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

ATLAS Collaboration

DOI
10.1038/s41567-021-01236-w

Publication date
2021

Document Version
Final published version

Published in
Nature Physics

License
CC BY

Citation for published version (APA):
Test of the universality of $\tau$ and $\mu$ 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 $\tau$ 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 $\tau$ lepton through the muon transverse impact parameter and differences in the muon transverse momentum spectra. The measured value of $R(\tau/\mu)$ is $0.992\pm0.013\,([\pm0.007\text{(stat)}\pm0.011\text{(syst)}])$ 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.

Experimental set-up
The ATLAS experiment 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 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 $|\eta| < 1.7$, and 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\text{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.
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 requiring a single high-$p_t$ isolated electron or muon. After the application of data-quality requirements, the data sample corresponds to an integrated luminosity of 139 fb$^{-1}$ with an uncertainty of 1.79%, obtained using the LUCID-2 detector 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 GEANT4. 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, $W \rightarrow \mu\nu$, or via an intermediate $\tau$ lepton, $W \rightarrow \tau\nu \rightarrow \mu\nu\nu$. 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 $W \rightarrow \tau \nu \rightarrow \mu\nu\nu$ referred to as $R_{\tau}$, to those that come from the process $W \rightarrow \mu\nu$, referred to as $R_{\mu}$. A fit is performed that exploits the difference in shape between these two components and the backgrounds of the distribution of the probe muon’s transverse impact parameter $|d_T^{\mu}|$ and its transverse momentum $p_T^{\mu}$.

Muon transverse impact parameter distribution calibration

The muon’s transverse impact parameter $|d_T^{\mu}|$ has particular importance for this analysis and requires careful treatment. It is measured in the $x-\gamma$ plane as the closest distance of approach of the track to the beamline. The shape of the $|d_T^{\mu}|$ 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 $|d_T^{\mu}|$ 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 $|d_T^{\mu}|$ 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.
Fig. 2 | $\mu_{\text{had}}$ background normalization. A region enriched in $\mu_{\text{had}}$ events is defined by selecting events with two same-sign muons. This control region is used to extract normalization factors to correct the $\mu_{\text{had}}$ prediction to match the data. The probe muon transverse impact parameter (left, $|d_{0}\mu|$) and transverse momentum (right, $p_{T}\mu$) 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, $\mu_{\text{had}}$ (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 $\mu_{\text{had}}$ 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 ±1σ 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 ~14 μm. 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 normalization estimation

The two largest backgrounds are $Z(\rightarrow \mu\mu)$ + 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 normalization of these backgrounds.

The $Z(\rightarrow \mu\mu)$ + jets background is important at small values of $|d_{0}\mu|$. The normalization of the $Z(\rightarrow \mu\mu)$ + jets background in the $\mu-\mu$ 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 profile 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 $Z(\rightarrow \tau\tau)$ + 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 $\pi^0$ and $K^0$. 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 $\mu_{\text{had}}$. A data-driven method is used to determine the normalization 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. This results in a sample with a high purity of this $\mu_{\text{had}}$ background. The largest source of $\mu_{\text{had}}$ is from decays of $b$ and $c$ 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 $\mu_{\text{had}}$ at high $p_{T}\tau$, $t\bar{t} + V$, and $t\bar{t}$, which occurs through electron charge misidentification in the $e-\mu$ 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 $\mu_{\text{had}}$ background. The normalization factors to scale the simulation to data for the $\mu_{\text{had}}$ background are found to be 1.39 and 1.37 in the $e-\mu$ and $\mu-\mu$ channels, respectively. Figure 2 shows that the simulation and data are consistent within uncertainties in the $\mu-\mu$ channel same-sign control region, providing confidence that the differential distributions of $p_{T}\mu$ 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 $p_T^\mu$ 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 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 $R(\tau/\mu)$, $\mu_{\text{top}}$ from top quark decays (Prompt $\mu$ (top)) and $\mu_{\text{cut}}$ from top decays ($\tau \rightarrow \mu$ (top)). The main backgrounds are also shown: events with a $\mu_{\text{had}}$ ($\mu$ (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 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.
Fig. 4 | Summary of ATLAS and LEP results. The new ATLAS measurement of \( R(\tau/\mu) \) and the previous LEP result\(^*\) 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 \( \mu_{\text{prompt}} \) 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 \( \mu_{\text{had}} \) 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 \( Z + \text{jets} \) 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 \( \mu_{\text{prompt}}(\mu_{\text{incl}}) \) and \( \mu_{\text{had}} \) distributions due to the modelling of the simulated \( \tau \) samples are derived. The combined yield of the \( \mu_{\text{prompt}} \) and \( \mu_{\text{incl}} \) 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 \( \mu_{\text{prompt}} \) and \( \mu_{\text{incl}} \) template yields in each bin, leading to an uncertainty in \( R(\tau/\mu) \). For the \( \mu_{\text{had}} \) background, in addition to the uncertainties in the normalization, 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 hadronization model.

