0.03^{+0.04}_{-0.04}$
e + jets	$-0.031 \pm 0.028^{+0.043}_{-0.040}$	$0.001 \pm 0.031^{+0.019}_{-0.019}$
μ + jets	$-0.033 \pm 0.021^{+0.039}_{-0.039}$	$0.036 \pm 0.023^{+0.018}_{-0.017}$
ℓ + jets	$-0.034 \pm 0.017^{+0.038}_{-0.037}$	$0.023 \pm 0.019^{+0.012}_{-0.011}$
Combined	$-0.035 \pm 0.014^{+0.037}_{-0.037}$	$0.020 \pm 0.016^{+0.013}_{-0.017}$

in the CP violating scenario. The polarization in both scenarios agrees with the SM prediction of negligible polarization. The fitted $\sigma_{t\bar{t}}$ is in good agreement with the SM prediction as obtained from NNLO QCD calculations [50,51].

In conclusion, the first measurement of top quark polarization in $t\bar{t}$ events has been performed for two different scenarios with 4.7 fb^{-1} of proton-proton collision data at 7 TeV center-of-mass energy with the ATLAS detector at

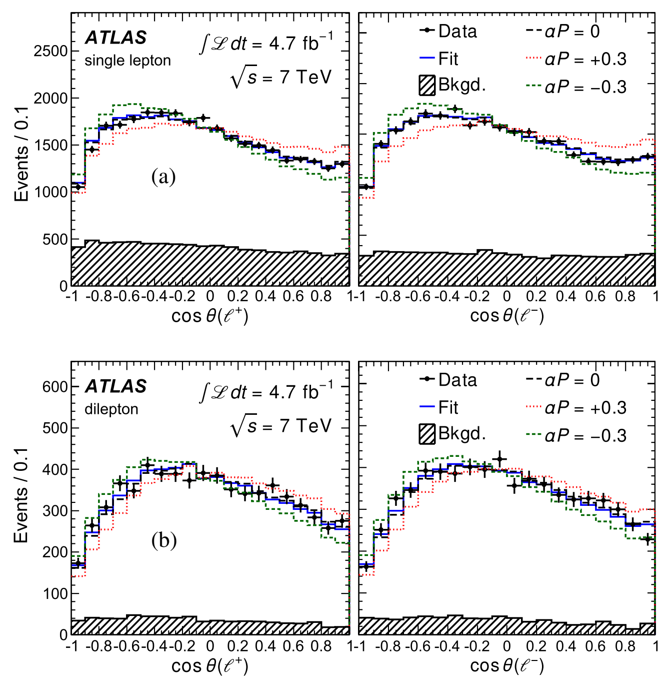

FIG. 1 (color online). The result of the full combined fit to the data with the CP conserving polarization hypothesis in (a) the single-lepton channel and (b) the dilepton channel, adding together electrons and muons. It is compared to the polarization templates used and the SM prediction of zero polarization. Positively charged leptons are on the left, and negatively charged leptons are on the right.

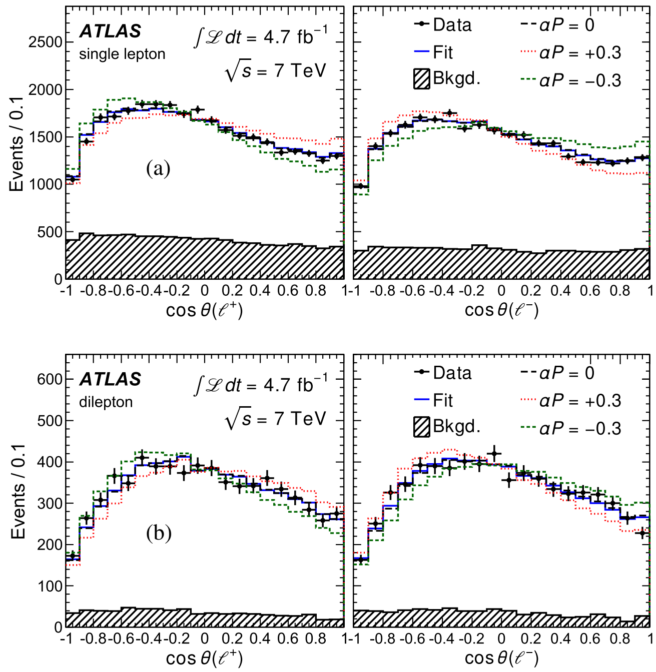

FIG. 2 (color online). The result of the full combined fit to the data with the CP violating polarization hypothesis in (a) the single-lepton channel and (b) the dilepton channel, adding together electrons and muons. It is compared to the polarization templates used and the SM prediction of no polarization. Positively charged leptons are on the left, and negatively charged leptons are on the right.

the LHC. Single-lepton and dilepton final states have been analyzed and no deviation from the SM prediction of negligible polarization is observed for either the CP conserving or maximally CP violating scenario.

