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Letter

Measurement of t-channel single-top-quark production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector

The ATLAS Collaboration ⋆

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ABSTRACT

The observation of the electroweak production of single-top-quarks is made using 255 pb^{-1} of proton-proton collision data recorded at $\sqrt{s} = 5.02$ TeV with the ATLAS detector at the Large Hadron Collider. An event selection is used to identify single-top-quark candidates arising from t-channel production with the top quark decaying semi-leptonically. Events passing the selection are then used to measure the inclusive cross-section for the combined production of single-top-quarks and antiquarks, $\sigma(tq + \bar{t}q)$, and the ratio R_t between these two. They are measured to be $\sigma(tq + \bar{t}q) = 27.1^{+4.4}_{-4.1}(\text{stat.})^{+4.4}_{-3.7}(\text{syst.})$ pb and $R_t = 2.73^{+1.43}_{-0.82}(\text{stat.})^{+1.01}_{-0.29}(\text{syst.})$. The individual single-top-quark (tq) and single-top-antiquark ($\bar{t}q$) production cross-sections are measured to be $\sigma(tq) = 19.8^{+3.9}_{-3.1}(\text{stat.})^{+2.9}_{-2.2}(\text{syst.})$ pb and $\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}(\text{stat.})^{+2.8}_{-1.5}(\text{syst.})$ pb. All measurements are in good agreement with the Standard Model predictions.

1. Introduction

Top quarks can be produced in pairs via the strong interaction or singly via the electroweak interaction at hadron colliders [1]. Single-top-quark production was first observed in anti-proton–proton collisions at the Tevatron [2–4] and since then it has been extensively studied as a window into the properties of the top quark itself [5]. These include studies of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix [4, 6–8], tests of higher-order corrections from quantum chromodynamics (QCD) [9], and constraints on the parton distribution functions (PDF) of the proton [10].

Electroweak theory predicts three primary mechanisms for single-top-quark production in proton–proton (pp) collisions at the Large Hadron Collider (LHC): t-channel, s-channel, and tW (or W-associated) production. The t-channel mechanism for single-top-quark production, shown in Fig. 1, has the largest cross-section of the three mechanisms and also the final-state topology with the highest signal-to-background ratio, due to the presence of a light-quark jet recoiling against the top quark that assists in identifying this topology. The t-channel production cross-section, $\sigma(tq + \bar{t}q)$, was measured by both the ATLAS and CMS collaborations at centre-of-mass energies of $\sqrt{s} = 7$ TeV [11–14], $\sqrt{s} = 8$ TeV [15,16] and $\sqrt{s} = 13$ TeV [17–19].

The observation of t-channel single-top-quark production and a measurement of its cross-section at $\sqrt{s} = 5.02$ TeV is reported using 255 pb^{-1} of pp collision data collected with the ATLAS detector. The analysis includes selection criteria to isolate the t-channel topology from the Standard Model (SM) backgrounds in the leptonic-decay channels of the W boson ($t \to e\nu b$, $t \to \mu\nu b$, and $t \to \tau\nu b$ with leptonic τ-lepton decays). Separate measurements of the single-top-quark final states with a top quark and a top-antiquark are used to measure the CKM matrix element V_{tb}. This measurement at a lower centre-of-mass energy than other proton-proton results provides an independent test of the SM, with different levels of backgrounds and instrumental uncertainties.

The backgrounds arise from the production of W bosons in association with jets (W + jets), top-quark pair ($t\bar{t}$) production, and either misidentified or non-prompt leptons, wherein a jet is mis-reconstructed as an electron, or a heavy-flavour quark that decays into a muon which satisfies the selection criteria. The two subleading single-top-quark production mechanisms, the production of Z bosons in association with jets (Z + jets), and diboson (WW, WZ, and ZZ) processes are additional minor backgrounds. Some of these processes were measured by the ATLAS and CMS collaborations [20–22] at $\sqrt{s} = 5.02$ TeV.

⋆ E-mail address: atlas.publications@cern.ch.

[1] 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 $\eta = -\ln\tan(\theta/2)$. Momentum in the transverse plane is denoted by p_{T}.

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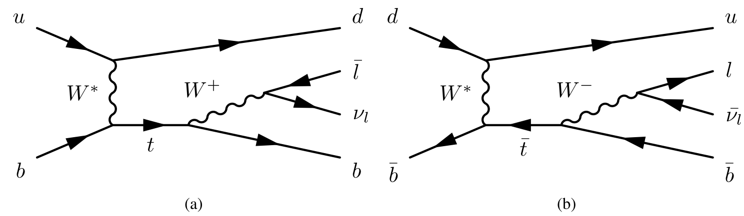


Fig. 1. Feynman diagrams at leading-order in QCD for (a) single-top-quark production and (b) single-top-antiquark production via the t-channel exchange of a virtual W boson (W^*). The diagrams include the leptonic decay of the top quark and top antiquark.

2. The ATLAS detector

The ATLAS detector [23] at the LHC is a multipurpose particle-physics detector with a cylindrical geometry.[1] It consists of an inner tracking detector (ID) surrounded by a 2 T superconducting solenoid, sampling electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets. A two-level trigger system is used to select events for storage.

An extensive software suite [24] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. Events used in this measurement were collected using single-electron or single-muon triggers [25].

3. Event selection

The measurement is performed on 255 pb^{-1} of pp collision data collected at $\sqrt{s} = 5.02$ TeV with the ATLAS detector, after applying data quality requirements [26]. Most triggered events also included signals from additional inelastic pp collisions in the same bunch crossing, referred to as pile-up. This special data sample was taken in November 2017 under low-pile-up conditions where the mean number of inelastic pp collisions per bunch crossing was ≈2 [27]. This analysis follows a measurement of the $t\bar{t}$ cross-section at the same centre-of-mass energy [20] and employs the same algorithms to calibrate the data.