The muon reconstruction and isolation efficiencies are determined in di-muon (\( Z \rightarrow \mu\mu \) and \( t\bar{t} \rightarrow \mu\mu \)) data and simulation using a tag and probe method\(^{35} \). 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\(^{35} \).

**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

**Fit configuration and systematic uncertainties**

A two-dimensional profile likelihood fit\(^{33} \) 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 \( \mu_{\text{prompt}} \) and \( \mu_{\text{had}} \) processes given the available data. This resulted in three bins in \( p_T^\mu \) (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 \( \mu_{\tau} \) events to the number \( \mu_{\text{prompt}} \) is fitted by minimizing the negative log-likelihood, to measure \( R(\tau/\mu) \). More than 100 (nuisance) parameter values representing the statistics and systematic uncertainties, which can be modified by the fit, are included. The relative uncertainty of 0.23% in the \( \tau \rightarrow \mu \nu \) 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 \( \tau \) and \( W \) processes contain two \( W \) bosons, both are treated as signal. Two fit parameters are allowed to float freely: \( R(\tau/\mu) \) and \( k(\tau) \). The \( k(\tau) \) parameter is a constant scaling factor applied to the normalization of both the \( \mu_{\text{prompt}} \) and \( \mu_{\tau} \) components of the signal, whereas \( R(\tau/\mu) \) only affects the \( \mu_{\text{had}} \) 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 \( \tau \) and \( W \) 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 \( \mu_{\text{prompt}} \) and \( \mu_{\tau} \) 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

Table 1 | Sources of uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact on ( R(\tau/\mu) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt ( d_0^\mu ) templates</td>
<td>0.0038</td>
</tr>
<tr>
<td>( \mu_{\text{prompt}} ) and ( \mu_{\text{incl}} ), parton shower variations</td>
<td>0.0036</td>
</tr>
<tr>
<td>Muon isolation efficiency</td>
<td>0.0033</td>
</tr>
<tr>
<td>Muon identification and reconstruction</td>
<td>0.0030</td>
</tr>
<tr>
<td>( \mu_{\text{had}} ) Normalization</td>
<td>0.0028</td>
</tr>
<tr>
<td>( t\bar{t} ) scale and matching variations</td>
<td>0.0027</td>
</tr>
<tr>
<td>Top ( p_\tau ) spectrum variation</td>
<td>0.0026</td>
</tr>
<tr>
<td>( \mu_{\text{had}} ) parton shower variations</td>
<td>0.0021</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.0018</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.0017</td>
</tr>
<tr>
<td>( \mu_{\tau} ) and ( \mu_0 ) shape</td>
<td>0.0017</td>
</tr>
<tr>
<td>Other detector systematic uncertainties</td>
<td>0.0016</td>
</tr>
<tr>
<td>( Z+\text{jets} ) normalization</td>
<td>0.0009</td>
</tr>
<tr>
<td>Other sources</td>
<td>0.0004</td>
</tr>
<tr>
<td>( B(\tau \rightarrow \mu e \mu \nu) )</td>
<td>0.0023</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.0109</td>
</tr>
<tr>
<td>Data statistics</td>
<td>0.0072</td>
</tr>
<tr>
<td>Total</td>
<td>0.013</td>
</tr>
</tbody>
</table>

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.
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 $\mu_{\text{prompt}}$ and $\mu_{\text{anom}}$ processes can be seen clearly. The $\mu_{\text{prompt}}$ processes dominate at low $|d_{\text{ch}}|$, whereas $\mu_{\text{anom}}$ dominates at high $|d_{\text{ch}}|$. The $\mu_{\text{had}}$ background is also important at high $|d_{\text{ch}}|$, but contributes most significantly at low $p_T^\tau$.

