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Test of the universality of τ and μ lepton couplings in W -boson decays with the ATLAS detector

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 τ leptons and muons, $R(\tau/\mu)$, constitutes an important test of this axiom. Using 139 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 τ 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 ± 0.013 [$\pm 0.007(\text{stat}) \pm 0.011(\text{syst})$] 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.

It is a fundamental axiom of the standard model (SM) that the couplings of the electroweak gauge bosons (W , Z) to charged leptons, g_ℓ (ℓ = electron (e), muon (μ), tau (τ)), are independent of the mass of the leptons. This fundamental assumption is referred to as ‘lepton-flavour universality’ and is tested in this Article by comparing the relative decay rates, or branching ratios (B), of on-shell W bosons to τ 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 τ leptons. The τ leptons are identified through their decay to muons. The τ 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 τ decay vertex and, on average, a lower muon transverse momentum (p_T). These features are used to distinguish between muons from the $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau$ 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 ± 0.026 (ref. 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 ℓ 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 LEP³, LHCb¹⁰ and ATLAS¹¹ experiments, and is found to be consistent with the SM prediction at the 1% level. Additionally, although most low-energy experiments¹² 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 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^{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 4π coverage in solid angle. More details of the ATLAS coordinate system are provided in the Methods. ATLAS consists of an inner tracking detector surrounded by a thin superconducting solenoid providing an axial magnetic field of 2 T, 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 a precise measurement of track impact parameters. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic 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 electromagnetic 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

*A list of authors and their affiliations appears online.

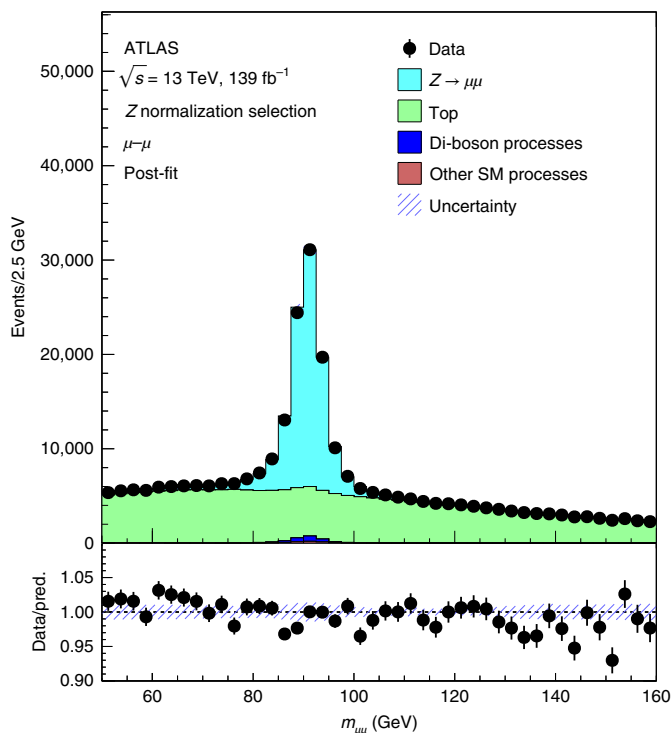


Fig. 1 | $Z \rightarrow \mu\mu$ background normalization. A region enriched in $Z \rightarrow \mu\mu$ events is defined by selecting events with two muons. This control region is used to extract the $Z \rightarrow \mu\mu$ normalization, which is applied in the signal region. A histogram with a fixed bin width of 2.5 GeV of the di-muon invariant mass ($m_{\mu\mu}$) distribution is shown in the figure. The data are shown by black markers and the different components contributing to this region, taken from simulation, are shown 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 (Di-boson processes) and the grouping of all remaining SM 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.

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. Owing 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 requirements³², the data sample corresponds to an integrated luminosity of 139 fb^{-1} with an uncertainty of 1.7%³³, obtained using the LUCID-2 detector³⁴ for the primary luminosity measurements.

Samples of simulated events were produced using Monte Carlo techniques to model the different SM processes. After event generation of the process of interest for each sample, the detector response was modelled using a simulation based on GEANT4³⁵. The data and Monte Carlo 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 are provided in the Methods.

Selecting a pure and unbiased sample of W bosons

Collisions are selected 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 τ lepton, $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\nu$. Events are categorized into signal regions, used to extract $R(\tau/\mu)$, and additional control regions, used to constrain the normalization of the major backgrounds.

