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Test of the universality of τ and μ lepton couplings in W-boson decays from $t\bar{t}$ events with the ATLAS detector

The ATLAS Collaboration

The Standard Model of particle physics encapsulates our current best understanding of physics at the smallest scales. A fundamental axiom of this theory is the universality of the couplings of the different generations of leptons to the electroweak gauge bosons. The measurement of the ratio of the rate of decay of W bosons to τ-leptons and muons, $R(\tau/\mu) = B(W \to \tau\nu_\tau)/B(W \to \mu\nu_\mu)$, constitutes an important test of this axiom. A measurement of this quantity with a novel technique using di-leptonic $t\bar{t}$ events is presented based on 139 fb^{-1} of data recorded with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 13$ TeV. Muons originating from W bosons and those originating from an intermediate τ-lepton are distinguished using the lifetime of the τ-lepton, through the muon transverse impact parameter, and differences in the muon transverse momentum spectra. The value of $R(\tau/\mu)$ is found to be 0.992 ± 0.013 [± 0.007 (stat) $\pm$ 0.011 (syst)] and is in agreement with the hypothesis of universal lepton couplings as postulated in the Standard Model. This is the most precise measurement of this ratio, and the only such measurement from the Large Hadron Collider, to date.

1 Introduction

It is a fundamental axiom and remarkable feature of the Standard Model (SM) that the couplings of the electroweak gauge bosons (W, Z) to charged leptons, g_ℓ ($\ell = e, \mu, \tau$), are independent of the mass of the leptons. This fundamental assumption is referred to as *lepton-flavour universality* and is tested in this paper by measuring the ratio of the fraction of on-shell W boson decays, branching ratios (B), to τ-leptons and muons, $R(\tau/\mu) = B(W \rightarrow \tau\nu_\tau)/B(W \rightarrow \mu\nu_\mu)$. The measurement exploits the large number of top and anti-top quark pair ($t\bar{t}$) events produced in proton-proton (pp) collisions at the Large Hadron Collider (LHC). Given the large $B(t \rightarrow Wq)$, close to 100%, this gives a very large sample of W boson pairs. These are used in a *tag* and *probe* technique to obtain a large sample of clean and unbiased W boson decays to muons and τ-leptons. The τ-leptons are identified through their decay to muons. The displacement of the τ decay vertex and the different muon transverse momentum (p_T) spectra are used to distinguish between muons from the $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ and $W \rightarrow \mu\nu_\mu$ processes, to extract $R(\tau/\mu)$. This is achieved by utilising the precise reconstruction of muon tracks obtainable by the ATLAS experiment.

Previously, $R(\tau/\mu)$ has been measured by the four experiments at the Large Electron–Positron Collider (LEP), yielding a combined value of 1.070 ± 0.026 [1]. This deviates from the SM expectation of unity[1] by 2.7σ, motivating a precise measurement of this ratio at the LHC. Other experimental measurements of the ratio $B(W \rightarrow \tau\nu_\tau)/B(W \rightarrow \ell\nu_\ell)$, where ℓ is either an electron or a muon, have not yet reached the precision of the LEP results [3–7]. The equivalent ratio for the two light generations, $B(W \rightarrow \mu\nu_\mu)/B(W \rightarrow e\nu_e)$, has been accurately measured by the LEP [1], LHCb [8] and ATLAS [9] experiments, and is found to be consistent with the SM prediction at the 1% level. Additionally, while most low-energy experiments show good agreement, to very high precision, with the hypothesis of universality of lepton couplings [10], recent results from LHCb [11, 12], Belle [13–15] and BaBar [16, 17] show some tension with the SM, further motivating this analysis.

This measurement relies on precise knowledge of the branching ratio of τ-leptons decaying to muons to extrapolate to the full $W \rightarrow \tau\nu_\tau$ branching ratio. The value of $(17.39 \pm 0.04)\%$ measured by the LEP experiments [2, 18–21] is used in the analysis. The relative uncertainty of 0.23% is included in the measured value of $R(\tau/\mu)$ and is a subdominant component of the overall uncertainty.

2 Experimental set-up

The ATLAS experiment [22–24] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[2] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors, and the innermost layer of the pixel detector is at a radius of 33 mm from the beamline[3] providing

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[1] The phase space effects due to the masses of the decay products on this ratio are very small ($\sim 5 \times 10^{-4}$) and hence can be neglected [2].

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

[3] The beamline is the path through the detector drawn by the (x–y) coordinates along the central axis of the luminous region.

precise measurement of track impact parameters. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accepted events at a rate of 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average, depending on the data-taking conditions.

The analysed pp collision data were recorded with the ATLAS detector from 2015 to 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. To achieve high instantaneous luminosity, in these data there are additional collisions in the same and neighbouring LHC proton bunch crossings (pile-up). This resulted in an average of 34 interactions per bunch crossing. Events were selected by single-lepton triggers [25–27] requiring a single high-p_{T} isolated electron or muon. After the application of data-quality requirements [28], the data sample corresponds to an integrated luminosity of 139 fb^{-1} with an uncertainty of 1.7% [29] obtained using the LUCID-2 detector [30] for the primary luminosity measurements.

3 Monte Carlo simulated samples

Monte Carlo (MC) samples of simulated events were produced to model the different Standard Model processes. After event generation of the process of interest, as detailed below for each sample, the detector response was modelled using a simulation based on GEANT4 [31]. The data and MC simulated events were passed through the same reconstruction and analysis procedures. Samples were simulated for the signal processes, the production of $t\bar{t}$ and single top quarks in association with a W boson (Wt), as well as the different backgrounds.

The top-pair and single-top-quark events were generated using the POWHEGBOX v2 [32–35] generator with the `NNPDF3.0NLO` [36] set of parton distribution functions (PDFs) interfaced to the PYTHIA v8.230 [37–39] parton shower and hadronisation model. The decays of bottom and charm hadrons were modelled using the EVTGEN v1.6.0 [40] program. The $t\bar{t}$ and single-top processes were normalised to the inclusive cross-section calculation of the highest available precision [41–49] and $t\bar{t}$ events additionally have a differential reweighting applied to match the next-to-next-to-leading order (NNLO) in QCD top quark p_{T} calculation [50]. For single top quark production in the Wt-channel, the diagram removal scheme [51] was used to remove overlap with $t\bar{t}$ production.

The background from $V(= W, Z)$+jets events was simulated with the SHERPA v2.2 [52–61] generator with the `NNPDF3.0nnlo` set of PDFs [36]. Smaller backgrounds of di-boson processes and $t\bar{t} + V$ were simulated with SHERPA v2.2 and MADGRAPH5_aMC@NLO v2.3.3 [62] interfaced with PYTHIA v8.210, respectively. All processes were normalised to their highest order available cross sections [63, 64].

Simulated inelastic pp collisions [65] were overlaid on events in all samples to model the observed data distribution of pile-up from addition collisions in the same and neighbouring bunch crossings.

4 Event selection, object identification and calibration

The analysis exploits the two leptonic W boson decays in a *tag and probe* approach: in each event *tag* leptons are used to select the events, after which the *probe* muon can be used in an unbiased way to test whether it originates from a prompt decay, $W \to \mu\nu_\mu$, or via an intermediate τ-lepton, $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$. Events are categorised into *signal* regions, used to extract $R(\tau/\mu)$, and additional *control* regions, used to constrain the normalisation of the major backgrounds, as described in Section 5. The selection for these regions relies on reconstructed muons, electrons and hadronic jets.

Muons are reconstructed using combined fits of inner detector [66, 67] and muon spectrometer tracks [68]. They are required to satisfy the 'medium' identification critera. They are also required to be strictly isolated from other activity by requiring that the sum of the p_{T} of other tracks within a surrounding cone of size $\Delta R = 0.3$ and the sum of p_{T} calculated from calorimeter energy deposits within a cone of size $\Delta R = 0.2$ around the muons are below certain thresholds. *Tag* muons are required to have $p_{\mathrm{T}}^{\mu} > 27.3$ GeV to pass the trigger thresholds, while *probe* muons are required to have $p_{\mathrm{T}}^{\mu} > 5$ GeV. Both the *tag* and *probe* muons are required to have $|\eta| < 2.5$ and to originate close to the primary vertex[4] with a distance of closest approach in the r–z plane of less than 0.3 mm and a transverse impact parameter relative to the beamline, $|d_0^{\mu}|$, of less than 0.5 mm. Additional criteria are applied to test the compatibility of the momenta measured separately in the inner detector and the muon spectrometer, in order to remove reconstructed muons which result from in-flight decays of $\pi^{\pm}$ and $K^{\pm}$ mesons.

Electrons are reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters [69]. They are required to satisfy the 'tight' identification criteria and the same strict isolation criteria as applied to muons. *Tag* electrons are required to have $p_{\mathrm{T}}^{e} > 27$ GeV, to pass the trigger requirements and satisfy $|\eta| < 2.47$, excluding the transition region between the barrel and end-cap calorimeter, $1.37 < |\eta| < 1.52$. They must also satisfy the same criteria as for muons for their distance of closest approach to the primary vertex in the transverse and r–z plane.