The selected pp interaction vertex is the one with the highest p_T^2 sum of matched tracks with at least two matched tracks required to have a transverse momentum $p_{\mathrm{T}} > 0.5$ GeV. Electron candidates are reconstructed from localised clusters of energy deposits in the EM calorimeter that are matched with tracks found in the ID. Muon candidates are reconstructed by combining and matching tracks reconstructed in the ID with tracks or track segments found in the MS. Electrons (muons) must have $p_{\mathrm{T}} > 18$ GeV and be reconstructed in a pseudorapidity range of $|\eta| < 2.47$ ($|\eta| < 2.5$); electrons in the range of $1.37 < |\eta| < 1.52$ are excluded. To ensure that selected leptons originate from the primary vertex, their tracks are required to have $|d_0/\sigma_{d_0}| < 5$ (3) for electrons (muons) and $|z_0 \sin\theta| < 0.5$ mm for both the lepton flavours. Here d_0 and σ_{d_0} are the transverse impact parameter and its uncertainty, while z_0 is the longitudinal impact parameter. Electrons are required to satisfy the 'medium' likelihood-based identification criterion defined in Ref. [28] while muons must satisfy the 'medium' cut-based identification criterion defined in Ref. [29]. Leptons likely to originate from light-hadron decays or heavy-flavour decays are rejected by applying a 'tight' isolation requirement as defined in Ref. [30]. Particle-flow jets are reconstructed from tracks in the ID and topological clusters of calorimeter energy deposits [31] using the anti-k_t algorithm [32,33] with a radius parameter $R = 0.4$. These jets are calibrated according to the standard calibration used for $\sqrt{s} = 13$ TeV high-pile-up data [34]. An additional correction to the jet-energy scale, of 2%-12%, is derived using the technique of balancing the p_{T} of Z + jet events and applied to data. This additional correction is used to account for the modified calorimeter response in the low-pile-up data sample [20]. Jet candidates are required to have $p_{\mathrm{T}} > 23$ GeV and $|\eta| < 4.0$. Jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ are subject to additional pile-up rejection criteria using a multivariate jet-vertex tagger [35].

Jets originating from long-lived b-hadrons are identified using the DL1r algorithm [36], a multivariate discriminant based on deep-learning techniques using information from track impact parameters and reconstructed secondary vertices. A working point with 60% efficiency for tagging b-quark jets from top-quark decays in simulated $t\bar{t}$ events is used. At this working point, the tagger has rejection factors of 30 against charm jets and 1200 against light-quark jets. Jets passing this requirement are denoted as b-tagged jets.

The missing transverse momentum, whose magnitude is denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$, is reconstructed as the negative vector sum of the transverse momenta of all identified physics objects (electrons, muons, and jets), together with a 'soft term' built from all tracks matched with the reconstructed primary vertex but not with any of the identified physics objects [37].

Selected events are required to have exactly one electron or muon candidate, and exactly two jets. Exactly one of the jets must be b-tagged and be in the central region $|\eta| < 2.5$. Since the spectator-quark jet tends to be produced in the forward direction in the t-channel process, the pseudorapidity of the untagged jet must satisfy $1.5 < |\eta| < 4.0$. To reduce contributions from the $t\bar{t}$ process, the pseudorapidity separation between the untagged jet and the b-tagged jet is required to be >1.5. A W boson candidate is identified by the electron or muon candidate and the missing transverse momentum. To suppress contributions from misidentified leptons, the following cuts on $E_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse mass of the W boson[2] ($m_{\mathrm{T}}^{\mathrm{W}}$) are applied: $m_{\mathrm{T}}^{\mathrm{W}} > 35$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 15$ GeV, and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 70$ GeV. To increase the purity of the signal events, the H_{T} is required to be greater than 185 GeV, where H_{T} is defined as the scalar sum of the p_{T} of the jets, the p_{T} of the lepton, and $E_{\mathrm{T}}^{\mathrm{miss}}$.

A top-quark candidate is reconstructed in each event by combining the b-tagged jet with a W boson candidate. The latter is kinematically reconstructed by imposing the W boson mass as a kinematic constraint on the sum of the electron or muon candidate and the missing transverse momentum, leading to a quadratic equation in the longitudinal neutrino momentum, $p_{\nu,z}$. When two solutions are found, the one that gives a reconstructed top-quark mass closest to the on-shell mass (172.5 GeV) is chosen. For complex solutions only the real component is considered, which results in a reconstructed mass greater than the W boson mass. This phenomena is observed in approximately 30% of the events. To further suppress contributions from processes not involving top quarks, the invariant mass of the lepton and the b-tagged jet must be <165 GeV, the invariant mass of the reconstructed W boson must be <102 GeV, and the invariant mass of the reconstructed top quark must be between 140 GeV and 225 GeV.

4. Modelling and theoretical predictions

The MCFM program [38–40] employing the NNPDF3.0NLO PDFs [41] was used to calculate predictions for the single-top-quark (tq)

[2] $m_{\mathrm{T}}^{\mathrm{W}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\phi)}$, where p_{T}^{ℓ} is the transverse momentum of the charged lepton and ϕ is the opening azimuthal angle between the charged lepton and the missing transverse momentum.

and single-top-antiquark ($\bar{t}q$) production cross-sections in the t-channel at next-to-next-to-leading-order (NNLO) in QCD for pp collisions at $\sqrt{s} = 5.02$ TeV. The predicted values are $\sigma(tq) = 20.3^{+0.5}_{-0.4}$ pb, $\sigma(\bar{t}q) = 10.0^{+0.2}_{-0.3}$ pb, $\sigma(tq + \bar{t}q) = 30.3^{+0.7}_{-0.5}$ pb. The ratio of $\sigma(tq)$ to $\sigma(\bar{t}q)$, R_t is predicted to be $R_t = 2.03^{+0.06}_{-0.07}$. All predictions are assuming a top-quark mass of 172.5 GeV. The quoted uncertainties include contributions from the choice of renormalisation scale μ_r and the factorisation scale μ_f, the uncertainty in the PDFs, and uncertainty in the value of α_s.

Monte Carlo (MC) simulated samples are used to model the single-top-quark t-channel signal process and contributions from other physics processes with prompt leptons. The signal was simulated using the next-to-leading-order (NLO) in QCD MC event generator Powheg Box v2 [42] with the four-flavour scheme. The parton showering, hadronisation, and the underlying event was modelled using the Pythia 8.2 [43] program with the A14 tune [44]. The Powheg Box v2 program also was used to simulate $t\bar{t}$, single-top-quark s- and tW-channel backgrounds. All these samples use Pythia 8.2 with the NNPDF3.0nlo PDFs and the A14 tune as the parton-shower and hadronisation models. The $t\bar{t}$ background is normalised using an NNLO cross-section, while the tW background is normalised using an approximate NNLO cross-section including the resummation of next-to-next-to-leading logarithmic soft-gluon terms [45,46]. The s-channel sample is normalised to the generator-level NLO cross-section prediction.