The selections rely on reconstructed muons, electrons and hadronic jets. Details of the physics object reconstruction definitions used are provided in the Methods. Events entering the signal region are required to contain either one electron and one muon of opposite electric charge ($e-\mu$ channel) or two muons of opposite electric charge ($\mu-\mu$ channel). In the $e-\mu$ channel, the electron is required to pass the trigger, and in the $\mu-\mu$ 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 $\mu-\mu$ 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 that are identified as containing a b hadron. Finally, to reduce the 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 $\mu-\mu$ 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% in the $e-\mu$ channel and 85% in the $\mu-\mu$ channel. This sample is used to test the origin of the probe muons and extract the measurement of $R(\tau/\mu)$. This is extracted from the ratio of the number of events in which the probe muon originates from the process $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\nu$, referred to as $\mu_{\tau(\rightarrow\mu)}$, to those that come from the process $W \rightarrow \mu\nu_\mu$, referred to as μ_{prompt} . A fit is performed that 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^μ .

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 $x-y$ 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 that 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 ~ 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^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.

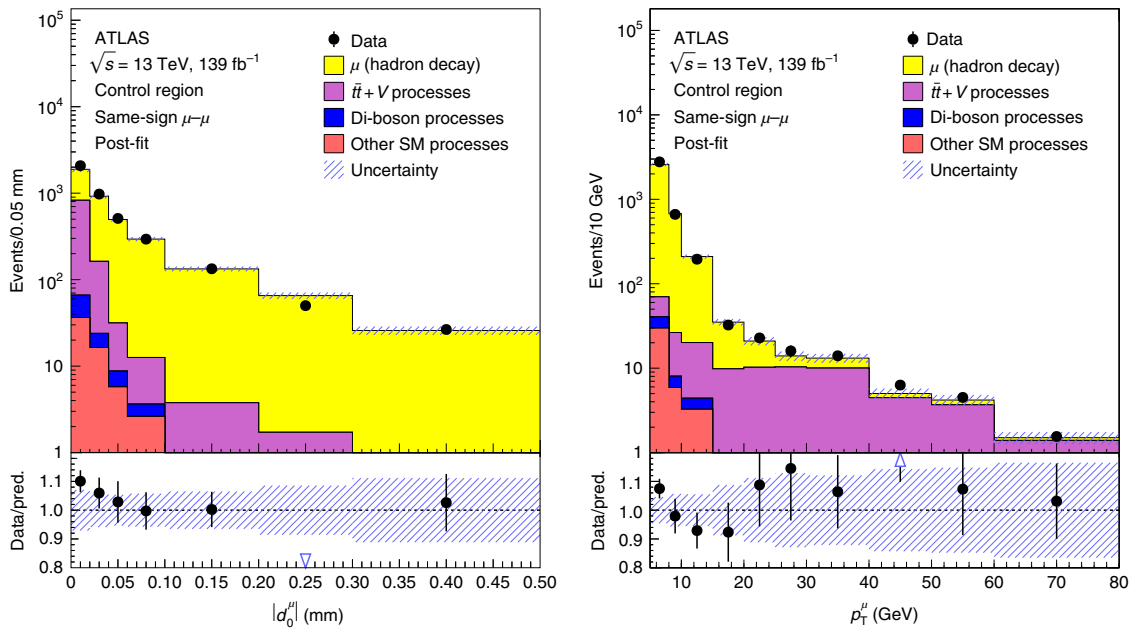


Fig. 2 μ_{had} background normalization. A region enriched in μ_{had} events is defined by selecting events with two same-sign muons. This control region is used to extract normalization factors to correct the μ_{had} prediction to match the data. The probe muon transverse impact parameter (left, $|d_0^\mu|$) and transverse momentum (right, p_T^μ) distributions in this region are shown. The data are shown by black markers and the different components contributing to this region, taken from simulation, are shown by stacked histograms. The different contributions are the primary process of interest, μ_{had} (μ (hadron decay)), along with the main backgrounds from events involving a top quark pair produced in association with a W or Z boson ($t\bar{t} + V$ processes), a pair of W and/or Z bosons (Di-boson processes) and the grouping of all remaining SM processes (Other SM processes). The y-axis label includes the value that defines the scaling of the variable bin width histogram. The extracted normalization factor is applied to the μ_{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 panels show 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 open blue arrowheads in the ratio panel indicate points where the ratio values lie outside the y-axis range shown.

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 $\sim 14\mu\text{m}$. Corrections to account for differences in the resolution of the detector between the data and simulation are applied to the muons from τ 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 normalization 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 normalization of these backgrounds.

