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Measurement of the top-quark mass in $t\bar{t}+1$-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s}=8$ TeV

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Abstract: A determination of the top-quark mass is presented using 20.2 fb^{-1} of 8 TeV proton-proton collision data produced by the Large Hadron Collider and collected by the ATLAS experiment. The normalised differential cross section of top-quark pair production in association with an energetic jet is measured in the lepton+jets final state and unfolded to parton and particle levels. The unfolded distribution at parton level can be described using next-to-leading-order QCD predictions in terms of either the top-quark pole mass or the running mass as defined in the (modified) minimal subtraction scheme. A comparison between the experimental distribution and the theoretical prediction allows the top-quark mass to be extracted in the two schemes. The value obtained for the pole-mass scheme is:

$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat}) \pm 0.9\ (\text{syst})\ ^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}.$$

The extracted value in the running-mass scheme is:

$$m_t(m_t) = 162.9 \pm 0.5\ (\text{stat}) \pm 1.0\ (\text{syst})\ ^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}.$$

The results for the top-quark mass using the two schemes are consistent, when translated from one scheme to the other.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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Contents

1 Introduction

The mass of the top quark, the heaviest known elementary particle, is a key parameter of the Standard Model (SM) of particle physics and must be determined experimentally. In the SM, the gauge structure of the interaction of the top quark with other particles establishes a relation between the top-quark, Higgs-boson and W-boson masses. A precise determination of these three parameters forms an important check of the internal consistency of the SM [1–5]. Precise measurements of the top-quark mass are also required in order to accurately predict the evolution of the Higgs quartic coupling at high scales, which affects the shape of the Higgs potential and is associated in the SM with the stability of the quantum vacuum [6, 7]. In this article the top-quark mass is inferred from the shape of a differential cross-section distribution.

Any quantitative statement about the value of a quark mass requires a precise reference to the *mass scheme* in which the mass is defined. The mass scheme which is used most often in top-quark mass measurements is the pole-mass scheme [8–14], where the renormalised top-quark mass (the pole mass, m_t^{pole}) coincides with the pole of the top-quark propagator. Several groups have extracted the running[1] top-quark mass in the modified

[1]The scale $\mu = m_t$ is used to express the value of top-quark running mass, $m_t(m_t)$.

minimal subtraction scheme ($\overline{\text{MS}}$) from the total top-quark pair ($t\bar{t}$) production cross section [15, 16] or the differential cross section [17]. The two mass schemes can be related precisely, with up to four-loop accuracy [18].

Direct top-quark mass measurements at hadron colliders, based on the reconstruction of the top-quark decay products and using Monte Carlo (MC) event generators in the fit to extract the mass, are frequently interpreted as the pole mass. Recent works estimate that such an interpretation is affected by a 0.5–1 GeV [19–24] uncertainty due to non-perturbative effects from below the MC lower scale at which perturbative quark and gluon radiation is terminated in the parton shower. With direct top-quark mass measurements reaching sub-percent precision [20] it becomes important to evaluate uncertainties associated with the interpretation of the measured mass at the same level of accuracy.

It is therefore of paramount importance to extract the top-quark mass by comparing data with predictions computed in a well-defined mass scheme. In this case the ambiguity related to the top-quark mass interpretation is avoided, allowing a precise evaluation of the uncertainty associated with the mass scheme chosen. In such measurements the Monte Carlo event generator is only used to correct distributions obtained from measured data for effects originating from the detector and the modelling of non-perturbative physics. The uncertainty associated to such effects can be estimated comparing Monte Carlo simulations produced with different sets of parameters, without specific assumptions on the top-quark mass interpretation. The theory uncertainty can then be estimated using the conventional techniques (scale variations and error sets of the parton distribution functions). Such mass measurements also yield greater flexibility in choosing the mass scheme [8, 9].

In this article, results are presented in both the pole-mass and $\overline{\text{MS}}$ schemes. The measurement reported in this study follows the approach developed in refs. [17, 25, 26], which takes advantage of the sensitivity to the top-quark mass of the differential cross section of $t\bar{t}$ production in association with at least one energetic jet. The presence of the additional jet enhances the sensitivity to the top-quark mass in comparison with similar observables defined for the $t\bar{t}$ system only [25]. In particular, the observable used to extract the top-quark mass, $\mathcal{R}$, is defined as the normalised differential $t\bar{t}+1\text{-jet}$ cross section:

$$\mathcal{R}(m_t^{\text{pole}}, \rho_{\text{s}}) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_{\text{s}}},$$

where

$$\rho_{\text{s}} = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}},$$

with m_0 representing a constant fixed to 170 GeV and $m_{t\bar{t}+1\text{-jet}}$ being the invariant mass of the $t\bar{t}+1\text{-jet}$ system.[2]

The normalised differential cross sections are presented at the so-called *particle level* in which data are only unfolded for detector effects and at the *parton level* where $\mathcal{R}$ can be directly compared with available fixed-order calculations [17, 25]. The *particle-level* distribution is provided to allow comparisons with possible future calculations. A measurement of the top-quark pole mass [11] with this method using 4.6 fb^{-1} of 7 TeV pp

[2]The definition $\rho_{\text{s}} = 2m_0/\sqrt{s_{t\bar{t}+1\text{-jet}}}$ is also used in the literature [17, 25], with $\sqrt{s_{t\bar{t}+1\text{-jet}}} = m_{t\bar{t}+1\text{-jet}}$

collisions collected by ATLAS yielded an uncertainty of 2.3 GeV (1.3%) in the top-quark pole mass. In the current analysis the top-quark mass is determined using a sample of 8 TeV pp collisions collected in 2012. The large statistics of the 8 TeV dataset make it possible to achieve a high precision in the measurement of the $\mathcal{R}$ distribution, in particular in the region where it is most sensitive to the top-quark mass, ultimately allowing the top-quark mass to be extracted with high accuracy.

