



# Test of the universality of $\tau$ and $\mu$ lepton couplings in $W$ -boson decays with the ATLAS detector

The ATLAS Collaboration

The Standard Model of particle physics encapsulates our best current 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 decay rate of  $W$  bosons to  $\tau$ -leptons and muons,  $R(\tau/\mu)$ , constitutes an important test of this axiom. Using  $139 \text{ fb}^{-1}$  of proton–proton collisions recorded with the ATLAS detector at a centre-of-mass energy of 13 TeV, we report a measurement of this quantity from di-leptonic  $t\bar{t}$  events where the top quarks decay into a  $W$  boson and a bottom quark. We can distinguish muons originating from  $W$  bosons and those originating from an intermediate  $\tau$ -lepton through the muon transverse impact parameter and differences in the muon transverse momentum spectra. The measured value of  $R(\tau/\mu)$  is  $0.992 \pm 0.013$  [ $\pm 0.007$  (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 only such measurement from the Large Hadron Collider, so far, and obtains twice the precision of previous measurements.

## Main

It is a fundamental axiom of the Standard Model (SM) that the couplings of the electroweak gauge bosons ( $W, Z$ ) to charged leptons,  $g_\ell$  ( $\ell = \text{electron } (e), \text{ muon } (\mu), \text{ tau } (\tau)$ ), 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 comparing the relative decay rates, or branching ratios ( $B$ ), of on-shell  $W$ -bosons to  $\tau$ -leptons and muons, by measuring the ratio  $R(\tau/\mu) = B(W \rightarrow \tau\nu_\tau)/B(W \rightarrow \mu\nu_\mu)$ .

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 that  $B(t \rightarrow Wq)$  is close to 100%, this gives a very large sample of  $W$  boson pairs. These are used to obtain a large sample of clean and unbiased  $W$  boson decays to muons and  $\tau$ -leptons. The  $\tau$ -leptons are identified through their decay to muons. The  $\tau$ -lepton has a significant lifetime [1, 2] compared to the  $W$  boson and undergoes a multi-body decay to a muon and neutrinos. This leaves two distinctive signatures in the detector, the displacement of the  $\tau$  decay vertex and on average a lower muon transverse momentum ( $p_T$ ). These features 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  $R(\tau/\mu)$ . The precision of the measurement relies on the highly accurate reconstruction of muon tracks obtainable by the ATLAS experiment.

Previously,  $R(\tau/\mu)$  has been measured at the Large Electron-Positron Collider (LEP), yielding a combined value of  $1.070 \pm 0.026$  [3]. The SM expectation of  $R(\tau/\mu)$  is unity (neglecting very small phase space effects due to the masses of the decay products ( $\sim 5 \times 10^{-4}$ ) [4]) which differs from the measured value, 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  $\ell$  is either an electron or a muon, have not yet reached the precision of the LEP results [5–9]. 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 [3], LHCb [10] and ATLAS [11] experiments, and is found to be consistent with the SM prediction at the 1% level. Additionally, while most low-energy experiments [12] show good agreement, to very high precision, with the hypothesis of universality of lepton couplings, recent results from LHCb [13–16], Belle [17–19] and BaBar [20, 21] show some tension with the SM, further motivating this analysis.

This measurement relies on precise knowledge of the branching ratio of  $\tau$ -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 [4, 22–25] is used in the analysis.

## Experimental set-up

The ATLAS experiment [26–28] at the LHC is a multipurpose particle detector with nearly hermetic coverage for recording particles produced in LHC collisions through a combination of particle position and energy measurements. ATLAS has a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle. More details of the ATLAS coordinate system can be found in *Methods*. ATLAS 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 providing 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 of the detector 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 accept 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. Due to the conditions required 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 collisions per bunch crossing.

Events in this measurement were selected by single-lepton triggers [29–31] requiring a single high- $p_T$  isolated electron or muon. After the application of data-quality requirements [32], the data sample corresponds to an integrated luminosity of  $139 \text{ fb}^{-1}$  with an uncertainty of 1.7% [33] obtained using the LUCID-2 detector [34] for the primary luminosity measurements.