The $Z+\text{jets}$ and $W+\text{jets}$ events were simulated with the Sherpa 2.2 generator [47] using NLO matrix elements with up to two partons, and leading-order (LO) matrix elements for up to four partons, and normalised using an NNLO cross-section prediction [48]. The NNPDF3.0nnlo PDF sets [49] were used for all $Z+\text{jets}$ and $W+\text{jets}$ simulated samples. The smaller backgrounds from diboson production with additional jets were simulated using the Sherpa 2.1 generator with the CT10 PDF set [50].

All generated events underwent a full simulation of the ATLAS detector response based on the Geant4 [51] framework. The effects of pile-up are included in the simulation. To improve the agreement with the response observed in data, small corrections derived from comparisons of data and simulation at both $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV were applied as scale factors to the simulated lepton-trigger and lepton-reconstruction efficiencies.

The backgrounds arising from the non-prompt and misidentified leptons were determined using the 'matrix method' technique [52]. Events were selected using looser isolation or identification requirements for the lepton and were then weighted according to the efficiencies for both the prompt and background (misidentified and non-prompt) leptons to pass the tighter baseline selection. The method was validated by comparing predictions with data in dedicated validation regions with a larger fraction of misidentified-lepton candidates than expected in the analysis regions. Good agreement between data and the prediction in these validation regions was found.

5. Signal and cross-section extraction

Boosted decision trees (BDT) are used to enhance the separation between signal and background. A single BDT is trained using nine input variables that include information about object kinematics, variables based on combinations of four-vectors, and the global event topology. The BDT is trained with the XGBoost [53] package using MC signal, MC background, and the data-driven misidentified-lepton background events. The variables with the highest discriminating power between signal and background are the total scalar sum of the transverse momentum from all objects in an event (H_T), and the magnitude of the p_T difference between the reconstructed W boson and the four-vector sum of the untagged and b-tagged jet ($|\Delta p_T(W, ub)|$).

A three-fold cross-validation procedure is used to produce the final discriminant that is calculated for the observed data and the predictions. The sample is divided into three subsamples while the training is performed on a pair of the subsamples and tested against the third. The procedure is iterated with three different pairings to produce a combined BDT discriminant, which is applied to the data events. A binned profile-likelihood fit of the sum of the BDT response distribution for signal and background MC samples to the observed BDT response distribution is performed.

The $\sigma(tq)$ and $\sigma(\bar{t}q)$ cross-sections are determined by dividing the event sample into a top-quark and top-antiquark subsample defined by the charge of the reconstructed lepton, ℓ^++jets and ℓ^-+jets, respectively. These cross-sections are parameterised as functions of $\sigma(tq + \bar{t}q)$ and R_t, and are determined by the fit to the observed BDT distributions in these two subsamples. The H_T and $|\Delta p_T(W, ub)|$ distributions for the inclusive ℓ+jets sample (the sum of the ℓ^++jets and ℓ^-+jets regions) are shown in Fig. 2, along with the predictions from the signal and background model. The predicted distributions show the signal assuming the SM single-top-quark t-channel production cross-section and the estimated backgrounds for the two subsamples before the fit is performed (pre-fit). The predicted shapes of the distributions for this variable and the others used in the analysis are found to be in good agreement with the observed distributions.

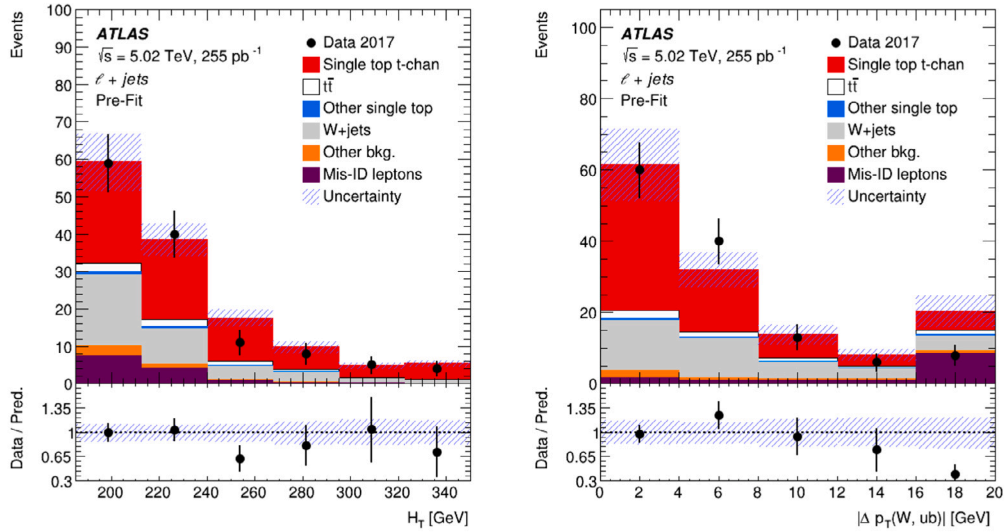
6. Systematic uncertainties

Systematic uncertainties are included in the likelihood fit as nuisance parameters constrained by Gaussian probability density functions. Correlations between systematic uncertainties arising from common sources are maintained across processes and bins in the two regions.

Uncertainties arising from the modelling of signal- and background-related processes are evaluated using alternative MC samples. The $tq + \bar{t}q$ signal has uncertainties arising from the matrix-element matching, the parton-shower and hadronisation model, initial and final-state radiation (ISR and FSR), the μ_r and μ_f scales in the matrix element, and the proton PDFs [44,54]. Two alternative t-channel samples were used to evaluate the matching uncertainty and uncertainties in the parton-shower model: one was generated using the nominal matrix-element model and the pTHard parameter in Pythia 8 changed from zero to one, and the second generated using the Powheg+Herwig 7.1.6 generator.

The $W+\text{jets}$ modelling uncertainties are evaluated by first splitting the MC generated $W+\text{jets}$ background into three categories $W + \geq 1b$, $W + \geq 1c$, and $W + \geq 1l$ (light quarks or gluons) based on the flavour of additional jets in the event, with fractions in each category of 57%, 39%, and 4%, respectively. The uncertainty in each fraction is calculated by adding in quadrature a 24% uncertainty for each successive jet in the event using Berends scaling [55]. Thus, a conservative $W+\text{jets}$ normalisation uncertainty of 34% is used for all categories of $W+\text{jets}$ background in lieu of generator comparisons since alternate MC event samples were not available at $\sqrt{s} = 5.02$ TeV. The μ_r and μ_f scales are varied by factors of 1/2 and 2 and an envelope built from six possible variations is used to estimate additional shape uncertainties for the three categories of $W+\text{jets}$ background.