2 ATLAS experiment

The ATLAS experiment [27] at the Large Hadron Collider (LHC) is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and almost 4π coverage in solid angle.[3]

Its core consists of an inner tracking detector surrounded by a thin superconducting solenoid, which provides a 2 T axial magnetic field. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It is equipped with silicon pixel, silicon microstrip, and transition radiation tracking detectors.

The inner detector is surrounded by the calorimeters and a muon spectrometer. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. An iron/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$.

The muon spectrometer consists of precision tracking chambers and fast detectors for triggering in a magnetic field with bending power in the range from 2.0 to 6.5 T m generated by three large air-core toroidal superconducting magnets with eight coils each.

A three-level trigger system is used to select events [28]. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted event rate to 400 Hz on average.

3 Data sample

Collision events are selected with a combination of single-electron and single-muon triggers. Electrons (muons) are required to have transverse energy (transverse momentum, p_{T}) above a certain threshold. During the 2012 run the thresholds were set to 36 GeV for muons and 60 GeV for electrons, and reduced to 24 GeV for isolated muons and electrons.

The analysed data set is limited to periods with stable beam conditions when all detector subsystems were operational. The analysed sample corresponds to an integrated luminosity of 20.2 ± 0.6 fb^{-1} [29].

[3] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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4 Monte Carlo simulation

The nominal $t\bar{t}$ sample that is used to unfold the data was generated using the POWHEG-hvq package [30–33], which is based on next-to-leading-order (NLO) QCD matrix elements. The CT10 [34] set of parton distribution functions (PDF) was used. The h_{damp} parameter [35] controls the scale of the damping of the real radiation in POWHEG and thus effectively regulates the high-transverse-momentum radiation of the matrix element (ME) calculation. It was set to the top-quark mass unless indicated otherwise. The sample is normalised to the most precise $t\bar{t}$ cross-section prediction for pp collisions at $\sqrt{s} = 8$ TeV, corresponding to $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb for a top-quark mass $m_t = 172.5$ GeV, calculated at NNLO+NNLL [36–41] with the top++2.0 [42, 43] program using the MSTW2008 [44, 45], CT10 [34, 46] and NNPDF2.3 [47] PDF sets. The parton shower (PS), hadronisation, and the underlying event were simulated with PYTHIA 6.427 [48] using the CTEQ6L1 PDF [49] set and a set of tuned parameters called the Perugia 2011 [50] tune.

Several $t\bar{t}$ event samples with different choices of the value of the Monte Carlo top-quark mass, but otherwise the same settings as the nominal sample, are used to validate the analysis. Alternative samples are used to evaluate uncertainties in modelling the $t\bar{t}$ signal. These include samples produced with MC@NLO 4.01 [51] interfaced with HERWIG 6.520 [52] and JIMMY 4.31 [53] and samples generated with POWHEG + HERWIG, with the ATLAS AUET2 tune [54] and JIMMY [53] for multiple parton interactions. Some POWHEG samples were generated with $h_{\mathrm{damp}} = \infty$ and reweighted to $h_{\mathrm{damp}} = m_t$, following the strategy presented in ref. [13]. Two samples with variations of the renormalisation and factorisation scales, the value of the h_{damp} factor and the choice of parton-shower tune are used to estimate the uncertainty in modelling of initial- and final-state radiation [55].

Electroweak single-top-quark production was simulated with POWHEG matched with PYTHIA 6.425, with the CTEQ6L1 PDF set and the Perugia 2011C [50] tune. The cross sections are normalised to NNLO+NNLL calculations for t-channel [56], Wt [57], and s-channel production [58].

Leptonic decays of vector bosons produced in association with several high-p_{T} jets, referred to as W+jets and Z+jets events, with up to five additional final-state partons in the leading-order (LO) matrix elements, were produced with the ALPGEN generator [59] interfaced with HERWIG for parton fragmentation using the MLM matching scheme [60]. Samples corresponding to the production of a W boson in association with heavy-flavour quarks (b- and c-quarks) were generated separately, at leading order and including effects from the value of the mass of the heavy quarks. Overlap between heavy-flavour quarks that originate from matrix-element production and those that originate from the parton shower was removed. The W+jets samples are normalised to the inclusive W-boson NNLO cross section [61, 62].

Diboson events were generated with HERWIG with the CTEQ6L1 PDF. The multijet background is estimated using a data-driven matrix method described in ref. [63].

At the LHC, multiple, simultaneous pp interactions occur in each bunch crossing. The average number of additional pp interactions was 21 during the 2012 run. These pile-up collisions were simulated using PYTHIA 8.1 [64] with the MSTW2008 leading-order PDF

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set [44] and the A2M tune [65]. The number of simulated pile-up events superimposed on each hard-scatter event was reweighted to match the distribution of the number of interactions per bunch crossing in data.

The response of the detector and trigger was simulated [66] using a detailed model implemented in GEANT4 [67]. For some samples used to evaluate systematic uncertainties, the detailed description of the calorimeter response was parameterised using the ATLFAST-II simulation [66]. For all the non-$t\bar{t}$ samples the top-quark mass was set to $m_t = 172.5$ GeV. Simulated events are reconstructed with the same software as the data.

5 Lepton and jet reconstruction

Electron candidates are reconstructed from clusters of energy deposits in the electromagnetic calorimeter, matched with a reconstructed inner-detector track [68]. Electrons are required to fulfill the tight identification requirement of ref. [68].The calorimeter cluster is required to have transverse energy $E_{\mathrm{T}} > 25$ GeV and pseudorapidity $|\eta| < 2.47$. Clusters in the transition region between the barrel and endcaps with $1.37 < |\eta| < 1.52$ are excluded. Non-prompt electrons are suppressed by cuts on the sum of transverse energy deposited in a cone of size $\Delta R = 0.2$ around the calorimeter cells associated with the electron and on the sum of track p_{T} in a cone of size $\Delta R = 0.3$. The longitudinal impact parameter (z_0) of the electron track relative to the selected event primary vertex[4] is required to be smaller than 2 mm [69].