Samples of simulated events were produced using Monte Carlo (MC) techniques to model the different Standard Model processes. After event generation of the process of interest for each sample, the detector response was modelled using a simulation based on GEANT4 [35]. 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. Precise details of the theoretical predictions and event generators used to create the simulated events is given in *Methods*.

## Selecting a pure and unbiased sample of $W$ bosons

Collisions are selected in order to obtain a high purity sample of  $t\bar{t}$  events in which the top quarks decay into a  $W$  boson and a  $b$ -quark, and the two  $W$  bosons then decay to leptons. This is referred to as di-leptonic  $t\bar{t}$ . The two leptonic  $W$  boson decays are exploited in a *tag and probe* approach: in each event *tag* leptons (electrons or muons) are used to select the event, after which a test is performed to determine, in an unbiased way, whether the probe muon was directly produced by a  $W$  boson,  $W \rightarrow \mu\nu_\mu$ , or via an intermediate  $\tau$ -lepton,  $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ . 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.

The selections rely on reconstructed muons, electrons and hadronic jets. Details of the physics object reconstruction definitions used are given in *Methods*. Events entering the signal region are required to contain either one electron and one muon of opposite electric charge ( $e\text{--}\mu$  channel), or two muons of opposite electric charge ( $\mu\text{--}\mu$  channel). In the  $e\text{--}\mu$  channel the electron is required to pass the trigger and in the  $\mu\text{--}\mu$  channel the *tag* muon is required to pass the trigger. This ensures that the *probe* muons have no trigger bias. If both leptons in the  $\mu\text{--}\mu$  channel satisfy the *tag* and *probe* criteria, both muons in turn 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 where the invariant mass of the two muons,  $m_{\mu\mu}$ , satisfies  $85 < m_{\mu\mu} < 95$  GeV are excluded in the  $\mu\text{-}\mu$  channel, and events with di-lepton mass  $m_{\ell\ell} < 15$  GeV are excluded in both channels.

This selection results in a sample of approximately half a million collision events, with a di-leptonic  $t\bar{t}$  purity of over 95% (85%) in the  $e\text{-}\mu$  ( $\mu\text{-}\mu$ ) channel. This sample is used to test the origin of the *probe* muons and extract the measurement of  $R(\tau/\mu)$ . This is the ratio of the number of events in which the *probe* muon originates from the process  $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau\nu_\tau$ , referred to as  $\mu_{\tau(\rightarrow\mu)}$ , to those which come from the process  $W \rightarrow \mu\nu_\mu$ , referred to as  $\mu_{prompt}$ . A fit is performed which exploits the difference in shape between these two components and the backgrounds of the distributions of the *probe* muon's transverse impact parameter  $|d_0^\mu|$  and its transverse momentum  $p_T^\mu$ .

## Muon transverse impact parameter distribution calibration

The muon's transverse impact parameter  $|d_0^\mu|$  has particular importance for this analysis and requires careful treatment. It is measured in the  $x\text{-}y$  plane as the closest distance of approach of the track to the beamline. The shape of the  $|d_0^\mu|$  distribution of prompt muons is determined using a  $Z \rightarrow \mu\mu$  calibration region to create templates that are used to predict the distribution in the signal region.

The calibration region is defined by requiring two muons satisfying the same kinematic criteria as in the signal region, but with the di-muon 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  $> 99.9\%$ .

Templates of the shape of the  $|d_0^\mu|$  distribution are then taken from this data sample after subtracting the expected contributions from the simulation of processes with significant muon parent lifetimes, primarily  $Z \rightarrow \tau\tau$ . These  $|d_0^\mu|$  templates are extracted in 33 bins in  $p_T^\mu$  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 part 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  $p_T^\mu = 20$  GeV the resolution is approximately 14  $\mu\text{m}$ . Corrections to account for differences in the resolution of the detector between the data and simulation are applied to the muons from  $\tau$  decays and hadron decays. For the range of  $|d_0^\mu|$  values considered in this analysis,  $|d_0^\mu| < 0.5$  mm, the resolution measured from prompt muons is applicable to those with significant displacement.

