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 $0.992 \pm 0.013$ [$\pm 0.007$(stat) $\pm 0.011$(syst)] and is in agreement with the hypothesis of universal lepton couplings as postulated in the standard model. This is the only such measurement from the Large Hadron Collider, so far, and obtains twice the precision of previous measurements.

Experimental set-up

The ATLAS experiment at the LHC is a multi-purpose particle detector with nearly hermetic coverage for recording particles produced in LHC collisions through a combination of particle identification 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 $|\eta| < 2.5$. 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.
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\cite{bib1,bib2,bib3} requiring a single high-$p_T$ isolated electron or muon. After the application of data-quality requirements\cite{bib4}, the data sample corresponds to an integrated luminosity of 139 fb$^{-1}$ with an uncertainty of 1.7%\cite{bib5}, obtained using the LUCID-2 detector\cite{bib6} 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\cite{bib7}. 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 $\mu_{\text{prompt}}$, to those that come from the process $W \rightarrow \mu \nu$, referred to as $\mu_{\text{non-prompt}}$. 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 $|d_T^\mu|$ 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 $x$–$y$ 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 $|p_T^\mu|$ 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. 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 ±1σ systematic uncertainties on the prediction, with the constraints from the analysis fit applied.
Additionally, using this calibration region, the Gaussian part of the $|d^0_t|$ resolution is estimated in data and simulation by fitting the $|d^0_t|$ distribution in the range $|d^0_t| < 0.02$ mm. For $p_T^\mu = 20$ GeV, the resolution is $\sim 14 \mu$m. Corrections to account for differences in the resolution of the detector between the data and simulation are applied to the muons from $\tau$ decays and hadron decays. For the range of $|d^0_t|$ values considered in this analysis, $|d^0_t| < 0.5$ 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 $|d^0_t|$. 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 $1.36 \pm 0.01$. 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 $|d^0_t|$ 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 $\pi$ and $K$. This occurs primarily in $t\bar{t}$ events where one $W$ boson decays leptically 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 $b$ 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 $p_T^\mu$, $t\bar{t} + V$, and $t\bar{t}$, which occurs through electron charge misidentification in the $\mu$--$\mu$ 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 $|d^0_t|$ 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 $\ell\ell$ 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 $R(\tau/\mu)$, $\mu_{\text{hadron}}$ from top quark decays (Prompt $\mu$ (top)) and $\mu_{\text{hadron}}$ from top decays ($\tau \rightarrow \mu$ (top)). The main backgrounds are also shown: events with a $\mu_{\text{hadron}}$ (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 $\ell\ell + V$ production. The chi-squared statistic values range from 3.5 to 10.2 for eight degrees of freedom for the distributions.
Fit configuration and systematic uncertainties

A two-dimensional profile likelihood fit is performed in the \( |d_{\mu}^0| \) and \( p_T^\mu \) distributions. The bin boundaries were chosen to provide the best separation between the different \( \mu_{\text{prompt}} \mu_{(\tau\rightarrow\mu)} \) 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 \( |d_{\mu}^0| \) (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 \( \mu_{\text{prompt}} \) 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 \( \tau \rightarrow \mu \) 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 \( \vec{t} \) and \( Wt \) processes contain two \( W \) bosons, both are treated as signal. Two fit parameters are allowed to float freely: \( R(\tau/\mu) \) and \( k(\vec{t}) \). The \( k(\vec{t}) \) parameter is a constant scaling factor applied to the normalization of both the \( \mu_{\text{prompt}} \) and \( \mu_{(\tau\rightarrow\mu)} \) 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 \( \vec{t} \) 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 \( \mu_{\text{prompt}} \) 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 are described in the following and further details are provided in the Methods.

An uncertainty associated with the data-driven templates for the \( |d_{\mu}^0| \) 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 \( \mu_{\text{prompt}} \mu_{(\tau\rightarrow\mu)} \) and \( \mu_{\text{had}} \) distributions due to the modelling of the simulated \( \vec{t} \) samples are derived. The combined yield of the \( \mu_{\text{prompt}} \) and \( \mu_{(\tau\rightarrow\mu)} \) templates is allowed to float in the fit, but changes in generator configuration choices can result in modifications to the muon \( p_T^\mu \) and subsequently the \( |d_{\mu}^0| \) distribution, such that there can be relative changes in the \( \mu_{\text{prompt}} \) and \( \mu_{(\tau\rightarrow\mu)} \) 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 \( |d_{\mu}^0| \) 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 \( (W \rightarrow \mu\mu) \) data and simulation using a tag and probe method\(^{36}\). Corrections are applied to the simulated samples to account for the differences between data and simulation, and the uncertainties on these correction factors are included in the analysis. Additionally, an uncertainty due to the modelling of pile-up is obtained by reweighting the simulated events\(^{39}\).