Muon candidate reconstruction is based on track segments in the muon spectrometer combined with inner-detector tracks [70]. The combined track must satisfy $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. Muon candidates have to be separated from any jet by $\Delta R > 0.4$ and the sum of the transverse momenta of tracks within a cone of size $\Delta R = 10\ \mathrm{GeV}/p_{\mathrm{T}}^{\mu}$ around the muon candidate is required to be less than 5% of the muon transverse momentum, p_{T}^{μ}. The muon longitudinal impact parameter (z_0) relative to the primary vertex is required to be smaller than 2 mm.

Jet reconstruction starts from topological clusters [71] of energy deposits in the calorimeters. A local calibration scheme [72] corrects for the non-compensating response of the calorimeter, dead material and out-of-cluster leakage. Jets are reconstructed from these topological clusters using the anti-k_t algorithm [73, 74] with a radius parameter of $R = 0.4$. Jets are calibrated to the level of stable-particle jets using Monte Carlo simulation and the response is verified in situ [75]. Jet reconstruction is implemented in the FastJet package [76]. Jets are accepted if $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ after the calibration. To reduce the contribution from pile-up, jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$ must have a jet-vertex-fraction (p_{T}-weighted fraction of tracks associated with the jet that point to the primary vertex) greater than 0.5 [77]. The closest jet within $\Delta R = 0.2$ of selected electrons is discarded to avoid double-counting of the electron candidate as a jet.

[4] A primary vertex candidate is defined as a vertex with at least two associated tracks, consistent with the beam collision region. The vertex candidate with the largest sum of squared transverse momenta of its associated tracks is taken as the primary vertex.

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Jets with b-hadrons (b-jets) are tagged with the MV1 algorithm, based on multivariate techniques exploiting impact parameter and secondary vertex information [78]. The efficiency to tag b-jets in $t\bar{t}$ events is 70%, with a light-parton jet rejection factor of 130 and a c-jet rejection factor of 5. The simulated b-tagging efficiency is corrected to match the efficiency measured in data.

The missing transverse momentum (and its magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) is reconstructed from the vector sum of the transverse momenta of the reconstructed calibrated leptons, jets and the transverse energy deposited in the calorimeter cells not associated with these objects [79].

6 Event selection and reconstruction

Events are selected (preselection) if they pass several quality cuts and requirements to select final states with one reconstructed electron or muon and five or more jets [80, 81]. A reconstructed primary vertex with at least five associated tracks is required. Exactly one high-quality, isolated lepton with $p_{\mathrm{T}} > 25$ GeV must be present. It must match the lepton that triggered the event within $\Delta R < 0.15$. At least five jets are required, exactly two of which must be b-jets. The magnitude of the missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ and the W-boson transverse mass[5] must both be greater than 30 GeV. After these requirements the data sample contains 12419 events in the electron channel and 15495 events in the muon channel. Of these events $\sim 93\%$ are expected to be $t\bar{t}$ events.

The reconstruction of the $t\bar{t} + 1$-jet system follows that of ref. [11]. Candidates for the hadronically decaying W boson are formed by pairing all jets not tagged as b-jets and selecting pairs i, j that satisfy:

- $0.9 < m_W/m_{ij} < 1.25$
- $\min\left(p_{\mathrm{T}}^{i},\ p_{\mathrm{T}}^{j}\right) \cdot \Delta R_{ij} < 90$ GeV

where p_{T}^{i} is the transverse momentum of the jet i, m_{ij} is the invariant mass of the jet pair, ΔR_{ij} their angular distance and m_W is the value of the W-boson mass reported by the Particle Data Group [5]. The application of these two requirements reduces the multijet and combinatorial backgrounds.

The neutrino momentum is reconstructed, up to a twofold ambiguity, by identifying the $E_{\mathrm{T}}^{\mathrm{miss}}$ with its transverse momentum and using the W-boson mass constraint to infer its longitudinal momentum [11]. Only events where at least one neutrino candidate exists are considered. If there are two solutions, each of the neutrino candidates is added to the charged lepton, leading to two W-boson candidates.

Pairs of hadronic and semileptonic top-quark candidates are formed by combining all the hadronic and leptonic W-boson candidates with the two b-tagged jets. Among all possible combinations the one selected is that which minimises the absolute difference

[5]The transverse mass of the W boson is determined as $m_{\mathrm{T}}^{W} = \sqrt{2p_{\mathrm{T},\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}}[1 - \cos(\phi_\ell - \phi_{E_{\mathrm{T}}^{\mathrm{miss}}})]}$, where ℓ is the selected lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ is the missing transverse momentum.

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Channel	e+jets	μ+jets
$t\bar{t}$	5530 ± 470	7080 ± 600
Single top	191 ± 15	226 ± 18
W+jets	100 ± 33	121 ± 37
Z+jets	24 ± 8	13 ± 4
Multijet	21 ± 11	< 11
Prediction	5870 ± 540	7440 ± 660
Data	6379	7824

Table 1. Summary of the event yield after the final selection. The observed event yield is compared with the prediction of the Monte Carlo simulation for top-quark pair production and the most important SM background processes. The estimate of the uncertainty in the normalisation of the expected signal and backgrounds yields includes the theoretical uncertainty in the cross section, as well as experimental systematic uncertainties as discussed in section 8. The contribution from diboson production is negligible.

between the masses of the reconstructed hadronic top ($m_{t_{\mathrm{had}}}$) and the semileptonic top ($m_{t_{\mathrm{lept}}}$) candidates, divided by their sum:

$$\frac{|m_{t_{\mathrm{lept}}} - m_{t_{\mathrm{had}}}|}{m_{t_{\mathrm{lept}}} + m_{t_{\mathrm{had}}}}$$

The $t\bar{t}$ candidates must satisfy $m_{t_{\mathrm{lept}}}/m_{t_{\mathrm{had}}} > 0.9$.