The $Z(\rightarrow\mu\mu) + \text{jets}$ background is important at small values of $|d_0^\mu|$. The normalization 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 to the signal region using simulation. In the control region, the peak of the invariant mass distribution of the di-muon system is fitted over the range $50 < m_{\mu\mu} < 140$ GeV. A Voigt profile³⁶ 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 normalization factor required to scale the simulated sample to data is found to be 1.36 ± 0.01 . The di-muon invariant mass in the control region is shown in Fig. 1 after this normalization is applied.

This normalization factor is also applied to the small $Z(\rightarrow\tau\tau) + \text{jets}$ 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 π^\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 μ_{had} . A data-driven method is used to determine the normalization of this background from two control regions, one each for the $e\text{--}\mu$ and $\mu\text{--}\mu$ 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. This results in a sample with a high purity of this μ_{had} background. The largest source of μ_{had} is from decays of b hadrons, and this contributes equally to same-sign and opposite-sign selections, while the other substantial source, c hadrons, has a component in both selections, but they are not equal. 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 μ_{had} at high p_T^μ : $t\bar{t} + V$, and $t\bar{t}$, which occurs through electron charge misidentification in the $e\text{--}\mu$ channel. A normalization correction factor is applied to these processes based on the number of events observed with a probe muon with $p_T^\mu > 30$ GeV. This is done before extracting the normalization of the μ_{had} background. The normalization factors to scale the simulation to data for the μ_{had} background are found to be 1.39 and 1.37 in the $e\text{--}\mu$ and $\mu\text{--}\mu$ channels, respectively. Figure 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^μ and $|d_0^\mu|$ are well-modelled.