Hadronic jets are built from the energy in clusters of calorimeter cells [70] at the electromagnetic energy scale, using the anti-k_t algorithm [71] with a radius parameter of 0.4. They are then calibrated to the energy scale of jets created from stable generator-level particles excluding muons and neutrinos using the same algorithm [72]. For jets with $25 < p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$, pile-up suppression requirements in the form of a jet vertex tagger [73] are applied. Only jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ are considered in the analysis. To classify jets as containing a b-hadron, the 70% efficiency working point of the MV2c10 b-tagging algorithm [74, 75] is used.

An overlap removal procedure is applied to resolve the ambiguity of lepton signals in the calorimeter being reconstructed as hadronic jets as described in Ref. [76].

To obtain a pure sample of di-leptonic $t\bar{t}$, events entering the signal region are required to contain either one electron and one muon of opposite electric charge (e–μ channel), or two muons of opposite electric charge (μ–μ channel). Events must be triggered by the electron in the e–μ channel or by the *tag* muon in the μ–μ channel. This ensures the *probe* muons have no trigger bias. If both leptons in the μ–μ channel satisfy the *tag* and *probe* criteria, both muons are used as *probes*. Events with more than two leptons are rejected. In addition, events must have at least two reconstructed hadronic jets which are identified as containing a b-hadron. Finally, to reduce backgrounds from Z bosons and hadron decays, events with di-muon mass

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[4] The primary vertex is defined as the vertex with the highest Σp_{T}^2 of the tracks associated with it.

$85 < m_{\mu\mu} < 95$ GeV are excluded in the μ–μ channel, and events with di-lepton mass $m_{\ell\ell} < 15$ GeV are excluded in both channels.

The muon's transverse impact parameter $|d_0^\mu|$ has particular importance for this analysis. It is measured in x–y plane as the closest distance of approach of the track to the beamline. It is defined relative to the beamline rather than the primary vertex so that the resolution of $|d_0^\mu|$ is independent of the vertex (x–y)-resolution, which depends on the physics process. The shape of the $|d_0^\mu|$ distribution of prompt muons is determined using a $Z \to \mu\mu$ *calibration* region and then applied in the $t\bar{t}$ signal region through templates.

The $Z \to \mu\mu$ events are selected by requiring two muons satisfying the same kinematic criteria as in the signal region, with the invariant mass requirement changed to $85 < m_{\mu\mu} < 100$ GeV. No requirements on hadronic jets are applied. This gives a sample of approximately 95 million prompt muons with a purity of $> 99.9\%$.

The shape of the $|d_0^\mu|$ distribution is then taken from this data sample after subtracting the expected contributions from the simulation of processes with significant parent lifetimes, primarily $Z \to \tau\tau$. These $|d_0^\mu|$ *templates* are extracted in 33 bins in p_{T}^μ and $|\eta^\mu|$ to capture the dependence of the distribution on these variables. Separate templates are used for 2015+2016, 2017 and 2018 data to account for differences in the beam conditions and in the alignment of the inner detector.

Additionally, using this *calibration* region, the Gaussian core of the $|d_0^\mu|$ resolution is estimated in data and simulation by fitting the $|d_0^\mu|$ distribution in the range $|d_0^\mu| < 0.02$ mm. For $p_{\mathrm{T}}^\mu = 20$ GeV the resolution is approximately 14 μm. Corrections to account for differences in the resolution of the detector between the data and simulation are applied to the samples simulating the processes with significant decay-vertex displacement, i.e. muons from τ decays and hadron decays. For the range of $|d_0^\mu|$ values considered in this analysis, the resolution measured from prompt muons is applicable to those with significant displacement.

5 Background normalisation

The two largest backgrounds are $Z(\to \mu\mu)$+jets and events in which the *probe* muon does not originate from a W boson decay. Three dedicated *control* regions are used to extract the normalisation of these backgrounds.

The $Z(\to \mu\mu)$+jets background is important at small values of $|d_0^\mu|$. The normalisation of the $Z(\to \mu\mu)$+jets background in the μ–μ channel is extracted from the data in a *control* region where the same event selection is applied, including the hadronic jet requirements, but without the $m_{\mu\mu}$ criterion. Then the peak of the invariant mass distribution of the dimuon system is fitted over the range $50 < m_{\mu\mu} < 140$ GeV. A Voigt profile [77] is used for the $Z \to \mu\mu$ resonance and a third-order Chebychev polynomial for the background, which provides a good description of the data. Other functions are tested to provide a systematic uncertainty which is combined with the statistical uncertainties. The normalisation factor required to scale the simulated sample to data is found to be 1.36 ± 0.01. The dimuon mass is shown in Figure 1 after this normalisation is applied. This normalisation factor is also applied to the small $Z(\to \tau\tau)$+jets background.

The most important background at large values of $|d_0^\mu|$ is from events in which the *probe* muon originates from the decay of b- or c-hadrons, or more rarely from in-flight decays of $\pi^\pm$ and $K^\pm$, primarily in semileptonic $t\bar{t}$ events. These muons are referred to as $\mu_{(had.)}$. The largest source of $\mu_{(had.)}$ is from decays of b-hadrons, and this contributes equally to same-sign and opposite-sign selections, and the other significant

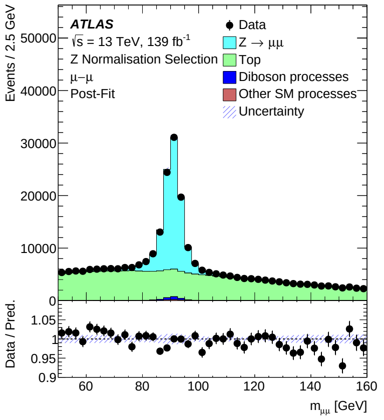
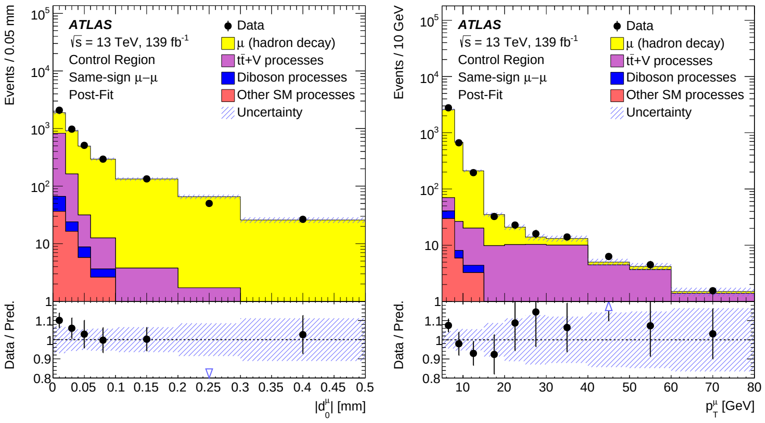


Figure 1: The $m_{\mu\mu}$ distribution in the $Z \longrightarrow \mu\mu$ *control* region used to extract the $Z \longrightarrow \mu\mu$ normalisation, which is applied in the signal region. The bottom panel shows the ratio of the data to the expectation. Blue bands indicate the systematic uncertainties with the constraints from the analysis fit of the signal region data applied.



(a): *Probe* muon $|d_0^\mu|$ distribution (b): *Probe* muon p_T^μ distribution

Figure 2: The *probe* muon $|d_0^\mu|$ and p_T^μ distributions in the μ–μ same-sign $\mu_{(had.)}$ *control* region. The extracted normalisation factors have been applied. The bottom panel shows the ratio of the data to the expectation. Blue bands indicate the systematic uncertainties with the constraints from the analysis fit of the signal region data applied.

source, c-hadrons, has a component in both selections, but they are not equal. A data-driven method is used to determine the normalisation of this background from two *control* regions, one each for the μ–μ and e–μ channels, which have the same event selection as the signal regions but where the two leptons have same-sign electric charge. This results in a sample with a high purity of this $\mu_{(had.)}$ background. The extrapolation from same-sign *control* region to opposite-sign signal region is estimated from simulation. In the same-sign *control* region there are also two backgrounds to $\mu_{(had.)}$at high p_T^μ which do not originate from hadron decays: $t\bar{t} + V$ and $t\bar{t}$ through electron charge misidentification in the e–μ channel. Therefore, before extracting the normalisation of the $\mu_{(had.)}$ background, a normalisation correction factor is also applied to these processes, based on the number of events observed with *probe* muon $p_\mathrm{T}^\mu > 30$ GeV. Normalisation factors to scale the simulation to data for the $\mu_{(had.)}$ background are found to be 1.39 (1.37) in the e–μ (μ–μ) channels, respectively. Figure 2 shows that the simulation and data are consistent within uncertainties in the μ–μ channel same-sign *control* region, providing confidence that the differential distributions of p_T^μ and $|d_0^\mu|$ are well-modelled.