The four-momenta of the jets which are identified with the hadronic decay of the W boson are corrected by the factor $\frac{m_W}{m_{ij}}$. Among the jets not used in either top-quark candidate, the leading jet in p_{T} is taken as the jet produced in association with the top quarks, before their decay. Only events where this extra jet has a transverse momentum larger than 50 GeV are considered. Due to this requirement the selected $t\bar{t}$+1-jet events are reconstructed with a topology similar to the one used in the theoretical NLO calculation, where a similar p_{T} cut is applied [25].

In table 1 the event yield after the final selection cuts is presented. The contribution from diboson production is negligible and is hence not reported. The efficiency of the signal selection, relative to the events that passed the preselection cuts, is $\sim 51\%$. The purity of the sample is 94.3% for the electron channel and 95.2% for the muon channel. The yield predicted by the Monte Carlo simulation is lower than the observed yield in both channels, but is compatible within the MC normalisation uncertainty.

The $t\bar{t} + 1$-jet system is reconstructed adding the four-vectors corresponding to the b-jets, the selected W-boson candidates and the additional jet. The inclusive quantity ρ_{s} defined in section 1 is insensitive to ambiguities in the combinatorics and is not affected by an incorrect pairing of b-jets with W-boson candidates. The observed ρ_{s} detector-level distribution is presented in figure 1.

7 Data unfolding

This analysis follows the approach of ref. [11] in which the measured $\mathcal{R}$ distribution is unfolded for detector, hadronisation and top-quark decay effects to the parton level where

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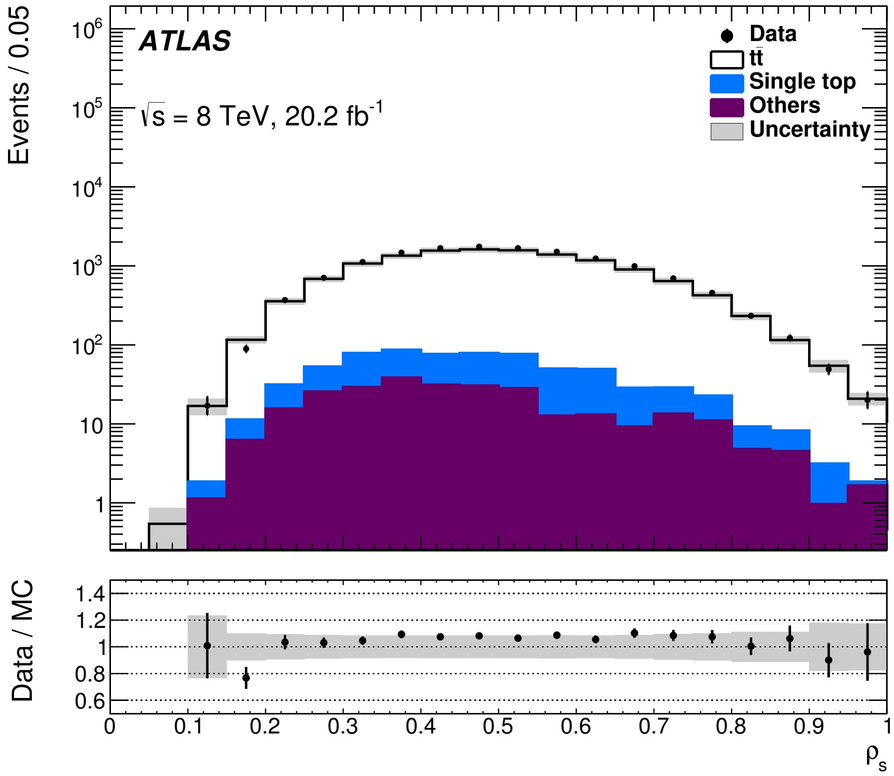

Figure 1. Distributions of the ρ_{s} variable in the $t\bar{t}+1$-jet system after the final selection. Data are compared with the SM expectation as obtained with Monte Carlo calculation which includes a full simulation of the ATLAS detector. Statistical uncertainties in the observed event counts are indicated with error bars. The band estimates the uncertainty on the expected yields. It includes the uncertainty on the luminosity, effects from the cross-section normalisation computed as $8.5\%\sigma_{t\bar{t}} \oplus 7.8\%\sigma_{\text{single-}t} \oplus 33\%\sigma_{\mathrm{V+jets}} \oplus 50\%\sigma_{\text{multijet}}$ and detector plus $t\bar{t}$ modelling uncertainties, as described in section 8. Sub-leading background contributions have been merged into the "Others" category to improve their visibility and reduce statistical fluctuations in the plot. The bin of the highest ρ_{s} interval includes events reconstructed with $\rho_{\mathrm{s}} > 1$.

top quarks are on-shell. The distribution obtained at this level is then compared with theoretical predictions at fixed order, allowing the determination of the top-quark mass in a well-defined theoretical framework. In addition, in this paper, the $\mathcal{R}$ distribution is also presented at particle level, where data are unfolded for detector effects only. This will allow direct comparisons with possible future theoretical calculations which include top-quark decay and hadronisation effects.