## Background normalisation estimation

The two largest backgrounds are  $Z(\rightarrow \mu\mu)\text{+jets}$  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  $Z(\rightarrow \mu\mu)\text{+jets}$  background is important at small values of  $|d_0^\mu|$ . The normalisation of the  $Z(\rightarrow \mu\mu)\text{+jets}$  background in the  $\mu\text{-}\mu$  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 and is then extrapolated

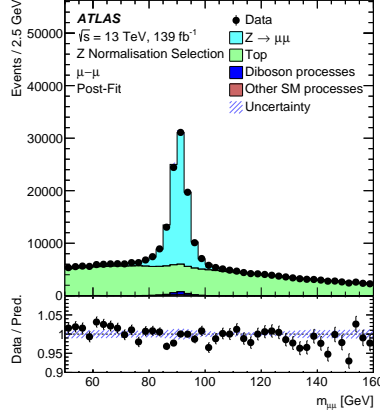


Figure 1:  $Z \rightarrow \mu\mu$  background normalisation A region enriched in  $Z \rightarrow \mu\mu$  events is defined by selecting events with two muons. This control region used to extract the  $Z \rightarrow \mu\mu$  normalisation, which is applied in the signal region. The di-muon invariant mass,  $m_{\mu\mu}$ , distribution is shown in the figure. The data are shown by black markers, the different components contributing to this region, taken from simulation, are given by stacked histograms. The different contributions are the primary process of interest,  $Z \rightarrow \mu\mu$ , along with the main backgrounds from events involving: top quarks, *Top*; a pair of  $W$  and/or  $Z$  bosons, *Diboson processes*; and the grouping of all remaining Standard Model processes, *Other SM processes*. The bottom panel shows the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the  $\pm 1\sigma$  systematic uncertainties on the prediction with the constraints from the analysis fit applied.

to the signal region using simulation. In the control region 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 [36] is used for the  $Z \rightarrow \mu\mu$  resonance and a third-order Chebychev polynomial for all non-resonant processes, which provides a good description of the data. Other functions were 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  $1.36 \pm 0.01$ . The di-muon invariant mass in the control region is shown in Figure 1 after this normalisation is applied. This normalisation factor is also applied to the small  $Z(\rightarrow \tau\tau)$ +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  $K^\pm$ . This occurs primarily in  $t\bar{t}$  events where one  $W$  boson decays leptonically and the other hadronically, referred to as semi-leptonic  $t\bar{t}$ . These muons are referred to as  $\mu_{had}$ . A data-driven method is used to determine the normalisation of this background from two control regions, one each for the  $e-\mu$  and  $\mu-\mu$  channels. The control regions have the same event selection as the signal regions but the two leptons are required to have same-sign electric charge. 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 source,  $c$ -hadrons, has a component in both selections, but they are not equal. 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 two backgrounds to  $\mu_{had}$  at high  $p_T^\mu$ :  $t\bar{t} + V$  and  $t\bar{t}$  which occurs through electron charge misidentification in the  $e-\mu$  channel. A normalisation correction factor is applied to these processes based on the number of events observed with *probe* muon  $p_T^\mu > 30$  GeV. This is done prior to extracting the normalisation of the  $\mu_{had}$  background. Normalisation factors to scale the simulation to data for the  $\mu_{had}$  background are found to be 1.39 (1.37) in the  $e-\mu$  ( $\mu-\mu$ ) channels, respectively. Figure