6 Systematic uncertainties and fit configuration

A profile likelihood fit [78] is performed in three bins in p_T^μ (boundaries of: 5, 10, 20, 250 GeV) and eight bins in the transverse impact parameter, $|d_0^\mu|$ (boundaries of: 0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5 mm), of the *probe* muon for each channel (e–μ and μ–μ), making 48 bins in total.

To extract the ratio of the number of events in which the *probe* muon orginates from the process $W \longrightarrow \tau\nu_\tau \longrightarrow \mu\nu_\mu\nu_\tau\nu_\tau$, referred to as $\mu_{(\tau\rightarrow\mu)}$, to those which come from the process $W \longrightarrow \mu\nu_\mu$, referred to as $\mu_{(prompt)}$, the negative-log-likelihood minimisation is performed. Several (nuisance) parameter values

Table 1: The alternative settings and, in the case of the parton shower and hadronisation model, the alternative sample which are used to assess the theoretical uncertainties in the modelling of $t\bar{t}$. In the cases where a single alternative is given, the uncertainty is taken to be the deviation from the nominal result and then symmetrised.

Uncertainty	**Alternative Settings / Sample**
Inital- and final-state radiation	A14 eigen-tune variations [38] of the strong coupling (α_s)
Missing higher-order QCD corrections	Factorisation and renormalisation scales up by a factor of 2 and down by a factor of 0.5
Resummation scale uncertainty	Powheg h_{damp} parameter varied from 1.5 to 3 m_{top}
Parton shower and hadronisation model	Herwig v7.04 [79, 80], H7UE tune [80], `MMHT2014LO` PDF set [81]
Top p_T spectrum	Removing the NNLO top p_T reweighting

representing the statistical and systematic uncertainties are included which can be modified by the fit. As both the $t\bar{t}$ and Wt processes contain two W bosons both are treated as signal. Two fit parameters are allowed to float freely: $R(\tau/\mu)$ and $k(t\bar{t})$. The $k(t\bar{t})$ parameter is a constant scaling factor applied to the normalisation of both the $\mu_{(prompt)}$ and $\mu_{(\tau\rightarrow\mu)}$ components of the $t\bar{t}$ and Wt signal whilst $R(\tau/\mu)$ only affects the $\mu_{(\tau\rightarrow\mu)}$ components, and both are applied across all bins and in both channels. This means that $R(\tau/\mu)$ forms the parameter of interest and it is not affected by the overall normalisation scaling factors of the $t\bar{t}$ and Wt processes. The fit is performed after applying the normalisation scaling factors derived in the *control* regions. Other processes are normalised to their theoretical cross-sections with nuisance parameters representing the uncertainty in these predictions.

Since many systematic uncertainties are correlated between the $\mu_{(prompt)}$ and $\mu_{(\tau\rightarrow\mu)}$ templates, they have minimal impact on the ratio $R(\tau/\mu)$. These include uncertainties related to jet reconstruction, flavour tagging and trigger efficiencies. Only the remaining dominant uncertainties in the data driven methods, the theoretical modelling uncertainties and the reconstruction uncertainties are described in the following.

An uncertainty associated with the data-driven templates for the $|d_0^\mu|$ distribution of $\mu_{(prompt)}$ is derived to account for the fact that the templates are constructed in a $Z \rightarrow \mu\mu$ *calibration* region, but applied to a $t\bar{t}$ final state. Due to differences in the hadronic environment around the lepton between Z and $t\bar{t}$ final states and the coarse binning in p_T^μ and $|\eta|$, which may not be able to encapsulate the full shape information, small biases can exist in the template distributions. The size of such a possible bias is estimated from the full difference between $\mu_{(prompt)}$ $|d_0^\mu|$ templates from Z and $t\bar{t}$ in simulation. This uncertainty is split into two components corresponding to the tail, $|d_0^\mu| \gtrsim 0.05$ mm, and core, $|d_0^\mu| \lesssim 0.05$ mm, to prevent the data from constraining the uncertainty by using the full $|d_0^\mu|$ distribution.

Uncertainties in the $\mu_{(had.)}$ background *control* region normalisation in the e–μ (μ–μ) channels are: 4% (4%) due to the size of the same-sign dataset; 8% (3%) due to the choice of MC generators used; and 1.0% (1.3%) due the uncertainty in the subtraction of the other processes in the same-sign *control* region. The uncertainties associated with the Z+jets normalisation derived from data and the higher-order cross-section uncertainties, including that in the integrated luminosity, applied to all other backgrounds estimated from simulation are also included in the fit but have minor impact on the result.

Uncertainties in the $\mu_{(prompt)}$, $\mu_{(\tau\rightarrow\mu)}$ and $\mu_{(had.)}$ distributions due to the modelling of the simulated $t\bar{t}$ samples are derived. The combined yield of the $\mu_{(prompt)}$ and $\mu_{(\tau\rightarrow\mu)}$ templates is allowed to float in the fit, but different generators or scale choices can result in changes to the modelling of the muon p_T^μ, and subsequently the $|d_0^\mu|$ distribution, such that there can be relative changes in the $\mu_{(prompt)}$ and $\mu_{(\tau\rightarrow\mu)}$

template yields in each bin. For the $\mu_{(had.)}$ background, in addition to the uncertainties in the normalisation, there can be changes to the muon p_{T}^{μ} modelling and the relative fractions of muons from different sources, both of which can change the shape of the $|d_0^{\mu}|$ distribution. The uncertainties due to the choice of MC event generator for all of these processes are estimated by varying different components of the modelling in a factorised way as shown in Table 1. The effects on $\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ (collectively referred to as 'signal') are treated as correlated and the effects on $\mu_{(had.)}$ are treated separately. The parton shower and hadronisation uncertainty is separated into four nuisance parameters: one each corresponding to low and middle probe-muon p_{T}^{μ} bins used in the fit, and two corresponding to the high p_{T}^{μ} bin where the uncertainty is further separated into components related to normalisation and shape differences.

The muon reconstruction and isolation efficiencies are determined in di-muon ($Z \to \mu\mu$ and $J/\psi \to \mu\mu$) data and simulation using a *tag* and *probe* method [68]. Corrections are applied to the simulated samples to account for the differences between data and simulation and the uncertainties on these correction factors are included in the analysis. Additionally, an uncertainty due to the modelling of pile-up is obtained by reweighting the simulated events to change the amount of pile-up [65].

7 Results

Figure 3 shows the differential distributions of $|d_0^{\mu}|$ in the six signal regions for the data and the expectation after the fit to data. Good agreement is observed between the corrected simulation samples and the data. The global goodness of fit when fitting the expectation from simulation, defined as twice the change in negative log-likelihood relative to a fit performed assuming the pre-fit expectation per degree of freedom, has a value of 1.11 (p-value of 0.29).

The separation between the $\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ processes can be seen clearly. The $\mu_{(prompt)}$ processes dominate at low $|d_0^{\mu}|$ while $\mu_{(\tau\to\mu)}$ dominates at high $|d_0^{\mu}|$. The $\mu_{(had.)}$background is also important at high $|d_0^{\mu}|$ but contributes most significantly at low p_{T}^{μ}.

The analysis was finalised prior to looking at the value of $R(\tau/\mu)$ in data in order to minimise bias. It was also checked that the result is consistent with respect to different channels, kinematic bins, data-taking periods and the charge of the *probe* lepton.

The total systematic uncertainty is 0.011, including the uncertainty in the $\tau \to \mu\nu_{\mu}\nu_{\tau}$ branching ratio, and the statistical uncertainty resulting from the dataset size is 0.007. Table 2 lists the different contributions of systematic uncertainty grouped into categories. The leading contributions come from the imperfect knowledge of the tail of the $|d_0^{\mu}|$ distribution, in particular from the imperfect knowledge of the tail of the $|d_0^{\mu}|$ distribution, the parton shower and hadronisation model uncertainty, and the muon selection uncertainties.

The measured value of $R(\tau/\mu)$ is

$$R(\tau/\mu) = 0.992 \pm 0.013 \; [\pm 0.007 \text{ (stat)} \; \pm \; 0.011 \text{ (syst)}],$$

which is the most precise measurement to date. The result is shown in Figure 4 and compared with the combination of LEP measurements. The present result agrees with the Standard Model expectation of equal couplings for different lepton flavours and the hypothesis of lepton-flavour universality, and differs from the previous LEP measurement.