The parton level is defined using on-shell top quarks and including initial- and final-state radiation from quarks and gluons before the top-quark decay. Jets are reconstructed by clustering u-, d-, c-, s-, b-quarks and gluons, via the anti-k_t jet algorithm with $R = 0.4$. The $t\bar{t}+1$-jet fixed-order calculation at NLO is defined for a jet with p_{T} larger than 50 GeV and with absolute pseudorapidity smaller than 2.5, ensuring the observable is infrared-safe for calculation purposes. The same definition is also applied to MC reconstructed events.

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The particle level is constructed from the collection of stable particles[6] from full matrix-element plus parton-shower generators, including top-quark decay and final-state radiation effects. Particles produced from interactions with the detector components or from pile-up of additional pp collisions are not considered at this level. The leptons' four-momenta are defined by clustering photons and the leptons with the anti-k_t jet algorithm, using a jet-radius parameter of $R = 0.1$. No isolation condition is imposed. In order to choose prompt leptons from W/Z-boson decay, the parent of the lepton is required not to be a hadron. Leptons from τ decay are considered as valid final-state particles. The neutrino from the W/Z decay is treated as a detectable particle and is selected for consideration in the same way as electrons or muons, i.e. the parent is required not to be a hadron. Jets are defined by clustering all the stable particles which have not been used in the definitions of electrons, muons and neutrinos with the anti-k_t algorithm. The value of the jet-radius parameter is chosen to be $R = 0.4$. A jet is tagged as a b-jet if any rescaled b-hadron[7] is included in the jet. Events where the leptons overlap with the selected jets are discarded. The fiducial volume at particle level is defined by applying the detector-level selection algorithm to the aforementioned particles as for data, the only difference being that the neutrino four-momentum is known. This choice minimises the magnitude of the correction to the data.

The unfolding procedure is detailed in the following. First, the detector-level distribution of ρ_s in figure 1 is re-binned as in figure 2 to maximise the sensitivity of the observable to the top-quark mass while keeping enough statistics in each bin. This is achieved by choosing a fine binning in the region $\rho_\mathrm{s} \gtrsim 0.6$, where the observable is most sensitive to the top-quark mass [25]. Second, the predicted background contribution is subtracted and the distribution is normalised to unity. Finally, the distribution is unfolded with a procedure known as iterative Bayesian unfolding [82].

For the parton level the unfolding procedure takes the following form:

$$\mathcal{R}^{t\bar{t}+1\text{-jet}}(\rho_\mathrm{s}) = \left[\mathcal{M}^{-1} \otimes \mathcal{R}^{\mathrm{det}}(\rho_\mathrm{s})\right] \cdot f(\rho_\mathrm{s}) \cdot f^{\mathrm{ph.sp.}}\left(\rho_\mathrm{s}, \mathcal{R}_{\mathrm{ACC}}^{t\bar{t}+1\text{ jet}}\right).$$

The unfolded distribution is denoted by $\mathcal{R}^{t\bar{t}+1\text{-jet}}(\rho_\mathrm{s})$ and the detector-level distribution by $\mathcal{R}^{\mathrm{det}}(\rho_\mathrm{s})$. Migrations between the parton level and the detector level are described by the unfolding matrix $\mathcal{M}$. The matrix is built from the nominal ATLAS MC $t\bar{t}$ sample, using events which pass both the parton-level and detector-level selection cuts. The matrix is inverted and regularised with the Bayesian unfolding method of ref. [82]. The bin-by-bin correction factor f accounts for the acceptance and for the difference between the $t\bar{t}+g$ system in the nominal ATLAS MC sample (the first emission level of ref. [11]) and the $t\bar{t}+1$-jet system at parton level. It has a residual dependence on the value of the mass used in the MC generator for the correction, near the threshold production of $t\bar{t}+1$-jet events. This is due to the available phase space in this region, which depends on the top-quark mass. This effect is taken into account by a second factor $f^{\mathrm{ph.sp.}}$, which is parameterised in

[6]A particle is considered stable if its lifetime is greater than 3×10^{-11} s.

[7]Intermediate b-hadrons with $p_\mathrm{T} > 5$ GeV in the MC decay chain history are clustered in the stable-particle jets with their energies set to zero.

each bin as a function of the unfolded observable before acceptance correction, $\mathcal{R}^{t\bar{t}+1\text{ jet}}_{\text{ACC}}$,[8] removing any explicit dependence on the value of the top-quark mass. The $f^{\text{ph.sp.}}$ factor is very close to one and only affects those bins close to the $t\bar{t}+1$-jet production threshold region ($\rho_{\text{s}} > 0.775$). The unfolding to particle level is performed using the same tools, but is simpler in two ways: f is a pure acceptance correction in this case and the phase-space correction $f^{\text{ph.sp.}}$ is equal to one as the same event topologies are considered at detector and particle level.

The unfolded, normalised differential cross section at particle level is presented in figure 2, where it is compared with the prediction of the Powheg + Pythia 6 generator with the top-quark mass parameter set to 172.5 GeV. The distributions obtained from the electron and muon channels separately, unfolded following the nominal procedure, are also presented in the same figure to show their compatibility with the combined result.

In figure 3 the same measurement is presented after unfolding to parton level. The result is compared with the prediction for $t\bar{t}+1$-jet production of refs. [25, 83]. The fixed-order calculation at NLO accuracy in QCD is interfaced to the parton shower and is labelled as "NLO+PS" in the following. The prediction is shown for two values of the top-quark pole mass, to demonstrate the sensitivity of the observable to the top-quark mass.