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 $\tau \to \mu \tau$, 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 $|d_{\text{ch}}|$ 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 $\pm$ 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.

Received: 28 July 2020; Accepted: 30 March 2021; Published online: 5 July 2021

References

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 \(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}\).

The beamline is the central (x,y) axis of the luminous region. The transverse impact parameter, \(d_s\), 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 \(d_s\) 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\(^{46-48}\) generator interfaced to the PYTHIA\(^{8-47}\) parton shower and hadronization model (more details are available in ref. \(^{48}\)). The decays of bottom and charm hadrons are important for backgrounds in the analysis and were modelled using theEvtGen\(^{49}\) program. The \(\tau\) and single-top processes were normalized to the inclusive cross-section measurement of the highest available precision\(^{49-54}\) and the \(t\) events additionally have a differential reweighting applied to match the next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) top quark production calculation\(^{72,73}\). For single-top-quark production in the \(t\) channel, a diagram removal scheme\(^{60}\) was used to remove overlap with \(t\) events. The \(W + t\) and \(t + Z\) events were simulated with Sherpa and MadGraph5_AMC@NLO\(^{76,77}\) interfaced with Pythia8, respectively. The background processes were modelled using the EvtGen\(^{49}\) program. The \(W\) and \(t\) events were normalized to the high \(\sqrt{s}\) data. To model the observed data distribution of pile-up from addition collisions in the simulation, this uncertainty is split into two components corresponding to the tail, \(d_s > 0.05\) mm, and core, \(d_s \leq 0.05\) mm, to prevent the data from constraining the uncertainty by using the full \(d_s\) distribution.

The breakdown of uncertainties contributing to the \(p_{t,h}\) background control region normalization in the \(e-\mu\) (\(\mu-\mu\)) 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% (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 Monte Carlo event generator for the \(p_{t,h}\) 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 variations\(^{46}\) of the strong coupling \((\alpha_s)\)
- Missing higher-order QCD corrections: factorization and renormalization scales simultaneously varied up and down by a factor of two
- Resummation scale uncertainty: POWHEG \(\mu_R, \mu_F\) parameter varied from 1.5 to 3 \(\mu_R, \mu_F\) (symmetrized)
- Parton shower and hadronization model: Herwig7\(^{57-59}\), HTUE tune\(^{60}\) (symmetrized)
- Higher-order correction to top \(p_T\) spectrum: not applying the NNLO top \(p_T\) reweighting\(^{61}\) (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 \(p_{t,h}\) and \(p_{t,h}\) (collectively referred to as ‘signal’) are treated as correlated and the effects on \(p_{t,h}\) are treated separately. The parton shower and hadronization uncertainty is separated into four nuisance parameters: each corresponding to low and middle probe muon \(p_T\) bins used in the fit, and two corresponding to the high \(p_T\) bin where the uncertainty is further separated into components related to normalization and shape differences.

Object identification in ATLAS. Muons are reconstructed using combined fits of inner detector\(^{50-56}\) and muon spectrometer tracks\(^{57}\). They are required to satisfy the ‘medium’ identification criteria of ref. \(^{58}\). 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 \(p_T\) 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 \(p_T > 27.5\) GeV to pass the trigger requirements, while probe muons are required to have \(p_T > 5\) GeV. Both the tag and probe muons are required to have \(|\eta| < 2.5\) and to originate from 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, \(d_s\), 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, to reconstruct muons from in-flight decays of charged kaons and pions.