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J. Teuscher,[159,k] J. Therhaag,[21] T. Theveneaux-Pelzer,[34] S. Thoma,[48] J. P. Thomas,[18] E. N. Thompson,[35] P. D. Thompson,[18] P. D. Thompson,[159] A. S. Thompson,[53] L. A. Thomsen,[36] E. Thomson,[121] M. Thomson,[28] W. M. Thong,[87] R. P. Thun,[88,a] F. Tian,[35] M. J. Tibbetts,[15] T. Tic,[126] V. O. Tikhomirov,[95] Yu. A. Tikhonov,[108,h] S. Timoshenko,[97] E. Tiouchichine,[84] P. Tipton,[177] S. Tisserant,[84] T. Todorov,[5] S. Todorova-Nova,[128] B. Toggerson,[164] J. Tojo,[69] S. Tokár,[145a] K. Tokushuku,[65] K. Tollefson,[89] L. Tomlinson,[83] M. Tomoto,[102] L. Tompkins,[31] K. Toms,[104] A. Tonoyan,[14] C. Topfel,[17] N. D. Topilin,[64] E. Torrence,[115] H. Torres,[79] E. Torró Pastor,[168] J. Toth,[84,hh] F. Touchard,[84] D. R. Tovey,[140] H. L. Tran,[116] T. Trefzger,[175] L. Tremblet,[30] A. Tricoli,[30] I. M. Trigger,[160a] S. Trincaz-Duvoid,[79] M. F. Tripiana,[70] N. Triplett,[25] W. Trischuk,[159] B. Trocmé,[55] C. Troncon,[90a] M. Trottier-McDonald,[143] M. Trovatelli,[135a,135b] P. True,[89] M. Trzebinski,[39] A. Trzupek,[39] C. Tsarouchas,[30] J. C-L. Tseng,[119] P. V. Tsiareshka,[91] D. Tsionou,[137] G. Tsipolitis,[10] S. Tsiskaridze,[12] V. Tsiskaridze,[48] E. G. Tskhadadze,[51a] I. I. Tsukerman,[96] V. Tsulaia,[15] J.-W. Tsung,[21] S. Tsuno,[65] D. Tsybychev,[149] A. Tua,[140] A. Tudorache,[26a] V. Tudorache,[26a] J. M. Tuggle,[31] A. N. Tuna,[121] S. Turchikhin,[98,ll] D. Turecek,[127] I. Turk Cakir,[4d] R. Turra,[90a,90b] P. M. Tuts,[35] A. Tykhonov,[74] M. Tylmad,[147a,147b] M. Tyndel,[130] K. Uchida,[21] I. Ueda,[156] R. Ueno,[29] M. Ughetto,[84] M. Ugland,[14] M. Uhlenbrock,[21] F. Ukegawa,[161] G. Unal,[30] A. Undrus,[25] G. Unel,[164] F. C. Ungaro,[48] Y. Unno,[65] D. Urbaniec,[35] P. Urquijo,[21] G. Usai,[8] A. Usanova,[61] L. Vacavant,[84] V. Vacek,[127] B. Vachon,[86] S. Vahsen,[15] N. Valencic,[106] S. Valentinetti,[20a,20b] A. Valero,[168] L. Valery,[34] S. Valkar,[128] E. Valladolid Gallego,[168] S. Vallecorsa,[49] J. A. Valls Ferrer,[168] R. Van Berg,[121] P. C. Van Der Deijl,[106] R. van der Geer,[106] H. van der Graaf,[106] R. Van Der Leeuw,[106] D. van der Ster,[30] N. van Eldik,[30] P. van Gemmeren,[6] J. Van Nieuwkoop,[143] I. van Vulpen,[106] M. Vanadia,[100] W. Vandelli,[30] A. Vaniachine,[6] P. Vankov,[42] F. Vannucci,[79] R. Vari,[133a] E. W. Varnes,[7] T. Varol,[85] D. Varouchas,[15] A. Vartapetian,[8] K. E. Varvell,[151] V. I. Vassilakopoulos,[56]