The uncertainty in the cross-section of the $t\bar{t}$ background is taken to be $^{+7.5}_{-7.7}$% [45,46], while modelling uncertainties are estimated by using the techniques in Ref. [20]. Uncertainties in the cross-sections for the tW and s-channel single-top-quark background processes are taken to be $^{+5.6}_{-5.9}$% and 9.5%, respectively [56,57]. Uncertainties related to parton-shower, modelling of ISR and FSR, and the μ_r and μ_f scales for these three background processes are included in the fit. The PDF uncertainties are also included for the $t\bar{t}$ background. A conservative 50% uncertainty in the cross-section, acceptance, and modelling of the $Z+\text{jets}$ and diboson backgrounds is applied [38]. The fit also includes a 50% uncertainty in the normalisation of the misidentified-lepton background estimate that is determined by comparing different parameterisations and selections for extracting the lepton efficiencies used in the matrix method. The uncertainty is separated according to the flavour of the misidentified lepton.



(a) (b)

Fig. 2. The pre-fit (a) H_T and (b) $|\Delta p_T(W, ub)|$ distributions for data (dots) in the inclusive ℓ+jets channel. The MC simulation of the signal (red histograms) and various backgrounds (represented by histograms of different colours) are also included. The error bars on the dots represent the statistical uncertainty on the data while the blue cross-hatched lines correspond to the total uncertainties on the prediction. The lower panels show the ratio of the data and the prediction, along with the uncertainty in the ratio. The last bin includes any event overflows. The χ^2/degrees of freedom are evaluated to be 2.5/6 for (a) and 5.9/5 for (b).

Instrumental systematic uncertainties related to the lepton trigger efficiency [58,59], reconstruction, isolation and identification [28,29,60], lepton energy scale and resolution [61], and jet-energy scale and resolution [34] are measured in the $\sqrt{s} = 5.02$ TeV data sample or taken from high-pile-up $\sqrt{s} = 13$ TeV data with additional uncertainties to account for the extrapolation to the low-pile-up $\sqrt{s} = 5.02$ TeV data. Due to the additional correction to the jet-energy scale specific to this low-pile-up data sample, statistical and modelling uncertainties of 1%–2% on the jet-energy scale arising from the correction are incorporated into the systematic uncertainties in the fit. The uncertainty on the b-tagging efficiency is measured to be $\sim 1\%$ [36]. Additional uncertainties arise from jet-vertex tagging [35] and modelling of $E_\mathrm{T}^\mathrm{miss}$ [37]. The uncertainty in the integrated luminosity is 1.0% and the uncertainty in the beam energy is negligible.

7. Results

The results of the profile likelihood fit are $\sigma(tq + \bar{t}q) = 27.1^{+4.4}_{-4.1}$ (stat.) $^{+4.4}_{-3.7}$ (syst.) pb and $R_t = 2.73^{+1.43}_{-0.82}$ (stat.) $^{+1.01}_{-0.29}$ (syst.). The Pearson correlation coefficient between $\sigma(tq + \bar{t}q)$ and R_t is measured to be −30% and all other correlations are found to be small. Table 1 shows the fitted signal- and background-event yields (post-fit) and the observed yield in the ℓ^++jets and ℓ^-+jets regions. The fit to the BDT response distributions is shown in Fig. 3. The pulls of all nuisance parameters in the fit are found to be within 0.2 standard deviations of their input values.

Using the asymptotic approximation [62], the background-only hypothesis is rejected with an observed (expected) significance of 6.1 (6.4) standard deviations.

The statistical uncertainty from the sample size is the largest contribution to the total uncertainty in the single-top-quark t-channel production cross-section, followed by a 8.5% uncertainty contribution from signal-modelling and a 6.3% contribution from modelling uncertainties in the misidentified-lepton background. The signal-modelling uncertainty is dominated by the uncertainty in the choice of parton-shower and hadronisation models. Table 2 shows the breakdown of the sources of uncertainty in the cross-section and cross-section ratio measurements. The squared uncertainties are calculated by fixing the set of nuisance parameters corresponding to a category, repeating the fit, and taking a difference between the squares of the resulting uncertainty and the total uncertainty of the nominal fit. The total uncertainty is the sum in quadrature of the total systematic uncertainty and the data's statistical uncertainty.

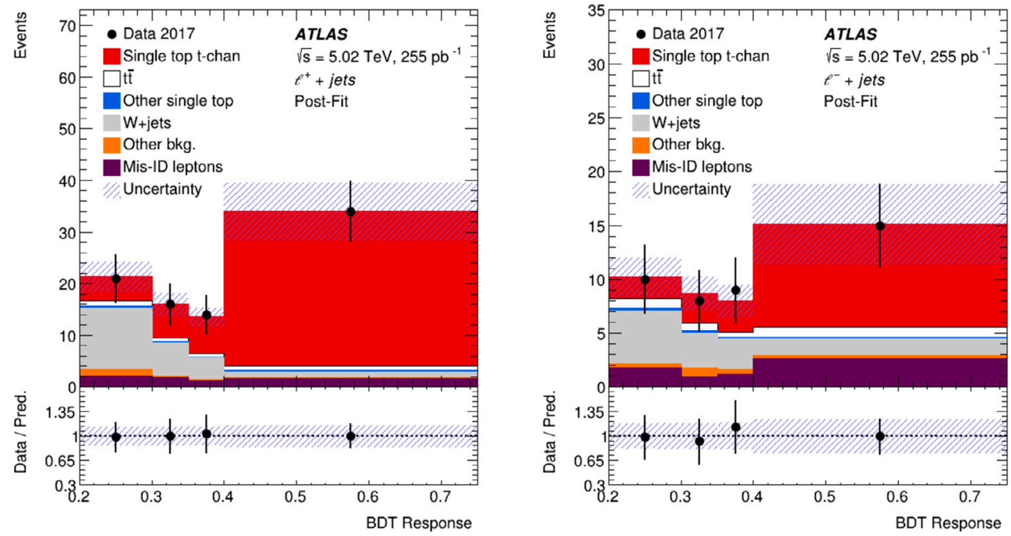
Table 1
Number of post-fit signal, background and observed data events in the ℓ^++jets and ℓ^-+jets regions. The 'Other single top' category contains the tW associated production and s-channel contributions. The uncertainties in the signal and background yields include the statistical uncertainties, all systematic uncertainties, and the correlations between them. The uncertainty in the total prediction includes correlations between all systematic uncertainties and thus does not equal the sum in quadrature from the individual components. In this table, the uncertainties have been symmetrised, but full asymmetric uncertainties are used to obtain the final results.