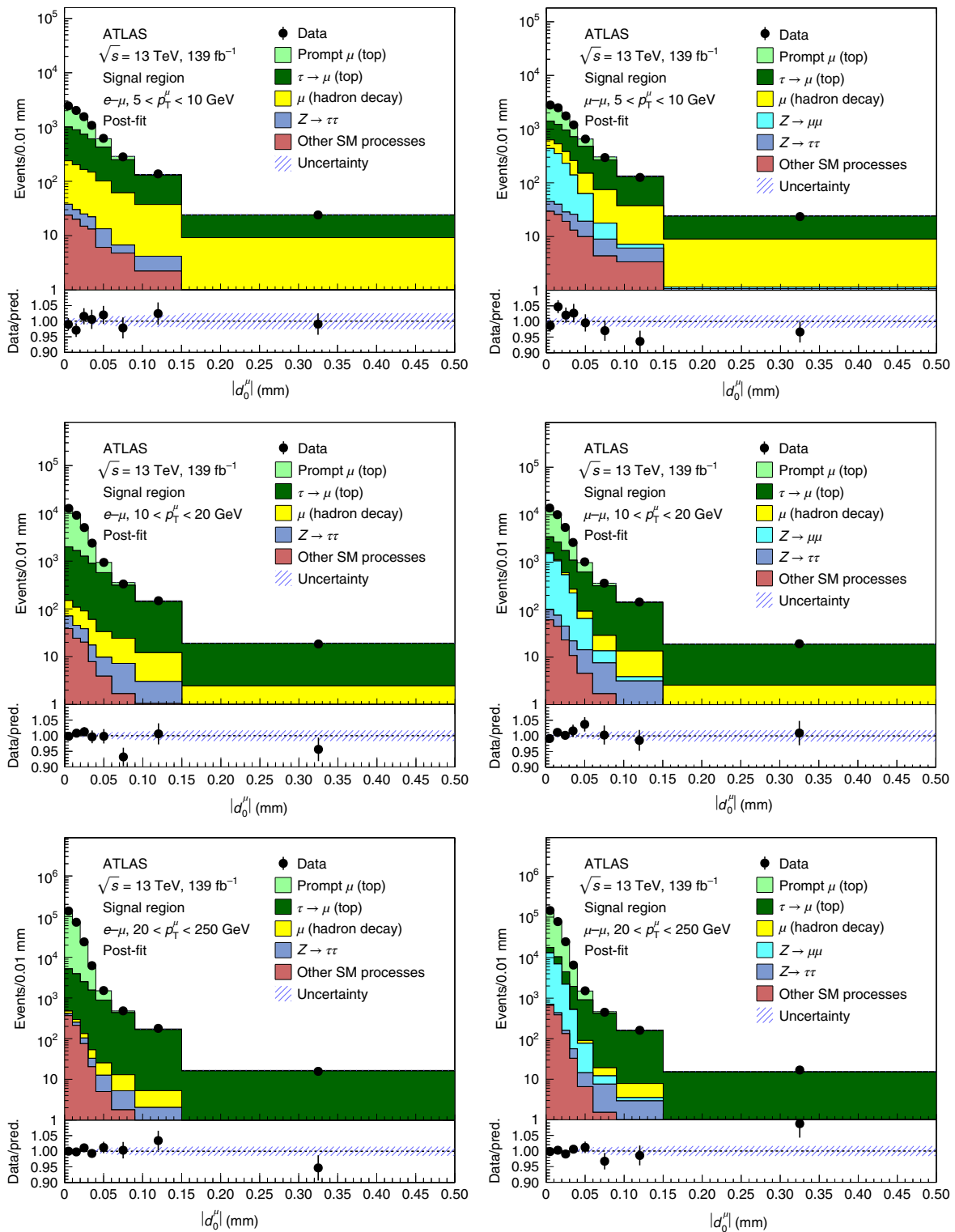


Fig. 3 | Transverse impact parameter distributions of probe muons in the signal region. The signal region used to extract $R(\tau/\mu)$ is enriched in di-lepton $t\bar{t}$ events. The $|d_0^\mu|$ distributions for each signal region (left, $e-\mu$ channel; right, $\mu-\mu$ channel) and probe muon p_T^μ 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 by stacked histograms. The data are represented by black markers and the different components contributing to this region, taken from simulation, are shown by stacked histograms. The different contributions are the two primary processes of interest used to extract $R(\tau/\mu)$, μ_{prompt} from top quark decays (Prompt μ (top)) and $\mu_{\tau \rightarrow \mu}$ from top decays ($\tau \rightarrow \mu$ (top)). The main backgrounds are also shown: events with a μ_{had} (μ (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- τ pair ($Z \rightarrow \tau\tau$) and the grouping of all remaining SM processes (Other SM processes). Distributions are shown after the fit has been performed. The y-axis label includes the value that defines the scaling of the variable bin width histogram. The bottom panels show 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 contribution from ‘Other SM processes’ is dominated by di-boson and $t\bar{t} + V$ production. The chi-squared statistic values range from 3.5 to 10.2 for eight degrees of freedom for the distributions.

Table 1 | Sources of uncertainty

Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalization	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectrum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\rightarrow\mu)}$ and μ_{had} d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalization	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
Total	0.013

The main sources of uncertainty on the measured value of $R(\tau/\mu)$ are shown. 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 refitting 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.

Fit configuration and systematic uncertainties

A two-dimensional profile likelihood fit³⁷ is performed in the $|d_0^\mu|$ and p_T^μ distributions. The bin boundaries were chosen to provide the best separation between the different μ_{prompt} , $\mu_{\tau(\rightarrow\mu)}$ and μ_{had} processes given the available data. This resulted in three bins in p_T^μ (boundaries of 5, 10, 20 and 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 and 0.5 mm), of the probe muon for both the $e-\mu$ and $\mu-\mu$ channels, making 48 bins in total.

The ratio of the number of $\mu_{\tau(\rightarrow\mu)}$ events to the number μ_{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 normalization of both the μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ components of the signal, whereas $R(\tau/\mu)$ 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 is not affected by the overall normalization scaling factors of the $t\bar{t}$ and Wt processes. The fit is performed after applying the normalization scaling factors derived in the control regions. Other processes are normalized to their theoretical cross-sections, taking into account the uncertainty in these predictions.

Because many systematic uncertainties are correlated between the μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ templates, they cancel out in the $R(\tau/\mu)$ ratio, minimizing 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; these

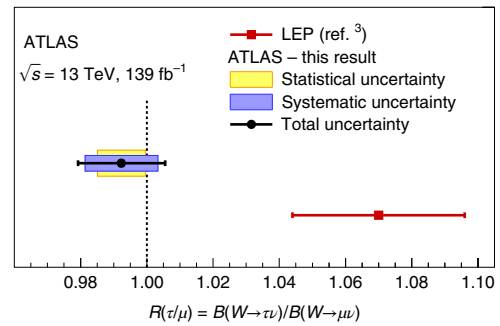


Fig. 4 | Summary of ATLAS and LEP results. The new ATLAS measurement of $R(\tau/\mu)$ and the previous LEP result³ of the same quantity. The new measurement from ATLAS is shown by the black filled circle and the LEP result by a red filled square. For the ATLAS result the statistical (yellow box) and 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 prediction lepton-flavour universality of the SM, with equal W -boson branching ratios to different lepton flavours.

are described in the following and further details are provided in the Methods.