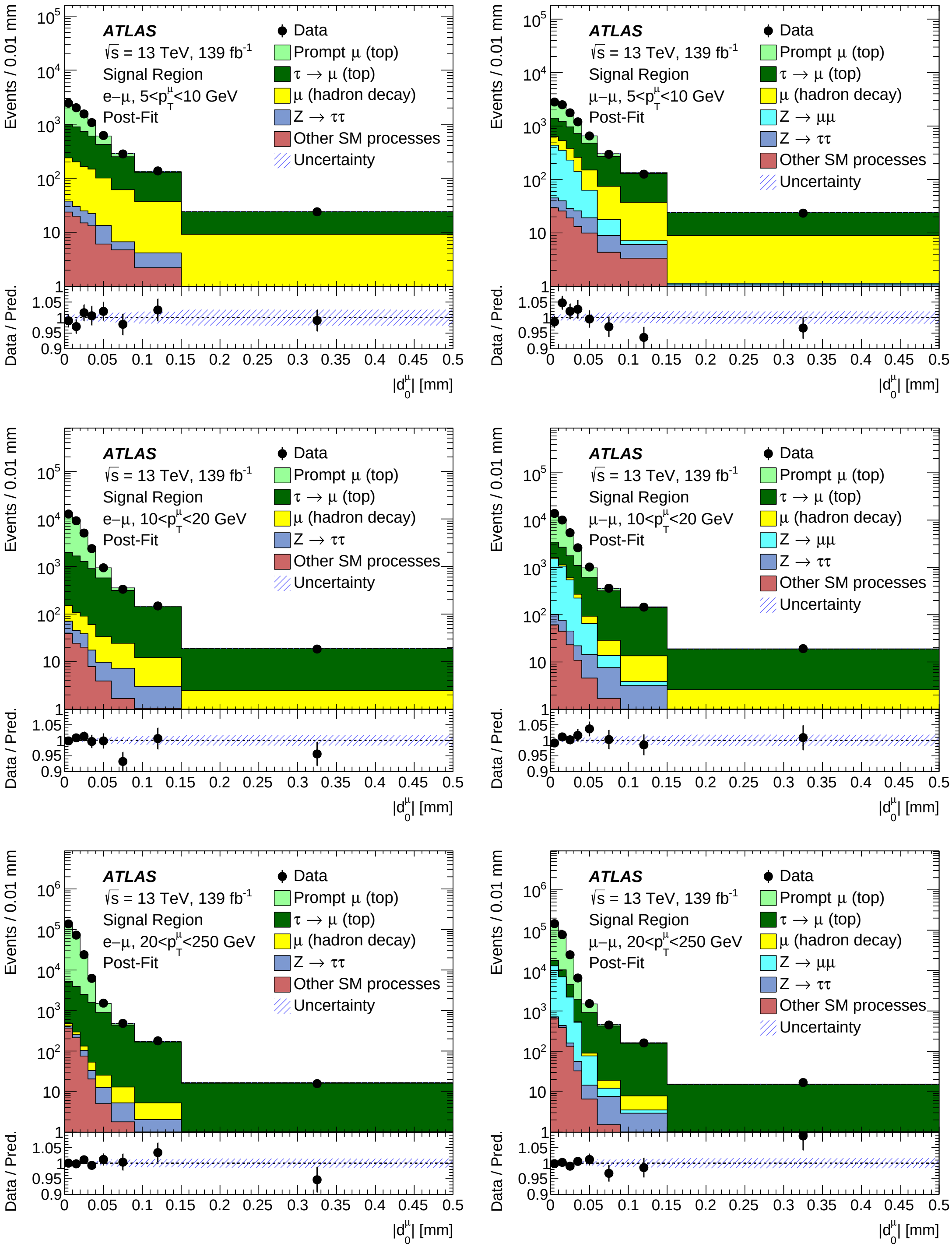


Figure 3: The $|d_0^{\mu}|$ distributions for each channel (left: e–μ channel, right: μ–μ channel) and *probe* muon p_{T}^{μ} bin (top: $5 < p_{\mathrm{T}}^{\mu} < 10$ GeV, middle: $10 < p_{\mathrm{T}}^{\mu} < 20$ GeV, bottom: $20 < p_{\mathrm{T}}^{\mu} < 250$ GeV) used in the analysis. Plots are shown after the fit has been performed. The data are represented by points and a stacked histogram represents the different simulated processes. The bottom panel shows the ratio of the data to the expectation. Blue bands indicate the systematic uncertainties with the constraints from the analysis fit applied. Different components are labelled according to the muon source and process. The contribution from 'other SM processes' is dominated by di-boson and $t\bar{t} + V$ production.

Table 2: A list of the sources of uncertainty affecting the measurement. The impact on $R(\tau/\mu)$ is assessed by fixing the relevant fit parameters for a given uncertainty and re-fitting to data. The size of the uncertainty reduction in this modified fit is the quoted impact. Different individual components used in the fit are combined into categories such that the leading sources can be seen clearly.

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

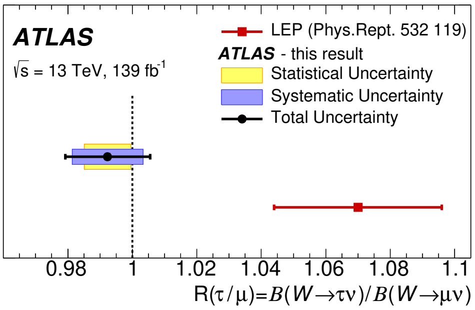


Figure 4: The measurement of $R(\tau/\mu)$ is shown (black circular marker) and compared with the previous LEP result (red square marker). The statistical and systematic errors are shown separately and also the total error of the measurement. The vertical dashed line indicates the Standard Model's prediction lepton-flavour universality, with equal W boson branching ratios to different lepton flavours.

8 Conclusions

A measurement of $R(\tau/\mu)$ has been performed using a novel method with $t\bar{t}$ events in the dilepton decay mode from a dataset corresponding to an integrated luminosity of 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded with the ATLAS detector at the LHC. This analysis provides a precise test of the fundamental assumption of the universality of the lepton couplings to the vector bosons in the Standard Model. The best-fit observed value is

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat})\ \pm\ 0.011\ (\text{syst})].$$

This agrees well with the Standard Model prediction and is the most precise measurement of $R(\tau/\mu)$ to date.