Source	Number of events	
	ℓ^++jets	ℓ^-+jets
$tq + \bar{t}q$	49 ± 9	17 ± 8
W + jets	23 ± 5	12 ± 3
Misidentified leptons	7 ± 3	7 ± 3
$t\bar{t}$	3 ± 0.5	3 ± 0.5
Z + jets and diboson	2 ± 1	2 ± 1
Other single-top-quark production	1 ± 0.2	1 ± 0.5
Total predicted	85 ± 9	42 ± 7
Data	85	42

Fig. 4 presents a summary of t-channel single-top-quark cross-section measurements by the ATLAS Collaboration as a function of the centre-of-mass energy and the measurement at $\sqrt{s} = 5.02$ TeV. The NLO prediction from the MCFM MC generator is compared with the measured cross-sections and describes well the evolution of the single-top-quark production cross-section in the t-channel as a function of $\sqrt{s}$.

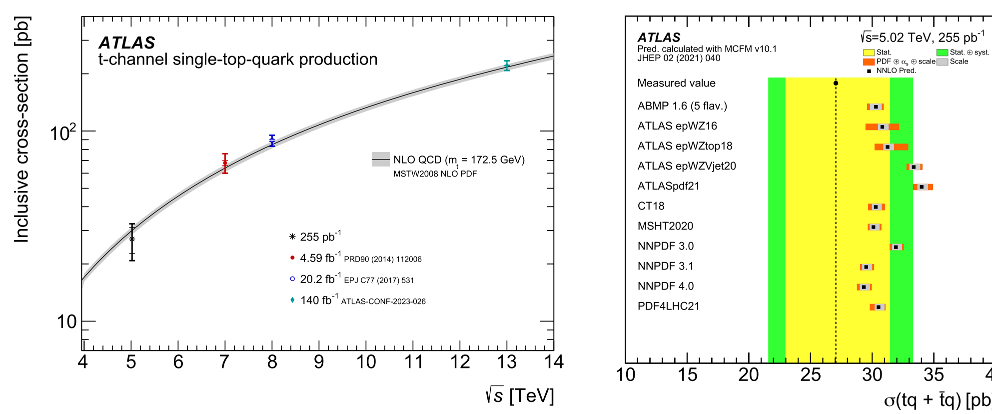
From the fitted ratio and the total cross-section, the individual single-top-quark and single-top-antiquark cross-sections are $\sigma(tq) = 19.8^{+3.9}_{-3.1}$ (stat.) $^{+2.9}_{-2.2}$ (syst.) pb and $\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}$ (stat.) $^{+2.8}_{-1.5}$ (syst.) pb.

The t-channel single-top-quark production cross-section depends on $f_\mathrm{LV}^2 \cdot |V_{tb}|^2$, where f_LV is a left-handed form factor that is unity in the



(a) (b)

Fig. 3. The post-fit BDT response distribution for data (dots) in the (a) ℓ^++jets and (b) ℓ^-+jets channels. The MC simulation of the signal (red histograms) and various backgrounds (represented by histograms of different colours) are also included. The error bars on the dots represent the statistical uncertainty on the data while the blue cross-hatched lines correspond to the total uncertainties on the prediction. The lower panels show the ratio of the data and the prediction, along with the uncertainty in the ratio. Bins with BDT response values outside of the bins shown are empty.



(a) (b)

Fig. 4. Summary of (a) ATLAS measurements of the t-channel single-top-quark production cross-sections as a function of the centre-of mass energy and (b) the measured $\sigma(tq+\bar{t}q)$ at $\sqrt{s}=5.02$ TeV. In (a), the measurements are compared with theoretical calculations at NLO in QCD [56,57]. In (b), the dashed line and the dot show the measured value, the yellow band displays the statistical uncertainty, and the green band displays the total uncertainty on the measurement. For comparison, the predictions of MCFM based on different PDFs are included. The gray (orange) band represents the uncertainty on the predictions arising from the scale variations (scale, PDF and α_s variations added in quadrature).

SM and V_{tb} is a component of the CKM matrix [8]. By assuming that the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ are much smaller than $|V_{tb}|$ and that the Wtb vertex is left-handed, the measured cross-section gives $f_{\mathrm{LV}} \cdot |V_{tb}| = 0.94^{+0.11}_{-0.10}$. The experimental uncertainties in the measured $\sigma(tq+\bar{t}q)$ and the uncertainties in the predicted $\sigma(tq+\bar{t}q)$ arising from scale variations, choice of PDF, α_s, and m_t dependence are all summed in quadrature.

8. Conclusions

The single-top-quark t-channel production cross-section is measured at $\sqrt{s}=5.02$ TeV using pp data collected with the ATLAS detector corresponding to an integrated luminosity of 255 pb^{-1}. The analysis is performed by selecting semileptonic decays of the top quark with exactly two jets in the final state, one of which is required to be b-tagged. After performing a profile maximum-likelihood fit to the BDT discriminant distributions in the ℓ^++jets and ℓ^-+jets channels, the combined single-top-quark and single-top-antiquark production cross-section in the t-channel is $27.1^{+4.4}_{-4.1}$ (stat.) $^{+4.4}_{-3.7}$ (syst.) pb.

This measurement of single-top-quark production at $\sqrt{s}=5.02$ TeV is in good agreement with the SM prediction. Although its uncertainty is four times larger than measurements at higher centre-of-mass energies, it provides another independent test of the SM predictions.

The ratio of the single-top-quark and single-top-antiquark production cross-sections is measured to be $R_t = 2.73^{+1.43}_{-0.82}$ (stat.) $^{+1.01}_{-0.29}$ (syst.) and is also in good agreement with the SM. The observed individual single-top-quark and single-top-antiquark production cross-sections are $\sigma(tq) = 19.8^{+3.9}_{-3.1}$ (stat.) $^{+2.9}_{-2.2}$ (syst.) pb and $\sigma(\bar{t}q) = 7.3^{+3.2}_{-2.1}$ (stat.) $^{+2.8}_{-1.5}$ (syst.) pb. Finally, the product of the left-handed form factor and V_{tb} extracted from the cross-section measurement at $\sqrt{s}=5.02$ TeV is $0.94^{+0.11}_{-0.10}$.