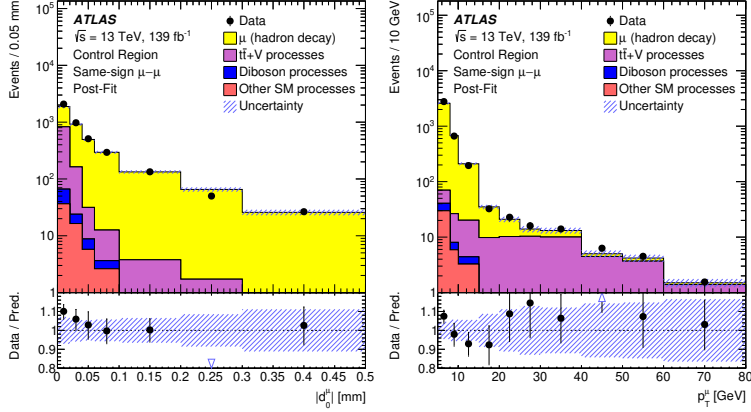


Figure 2:  $\mu_{had}$  background normalisation A region enriched in  $\mu_{had}$  events is defined by selecting events with two same-sign muons. This control region used to extract normalisation factors to correct the  $\mu_{had}$  prediction to match the data. The *probe* muon transverse impact parameter,  $|d_0^\mu|$ , and transverse momentum,  $p_T^\mu$ , distributions in this region are shown. The data are shown by black markers, the different components contributing to this region, taken from simulation, are given by stacked histograms. The different contributions are the primary process of interest,  $\mu_{had}$ ,  $\mu$  (*hadron decay*), along with the main backgrounds from events involving: a top quark pair produced in association with a  $W$  or  $Z$  boson,  $t\bar{t} + V$  *background*; a pair of  $W$  and/or  $Z$  bosons, *Diboson processes*; and the grouping of all remaining Standard Model processes, *Other SM processes*. The extracted normalisation factor is applied to the  $\mu_{had}$  prediction, along with the effect of any constraints and pulls on the systematic uncertainties from the fit to the signal region data. The bottom panel shows the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the  $\pm 1\sigma$  systematic uncertainties on the prediction with the constraints from the analysis fit applied. The empty blue arrows in the ratio panel indicate points where the ratio values lie outside the y-axis range shown.

2 shows that the simulation and data are consistent within uncertainties in the  $\mu\text{-}\mu$  channel same-sign control region, providing confidence that the differential distributions of  $p_T^\mu$  and  $|d_0^\mu|$  are well-modelled.

## Fit configuration and systematic uncertainties

A two dimensional profile likelihood fit [37] is performed in the  $|d_0^\mu|$  and  $p_T^\mu$  distributions. The bin boundaries were chosen to provide the best separation between the different  $\mu_{prompt}$ ,  $\mu_{\tau(\rightarrow\mu)}$  and  $\mu_{had}$  processes given the available data. This resulted in three bins in  $p_T^\mu$  (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 both the  $e\text{-}\mu$  and  $\mu\text{-}\mu$  channels, making 48 bins in total.

The ratio of the number of  $\mu_{\tau(\rightarrow\mu)}$  events to the number  $\mu_{prompt}$  is fitted by minimizing the negative log likelihood, to measure  $R(\tau/\mu)$ . More than 100 (nuisance) parameter values representing the statistical and systematic uncertainties, which can be modified by the fit, are included. The relative uncertainty of 0.23% in the  $\tau \rightarrow \mu\nu_\mu\nu_\tau$  branching ratio is also included in the measured value of  $R(\tau/\mu)$  and is a subdominant component of the overall uncertainty. 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 signal whilst  $R(\tau/\mu)$  only affects the  $\mu_{\tau(\rightarrow\mu)}$  components. Both are applied across all bins and in both channels.  $R(\tau/\mu)$  is 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 taking into account the uncertainty in these predictions.

Since many systematic uncertainties are correlated between the  $\mu_{prompt}$  and  $\mu_{\tau(\rightarrow\mu)}$  templates, they cancel out in the  $R(\tau/\mu)$  ratio, minimising their impact on the precision of the result. These include uncertainties related to jet reconstruction, flavour tagging and trigger efficiencies. The remaining dominant uncertainties are the uncertainties in the data driven methods, the theoretical modelling uncertainties and the reconstruction uncertainties are described in the following, and further details are given in *Methods*.

An uncertainty associated with the data-driven templates for the  $|d_0^\mu|$  distribution of  $\mu_{prompt}$  is derived to account for the differences between the  $Z \rightarrow \mu\mu$  calibration region where they were derived and the signal region.