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G. Aad[102], B. Abbott[128], D.C. Abbott[103], A. Abed Abud[36], K. Abeling[53], D.K. Abhayasinghe[94], S.H. Abidi[166], O.S. AbouZeid[40], N.L. Abraham[155], H. Abramowicz[160], H. Abreu[159], Y. Abulaiti[6], B.S. Acharya[67a,67b,n], B. Achkar[53], L. Adam[100], C. Adam Bourdarios[5], L. Adamczyk[84a], L. Adamek[166], J. Adelman[121], M. Adersberger[114], A. Adiguzel[12c], S. Adorni[54], T. Adye[143], A.A. Affolder[145], Y. Afik[159], C. Agapopoulou[65], M.N. Agaras[38], A. Aggarwal[119], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[139f,139a,ad], A. Ahmad[36], F. Ahmadov[80], W.S. Ahmed[104], X. Ai[18], G. Aielli[74a,74b], S. Akatsuka[86], M. Akbiyik[100], T.P.A. Åkesson[97], E. Akilli[54], A.V. Akimov[111], K. Al Khoury[65], G.L. Alberghi[23b,23a], J. Albert[175], M.J. Alconada Verzini[160], S. Alderweireldt[36], M. Aleksa[36], I.N. Aleksandrov[80], C. Alexa[27b], T. Alexopoulos[10], A. Alfonsi[120], F. Alfonsi[23b,23a], M. Alhroob[128], B. Ali[141], S. Ali[157], M. Aliev[165], G. Alimonti[69a], C. Allaire[36], B.M.M. Allbrooke[155], B.W. Allen[131], P.P. Allport[21], A. Aloisio[70a,70b], F. Alonso[89], C. Alpigiani[147], E. Alunno Camelia[74a,74b], M. Alvarez Estevez[99], M.G. Alviggi[70a,70b], Y. Amaral Coutinho[81b], A. Ambler[104], L. Ambroz[134], C. Amelung[26], D. Amidei[106], S.P. Amor Dos Santos[139a], S. Amoroso[46], C.S. Amrouche[54], F. An[79], C. Anastopoulos[148], N. Andari[144], T. Andeen[11], J.K. Anders[20], S.Y. Andrean[45a,45b], A. Andreazza[69a,69b], V. Andrei[61a], C.R. Anelli[175], S. Angelidakis[9], A. Angerami[39], A.V. Anisenkov[122b,122a], A. Annovi[72a], C. Antel[54], M.T. Anthony[148], E. Antipov[129], M. Antonelli[51], D.J.A. Antrim[170], F. Anulli[73a], M. Aoki[82], J.A. Aparisi Pozo[173], M.A. Aparo[155], L. Aperio Bella[46], N. Aranzabal Barrio[36], V. Araujo Ferraz[81a], R. Araujo Pereira[81b], C. Arcangeletti[51], A.T.H. Arce[49], F.A. Arduh[89], J-F. Arguin[110], S. Argyropoulos[52], J.-H. Arling[46], A.J. Armbruster[36], A. Armstrong[170], O. Arnaez[166], H. Arnold[120], Z.P. Arrubarrena Tame[114], G. Artoni[134], H. Asada[117], K. Asai[126], S. Asai[162], T. Asawatavonvanich[164], N. Asbah[59], E.M. Asimakopoulou[171], L. Asquith[155], J. Assahsah[35d], K. Assamagan[29], R. Astalos[28a], R.J. Atkin[33a], M. Atkinson[172], N.B. Atlay[19], H. Atmani[65], K. Augsten[141], V.A. Austrup[181], G. Avolio[36], M.K. Ayoub[15a], G. Azuelos[110,al], H. Bachacou[144], K. Bachas[161], F. Backman[45a,45b], P. Bagnaia[73a,73b], M. Bahmani[85], H. Bahrasemani[151], A.J. Bailey[173], V.R. Bailey[172], J.T. Baines[143], C. Bakalis[10], O.K. Baker[182], P.J. Bakker[120], E. Bakos[16], D. Bakshi Gupta[8], S. Balaji[156], R. Balasubramanian[120], E.M. Baldin[122b,122a], P. Balek[179], F. Balli[144], W.K. Balunas[134], J. Balz[100], E. Banas[85], M. Bandieramonte[138], A. Bandyopadhyay[24], Sw. Banerjee[180,i], L. Barak[160], W.M. Barbe[38], E.L. Barberio[105], D. Barberis[55b,55a], M. Barbero[102], G. Barbour[95], T. Barillari[115], M-S. Barisits[36], J. Barkeloo[131], T. Barklow[152], R. Barnea[159], B.M. Barnett[143], R.M. Barnett[18], Z. Barnovska-Blenessy[60a], A. Baroncelli[60a], G. Barone[29], A.J. Barr[134], L. Barranco Navarro[45a,45b], F. Barreiro[99], J. Barreiro Guimarães da Costa[15a], U. Barron[160], S. Barsov[137], F. Bartels[61a], R. Bartoldus[152], G. Bartolini[102], A.E. Barton[90], P. Bartos[28a], A. Basalaev[46], A. Basan[100], A. Bassalat[65,ai], M.J. Basso[166], R.L. Bates[57], S. Batlamous[35e], J.R. Batley[32], B. Batool[150], M. Battaglia[145], M. Bauce[73a,73b], F. Bauer[144], P. Bauer[24], H.S. Bawa[31], A. Bayirli[12c], J.B. Beacham[49], T. Beau[135], P.H. Beauchemin[169], F. Becherer[52], P. Bechtle[24], H.C. Beck[53], H.P. Beck[20,p], K. Becker[177], C. Becot[46], A. Beddall[12d], A.J. Beddall[12a], V.A. Bednyakov[80], M. Bedognetti[120], C.P. Bee[154], T.A. Beermann[181], M. Begalli[81b], M. Begel[29], A. Behera[154], J.K. Behr[46], F. Beisiegel[24], M. Belfkir[5], A.S. Bell[95], G. Bella[160], L. Bellagamba[23b], A. Bellerive[34], P. Bellos[9], K. Beloborodov[122b,122a], K. Belotskiy[112], N.L. Belyaev[112], D. Benchekroun[35a], N. Benekos[10], Y. Benhammou[160], D.P. Benjamin[6], M. Benoit[29], J.R. Bensinger[26], S. Bentvelsen[120], L. Beresford[134], M. Beretta[51], D. Berge[19], E. Bergeaas Kuutmann[171], N. Berger[5], B. Bergmann[141], L.J. Bergsten[26], J. Beringer[18], S. Berlendis[7], G. Bernardi[135], C. Bernius[152], F.U. Bernlochner[24], T. Berry[94], P. Berta[100], A. Berthold[48], I.A. Bertram[90], O. Bessidskaia Bylund[181], N. Besson[144], A. Bethani[101], S. Bethke[115], A. Betti[42], A.J. Bevan[93], J. Beyer[115], D.S. Bhattacharya[176], P. Bhattarai[26], V.S. Bhopatkar[6], R. Bi[138], R.M. Bianchi[138], O. Biebel[114], D. Biedermann[19], R. Bielski[36], K. Bierwagen[100], N.V. Biesuz[72a,72b], M. Biglietti[75a], T.R.V. Billoud[141], M. Bindi[53], A. Bingul[12d],

C. Bini[73a,73b], S. Biondi[23b,23a], C.J. Birch-sykes[101], M. Birman[179], T. Bisanz[53], J.P. Biswal[3], D. Biswas[180,i], A. Bitadze[101], C. Bittrich[48], K. Bjørke[133], T. Blazek[28a], I. Bloch[46], C. Blocker[26], A. Blue[57], U. Blumenschein[93], G.J. Bobbink[120], V.S. Bobrovnikov[122b,122a], S.S. Bocchetta[97], D. Boerner[46], D. Bogavac[14], A.G. Bogdanchikov[122b,122a], C. Bohm[45a], V. Boisvert[94], P. Bokan[171,171,53], T. Bold[84a], A.E. Bolz[61b], M. Bomben[135], M. Bona[93], J.S. Bonilla[131], M. Boonekamp[144], C.D. Booth[94], A.G. Borbély[57], H.M. Borecka-Bielska[91], L.S. Borgna[95], A. Borisov[123], G. Borissov[90], D. Bortoletto[134], D. Boscherini[23b], M. Bosman[14], J.D. Bossio Sola[104], K. Bouaouda[35a], J. Boudreau[138], E.V. Bouhova-Thacker[90], D. Boumediene[38], A. Boveia[127], J. Boyd[36], D. Boye[33c], I.R. Boyko[80], A.J. Bozson[94], J. Bracinik[21], N. Brahimi[60d], G. Brandt[181], O. Brandt[32], F. Braren[46], B. Brau[103], J.E. Brau[131], W.D. Breaden Madden[57], K. Brendlinger[46], R. Brener[159], L. Brenner[36], R. Brenner[171], S. Bressler[179], B. Brickwedde[100], D.L. Briglin[21], D. Britton[57], D. Britzger[115], I. Brock[24], R. Brock[107], G. Brooijmans[39], W.K. Brooks[146d], E. Brost[29], P.A. Bruckman de Renstrom[85], B. Brüers[46], D. Bruncko[28b], A. Bruni[23b], G. Bruni[23b], M. Bruschi[23b], N. Bruscino[73a,73b], L. Bryngemark[152], T. Buanes[17], Q. Buat[154], P. Buchholz[150], A.G. Buckley[57], I.A. Budagov[80], M.K. Bugge[133], F. Bührer[52], O. Bulekov[112], B.A. Bullard[59], T.J. Burch[121], S. Burdin[91], C.D. Burgard[120], A.M. Burger[129], B. Burghgrave[8], J.T.P. Burr[46], C.D. Burton[11], J.C. Burzynski[103], V. Büscher[100], E. Buschmann[53], P.J. Bussey[57], J.M. Butler[25], C.M. Buttar[57], J.M. Butterworth[95], P. Butti[36], W. Buttinger[36], C.J. Buxo Vazquez[107], A. Buzatu[157], A.R. Buzykaev[122b,122a], G. Cabras[23b,23a], S. Cabrera Urbán[173], D. Caforio[56], H. Cai[138], V.M.M. Cairo[152], O. Cakir[4a], N. Calace[36], P. Calafiura[18], G. Calderini[135], P. Calfayan[66], G. Callea[57], L.P. Caloba[81b], A. Caltabiano[74a,74b], S. Calvente Lopez[99], D. Calvet[38], S. Calvet[38], T.P. Calvet[102], M. Calvetti[72a,72b], R. Camacho Toro[135], S. Camarda[36], D. Camarero Munoz[99], P. Camarri[74a,74b], M.T. Camerlingo[75a,75b], D. Cameron[133], C. Camincher[36], S. Campana[36], M. Campanelli[95], A. Camplani[40], V. Canale[70a,70b], A. Canesse[104], M. Cano Bret[78], J. Cantero[129], T. Cao[160], Y. Cao[172], M.D.M. Capeans Garrido[36], M. Capua[41b,41a], R. Cardarelli[74a], F. Cardillo[173], G. Carducci[41b,41a], I. Carli[142], T. Carli[36], G. Carlino[70a], B.T. Carlson[138], E.M. Carlson[175,167a], L. Carminati[69a,69b], R.M.D. Carney[152], S. Caron[119], E. Carquin[146d], S. Carrá[46], G. Carratta[23b,23a], J.W.S. Carter[166], T.M. Carter[50], M.P. Casado[14,f], A.F. Casha[166], E.G. Castiglia[182], F.L. Castillo[173], L. Castillo Garcia[14], V. Castillo Gimenez[173], N.F. Castro[139a,139e], A. Catinaccio[36], J.R. Catmore[133], A. Cattai[36], V. Cavaliere[29], V. Cavasinni[72a,72b], E. Celebi[12b], F. Celli[134], K. Cerny[130], A.S. Cerqueira[81a], A. Cerri[155], L. Cerrito[74a,74b], F. Cerutti[18], A. Cervelli[23b,23a], S.A. Cetin[12b], Z. Chadi[35a], D. Chakraborty[121], J. Chan[180], W.S. Chan[120], W.Y. Chan[91], J.D. Chapman[32], B. Chargeishvili[158b], D.G. Charlton[21], T.P. Charman[93], M. Chatterjee[20], C.C. Chau[34], S. Che[127], S. Chekanov[6], S.V. Chekulaev[167a], G.A. Chelkov[80,ag], B. Chen[79], C. Chen[60a], C.H. Chen[79], H. Chen[15c], H. Chen[29], J. Chen[60a], J. Chen[39], J. Chen[26], S. Chen[136], S.J. Chen[15c], X. Chen[15b], Y. Chen[60a], Y-H. Chen[46], H.C. Cheng[63a], H.J. Cheng[15a], A. Cheplakov[80], E. Cheremushkina[123], R. Cherkaoui El Moursli[35e], E. Cheu[7], K. Cheung[64], T.J.A. Chevalérias[144], L. Chevalier[144], V. Chiarella[51], G. Chiarelli[72a], G. Chiodini[68a], A.S. Chisholm[21], A. Chitan[27b], I. Chiu[162], Y.H. Chiu[175], M.V. Chizhov[80], K. Choi[11], A.R. Chomont[73a,73b], Y.S. Chow[120], L.D. Christopher[33e], M.C. Chu[63a], X. Chu[15a,15d], J. Chudoba[140], J.J. Chwastowski[85], L. Chytka[130], D. Cieri[115], K.M. Ciesla[85], V. Cindro[92], I.A. Cioară[27b], A. Ciocio[18], F. Cirotto[70a,70b], Z.H. Citron[179,j], M. Citterio[69a], D.A. Ciubotaru[27b], B.M. Ciungu[166], A. Clark[54], M.R. Clark[39], P.J. Clark[50], S.E. Clawson[101], C. Clement[45a,45b], Y. Coadou[102], M. Cobal[67a,67c], A. Coccaro[55b], J. Cochran[79], R. Coelho Lopes De Sa[103], H. Cohen[160], A.E.C. Coimbra[36], B. Cole[39], A.P. Colijn[120], J. Collot[58], P. Conde Muiño[139a,139h], S.H. Connell[33c], I.A. Connelly[57], S. Constantinescu[27b], F. Conventi[70a,am], A.M. Cooper-Sarkar[134], F. Cormier[174], K.J.R. Cormier[166], L.D. Corpe[95], M. Corradi[73a,73b], E.E. Corrigan[97], F. Corriveau[104,ab], M.J. Costa[173], F. Costanza[5], D. Costanzo[148], G. Cowan[94], J.W. Cowley[32], J. Crane[101], K. Cranmer[125], R.A. Creager[136], S. Crépé-Renaudin[58], F. Crescioli[135], M. Cristinziani[24], V. Croft[169], G. Crosetti[41b,41a], A. Cueto[5], T. Cuhadar Donszelmann[170], H. Cui[15a,15d], A.R. Cukierman[152], W.R. Cunningham[57],