Table 2
Sources of uncertainty for measurements of $\sigma(tq+\bar{t}q)$ and R_t at $\sqrt{s}$ = 5.02 TeV. The systematic uncertainties for both the values do not add up in quadrature to the total systematic uncertainty because of correlations in the fit parameters. In this table, the uncertainties have been symmetrised, but full asymmetric uncertainties are used to obtain the final results.

Category	$\delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$[%]	$\delta R_t/R_t$[%]
Single-top quark signal modelling	8.6	4.1
Parton distribution functions	0.5	0.8
Misidentified leptons background	6.3	11.1
$W+\geq 1b$ jets modelling	3.9	4.4
$W+\geq 1c$ jets modelling	2.7	3.4
Z+jets normalisation	1.1	2.1
$t\bar{t}$ modelling	0.8	1.2
Single-top quark background modelling	0.6	2.1
$W+\geq 1$ light jets modelling	0.3	0.4
Diboson normalisation	0.1	0.3
Jet energy resolution	4.6	7.8
$\sqrt{s}=5.02$ TeV JES correction	4.4	5.1
Jet energy scale	4.0	5.3
Flavour tagging	2.0	1.3
Electron reconstruction	1.4	0.5
Muon reconstruction	1.3	0.7
Integrated luminosity	1.3	0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.6	2.4
Jet-vertex tagging	0.07	0.05
Simulation's statistical uncertainty	2.3	6.5
Data's statistical uncertainty	16	38
Total systematic uncertainty	15	18
Total uncertainty	21	42

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tikhonov [37], S. Timoshenko [37], D. Timoshyn [133], E.X.L. Ting [1], P. Tipton [172], S.H. Tlou [33g], A. Tnourji [40], K. Todome [154], S. Todorova-Nova [133], S. Todt [50], M. Togawa [84], J. Tojo [89], S. Tokár [28a], K. Tokushuku [84], O. Toldaiev [68], R. Tombs [32], M. Tomoto [84,111], L. Tompkins [143,n], K.W. Topolnicki [86b], E. Torrence [123], H. Torres [102,aa], E. Torró Pastor [163], M. Toscani [30], C. Tosciri [39], M. Tost [11], D.R. Tovey [139], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [166], A. Tricoli [29], I.M. Trigger [156a], S. Trincaz-Duvoid [127], D.A. Trischuk [26], B. Trocmé [60], C. Troncon [71a], L. Truong [33c], M. Trzebinski [87], A. Trzupek [87], F. Tsai [145], M. Tsai [106], A. Tsiamis [152,e], P.V. Tsiareshka [37], S. Tsigaridas [156a], A. Tsirigotis [152,r], V. Tsiskaridze [155], E.G. Tskhadadze [149a], M. Tsopoulou [152,e], Y. Tsujikawa [88], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [84], O. Tsur [150], K. Tsuri [118], D. Tsybychev [145], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [57b,57a], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [38,x], P.M. Tuts [41], S. Tzamarias [152,e], P. Tzanis [10], E. Tzovara [100], F. Ukegawa [157], P.A. Ulloa Poblete [137c,137b], E.N. Umaka [29], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [160], J. Urban [28b], P. Urquijo [105], G. Usai [8], R. Ushioda [154], M. Usman [108], Z. Uysal [21b], L. Vacavant [102], V. Vacek [132], B. Vachon [104], K.O.H. Vadla [125], T. Vafeiadis [36], A. Vaitkus [96], C. Valderanis [109], E. Valdes Santurio [47a,47b], M. Valente [156a], S. Valentinetti [23b,23a], A. Valero [163], E. Valiente Moreno [163], A. Vallier [102,aa], J.A. Valls Ferrer [163], D.R. Van Arneman [114], T.R. Van Daalen [138], A. Van Der Graaf [49], P. Van Gemmeren [6], M. Van Rijnbach [125,36], S. Van Stroud [96], I. Van Vulpen [114], M. Vanadia [76a,76b], W. Vandelli [36], M. Vandenbroucke [135], E.R. Vandewall [121], D. Vannicola [151], L. Vannoli [57b,57a], R. Vari [75a], E.W. Varnes [7], C. Varni [17b], T. Varol [148], D. Varouchas [66], L. Varriale [163], K.E. Varvell [147], M.E. Vasile [27b], L. Vaslin [40], G.A. Vasquez [165], A. Vasyukov [38], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [101], M.J. Veen [103], I. Veliscek [126], L.M. Veloce [155], F. Veloso [130a,130c], S. Veneziano [75a], A. Ventura [70a,70b], S. Ventura Gonzalez [135], A. Verbytskyi [110], M. Verducci [74a,74b], C. Vergis [24], M. Verissimo De Araujo [83b], W. Verkerke [114], J.C. Vermeulen [114], C. Vernieri [143], M. Vessella [103], M.C. Vetterli [142,ag], A. Vgenopoulos [152,e], N. Viaux Maira [137f], T. Vickey [139], O.E. Vickey Boeriu [139], G.H.A. Viehhauser [126], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [163], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Vishwakarma [52], A. Visibile [114], C. Vittori [36], I. Vivarelli [146], E. Voevodina [110], F. Vogel [109], P. Vokac [132], Yu. Volkotrub [86a], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [133], K. Vorobev [37], M. Vos [163], K. Voss [141], J.H. Vossebeld [92], M. Vozak [114], L. Vozdecky [94], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [114], R. Vuillermet [36], O. Vujinovic [100], I. Vukotic [39], S. Wada [157], C. Wagner [103], J.M. Wagner [17a], W. Wagner [171], S. Wahdan [171], H. Wahlberg [90], M. Wakida [111], J. Walder [134], R. Walker [109], W. Walkowiak [141], A. Wall [128], T. Wamorkar [6], A.Z. Wang [170], C. Wang [100], C. Wang [62c], H. Wang [17a], J. Wang [64a], R.-J. Wang [100], R. Wang [61], R. Wang [6], S.M. Wang [148], S. Wang [62b], T. Wang [62a], W.T. Wang [80], W. Wang [14a], X. Wang [14c], X. Wang [162], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [106], Z. Wang [62d,51,62c], Z. Wang [106], A. Warburton [104], R.J. Ward [20], N. Warrack [59], A.T. Watson [20], H. Watson [59], M.F. Watson [20], E. Watton [59,134], G. Watts [138], B.M. Waugh [96], C. Weber [29], H.A. Weber [18], M.S. Weber [19], S.M. Weber [63a], C. Wei [62a], Y. Wei [126], A.R. Weidberg [126], E.J. Weik [117], J. Weingarten [49], M. Weirich [100], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [110], N. Wermes [24], M. Wessels [63a], A.M. Wharton [91], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [160], L. Wickremasinghe [124], W. Wiedenmann [170], C. Wiel [50], M. Wielers [134], C. Wiglesworth [42], D.J. Wilbern [120], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams [128], S. Williams [32], S. Willocq [103], B.J. Wilson [101], P.J. Windischhofer [39], F.I. Winkel [30], F. Winklmeier [123], B.T. Winter [54], J.K. Winter [101], M. Wittgen [143], M. Wobisch [97], Z. Wolffs [114], J. Wollrath [160], M.W. Wolter [87], H. Wolters [130a,130c], A.F. Wongel [48], S.D. Worm [48], B.K. Wosiek [87], K.W. Woźniak [87], S. Wozniewski [55], K. Wraight [59], C. Wu [20], J. Wu [14a,14e], M. Wu [64a], M. Wu [113], S.L. Wu [170], X. Wu [56], Y. Wu [62a], Z. Wu [135],