Uncertainties in the data-driven normalisation of the  $\mu_{had}$  background due to the size of the same-sign dataset, the choice of MC generators used and the uncertainty in the subtraction of the other processes in the same-sign control region are included in the fit. The uncertainties associated with the  $Z$ +jets normalisation derived from data are also applied. Uncertainties on the cross-section calculations and the integrated luminosity are applied to all other backgrounds estimated from simulation, but have a minor impact on the result.

Uncertainties in the shape of 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 changes in generator configuration choices can result in modifications to the muon  $p_T^\mu$ , 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, leading to an uncertainty in  $R(\tau/\mu)$ . For the  $\mu_{had}$  background, in addition to the uncertainties in the normalisation, there can be changes to the muon  $p_T^\mu$  modelling and the relative fractions of muons from different sources, both of which can change the shape of the  $|d_0^\mu|$  distribution. The most important of these variations is in the parton shower and hadronisation model.

The muon reconstruction and isolation efficiencies are determined in di-muon ( $Z \rightarrow \mu\mu$  and  $J/\psi \rightarrow \mu\mu$ ) data and simulation using a *tag* and *probe* method [38]. 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 [39].

## Extraction of $R(\tau/\mu)$

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  $\mu_{\tau(\rightarrow\mu)}$  processes can be seen clearly. The  $\mu_{prompt}$  processes dominate at low  $|d_0^\mu|$  while  $\mu_{\tau(\rightarrow\mu)}$  dominates at high  $|d_0^\mu|$ . The  $\mu_{had}$  background is also important at high  $|d_0^\mu|$  but contributes most significantly at low  $p_T^\mu$ .