An uncertainty associated with the data-driven templates for the $|d_0^\mu|$ distribution of μ_{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 normalization of the μ_{had} background due to the size of the same-sign dataset, the choice of Monte Carlo 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 normalization 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 μ_{prompt} , $\mu_{\tau(\rightarrow\mu)}$ and μ_{had} distributions due to the modelling of the simulated $t\bar{t}$ samples are derived. The combined yield of the μ_{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^μ and subsequently the $|d_0^\mu|$ distribution, such that there can be relative changes in the μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ template yields in each bin, leading to an uncertainty in $R(\tau/\mu)$. For the μ_{had} background, in addition to the uncertainties in the normalization, 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 most important of these variations is in the parton shower and hadronization 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 method³⁸. 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 events³⁹.

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

The analysis was finalised before looking at the value of $R(\tau/\mu)$ in the data to minimize 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 hadronization 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 ± 0.026 . The result is shown in Fig. 4 alongside the combination of LEP measurements. The present result agrees with the SM 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.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41567-021-01236-w>.

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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, 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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 hadronization model (more details are available in ref. ⁴⁸). The decay of bottom and charm hadrons are important for backgrounds in the analysis and were modelled using the EvtGen⁴⁹ program. The $t\bar{t}$ and single-top processes were normalized 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 quantum chromodynamics (QCD) top quark p_T calculation⁵⁹. For single-top quark production in the Wt channel, the diagram removal scheme⁶⁰ was used to remove overlap with $t\bar{t}$ production. The $t\bar{t} + W$ and $t\bar{t} + Z$ events were simulated with Sherpa and MadGraph5_aMC@NLO⁶¹ 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 normalized to their highest-order available cross-sections^{74,75}.

Simulated inelastic pp collisions³⁹ 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.

Object identification in ATLAS. Muons are reconstructed using combined fits of inner detector^{76,77} and muon spectrometer tracks³⁸. 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 Σp_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, to remove reconstructed muons that result from in-flight decays of charged kaons and pions.

Electrons are reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters⁷⁸. 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 scale⁷⁹, using the anti- k_r algorithm⁸⁰ 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 algorithm⁸¹. For jets with $25 < p_T < 60$ GeV and $|\eta| < 2.4$, pile-up suppression requirements in the form of a jet vertex tagger⁸² 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.

Owing to differences in the hadronic environment around the lepton between the 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 data-driven μ_{prompt} template distributions. The size of such a possible bias is estimated from the full difference between $\mu_{\text{prompt}} |d_0^\mu|$ 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 μ_{had} background control region normalization in the e - μ (μ - μ) channels is as follows: 4% (4%) due to the size of the same-sign dataset; 8% (3%) due to the choice of Monte Carlo generators used; 1.0% (1.3%) due to the uncertainty in the subtraction of the other processes in the same-sign control region.

The uncertainties due to the choice of Monte Carlo event generator for the μ_{prompt} , $\mu_{\tau(\rightarrow\mu)}$ and μ_{had} processes are estimated by varying different components of the modelling in a factorized way. The following variations are considered targeting different sources of uncertainty:

- Initial- and final-state radiation: A14 eigen-tune variations⁴⁶ of the strong coupling (α_s)
- Missing higher-order QCD corrections: factorization and renormalization 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} (symmetrized)
- Parton shower and hadronization model: Herwig^{78,87}, H7UE tune^{87,88} (symmetrized)
- Higher-order correction to top p_T spectrum: not applying the NNLO top p_T reweighting⁵⁹ (symmetrized)

In the cases where only a single alternative is given, the uncertainty is taken to be the deviation from the nominal result and then symmetrized, as indicated above. The effects on μ_{prompt} and $\mu_{\tau(\rightarrow\mu)}$ (collectively referred to as ‘signal’) are treated as correlated and the effects on μ_{had} are treated separately. The parton shower and hadronization 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 normalization and shape differences.

Auxiliary material. Additional auxiliary figures can be found at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/POPQ-2018-29/>.

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>.

Code availability

The ATLAS software is available at the following link: <https://gitlab.cern.ch/atlas/athena>.

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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.

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ATLAS Collaboration

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