J. Wuerzinger [110,ae], T.R. Wyatt [101], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], M. Xie [62a], X. Xie [62a], S. Xin [14a,14e], A. Xiong [123], J. Xiong [17a], D. Xu [14a], H. Xu [62a], L. Xu [62a], R. Xu [128], T. Xu [106], Y. Xu [14b], Z. Xu [52], Z. Xu [14a], B. Yabsley [147], S. Yacoob [33a], Y. Yamaguchi [154], E. Yamashita [153], H. Yamauchi [157], T. Yamazaki [17a], Y. Yamazaki [85], J. Yan [62c], S. Yan [126], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [62a], S. Yang [62a], T. Yang [64c], X. Yang [62a], X. Yang [14a], Y. Yang [44], Y. Yang [62a], Z. Yang [62a], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], H. Ye [55], J. Ye [14a], S. Ye [29], X. Ye [62a], Y. Yeh [96], I. Yeletskikh [38], B.K. Yeo [17b], M.R. Yexley [96], P. Yin [41], K. Yorita [168], S. Younas [27b], C.J.S. Young [36], C. Young [143], C. Yu [14a,14e,ai], Y. Yu [62a], M. Yuan [106], R. Yuan [62b], L. Yue [96], M. Zaazoua [62a], B. Zabinski [87], E. Zaid [52], T. Zakareishvili [149b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [137d,137b], J. Zang [153], D. Zanzi [54], O. Zaplatilek [132], C. Zeitnitz [171], H. Zeng [14a], J.C. Zeng [162], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [94], S. Zerradi [35a], D. Zerwas [66], M. Zhai [14a,14e], B. Zhang [14c], D.F. Zhang [139], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14e], L. Zhang [14c], P. Zhang [14a,14e], R. Zhang [170], S. Zhang [106], T. Zhang [153], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Y. Zhang [96], Z. Zhang [17a], Z. Zhang [66], H. Zhao [138], P. Zhao [51], T. Zhao [62b], Y. Zhao [136], Z. Zhao [62a], A. Zhemchugov [38], J. Zheng [14c], K. Zheng [162], X. Zheng [62a], Z. Zheng [143], D. Zhong [162], B. Zhou [106], H. Zhou [7], N. Zhou [62c], Y. Zhou [7], C.G. Zhu [62b], J. Zhu [106], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [141], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [61], T.G. Zorbas [139], O. Zormpa [46], W. Zou [41], L. Zwalinski [36]

[1] Department of Physics, University of Adelaide, Adelaide; Australia
[2] Department of Physics, University of Alberta, Edmonton AB; Canada
[3] [(a)] Department of Physics, Ankara University, Ankara; [(b)] Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye
[4] LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France
[5] APC, Université Paris Cité, CNRS/IN2P3, Paris; France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America
[7] Department of Physics, University of Arizona, Tucson AZ; United States of America
[8] Department of Physics, University of Texas at Arlington, Arlington TX; United States of America
[9] Physics Department, National and Kapodistrian University of Athens, Athens; Greece
[10] Physics Department, National Technical University of Athens, Zografou; Greece
[11] Department of Physics, University of Texas at Austin, Austin TX; United States of America
[12] Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
[13] Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain
[14] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Physics Department, Tsinghua University, Beijing; [(c)] Department of Physics, Nanjing University, Nanjing; [(d)] School of Science, Shenzhen Campus of Sun Yat-sen University; [(e)] University of Chinese Academy of Science (UCAS), Beijing; China
[15] Institute of Physics, University of Belgrade, Belgrade; Serbia
[16] Department for Physics and Technology, University of Bergen, Bergen; Norway
[17] [(a)] Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; [(b)] University of California, Berkeley CA; United States of America
[18] Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
[19] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
[20] School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
[21] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(c)] Department of Physics, Istanbul University, Istanbul; Türkiye
[22] [(a)] Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá; [(b)] Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
[23] [(a)] Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; [(b)] INFN Sezione di Bologna; Italy
[24] Physikalisches Institut, Universität Bonn, Bonn; Germany
[25] Department of Physics, Boston University, Boston MA; United States of America
[26] Department of Physics, Brandeis University, Waltham MA; United States of America
[27] [(a)] Transilvania University of Brasov, Brasov; [(b)] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; [(c)] Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; [(d)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; [(e)] National University of Science and Technology Politechnica, Bucharest; [(f)] West University in Timisoara, Timisoara; [(g)] Faculty of Physics, University of Bucharest, Bucharest; Romania
[28] [(a)] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
[29] Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
[30] Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
[31] California State University, CA; United States of America
[32] Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
[33] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] iThemba Labs, Western Cape; [(c)] Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; [(d)] National Institute of Physics, University of the Philippines Diliman (Philippines); [(e)] University of South Africa, Department of Physics, Pretoria; [(f)] University of Zululand, KwaDlangezwa; [(g)] School of Physics, University of the Witwatersrand, Johannesburg; South Africa
[34] Department of Physics, Carleton University, Ottawa ON; Canada
[35] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)] Faculté des Sciences, Université Ibn-Tofail, Kénitra; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; [(e)] Faculté des sciences, Université Mohammed V, Rabat; [(f)] Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco