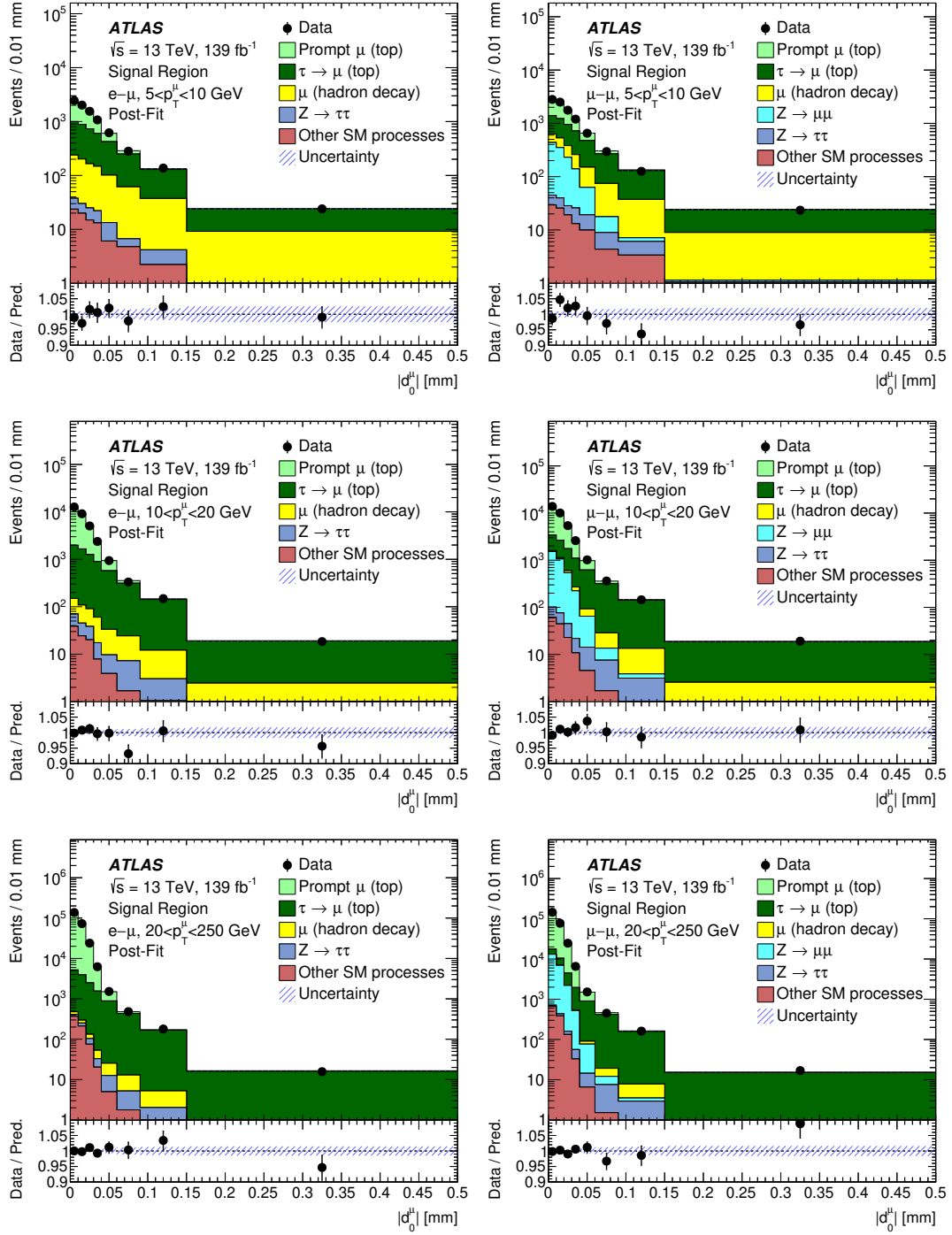


Figure 3: **Transverse impact parameter distributions of probe muons in the signal region** The signal region used to extract  $R(\tau/\mu)$  is enriched in di-lepton  $t\bar{t}$  events. The  $|d_0^\mu|$  distributions for each signal region (left:  $e-\mu$  channel, right:  $\mu-\mu$  channel) and *probe muon*  $p_T^\mu$  bin (top:  $5 < p_T^\mu < 10$  GeV, middle:  $10 < p_T^\mu < 20$  GeV, bottom:  $20 < p_T^\mu < 250$  GeV) used in the analysis are shown. The data are represented by black markers, the different components contributing to this region, taken from simulation, are given by stacked histograms. The different contributions are the two primary process of interest used to extract  $R(\tau/\mu)$ ,  $\mu_{prompt}$  from top quark decays, *Prompt  $\mu$  (top)* and  $\mu_{\tau(\rightarrow\mu)}$  from top decays,  $\tau \rightarrow \mu$  (*top*). The main backgrounds are also shown. These are: events with a  $\mu_{had}$ ,  $\mu$  (*hadron decay*); events with a Z boson decaying to a di-muon pair,  $Z \rightarrow \mu\mu$ ; events with a Z boson decaying to a di- $\tau$  pair,  $Z \rightarrow \tau\tau$ ; and the grouping of all remaining Standard Model processes, *Other SM processes*. Distributions are shown after the fit has been performed. The bottom panel shows the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the  $\pm 1\sigma$  systematic uncertainties on the prediction with the constraints from the analysis fit applied. The empty blue arrows in the ratio panel indicate points where the ratio values lie outside the y-axis range shown. The contribution from *Other SM processes* is dominated by di-boson and  $t\bar{t} + V$  production. The chi-square statistic values range from 3.5 to 10.2 for 8 degrees of freedom for the distributions.



Table 1: **Sources of uncertainty** The main sources of uncertainty on the measured value of  $R(\tau/\mu)$ . The size of the impact each uncertainty has on  $R(\tau/\mu)$  is assessed by fixing the relevant fit parameters for a given uncertainty and re-fitting to data. The reduction in the total uncertainty in this modified fit gives the quoted impact. Different individual components used in the fit are combined into categories.

| Source   | Impact on $R(\tau/\mu)$ |
|--|-------------------------|
| Prompt $d_0^\mu$ templates   | 0.0038                  |
| $\mu_{prompt}$ and $\mu_{\tau(\rightarrow\mu)}$ 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 $p_T$ spectrum variation   | 0.0026                  |
| $\mu_{had}$ parton shower variations                                     | 0.0021                  |
| Monte Carlo statistics   | 0.0018                  |
| Pile-up  | 0.0017                  |
| $\mu_{\tau(\rightarrow\mu)}$ and $\mu_{had}$ $d_0^\mu$ shape             | 0.0017                  |
| Other detector systematic uncertainties                                  | 0.0016                  |
| Z+jet normalisation  | 0.0009                  |
| Other sources  | 0.0004                  |
| $B(\tau \rightarrow \mu\nu_\tau\nu_\mu)$                                 | 0.0023                  |
| Total systematic uncertainty   | 0.0109                  |
| Data statistics  | 0.0072                  |
| <b>Total</b>   | <b>0.013</b>            |