Electrons are reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters\(^{59}\). They are required to satisfy the ‘tight’ identification criteria of ref. \(^{60}\) and the same strict isolation criteria as applied to muons. Tag electrons are required to have \(p_T > 27\) GeV to pass the trigger requirements and satisfy \(|\eta| < 2.47\), excluding the transition region between the barrel and end-cap calorimeter, \(1.35 < |\eta| < 1.52\). They also must 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\(^{61}\), using the anti-\(k_T\) algorithm\(^{62,63}\) 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\(^{64}\). For jets with \(25 < p_T < 60\) GeV and \(|\eta| < 2.4\), pile-up suppression requirements in the form of a jet vertex tagger\(^{65}\) are applied. Only jets with \(p_T > 25\) GeV and \(|\eta| < 2.3\) are considered in the analysis. To classify jets not containing a b hadron, the 70% efficiency working point of the MV2c10 b-tagging algorithm\(^{66,67}\) is used.

An overlap removal procedure as described in ref. \(^{58}\) 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 \(R(t\bar{t})/\rho\) merit a more detailed discussion, which is provided here.

Owing to differences in the hadronic environment around the lepton between the \(Z\) and \(t\) final states, the coarse binning in \(p_T\) and \(\eta\), which may not be able to encapsulate the full shape information, small biases can exist in the data-driven \(\mu_{syst}\) template distributions. The size of such a possible bias is estimated from the full difference between \(\mu_{syst}\) \(d_s\) templates from \(Z\) and \(t\) in simulation. This uncertainty is split into two components corresponding to the tail, \(d_s > 0.05\) mm, and core, \(d_s \leq 0.05\) mm, to prevent the data from constraining the uncertainty by using the full \(d_s\) distribution.

72. ATLAS Collaboration ATLAS Simulation of Boson Plus Jets Processes in Run 2 (CERN, 2017); https://cds.cern.ch/record/2261937
73. ATLAS Collaboration Multi-Boson Simulation for 13-TeV ATLAS Analyses (CERN, 2017); https://cds.cern.ch/record/2261933
77. ATLAS Collaboration Early Inner Detector Tracking Performance in the 2015 Data at $\sqrt{s} = 13$ TeV (CERN, 2015); https://cds.cern.ch/record/2110140

Acknowledgements
We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN, ANID, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DIPRIF and DUNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IFR, France; SRNSFG, Georgia; BMBF and MPG, Germany; GRST, Greece; BCC and Hong Kong SAR, China; ISF and Benzonetz Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNWF and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; INR, MESTD, Serbia; MSSR, Slovakia; ARRS and MIŽS, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNF and cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States. In addition, individuals and groups have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; ERC; ERDF, Horizon 2020, Marie Sklodowska-Curie Actions and COST, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Iex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; Greece; BFP-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Goren Gustafsson’s Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom) and BNL (United States), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed at https://cds.cern.ch/record/217821.

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.

Additional information
Correspondence and requests for materials should be addressed to G.A. Peer review information Nature Physics thanks Thomas Kuhr and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.
ATLAS Collaboration


1CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France. 2Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA. 3Department of Physics, University of Massachusetts, Amherst, MA, USA. 4CERN, Geneva, Switzerland. 5Illphysikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany. 6Department of Physics, Royal Holloway University of London, Egham, UK. 7Department of Physics, University of Toronto, Toronto, Ontario, Canada. 8Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. 9Department of Physics and Astronomy, University of Sussex, Brighton, UK. 10Raymond and Beverly Sacker School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel. 11Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel. 12High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA. 13INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy. 14ICTP, Trieste, Italy. 15Institut für Physik, Universität Mainz, Mainz, Germany. 16LAPP, Université Grenoble Alpes, Università Savoie Mont Blanc, CNRS/IN2P3, Annecy, France. 17AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland. 18Department of Physics, Northern Illinois University, DeKalb, IL, USA. 19Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany. 20Department of Physics, Bogazici University, Istanbul, Turkey. 21Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland. 22Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK. 23Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA. 24IIJLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France. 25LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France. 26Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands. 27Department of Physics, Alexandria loan Cuza University of Iasi, Iasi, Romania. 28Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisbon, Portugal. 29Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain. 30Joint Institute for Nuclear Research, Dubna, Russia. 31Department of Physics, McGill University, Montreal, Quebec, Canada. 32Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA. 33INFN Sezione di Roma Tor Vergata, Rome, Italy. 34Department of Physics, Roma Tor Vergata, Rome, Italy. 35Faculty of Science, Komazawa University, Komazawa, Tokyo, Japan. 36Fysika Institutionen, Lunds Universitet, Lund, Sweden. 37P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia. 38Instituto de Física, INFF Bologna and Università di Bologna, Bologna, Italy. 39INFN Sezione di Bologna, Bologna, Italy. 40Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada. 41Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania. 42Physics Department, National Technical University of Athens, Zografou, Greece. 43Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands. 44Czech Technical University in Prague, Prague, Czech Republic. 45Institute of Physics, Academia Sinica, Taipei, Taiwan. 46Tomsk State University, Tomsk, Russia. 47INFN Sezione di Milano, Milan, Italy. 48Institute for Fundamental Science, University of Oregon, Eugene, OR, USA. 49School of Physics and Astronomy, University of Birmingham, Birmingham, UK. 50INFN Sezione di Napoli, Naples, Italy. 51Department of Physics, University of Washington, Seattle, WA, USA. 52Department of Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain. 53Department Federal do Rio De Janeiro COPEPE/EE/IF, Rio de Janeiro, Brazil. 54Department of Physics, Oxford University, Oxford, UK. 55Department of Physics, Brandeis University, Waltham, MA, USA. 56Department of Physics, University of Michigan, Ann Arbor, MI, USA. 57Deutsches Elektronen-Synchrotron DESY,
Articles