[36] CERN, Geneva; Switzerland
[37] Affiliated with an institute covered by a cooperation agreement with CERN
[38] Affiliated with an international laboratory covered by a cooperation agreement with CERN
[39] Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
[40] LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
[41] Nevis Laboratory, Columbia University, Irvington NY; United States of America
[42] Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
[43] [(a)] Dipartimento di Fisica, Università della Calabria, Rende; [(b)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
[44] Physics Department, Southern Methodist University, Dallas TX; United States of America
[45] Physics Department, University of Texas at Dallas, Richardson TX; United States of America
[46] National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
[47] [(a)] Department of Physics, Stockholm University; [(b)] Oskar Klein Centre, Stockholm; Sweden
[48] Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[49] Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany
[50] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
[51] Department of Physics, Duke University, Durham NC; United States of America
[52] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
[53] INFN e Laboratori Nazionali di Frascati, Frascati; Italy
[54] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[55] II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
[56] Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[57] [(a)] Dipartimento di Fisica, Università di Genova, Genova; [(b)] INFN Sezione di Genova; Italy
[58] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
[59] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[60] LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
[61] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
[62] [(a)] Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; [(b)] Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; [(c)] School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; [(d)] Tsung-Dao Lee Institute, Shanghai; China
[63] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
[64] [(a)] Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, University of Hong Kong, Hong Kong; [(c)] Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
[65] Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
[66] IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
[67] Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
[68] Department of Physics, Indiana University, Bloomington IN; United States of America
[69] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
[70] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[71] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[72] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[73] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[74] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[75] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[76] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[77] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[78] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[79] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[80] University of Iowa, Iowa City IA; United States of America
[81] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[82] Istinye University, Sariyer, Istanbul; Türkiye
[83] [(a)] Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; [(b)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(c)] Instituto de Física, Universidade de São Paulo, São Paulo; [(d)] Rio de Janeiro State University, Rio de Janeiro; Brazil
[84] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[85] Graduate School of Science, Kobe University, Kobe; Japan
[86] [(a)] AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
[87] Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
[88] Faculty of Science, Kyoto University, Kyoto; Japan
[89] Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
[90] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
[91] Physics Department, Lancaster University, Lancaster; United Kingdom
[92] Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
[93] Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
[94] School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
[95] Department of Physics, Royal Holloway University of London, Egham; United Kingdom
[96] Department of Physics and Astronomy, University College London, London; United Kingdom
[97] Louisiana Tech University, Ruston LA; United States of America
[98] Fysiska institutionen, Lunds universitet, Lund; Sweden
[99] Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
[100] Institut für Physik, Universität Mainz, Mainz; Germany
[101] School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
[102] CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
[103] Department of Physics, University of Massachusetts, Amherst MA; United States of America
[104] Department of Physics, McGill University, Montreal QC; Canada
[105] School of Physics, University of Melbourne, Victoria; Australia
[106] Department of Physics, University of Michigan, Ann Arbor MI; United States of America
[107] Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[108] Group of Particle Physics, University of Montreal, Montreal QC; Canada
[109] Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
[110] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
[111] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan

[112] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
[113] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
[114] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
[115] Department of Physics, Northern Illinois University, DeKalb IL; United States of America
[116] [(a)] New York University Abu Dhabi, Abu Dhabi; [(b)] University of Sharjah, Sharjah; United Arab Emirates
[117] Department of Physics, New York University, New York NY; United States of America
[118] Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[119] Ohio State University, Columbus OH; United States of America
[120] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
[121] Department of Physics, Oklahoma State University, Stillwater OK; United States of America
[122] Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
[123] Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
[124] Graduate School of Science, Osaka University, Osaka; Japan
[125] Department of Physics, University of Oslo, Oslo; Norway
[126] Department of Physics, Oxford University, Oxford; United Kingdom
[127] LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
[128] Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
[129] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
[130] [(a)] Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; [(b)] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Departamento de Física, Universidade de Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Física, Universidade do Minho, Braga; [(f)] Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); [(g)] Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
[131] Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
[132] Czech Technical University in Prague, Prague; Czech Republic
[133] Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
[134] Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
[135] IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
[136] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
[137] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; [(c)] Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; [(d)] Universidad Andres Bello, Department of Physics, Santiago; [(e)] Instituto de Alta Investigación, Universidad de Tarapacá, Arica; [(f)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
[138] Department of Physics, University of Washington, Seattle WA; United States of America
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[140] Department of Physics, Shinshu University, Nagano; Japan
[141] Department Physik, Universität Siegen, Siegen; Germany
[142] Department of Physics, Simon Fraser University, Burnaby BC; Canada
[143] SLAC National Accelerator Laboratory, Stanford CA; United States of America
[144] Department of Physics, Royal Institute of Technology, Stockholm; Sweden
[145] Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
[146] Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
[147] School of Physics, University of Sydney, Sydney; Australia
[148] Institute of Physics, Academia Sinica, Taipei; Taiwan
[149] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi; [(c)] University of Georgia, Tbilisi; Georgia
[150] Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
[151] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
[152] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
[153] International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
[154] Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
[155] Department of Physics, University of Toronto, Toronto ON; Canada
[156] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON; Canada
[157] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
[158] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
[159] United Arab Emirates University, Al Ain; United Arab Emirates
[160] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[161] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[162] Department of Physics, University of Illinois, Urbana IL; United States of America
[163] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain
[164] Department of Physics, University of British Columbia, Vancouver BC; Canada
[165] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[166] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[167] Department of Physics, University of Warwick, Coventry; United Kingdom
[168] Waseda University, Tokyo; Japan
[169] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[170] Department of Physics, University of Wisconsin, Madison WI; United States of America
[171] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[172] Department of Physics, Yale University, New Haven CT; United States of America

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Center for High Energy Physics, Peking University; China.
[e] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[f] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[g] Also at CERN, Geneva; Switzerland.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[l] Also at Department of Physics, California State University, Sacramento; United States of America.
[m] Also at Department of Physics, King's College London, London; United Kingdom.

[n] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[o] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[p] Also at Department of Physics, University of Thessaly; Greece.
[q] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[r] Also at Hellenic Open University, Patras; Greece.
[s] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[t] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[u] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[v] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[w] Also at Institute of Particle Physics (IPP); Canada.
[x] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[y] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[z] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[aa] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ab] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ac] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ad] Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[ae] Also at Technical University of Munich, Munich; Germany.
[af] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ag] Also at TRIUMF, Vancouver BC; Canada.
[ah] Also at Università di Napoli Parthenope, Napoli; Italy.
[ai] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[aj] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ak] Also at Washington College, Chestertown, MD; United States of America.
[al] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.