S. Czekierda[85], P. Czodrowski[36], M.M. Czurylo[61b], M.J. Da Cunha Sargedas De Sousa[60b], J.V. Da Fonseca Pinto[81b], C. Da Via[101], W. Dabrowski[84a], F. Dachs[36], T. Dado[47], S. Dahbi[33e], T. Dai[106], C. Dallapiccola[103], M. Dam[40], G. D'amen[29], V. D'Amico[75a,75b], J. Damp[100], J.R. Dandoy[136], M.F. Daneri[30], M. Danninger[151], V. Dao[36], G. Darbo[55b], O. Dartsi[5], A. Dattagupta[131], T. Daubney[46], S. D'Auria[69a,69b], C. David[167b], T. Davidek[142], D.R. Davis[49], I. Dawson[148], K. De[8], R. De Asmundis[70a], M. De Beurs[120], S. De Castro[23b,23a], N. De Groot[119], P. de Jong[120], H. De la Torre[107], A. De Maria[15c], D. De Pedis[73a], A. De Salvo[73a], U. De Sanctis[74a,74b], M. De Santis[74a,74b], A. De Santo[155], J.B. De Vivie De Regie[65], D.V. Dedovich[80], A.M. Deiana[42], J. Del Peso[99], Y. Delabat Diaz[46], D. Delgove[65], F. Deliot[144], C.M. Delitzsch[7], M. Della Pietra[70a,70b], D. Della Volpe[54], A. Dell'Acqua[36], L. Dell'Asta[74a,74b], M. Delmastro[5], C. Delporte[65], P.A. Delsart[58], D.A. DeMarco[166], S. Demers[182], M. Demichev[80], G. Demontigny[110], S.P. Denisov[123], L. D'Eramo[121], D. Derendarz[85], J.E. Derkaoui[35d], F. Derue[135], P. Dervan[91], K. Desch[24], K. Dette[166], C. Deutsch[24], M.R. Devesa[30], P.O. Deviveiros[36], F.A. Di Bello[73a,73b], A. Di Ciaccio[74a,74b], L. Di Ciaccio[5], W.K. Di Clemente[136], C. Di Donato[70a,70b], A. Di Girolamo[36], G. Di Gregorio[72a,72b], B. Di Micco[75a,75b], R. Di Nardo[75a,75b], K.F. Di Petrillo[59], R. Di Sipio[166], C. Diaconu[102], F.A. Dias[120], T. Dias Do Vale[139a], M.A. Diaz[146a], F.G. Diaz Capriles[24], J. Dickinson[18], M. Didenko[165], E.B. Diehl[106], J. Dietrich[19], S. Díez Cornell[46], C. Diez Pardos[150], A. Dimitrievska[18], W. Ding[15b], J. Dingfelder[24], S.J. Dittmeier[61b], F. Dittus[36], F. Djama[102], T. Djobava[158b], J.I. Djuvsland[17], M.A.B. Do Vale[81c], M. Dobre[27b], D. Dodsworth[26], C. Doglioni[97], J. Dolejsi[142], Z. Dolezal[142], M. Donadelli[81d], B. Dong[60c], J. Donini[38], A. D'onofrio[15c], M. D'Onofrio[91], J. Dopke[143], A. Doria[70a], M.T. Dova[89], A.T. Doyle[57], E. Drechsler[151], E. Dreyer[151], T. Dreyer[53], A.S. Drobac[169], D. Du[60b], T.A. du Pree[120], Y. Duan[60d], F. Dubinin[111], M. Dubovsky[28a], A. Dubreuil[54], E. Duchovni[179], G. Duckeck[114], O.A. Ducu[36], D. Duda[115], A. Dudarev[36], A.C. Dudder[100], E.M. Duffield[18], M. D'uffizi[101], L. Duflot[65], M. Dührssen[36], C. Dülsen[181], M. Dumancic[179], A.E. Dumitriu[27b], M. Dunford[61a], A. Duperrin[102], H. Duran Yildiz[4a], M. Düren[56], A. Durglishvili[158b], D. Duschinger[48], B. Dutta[46], D. Duvnjak[1], G.I. Dyckes[136], M. Dyndal[36], S. Dysch[101], B.S. Dziedzic[85], M.G. Eggleston[49], T. Eifert[8], G. Eigen[17], K. Einsweiler[18], T. Ekelof[171], H. El Jarrari[35e], V. Ellajosyula[171], M. Ellert[171], F. Ellinghaus[181], A.A. Elliot[93], N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. 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Ferrari[71a], D.E. Ferreira de Lima[61b], A. Ferrer[173], D. Ferrere[54], C. Ferretti[106], F. Fiedler[100], A. Filipčič[92], F. Filthaut[119], K.D. Finelli[25], M.C.N. Fiolhais[139a,139c,a], L. Fiorini[173], F. Fischer[114], J. Fischer[100], W.C. Fisher[107], T. Fitschen[21], I. Fleck[150], P. Fleischmann[106], T. Flick[181], B.M. Flierl[114], L. Flores[136], L.R. Flores Castillo[63a], F.M. Follega[76a,76b], N. Fomin[17], J.H. Foo[166], G.T. Forcolin[76a,76b], B.C. Forland[66], A. Formica[144], F.A. Förster[14], A.C. Forti[101], E. Fortin[102], M.G. Foti[134], D. Fournier[65], H. Fox[90], P. Francavilla[72a,72b], S. Francescato[73a,73b], M. Franchini[23b,23a], S. Franchino[61a], D. Francis[36], L. Franco[5], L. Franconi[20], M. Franklin[59], G. Frattari[73a,73b], A.N. Fray[93], P.M. Freeman[21], B. Freund[110], W.S. Freund[81b], E.M. Freundlich[47], D.C. Frizzell[128], D. Froidevaux[36], J.A. Frost[134], M. Fujimoto[126], C. Fukunaga[163], E. Fullana Torregrosa[173], T. 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Theveneaux-Pelzer[46], F. Thiele[40], D.W. Thomas[94], J.O. Thomas[42], J.P. Thomas[21], E.A. Thompson[46], P.D. Thompson[21], E. Thomson[136], E.J. Thorpe[93], R.E. Ticse Torres[53], V.O. Tikhomirov[111,ah], Yu.A. Tikhonov[122b,122a], S. Timoshenko[112], P. Tipton[182], S. Tisserant[102], K. Todome[23b,23a], S. Todorova-Nova[142], S. Todt[48], J. Tojo[88], S. Tokár[28a], K. Tokushuku[82], E. Tolley[127], R. Tombs[32], K.G. Tomiwa[33e], M. Tomoto[82,117], L. Tompkins[152], P. Tornambe[103], E. Torrence[131], H. Torres[48], E. Torró Pastor[173], M. Toscani[30], C. Tosciri[134], J. Toth[102,aa], D.R. Tovey[148], A. Traeet[17], C.J. Treado[125], T. Trefzger[176], F. Tresoldi[155], A. Tricoli[29], I.M. Trigger[167a], S. Trincaz-Duvoid[135], D.A. Trischuk[174], W. Trischuk[166], B. Trocmé[58], A. Trofymov[65], C. Troncon[69a], F. Trovato[155], L. Truong[33c], M. Trzebinski[85], A. Trzupek[85], F. Tsai[46], J.C-L. Tseng[134], P.V. Tsiareshka[108,ae], A. Tsirigotis[161,u], V. Tsiskaridze[154], E.G. Tskhadadze[158a], M. Tsopoulou[161], I.I. Tsukerman[124], V. Tsulaia[18], S. Tsuno[82], D. Tsybychev[154], Y. Tu[63b], A. Tudorache[27b], V. Tudorache[27b], T.T. Tulbure[27a], A.N. Tuna[59], S. Turchikhin[80], D. Turgeman[179], I. Turk Cakir[4b,s], R.J. Turner[21], R. Turra[69a], P.M. Tuts[39], S. Tzamarias[161], E. Tzovara[100], K. Uchida[162], F. Ukegawa[168],