Department of Physics, University of Adelaide, Adelaide, South Australia, Australia. 192 Department de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal. 193 National Centre for Scientific Research 'Demokritos', Agia Paraskevi, Greece. 194 INFN Sezione di Pavia, Pavia, Italy.

Department de Física e Química, Universidade de Porto, Portugal. 195 Physics Department, University of Texas at Dallas, Richardson, TX, USA. 196 Departamento de Física, Universidade de Coimbra, Coimbra, Portugal. 197 INFN-INFN, Trento, Italy. 198 Università degli Studi di Trento, Trento, Italy. 199 Graduate School of Science and Technology, University of Tokyo, Tokyo, Japan. 200 Nagasaki Institute of Applied Science, Nagasaki, Japan. 201 Enrico Fermi Institute, University of Chicago, Chicago, IL, USA. 202 Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre ‘Kurchatov Institute’, Moscow, Russia. 203 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland. 204 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov State University, Moscow, Russia. 205 Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy.

Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco. 206 West University in Timisoara, Timisoara, Romania. 207 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA. 208 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria. 209 Division of Physics and Astronomy, California Institute of Technology, Pasadena, CA, USA. 210 University of California, Los Angeles, CA, USA. 211 U-form, Osaka University, Osaka, Japan. 212 University of Tokyo, Tokyo, Japan. 213 Graduate School of Science and Technology, Tohoku University, Sendai, Japan. 214 Graduate School of Science, Kyoto University, Kyoto, Japan. 215 Graduate School of Science, Kobe University, Kobe, Japan. 216 Graduate School of Science, Osaka University, Osaka, Japan. 217 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus. 218 Physics Department, SUNY Albany, Albany, NY, USA. 219 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia. 220 Waseda University, Tokyo, Japan. 221 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan.

Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. 222 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. 223 Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey. 224 Department of Physics, Universidad Andres Bello, Santiago, Chile.