The analysis was finalised prior to looking at the value of  $R(\tau/\mu)$  in data in order to minimise any 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  $\tau \rightarrow \mu\nu_\mu\nu_\tau$  branching ratio, and the statistical uncertainty is 0.007. Table 1 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, the parton shower and hadronisation model uncertainty, and the muon selection uncertainties.

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

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

exceeding the precision from LEP which measured  $1.070 \pm 0.026$ . The result is shown in Figure 4 alongside 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.

This result surpasses the precision of the previous LEP result and resolves the tension they observed with the SM prediction of lepton flavour universality. This precise measurement of  $R(\tau/\mu)$  achieved so far, this is an example of the ability of the ATLAS experiment to perform high-precision measurements.

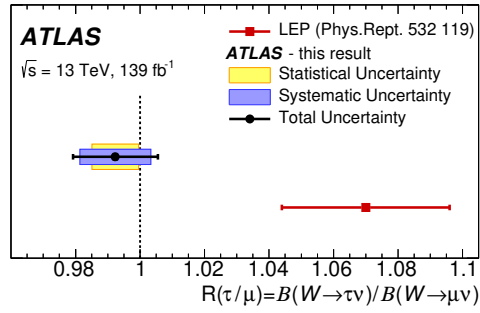


Figure 4: **Summary of ATLAS and LEP results** The new ATLAS measurement of  $R(\tau/\mu)$  and the previous LEP result [3] of the same quantity. The new measurement from ATLAS is shown by the black circular marker and the LEP result by a red square marker. For the ATLAS result the statistical (yellow box) and systematic (blue box) errors are shown separately along with the total error of the measurement (black bars). The total uncertainty on the LEP result is indicated by the red bars. The vertical dashed line indicates the Standard Model's prediction lepton-flavour universality, with equal  $W$  boson branching ratios to different lepton flavours.

## Methods

### ATLAS coordinate system and nomenclature

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  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

The beamline is the central ( $x$ - $y$ ) axis of the luminous region. The transverse impact parameter,  $|d_0^\mu|$ , is measured in the  $x$ - $y$  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.

### Monte Carlo simulation and theoretical predictions

The top-pair and single-top-quark events, including  $Wt$ -,  $t$ - and  $s$ -channel production, were generated using the POWHEGBOX [40–44] generator interfaced to the PYTHIA8 [45–47] parton shower and hadronisation model, more details can be found in Ref. [48]. The decays of bottom and charm hadrons are important for backgrounds in the analysis and were modelled using the EVTGEN [49] program. The  $t\bar{t}$  and single-top processes were normalised to the inclusive cross-section calculation of the highest available precision [50–58] 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 [59]. For single top quark production in the  $Wt$ -channel, the diagram removal scheme [60] was used to remove overlap with  $t\bar{t}$  production.  $t\bar{t} + W$  and  $t\bar{t} + Z$  events were simulated with SHERPA and MADGRAPH5\_AMC@NLO [61] interfaced with PYTHIA8, respectively. The background from  $V(= W, Z)$ +jets and  $VV$ +jets events was simulated with the SHERPA [44, 62–71] generator, more details can be found in Refs. [72, 73]. All processes were normalised to their highest order available cross sections [74, 75].

Simulated inelastic  $pp$  collisions [39] were overlaid on events in all samples to model the observed data distribution of pile-up from additional collisions in the same and neighbouring bunch crossings.