F. Vazeille,[34] T. Vazquez Schroeder,[54] J. Veatch,[7] F. Veloso,[125a] S. Veneziano,[133a] A. Ventura,[72a,72b] D. Ventura,[85] M. Venturi,[48] N. Venturi,[159] V. Vercesi,[120a] M. Verducci,[139] W. Verkerke,[106] J. C. Vermeulen,[106] A. Vest,[44] M. C. Vetterli,[143,f] I. Vichou,[166] T. Vickey,[146c,oo] O. E. Vickey Boeriu,[146c] G. H. A. Viehhauser,[119] S. Viel,[169] R. Vigne,[30] M. Villa,[20a,20b] M. Villaplana Perez,[168] E. Vilucchi,[47] M. G. Vincter,[29] V. B. Vinogradov,[64] J. Virzi,[15] O. Vitells,[173] M. Viti,[42] I. Vivarelli,[48] F. Vives Vaque,[3] S. Vlachos,[10] D. Vladoiu,[99] M. Vlasak,[127] A. Vogel,[21] P. Vokac,[127] G. Volpi,[47] M. Volpi,[87] G. Volpini,[90a] H. von der Schmitt,[100] H. von Radziewski,[48] E. von Toerne,[21] V. Vorobel,[128] M. Vos,[168] R. Voss,[30] J. H. Vossebeld,[73] N. Vranjes,[137] M. Vranjes Milosavljevic,[106] V. Vrba,[126] M. Vreeswijk,[106] T. Vu Anh,[48] R. Vuillermet,[30] I. Vukotic,[31] Z. Vykydal,[127] W. Wagner,[176] P. Wagner,[21] S. Wahrmund,[44] J. Wakabayashi,[102] S. Walch,[88] J. Walder,[71] R. Walker,[99] W. Walkowiak,[142] R. Wall,[177] P. Waller,[73] B. Walsh,[177] C. Wang,[45] H. Wang,[174] H. Wang,[40] J. Wang,[152] J. Wang,[33a] K. Wang,[86] R. Wang,[104] S. M. Wang,[152] T. Wang,[21] X. Wang,[177] A. Warburton,[86] C. P. Ward,[28] D. R. Wardrope,[77] M. Warsinsky,[48] A. Washbrook,[46] C. Wasicki,[42] I. Watanabe,[66] P. M. Watkins,[18] A. T. Watson,[18] I. J. Watson,[151] M. F. Watson,[18] G. Watts,[139] S. Watts,[83] A. T. Waugh,[151] B. M. Waugh,[77] S. Webb,[83] M. S. Weber,[17] J. S. Webster,[31] A. R. Weidberg,[119] P. Weigell,[100] J. Weingarten,[54] C. Weiser,[48] H. Weits,[106] P. S. Wells,[30] T. Wenaus,[25] D. Wendland,[16] Z. Weng,[152,x] T. Wengler,[30] S. Wenig,[30] N. Wermes,[21] M. Werner,[48] P. Werner,[30] M. Werth,[164] M. Wessels,[58a] J. Wetter,[162] K. Whalen,[29] A. White,[8] M. J. White,[87] R. White,[32b] S. White,[123a,123b] D. Whiteson,[164] D. Whittington,[60] D. Wicke,[176] F. J. Wickens,[130] W. Wiedenmann,[174] M. Wielers,[80,e] P. Wienemann,[21] C. Wiglesworth,[36] L. A. M. Wiik-Fuchs,[21] P. A. Wijeratne,[77] A. Wildauer,[100] M. A. Wildt,[42,u] I. Wilhelm,[128] H. G. Wilkens,[30] J. Z. Will,[99] E. Williams,[35] H. H. Williams,[121] S. Williams,[28] W. Willis,[35,a] S. Willocq,[85] J. A. Wilson,[18] A. Wilson,[88] I. Wingerter-Seez,[5] S. Winkelmann,[48] F. Winklmeier,[30] M. Wittgen,[144] T. Wittig,[43] J. Wittkowski,[99] S. J. Wollstadt,[82] M. W. Wolter,[39] H. Wolters,[125a,i] W. C. Wong,[41] G. Wooden,[88] B. K. Wosiek,[39] J. Wotschack,[30] M. J. Woudstra,[83] K. W. Wozniak,[39] K. Wraight,[53] M. Wright,[53] B. Wrona,[73] S. L. Wu,[174] X. Wu,[49] Y. Wu,[88] E. Wulf,[35] T. R. Wyatt,[83] B. M. Wynne,[46] S. Xella,[36] M. Xiao,[137] C. Xu,[33b,cc] D. Xu,[33a] L. Xu,[33b,pp] B. Yabsley,[151] S. Yacoob,[146b,qq] M. Yamada,[65] H. Yamaguchi,[156] Y. Yamaguchi,[156] A. Yamamoto,[65] K. Yamamoto,[63] S. Yamamoto,[156] T. Yamamura,[156] T. Yamanaka,[156] K. Yamauchi,[102] Y. Yamazaki,[66] Z. Yan,[22] H. Yang,[33e] H. Yang,[174] U. K. Yang,[83] Y. Yang,[110] Z. Yang,[147a,147b] S. Yanush,[92] L. Yao,[33a] Y. Yasu,[65] E. Yatsenko,[42] K. H. Yau Wong,[21] J. Ye,[40] S. Ye,[25] A. L. Yen,[57] E. Yildirim,[42] M. Yilmaz,[4b] R. Yoosoofmiya,[124] K. Yorita,[172] R. Yoshida,[6] K. Yoshihara,[156] C. Young,[144] C. J. S. Young,[119] S. Youssef,[22] D. R. Yu,[15] J. Yu,[8] J. Yu,[113] L. Yuan,[66] A. Yurkewicz,[107] B. Zabinski,[39] R. Zaidan,[62] A. M. Zaitsev,[129,dd] S. Zambito,[23] L. Zanello,[133a,133b] D. Zanzi,[100] A. Zaytsev,[25] C. Zeitnitz,[176] M. Zeman,[127] A. Zemla,[39] O. Zenin,[129] T. Ženiš,[145a] D. Zerwas,[116] G. Zevi della Porta,[57] D. Zhang,[88] H. Zhang,[89] J. Zhang,[6] L. Zhang,[152] X. Zhang,[33d] Z. Zhang,[116] Z. Zhao,[33b] A. Zhemchugov,[64] J. Zhong,[119] B. Zhou,[88] N. Zhou,[164] C. G. Zhu,[33d] H. Zhu,[42] J. Zhu,[88] Y. Zhu,[33b] X. Zhuang,[33a] A. Zibell,[99] D. Zieminska,[60] N. I. Zimin,[64] C. Zimmermann,[82] R. Zimmermann,[21] S. Zimmermann,[21] S. Zimmermann,[48] Z. Zinonos,[123a,123b] M. Ziolkowski,[142] R. Zitoun,[5] L. Živković,[35] G. Zobernig,[174] A. Zoccoli,[20a,20b] M. zur Nedden,[16] G. Zurzolo,[103a,103b] V. Zutshi,[107] and L. Zwalinski[30]