Instituto de Altas Investigaciones, Universidad de Tarapacá, Arica, Chile. 225 Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong. 226 Department of Physics, University of Hong Kong, Hong Kong, China. 227 Physics Department, Royal Institute of Technology, Stockholm, Sweden. 228 Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal. 229 Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia. 230 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan. 231 Transilvania University of Brașov, Brașov, Romania. 232 National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania. 233 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France. 234 Department of Physics, Universidad Nacional de Colombia, Bogotá, Colombia. 235 Louisiana Tech University, Ruston, LA, USA. 236 Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey. 237 Kyoto University of Education, Kyoto, Japan. 238 Present address: Department of Physics, University of Fribourg, Fribourg, Switzerland. 239 Present address: Departamento de Física de la Universidad Autónoma de Barcelona, Barcelona, Spain. 240 Present address: Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia. 241 Present address: Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel. 242 Present address: Università di Napoli Parthenope, Naples, Italy. 243 Present address: Institute of Particle Physics (IPP), Victoria, British Columbia, Canada. 244 Present address: Department of Physics, St Petersburg State Polytechnical University, St Petersburg, Russia. 245 Present address: Borough of Manhattan Community College, City University of New York, New York, NY, USA. 246 Present address: Department of Physics, California State University, Fresno, CA, USA. 247 Present address: Department of Financial and Management Engineering, University of the Aegean, Chios, Greece. 248 Present address: Centro Studi e Ricerche Enrico Fermi, Rome, Italy. 249 Present address: Department of Physics, California State University, East Bay, CA, USA. 250 Present address: Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. 251 Present address: Graduate School of Science, Osaka University, Osaka, Japan. 252 Present address: Physicalisch Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. 253 Present address: University of Chinese Academy of Sciences (UCAS), Beijing, China. 254 Present address: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. 255 Present address: Institute for Mathematics, Astrophysics and Particle Physics, University of Chinese Academy of Sciences, Beijing, China. 256 Present address: National Centre for Scientific Research 'Demokritos', Agia Paraskevi, Greece. 257 Present address: Joint Institute for Nuclear Research, Dubna, Russia. 258 Present address: Hellenic Open University, Patras, Greece. 259 Present address: CERN, Geneva, Switzerland. 260 Present address: Joint Institute for Nuclear Research, Dubna, Russia. 261 Present address: The City College of New York, New York, NY, USA. 262 Present address: Division of Physics, University of Athens, Athens, Greece. 263 Present address: Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France. 264 Present address: Centro Studi e Ricerche Enrico Fermi, Rome, Italy. 265 Present address: Department of Physics, California State University, East Bay, CA, USA. 266 Present address: Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. 267 Present address: Graduate School of Science, Osaka University, Osaka, Japan. 268 Present address: Physicalisch Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. 269 Present address: University of Chinese Academy of Sciences (UCAS), Beijing, China. 270 Present address: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. 271 Present address: Institute for Mathematics, Astrophysics and Particle Physics, University of Chinese Academy of Sciences, Beijing, China. 272 Present address: Joint Institute for Nuclear Research, Dubna, Russia. 273 Present address: Hellenic Open University, Patras, Greece. 274 Present address: The City College of New York, New York, NY, USA. 275 Present address: Division of Physics, California State University, East Bay, CA, USA. 276 Present address: Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. 277 Present address: Graduate School of Science, Osaka University, Osaka, Japan. 278 Present address: Physicalisch Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. 279 Present address: University of Chinese Academy of Sciences (UCAS), Beijing, China. 280 Present address: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. 281 Present address: Institute for Mathematics, Astrophysics and Particle Physics, University of Chinese Academy of Sciences, Beijing, China. 282 Present address: Joint Institute for Nuclear Research, Dubna, Russia. 283 Present address: Hellenic Open University, Patras, Greece. 284 Present address: The City College of New York, New York, NY, USA. 285 Present address: Division of Physics, California State University, East Bay, CA, USA. 286 Present address: Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. 287 Present address: Graduate School of Science, Osaka University, Osaka, Japan. 288 Present address: Physicalisch Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. 289 Present address: University of Chinese Academy of Sciences (UCAS), Beijing, China. 290 Present address: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. 291 Present address: Institute for Mathematics, Astrophysics and Particle Physics, University of Chinese Academy of Sciences, Beijing, China. 292 Present address: Joint Institute for Nuclear Research, Dubna, Russia. 293 Present address: Hellenic Open University, Patras, Greece. 294 Present address: The City College of New York, New York, NY, USA. 295 Present address: Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy. 296 Present address: Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia. 297 Present address: Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany. 298 Present address: CPPM, Aix-Marseille Université, Marseille, France. 299 Present address: National Research Nuclear University MEPhI, Moscow, Russia. 300 Present address: Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary. 301 Present address: Giresun University, Faculty of Engineering, Giresun, Turkey. 302 Deceased: F. Bauer, O. Igonkina, D. Lellouch, A. Ouraou, V. Vrba, S. Zimmermann. 303 E-mail: atlas.publications@cern.ch.

www.nature.com/naturephysics