### Object identification in ATLAS

Muons are reconstructed using combined fits of inner detector [76, 77] and muon spectrometer tracks [38]. They are required to satisfy the ‘medium’ identification criteria of Ref. [38]. 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  $p_T^\mu > 27.3$  GeV to pass the trigger thresholds, while *probe* muons are required to have  $p_T^\mu > 5$  GeV. Both the *tag* and *probe* muons are required to have  $|\eta| < 2.5$  and to originate close to the primary vertex 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. The primary vertex is defined as the vertex with the highest  $\Sigma p_T^2$  of the tracks associated with it. 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 charged kaons and pions.

Electrons are reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters [78]. They are required to satisfy the ‘tight’ identification criteria of Ref. [78] and the same strict isolation criteria as applied to muons. *Tag* electrons are required to have  $p_T^e > 27$  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 calorimeter cells at the electromagnetic energy scale [79], using the anti- $k_t$  algorithm [80] 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 jet algorithm [81]. For jets with  $25 < p_T < 60$  GeV and  $|\eta| < 2.4$ , pile-up suppression requirements in the form of a jet vertex tagger [82] are applied. Only jets with  $p_T > 25$  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 [83, 84] is used.

An overlap removal procedure as described in Ref. [85] is applied to resolve the ambiguity if lepton signals in the calorimeter are also reconstructed as hadronic jets.

## Systematic uncertainties

Several of the most important systematic uncertainties in the measurement of  $R(\tau/\mu)$  merit a more detailed discussion, which is provided here.

Due to differences in the hadronic environment around the lepton between  $Z$  and  $t\bar{t}$  final states and the coarse binning in  $p_T^\mu$  and  $|\eta|$ , which may not be able to encapsulate the full shape information, small biases can exist in the data-driven  $\mu_{prompt}$  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.

The breakdown of uncertainties contributing to the  $\mu_{had}$  background control region normalisation in the  $e-\mu$  ( $\mu-\mu$ ) channels is: 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 due to the choice of MC event generator for the  $\mu_{prompt}$ ,  $\mu_{\tau(\rightarrow\mu)}$  and  $\mu_{had}$  processes are estimated by varying different components of the modelling in a factorised way. The following variations are considered targeting different sources of uncertainty:

- **Initial- and final-state radiation:** A14 eigen-tune variations [46] of the strong coupling ( $\alpha_s$ ),
- **Missing higher-order QCD corrections:** Factorisation and renormalisation scales simultaneously varied up and down by a factor of two,
- **Resummation scale uncertainty:** POWHEG  $h_{damp}$  parameter varied from 1.5 to  $3 m_{top}$  (symmetrised),
- **Parton shower and hadronisation model:** HERWIG 7 [86, 87], H7UE tune [87, 88] (symmetrised),

- **Higher-order correction to top  $p_T$  spectrum:** Not applying the NNLO top  $p_T$  reweighting [59] (symmetrised).

In the cases where only a single alternative is given, the uncertainty is taken to be the deviation from the nominal result and then symmetrised, as indicated above. The effects on  $\mu_{prompt}$  and  $\mu_{\tau(\rightarrow\mu)}$  (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  $p_T^\mu$  bins used in the fit, and two corresponding to the high  $p_T^\mu$  bin where the uncertainty is further separated into components related to normalisation and shape differences.

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## **Author contributions**

All authors have contributed to the publication, being variously involved in the design and the construction of the detectors, in writing software, calibrating subsystems, operating the detectors and acquiring data, and finally analysing the processed data. The ATLAS Collaboration members discussed and approved the scientific results. The manuscript was prepared by a subgroup of authors appointed by the collaboration and subject to an internal collaboration-wide review process. All authors reviewed and approved the final version of the manuscript.

## **Competing interests**

The authors declare no competing interests.

## **Data availability**

The experimental data that support the findings of this study are available in HEPData with the identifier <https://www.hepdata.net/record/100232>. The ATLAS software is available at the following link: <https://gitlab.cern.ch/atlas/athena>.

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L. Franconi<sup>20</sup>, M. Franklin<sup>59</sup>, G. Frattari<sup>73a,73b</sup>, A.N. Fray<sup>93</sup>, P.M. Freeman<sup>21</sup>, B. Freund<sup>110</sup>,  
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