8 Extraction of the top-quark mass

The top-quark pole mass is extracted from the parton-level result with an NLO+PS calculation of $t\bar{t}+1$-jet production [25, 83]. The fit finds the optimal value of m_t^{pole} by minimising the following expression with the least-squares method:

$$\chi^2 = \sum_{i,j} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_i \left[V^{-1}\right]_{ij} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_j ,$$

where indices $i, j \in \{1, 2, \ldots, 8\}$ refer to the bin number of the unfolded observable. covariance matrix, of which diagonal terms are the experimental statistical uncertainties in the measured observable, bin-by-bin. Per-bin uncertainties are assumed to be Gaussian. Correlations between bins are taken into account via off-diagonal entries in V. The term $\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}}$ represents the measured differential cross section. In each bin i a continuous parameterisation $[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})]_i$ is obtained by interpolating with a second-order polynomial between different $\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}$ predictions computed at fixed m_t^{pole} values.

Experimental systematic uncertainties are assigned to account for imperfections in the modelling of the detector response and signal and background simulations. Monte Carlo simulations with varied response or simulation parameters are used to compute a set of $\mathcal{R}$ distributions at detector level. These distributions are then unfolded using the nominal procedure described in the previous section to particle or parton levels. Systematic uncertainties in the unfolded distribution are evaluated by taking into account the difference of the variation bin-by-bin where the unfolded alternative MC samples are compared to their generator-level distribution. Uncertainties in the top-quark mass are evaluated instead

[8]The observable is defined at parton level, but only for those events which pass detector-level selection.

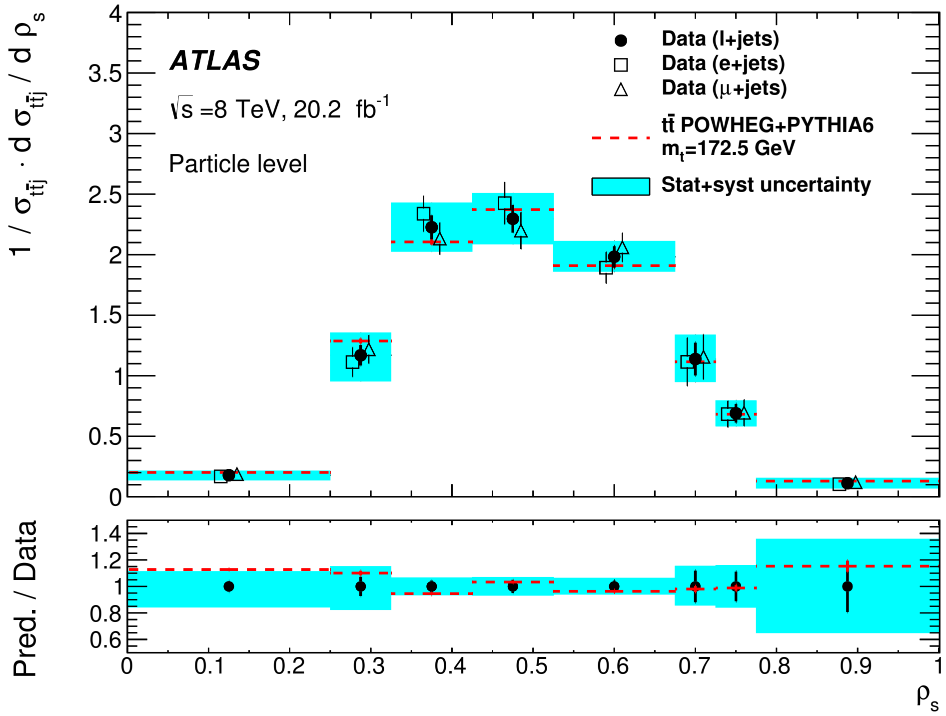

Figure 2. The normalised differential cross section for $pp \to t\bar{t} + 1$-jet production in pp collisions at $\sqrt{s} = 8$ TeV, as a function of ρ_s. The results in the electron and muon channels, and the combination of the two, are shown with different marker styles. The data are unfolded to the particle level and are compared with the prediction from the nominal MC generator, Powheg + Pythia 6, with the top-quark mass parameter set to 172.5 GeV.

by comparing the values of the top-quark mass extracted from the unfolded distributions covering the systematic variations, and their numerical values are reported in table 2. A detailed description of the systematic uncertainties evaluated is given in the following.

Uncertainties in the modelling of the jet energy response are taken into account by varying the jet energy scale (*JES*) within its uncertainty for a number of uncorrelated components [84–86]. A separate uncertainty is assigned to the b-quark jet energy scale (*bJES*), which is uncorrelated with the *JES*. Systematic effects that affect the jet energy resolution (*JER*) and jet reconstruction efficiency are taken into account by smearing the jet energy and by randomly removing a fraction of the jets, respectively. Uncertainties originating from b-jet tagging/mistagging efficiency are also considered (*b-tagging efficiency and mistag*). Scale factors are applied to correct for the difference between efficiencies measured in data and in simulated events [68, 70]. The uncertainties in these correction factors are propagated to the measurement (*Lepton*). The modelling of $E_\mathrm{T}^\mathrm{miss}$ is affected by uncertainties in the jet energy and lepton momentum scales, as well as the response for the soft-term and pile-up modelling [79].

Modelling uncertainties cover a possible bias of the measurement due to imperfections in the description of signal and background processes in Monte Carlo generators. Several alternative models are used for $t\bar{t}$ production as introduced in section 4. Monte Carlo sim-