**Extraction of \( R(\tau/\mu) \)**

Figure 3 shows the differential distributions of \( |d_{\mu}^0| \) 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 ρ_{prompt} and μ_{τ→ντ} processes can be seen clearly. The ρ_{prompt} processes dominate at low |d_{0}^{τ}|, whereas μ_{τ→ντ} dominates at high |d_{0}^{τ}|. The ρ_{had} background is also important at high |d_{0}^{τ}| but contributes most significantly at low p_{T}^{τ}.

The analysis was finalised before looking at the value of R(τ/μ) 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 τ→μτ, 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}^{τ}| distribution, the parton shower and hadronization model uncertainty, and the muon selection uncertainties.

The measured value of R(τ/μ) 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(τ/μ) achieved so far, 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

33. ATLAS Collaboration Luminosity Determination in pp Collisions at √s = 13 TeV using the ATLAS Detector at the LHC (CERN, 2019); https://cds.cern.ch/record/2677054
39. ATLAS Collaboration The Pythia 8.23 Tune Description of ATLAS Minimum Bias and Inelastic Measurements Incorporating the Donnachie–Landshoff Diffractive Model (CERN, 2016); https://cds.cern.ch/record/2206965

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.
© The Author(s) 2021
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 upward. 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 \( \eta = -\ln \tan(θ/2) \). Angular distance is measured in units of \( ΔR = \sqrt{Δr^2 + Δφ^2} \).

The beamline is the central (x-y) axis of the luminous region. The transverse impact parameter, \( |d_0| \), 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 \( |d_0| \) 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 POWHEGBOX46–47 generator interfaced to the PYTHIA8–47 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 theEvtGen47 program. The \( \mathcal{R} \) and single-top processes were normalized to the inclusive cross-section calculation of the highest available precision48–50 and \( \mathcal{R} \) events additionally have a differential reweighting applied to match the next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) top quark production51 calculation. For single-top-quark production in the \( \mathcal{W}t \) channel, the diagram removal scheme52 was used to remove overlap with \( \mathcal{W}t \) production. The \( \mathcal{W}t \) and \( \mathcal{Z}t \) events were simulated with Sherpa and MadGraph5_aMC@NLO61 interfaced with Pythia8, respectively. The background model of uncaptured 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. For single-top-quark production in the \( \mathcal{W}t \) channel, the diagram removal scheme was used to remove overlap with \( \mathcal{W}t \) production. The \( \mathcal{W}t \) and \( \mathcal{Z}t \) events were simulated with Sherpa and MadGraph5_aMC@NLO interfaced with Pythia8, respectively. The background from \( V=W, Z \) events was simulated with the Sherpa generator (more details can be found in refs. 41, 62, 63). All processes were normalized to their highest-order available cross-sections.

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

Object identification in ATLAS. Muons are reconstructed using combined fits of inner detector53–55 and muon spectrometer tracks56. They are required to satisfy the ‘medium’ identification criteria of ref. 57. 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 \( ΔR=0.3 \) and the sum of \( p_T \) calculated from calorimeter energy deposits within a cone of size \( ΔR=0.2 \) around the muons be below certain thresholds. Tag electrons are reconstructed from inner detector tracks matched to clusters in the electromagnetic calorimeter, with at least one of the tracks associated with it. The parton shower and hadronization model: Herwig76–87 interfaced with Pythia8, respectively. The background from \( V=W, Z \) events was simulated with the Sherpa generator (more details can be found in refs. 41, 62, 63). All processes were normalized to their highest-order available cross-sections. Simulated inelastic collisions were overlaid on events in all samples to model the observed data distribution of pile-up from additional collisions in the same and neighbouring bunch crossings.

Data availability

The experimental data that support the findings of this study are available in HEEData 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.

References

46. ATLAS Collaboration ATLAS Pythia 8 Tunes to 7-TeV Data (CERN, 2014); https://cds.cern.ch/record/1966419
48. ATLAS Collaboration Studies on Top-Quark Monte Carlo Modelling for Top-2016 (CERN, 2016); https://cds.cern.ch/record/2216168
52. Bärnreuther, P., Czakon, M. & Mitov, A. Percent-level-precision physics at the tevatron: next-to-next-to-leading order QCD corrections to \( q\bar{q} \rightarrow t\bar{t}X \). Phys. Rev. Lett. 109, 132001 (2012).
76. 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; STScI, Brazil; NSERC, NRC and CFI, Canada; CERN, ANID, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSTMT CR, MPO CR and VSC CR, Czech Republic; DIPRIF and DANSRC, Denmark; IN2P3-CNRS and CEA-DRF/IFRF, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSI, Germany; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNWiN and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR, MESTD, Serbia; MSSR, Slovakia; ARRS and MIZS, 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, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; ERC, ERDF, Horizon 2020, Marie Skłodowska-Curie Actions and COST, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Góran Gustafsson 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/2717821.

**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