G. Unal[36], M. Unal[11], A. Undrus[29], G. Unel[170], F.C. Ungaro[105], Y. Unno[82], K. Uno[162], J. Urban[28b], P. Urquijo[105], G. Usai[8], Z. Uysal[12d], V. Vacek[141], B. Vachon[104], K.O.H. Vadla[133], T. Vafeiadis[36], A. Vaidya[95], C. Valderanis[114], E. Valdes Santurio[45a,45b], M. Valente[167a], S. Valentinetti[23b,23a], A. Valero[173], L. Valéry[46], R.A. Vallance[21], A. Vallier[36], J.A. Valls Ferrer[173], T.R. Van Daalen[14], P. Van Gemmeren[6], S. Van Stroud[95], I. Van Vulpen[120], M. Vanadia[74a,74b], W. Vandelli[36], M. Vandenbroucke[144], E.R. Vandewall[129], A. Vaniachine[165], D. Vannicola[73a,73b], R. Vari[73a], E.W. Varnes[7], C. Varni[55b,55a], T. Varol[157], D. Varouchas[65], K.E. Varvell[156], M.E. Vasile[27b], G.A. Vasquez[175], F. Vazeille[38], D. Vazquez Furelos[14], T. Vazquez Schroeder[36], J. Veatch[53], V. Vecchio[101], M.J. Veen[120], L.M. Veloce[166], F. Veloso[139a,139c], S. Veneziano[73a], A. Ventura[68a,68b], A. Verbytskyi[115], V. Vercesi[71a], M. Verducci[72a,72b], C.M. Vergel Infante[79], C. Vergis[24], W. Verkerke[120], A.T. Vermeulen[120], J.C. Vermeulen[120], C. Vernieri[152], P.J. Verschuuren[94], M.C. Vetterli[151,al], N. Viaux Maira[146d], T. Vickey[148], O.E. Vickey Boeriu[148], G.H.A. Viehhauser[134], L. Vigani[61b], M. Villa[23b,23a], M. Villaplana Perez[3], E.M. Villhauer[50], E. Vilucchi[51], M.G. Vincter[34], G.S. Virdee[21], A. Vishwakarma[50], C. Vittori[23b,23a], I. Vivarelli[155], M. Vogel[181], P. Vokac[141], S.E. von Buddenbrock[33e], E. Von Toerne[24], V. Vorobel[142], K. Vorobev[112], M. Vos[173], J.H. Vossebeld[91], M. Vozak[101], N. Vranjes[16], M. Vranjes Milosavljevic[16], V. Vrba[141], M. Vreeswijk[120], N.K. Vu[102], R. Vuillermet[36], I. Vukotic[37], S. Wada[168], P. Wagner[24], W. Wagner[181], J. Wagner-Kuhr[114], S. Wahdan[181], H. Wahlberg[89], R. Wakasa[168], V.M. Walbrecht[115], J. Walder[143], R. Walker[114], S.D. Walker[94], W. Walkowiak[150], V. Wallangen[45a,45b], A.M. Wang[59], A.Z. Wang[180], C. Wang[60a], C. Wang[60c], F. Wang[180], H. Wang[18], H. Wang[3], J. Wang[63a], P. Wang[42], Q. Wang[128], R.-J. Wang[100], R. Wang[60a], R. Wang[6], S.M. Wang[157], W.T. Wang[60a], W. Wang[15c], W.X. Wang[60a], Y. Wang[60a], Z. Wang[106], C. Wanotayaroj[46], A. Warburton[104], C.P. Ward[32], R.J. Ward[21], N. Warrack[57], A.T. Watson[21], M.F. Watson[21], G. Watts[147], B.M. Waugh[95], A.F. Webb[11], C. Weber[29], M.S. Weber[20], S.A. Weber[34], S.M. Weber[61a], A.R. Weidberg[134], J. Weingarten[47], M. Weirich[100], C. Weiser[52], P.S. Wells[36], T. Wenaus[29], B. Wendland[47], T. Wengler[36], S. Wenig[36], N. Wermes[24], M. Wessels[61a], T.D. Weston[20], K. Whalen[131], A.M. Wharton[90], A.S. White[106], A. White[8], M.J. White[1], D. Whiteson[170], B.W. Whitmore[90], W. Wiedenmann[180], C. Wiel[48], M. Wielers[143], N. Wieseotte[100], C. Wiglesworth[40], L.A.M. Wiik-Fuchs[52], H.G. Wilkens[36], L.J. Wilkins[94], H.H. Williams[136], S. Williams[32], S. Willocq[103], P.J. Windischhofer[134], I. Wingerter-Seez[5], E. Winkels[155], F. Winklmeier[131], B.T. Winter[52], M. Wittgen[152], M. Wobisch[96], A. Wolf[100], R. Wölker[134], J. Wollrath[52], M.W. Wolter[85], H. Wolters[139a,139c], V.W.S. Wong[174], N.L. Woods[145], S.D. Worm[46], B.K. Wosiek[85], K.W. Woźniak[85], K. Wraight[57], S.L. Wu[180], X. Wu[54], Y. Wu[60a], J. Wuerzinger[134], T.R. Wyatt[101], B.M. Wynne[50], S. Xella[40], L. Xia[177], J. Xiang[63c], X. Xiao[106], X. Xie[60a], I. Xiotidis[155], D. Xu[15a], H. Xu[60a], H. Xu[60a], L. Xu[29], T. Xu[144], W. Xu[106], Y. Xu[15b], Z. Xu[60b], Z. Xu[152], B. Yabsley[156], S. Yacoob[33a], D.P. Yallup[95], N. Yamaguchi[88], Y. Yamaguchi[164], A. Yamamoto[82], M. Yamatani[162], T. Yamazaki[162], Y. Yamazaki[83], J. Yan[60c], Z. Yan[25], H.J. Yang[60c,60d], H.T. Yang[18], S. Yang[60a], T. Yang[63c], X. Yang[60b,58], Y. Yang[162], Z. Yang[60a], W-M. Yao[18], Y.C. Yap[46], E. Yatsenko[60c], H. Ye[15c], J. Ye[42], S. Ye[29], I. Yeletskikh[80], M.R. Yexley[90], E. Yigitbasi[25], P. Yin[39], K. Yorita[178], K. Yoshihara[79], C.J.S. Young[36], C. Young[152], J. Yu[79], R. Yuan[60b,h], X. Yue[61a], M. Zaazoua[35e], B. Zabinski[85], G. Zacharis[10], E. Zaffaroni[54], J. Zahreddine[135], A.M. Zaitsev[123,ag], T. Zakareishvili[158b], N. Zakharchuk[34], S. Zambito[36], D. Zanzi[36], S.V. Zeißner[47], C. Zeitnitz[181], G. Zemaityte[134], J.C. Zeng[172], O. Zenin[123], T. Ženiš[28a], D. Zerwas[65], M. Zgubič[134], B. Zhang[15c], D.F. Zhang[15b], G. Zhang[15b], J. Zhang[6], Kaili. Zhang[15a], L. Zhang[15c], L. Zhang[60a], M. Zhang[172], R. Zhang[180], S. Zhang[106], X. Zhang[60c], X. Zhang[60b], Y. Zhang[15a,15d], Z. Zhang[63a], Z. Zhang[65], P. Zhao[49], Z. Zhao[60a], A. Zhemchugov[80], Z. Zheng[106], D. Zhong[172], B. Zhou[106], C. Zhou[180], H. Zhou[7], M.S. Zhou[15a,15d], M. Zhou[154], N. Zhou[60c], Y. Zhou[7], C.G. Zhu[60b], C. Zhu[15a,15d], H.L. Zhu[60a], H. Zhu[15a], J. Zhu[106], Y. Zhu[60a], X. Zhuang[15a], K. Zhukov[111], V. Zhulanov[122b,122a], D. Zieminska[66], N.I. Zimine[80], S. Zimmermann[52], Z. Zinonos[115], M. Ziolkowski[150], L. Živković[16], G. Zobernig[180], A. Zoccoli[23b,23a], K. Zoch[53], T.G. Zorbas[148], R. Zou[37], L. Zwalinski[36].