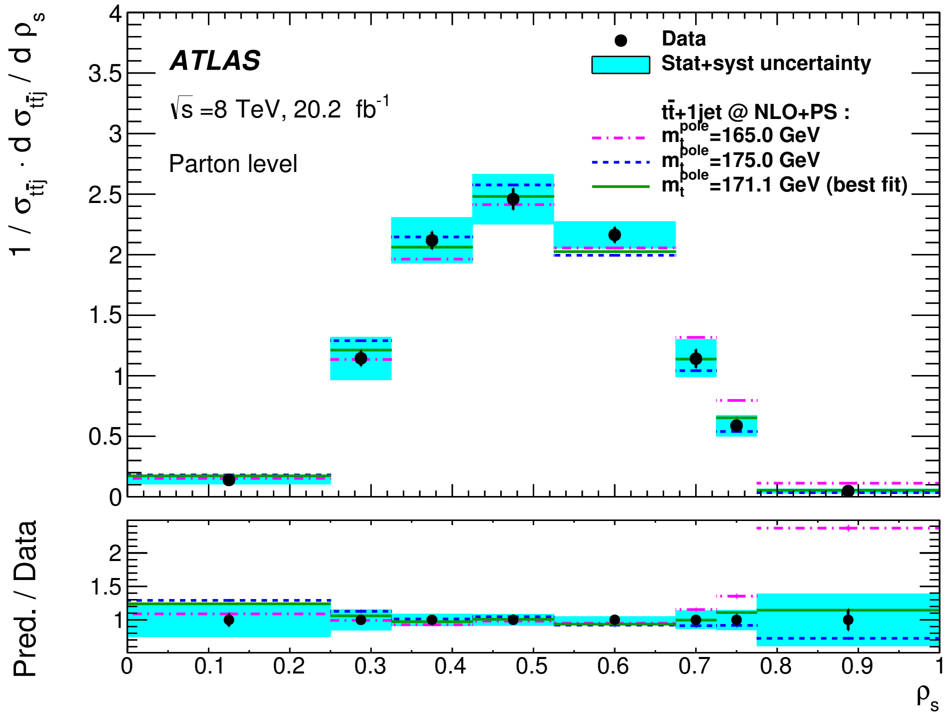

Figure 3. The normalised differential cross section for $pp \to t\bar{t} + 1$-jet production in pp collisions at $\sqrt{s} = 8$ TeV, as a function of ρ_s. The data are unfolded to the parton level as described in the text. The predictions of the NLO+PS calculation of refs. [25, 83] are shown for a top-quark pole mass of 165 GeV, 175 GeV and 171.1 GeV. Statistical errors are represented by error bars, while the shaded area represents the bin-by-bin sum in quadrature of the statistical and systematics uncertainties, as described in section 8. Bin-by-bin correlations are not shown in the plot.

ulations produced with a different matrix-element generator (Powheg and aMC@NLO) are compared to evaluate the uncertainties in the calculation of the matrix elements (*Signal MC generator*). Uncertainties in $t\bar{t}$ modelling coming from the parton shower and hadronisation model (*Shower and hadronisation*) are evaluated by comparing Pythia 6 with Herwig, both interfaced with Powheg. Uncertainties due to the choice of proton PDF (*Proton PDF*) are evaluated following the prescriptions of ref. [87]. Uncertainties coming from the choice of parameter values that control initial- and final-state radiation (*ISR/FSR*), the colour reconnection (*Colour reconnection*) and underlying-event modelling (*Underlying event*) are estimated following the scheme of ref. [88]. The uncertainty in the modelling of background processes is evaluated by varying the normalisation and shape of several sources (*Background*). The normalisation is varied within the cross-section uncertainty for single-top (±7.8%) and V+jets (±33%) backgrounds, while the data-driven multijet contribution is scaled by ±50% [63]. Background shape uncertainties and luminosity uncertainty are found to be negligible.

The uncertainty due to the limited size of the Monte Carlo sample used to unfold the data (*MC statistics*) is evaluated by repeating the unfolding procedure 5000 times, varying the unfolding matrix within its uncertainties.

Finally, additional systematic uncertainties are assigned to the top-quark mass extraction procedure. The top-quark mass value is obtained by fitting the $\mathcal{R}(m_t)$ prediction to the data unfolded at parton level. One uncertainty is assigned to the fit procedure (*Fit parameterisation*) to account for a possible bias from the continuous parameterisation of the theoretical prediction and for non-closure effects. Another uncertainty is assigned to the phase-space correction factor $f^{\text{ph.sp.}}$ (*Unfolding modelling*). It is evaluated as half the difference between top-quark mass results obtained with and without the phase-space correction.

The theoretical uncertainty in the mass consists of two contributions. The uncertainty due to the truncation of the perturbative series is evaluated with the conventional procedure of varying the factorisation (μ_{F}) and renormalisation (μ_{R}) scales by factors of 2 and then 1/2 from the nominal scale $\mu_{\text{F}} = \mu_{\text{R}} = m_t$ (*Scale variations*). The scale uncertainty is taken as the mass shift for the alternative scale choices and is typically asymmetric. A positive (negative) shift of the extracted top-quark mass is found when decreasing (increasing) the renormalisation scale. Additional tests were performed in order to gain confidence in the values presented in table 2. The scale variation has a larger impact in the $\overline{\text{MS}}$ mass scheme, as already observed in ref. [17]. A redundancy exists between the theoretical uncertainty obtained from the scale variations and the one considered by the initial/final radiation, which is not subtracted. The uncertainty due to PDFs and the parametric uncertainty in the strong coupling constant, α_{s}, is evaluated by generating the prediction for three consistent choices of PDF set and α_{s}: CT10nlo with $\alpha_{\text{s}}(m_Z) = 0.118$ (nominal), MSTW2008nlo90cl with $\alpha_{\text{s}}(m_Z) = 0.120$ and NNPDF23 with $\alpha_{\text{s}}(m_Z) = 0.119$. The uncertainty is taken as half the envelope of the mass values extracted from the three choices mentioned above (*Theory PDF*$\oplus\alpha_{\text{s}}$). The total theory uncertainty is obtained by adding the scale and PDF uncertainties in quadrature. The parton shower barely affects the theoretical prediction [11] and its associated uncertainty is negligible.