(ATLAS Collaboration)

[1]*School of Chemistry and Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Department of Physics, Gazi University, Ankara, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[4d]*Turkish Atomic Energy Authority, Ankara, Turkey*
[5]*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[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*
[13a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*

[13b]*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, California, USA*
[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*
[19a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[19b]*Department of Physics, Dogus University, Istanbul, Turkey*
[19c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[20a]*INFN Sezione di Bologna, Italy*
[20b]*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, Massachusetts, USA*
[23]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[24a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[24b]*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[24c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[24d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[26a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[26b]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania*
[26c]*University Politehnica Bucharest, Bucharest, Romania*
[26d]*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, Ontario, Canada*
[30]*CERN, Geneva, Switzerland*
[31]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[32a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[32b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[33b]*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
[33c]*Department of Physics, Nanjing University, Jiangsu, China*
[33d]*School of Physics, Shandong University, Shandong, China*
[33e]*Physics Department, Shanghai Jiao Tong University, Shanghai, China*
[34]*Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[36]*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37a]*INFN Gruppo Collegato di Cosenza, Italy*
[37b]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[38a]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[38b]*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, Texas, USA*
[41]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[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, North Carolina, USA*
[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*
[50a]*INFN Sezione di Genova, Italy*
[50b]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[51b]*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, Virginia, USA
[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[58a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[58b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[58c]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, Indiana, USA
[61]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62]University of Iowa, Iowa City, Iowa, USA
[63]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[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
[72a]INFN Sezione di Lecce, Italy
[72b]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]Louisiana Tech University, Ruston, Louisiana, USA
[79]Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[80]Fysiska institutionen, Lunds universitet, Lund, Sweden
[81]Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[82]Institut für Physik, Universität Mainz, Mainz, Germany
[83]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[84]CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[85]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[86]Department of Physics, McGill University, Montreal, Quebec, Canada
[87]School of Physics, University of Melbourne, Victoria, Australia
[88]Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
[89]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[90a]INFN Sezione di Milano, Italy
[90b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[91]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[92]National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[93]Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[94]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
[95]P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[96]Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[97]Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[98]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[99]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[100]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[101]Nagasaki Institute of Applied Science, Nagasaki, Japan
[102]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[103a]INFN Sezione di Napoli, Italy
[103b]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[104]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[105]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[106]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[107]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[108]Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

[109]*Department of Physics, New York University, New York, New York, USA*
[110]*Ohio State University, Columbus, Ohio, USA*
[111]*Faculty of Science, Okayama University, Okayama, Japan*
[112]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[113]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[114]*Palacký University, RCPTM, Olomouc, Czech Republic*
[115]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[116]*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
[117]*Graduate School of Science, Osaka University, Osaka, Japan*
[118]*Department of Physics, University of Oslo, Oslo, Norway*
[119]*Department of Physics, Oxford University, Oxford, United Kingdom*
[120a]*INFN Sezione di Pavia, Italy*
[120b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[121]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[122]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[123a]*INFN Sezione di Pisa, Italy*
[123b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[124]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[125a]*Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal*
[125b]*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[126]*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[127]*Czech Technical University in Prague, Praha, Czech Republic*
[128]*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[129]*State Research Center Institute for High Energy Physics, Protvino, Russia*
[130]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[131]*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
[132]*Ritsumeikan University, Kusatsu, Shiga, Japan*
[133a]*INFN Sezione di Roma I, Italy*
[133b]*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[134a]*INFN Sezione di Roma Tor Vergata, Italy*
[134b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[135a]*INFN Sezione di Roma Tre, Italy*
[135b]*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[136a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco*
[136b]*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*
[136c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[136d]*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
[136e]*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, California, USA*
[139]*Department of Physics, University of Washington, Seattle, Washington, USA*
[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, British Columbia, Canada*
[144]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[145a]*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
[145b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[146a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[146b]*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
[146c]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[147a]*Department of Physics, Stockholm University, Sweden*
[147b]*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, New York, USA*
[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, Ontario, Canada*
[160a]*TRIUMF, Vancouver, British Columbia, Canada*
[160b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[161]*Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[162]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[163]*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[164]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[165a]*INFN Gruppo Collegato di Udine, Italy*
[165b]*ICTP, Trieste, Italy*
[165c]*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
[166]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[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, British Columbia, Canada*
[170]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, 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, Wisconsin, USA*
[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, Connecticut, USA*
[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]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal.
[d]Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[e]Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[f]Also at TRIUMF, Vancouver, British Columbia, Canada.
[g]Also at Department of Physics, California State University, Fresno, CA, USA.
[h]Also at Novosibirsk State University, Novosibirsk, Russia.
[i]Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[j]Also at Università di Napoli Parthenope, Napoli, Italy.
[k]Also at Institute of Particle Physics (IPP), Canada.
[l]Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[m]Also at Louisiana Tech University, Ruston, LA, USA.
[n]Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
[o]Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, USA.
[p]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[q]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[r]Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
[s]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[t]Also at CERN, Geneva, Switzerland.
[u]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[v]Also at Manhattan College, New York, NY, USA.
[w]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[x]Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[y]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

[z]Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[aa]Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
[bb]Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
[cc]Also at 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.
[dd]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[ee]Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[ff]Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[gg]Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
[hh]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ii]Also at DESY, Hamburg and Zeuthen, Germany.
[jj]Also at International School for Advanced Studies (SISSA), Trieste, Italy.
[kk]Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[ll]Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
[mm]Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.
[nn]Also at Physics Department, Brookhaven National Laboratory, Upton, NY, USA.
[oo]Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[pp]Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
[qq]Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.