[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)Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul;(c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.
[5]LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; 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, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12](a)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;(b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;(c)Department of Physics, Bogazici University, Istanbul;(d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
[13]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[14]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[15](a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;(b)Physics Department, Tsinghua University, Beijing;(c)Department of Physics, Nanjing University, Nanjing;(d)University of Chinese Academy of Science (UCAS), Beijing; China.
[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[18]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[22](a)Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;(b)Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia; Colombia.
[23](a)INFN Bologna and Universita' di Bologna, Dipartimento di Fisica;(b)INFN Sezione di Bologna; Italy.
[24]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[25]Department of Physics, Boston University, Boston MA; United States of America.
[26]Department of Physics, Brandeis University, Waltham MA; United States of America.
[27](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;(e)University Politehnica Bucharest, Bucharest;(f)West University in Timisoara, Timisoara; Romania.
[28](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[29]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
[31]California State University, CA; United States of America.

[32]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[33](a)Department of Physics, University of Cape Town, Cape Town;(b)iThemba Labs, Western Cape;(c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;(d)University of South Africa, Department of Physics, Pretoria;(e)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[34]Department of Physics, Carleton University, Ottawa ON; Canada.
[35](a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;(b)Faculté des Sciences, Université Ibn-Tofail, Kénitra;(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, Rabat; Morocco.
[36]CERN, Geneva; Switzerland.
[37]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[38]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[39]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[40]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[41](a)Dipartimento di Fisica, Università della Calabria, Rende;(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[42]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[43]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[44]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[45](a)Department of Physics, Stockholm University;(b)Oskar Klein Centre, Stockholm; Sweden.
[46]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[47]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.
[48]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[49]Department of Physics, Duke University, Durham NC; United States of America.
[50]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[51]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[52]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[53]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[54]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[55](a)Dipartimento di Fisica, Università di Genova, Genova;(b)INFN Sezione di Genova; Italy.
[56]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[57]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[58]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[59]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[60](a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(c)School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai;(d)Tsung-Dao Lee Institute, Shanghai; China.
[61](a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[62]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.
[63](a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;(b)Department of Physics, University of Hong Kong, Hong Kong;(c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.

[64]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[65]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[66]Department of Physics, Indiana University, Bloomington IN; United States of America.
[67](a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;(b)ICTP, Trieste;(c)Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
[68](a)INFN Sezione di Lecce;(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[69](a)INFN Sezione di Milano;(b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
[70](a)INFN Sezione di Napoli;(b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[71](a)INFN Sezione di Pavia;(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[72](a)INFN Sezione di Pisa;(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[73](a)INFN Sezione di Roma;(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[74](a)INFN Sezione di Roma Tor Vergata;(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[75](a)INFN Sezione di Roma Tre;(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[76](a)INFN-TIFPA;(b)Università degli Studi di Trento, Trento; Italy.
[77]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
[78]University of Iowa, Iowa City IA; United States of America.
[79]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[80]Joint Institute for Nuclear Research, Dubna; Russia.
[81](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Universidade Federal de São João del Rei (UFSJ), São João del Rei;(d)Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
[82]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[83]Graduate School of Science, Kobe University, Kobe; Japan.
[84](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.
[85]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[86]Faculty of Science, Kyoto University, Kyoto; Japan.
[87]Kyoto University of Education, Kyoto; Japan.
[88]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[89]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[90]Physics Department, Lancaster University, Lancaster; United Kingdom.
[91]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[92]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[93]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[94]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[95]Department of Physics and Astronomy, University College London, London; United Kingdom.
[96]Louisiana Tech University, Ruston LA; United States of America.
[97]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[98]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[100]Institut für Physik, Universität Mainz, Mainz; Germany.
[101]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[103]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[104]Department of Physics, McGill University, Montreal QC; Canada.
[105]School of Physics, University of Melbourne, Victoria; Australia.
[106]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[107]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[108]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
[109]Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
[110]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[111]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
[112]National Research Nuclear University MEPhI, Moscow; Russia.
[113]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
[114]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[115]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[116]Nagasaki Institute of Applied Science, Nagasaki; Japan.
[117]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[118]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[119]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
[120]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[121]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[122(a)]Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk;[(b)]Novosibirsk State University Novosibirsk; Russia.
[123]Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia.
[124]Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow; Russia.
[125]Department of Physics, New York University, New York NY; United States of America.
[126]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[127]Ohio State University, Columbus OH; United States of America.
[128]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[129]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[130]Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
[131]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[132]Graduate School of Science, Osaka University, Osaka; Japan.
[133]Department of Physics, University of Oslo, Oslo; Norway.
[134]Department of Physics, Oxford University, Oxford; United Kingdom.
[135]LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris; France.
[136]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[137]Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.
[138]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

[139](a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(c)Departamento de Física, Universidade de Coimbra, Coimbra;(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(e)Departamento de Física, Universidade do Minho, Braga;(f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);(g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica;(h)Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[140]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[141]Czech Technical University in Prague, Prague; Czech Republic.
[142]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[143]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[144]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[145]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[146](a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(b)Universidad Andres Bello, Department of Physics, Santiago;(c)Instituto de Alta Investigación, Universidad de Tarapacá;(d)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[147]Department of Physics, University of Washington, Seattle WA; United States of America.
[148]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[149]Department of Physics, Shinshu University, Nagano; Japan.
[150]Department Physik, Universität Siegen, Siegen; Germany.
[151]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[152]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[153]Physics Department, Royal Institute of Technology, Stockholm; Sweden.
[154]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[155]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[156]School of Physics, University of Sydney, Sydney; Australia.
[157]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[158](a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.
[159]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[160]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[161]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[162]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[163]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
[164]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
[165]Tomsk State University, Tomsk; Russia.
[166]Department of Physics, University of Toronto, Toronto ON; Canada.
[167](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
[168]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[169]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[170]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

[171]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[172]Department of Physics, University of Illinois, Urbana IL; United States of America.
[173]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[174]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[175]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[176]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[177]Department of Physics, University of Warwick, Coventry; United Kingdom.
[178]Waseda University, Tokyo; Japan.
[179]Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.
[180]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[181]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[182]Department of Physics, Yale University, New Haven CT; United States of America.
[a] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[b] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[c] Also at CERN, Geneva; Switzerland.
[d] Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[e] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[f] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[g] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[h] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[i] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[j] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[k] Also at Department of Physics, California State University, East Bay; United States of America.
[l] Also at Department of Physics, California State University, Fresno; United States of America.
[m] Also at Department of Physics, California State University, Sacramento; United States of America.
[n] Also at Department of Physics, King's College London, London; United Kingdom.
[o] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
[p] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[q] Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine; Italy.
[r] Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
[s] Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
[t] Also at Graduate School of Science, Osaka University, Osaka; Japan.
[u] Also at Hellenic Open University, Patras; Greece.
[v] Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[w] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[x] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[y] Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
[z] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[aa] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.

[ab] Also at Institute of Particle Physics (IPP), Vancouver; Canada.
[ac] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ad] Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain.
[ae] Also at Joint Institute for Nuclear Research, Dubna; Russia.
[af] Also at Louisiana Tech University, Ruston LA; United States of America.
[ag] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
[ah] Also at National Research Nuclear University MEPhI, Moscow; Russia.
[ai] Also at Physics Department, An-Najah National University, Nablus; Palestine.
[aj] Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[ak] Also at The City College of New York, New York NY; United States of America.
[al] Also at TRIUMF, Vancouver BC; Canada.
[am] Also at Universita di Napoli Parthenope, Napoli; Italy.
[an] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[*] Deceased