9 Results

The fit to the parton-level differential cross section yields a top-quark pole mass of

$$m_t^{\text{pole}} = 171.1 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)} \ {}^{+0.7}_{-0.3} \text{ (theo) GeV}. \tag{9.1}$$

The procedure for the extraction of the $\overline{\text{MS}}$ mass with the calculation from ref. [17] is completely analogous to the pole-mass fit described above. The result for the running mass in the $\overline{\text{MS}}$ scheme is:

$$m_t(m_t) = 162.9 \pm 0.5\text{(stat)} \pm 1.0\text{(syst)} \ {}^{+2.1}_{-1.2} \text{ (theo) GeV}.$$

The statistical uncertainty in the mass is evaluated by repeating the unfolding and fit procedure on pseudo-data samples, where the number of events in each bin is varied within the statistical uncertainty. The experimental systematic uncertainty is evaluated as described in section 8 and corresponds to those values quoted in table 2.

Several tests were performed to verify the consistency and robustness of the result.

The measured value of the top-quark mass is stable with respect to variations of the p_{T} cut on the additional jet and the choice of binning of the ρ_{s} variable. The analysis

Mass scheme	$m_t^{\rm pole}$ [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	$(+0.6, -0.2)$	$(+2.1, -1.2)$
Theory PDF$\oplus\alpha_{\rm s}$	0.2	0.4
Total theory uncertainty	$(\mathbf{+0.7}, -0.3)$	$(\mathbf{+2.1}, -1.2)$
Total uncertainty	$(\mathbf{+1.2}, -1.1)$	$(\mathbf{+2.3}, -1.6)$

Table 2. Summary table of the uncertainties in the measurement of the pole mass, $m_t^{\rm pole}$, and the running $\overline{\rm MS}$ mass, $m_t(m_t)$.

is repeated using six bins, eight bins and ten bins. The central values of $m_t^{\rm pole}$ obtained with these different binning configurations agree within 0.3 GeV with the default setup. A higher number of bins increases the sensitivity and leads to a slightly reduced uncertainty of the measurement. However, the use of ten bins is affected by fluctuations in the unfolding procedure and the χ^2, originating from the limited statistics of the available simulations. The result obtained with eight bins is very stable in all aspects of the analysis and therefore this choice is finally adopted. The fits are also repeated excluding different bins in the χ^2 sum, with an agreement of the results obtained within 0.1 GeV.

Correlations between the extracted top-quark mass and the assumed value of m_W used in event selection are negligible.

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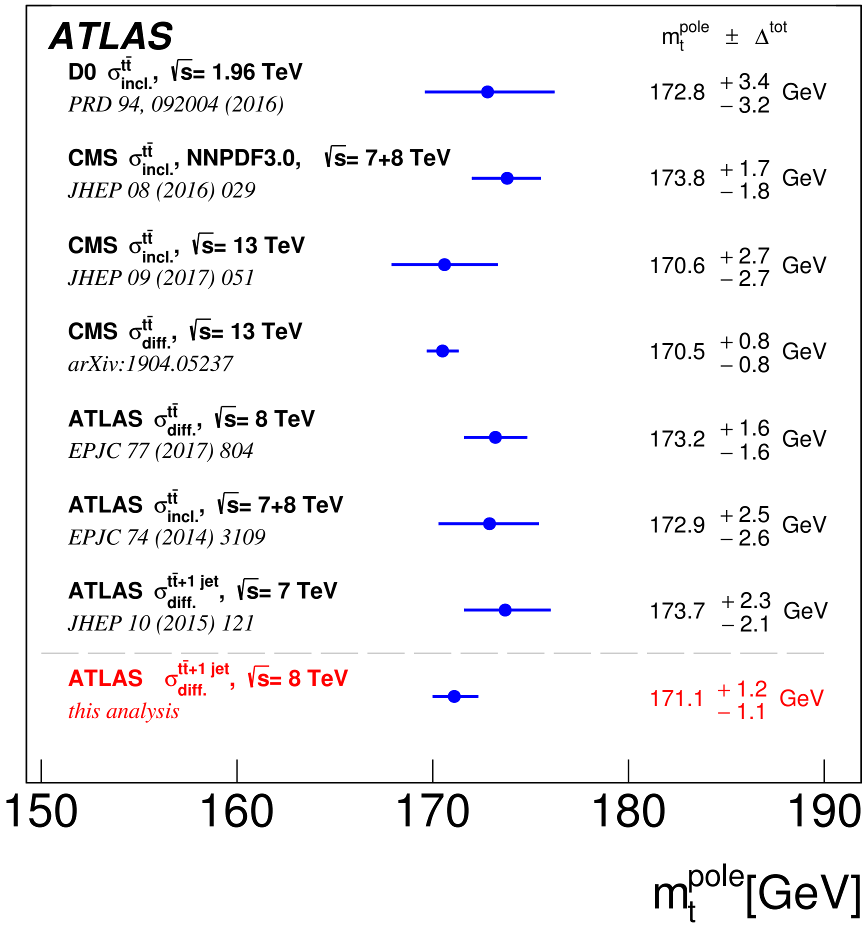

Figure 4. Summary of top-quark pole mass measurements at the Tevatron and the LHC.

The masses extracted from the electron channel and the muon channel separately are compatible. Effects associated to the top-quark finite width, off-shell effects and non-resonant contributions are small and covered by the $t\bar{t}$ MC modelling uncertainties. In addition, the measured top-quark mass is independent of the assumed top-quark mass in the MC simulation that is used to unfold the data. The fit is repeated for MC samples using different top-quark masses between 165 GeV and 180 GeV. For all samples the unfolding is based on MC simulation with a top mass of 172.5 GeV. The difference between simulated top-quark mass and the fit result is found to be compatible with zero over the entire range of top-quark masses tested.

The unfolding procedure is validated using pseudo-data samples which were generated by varying the bin contents of the observable at detector level according to their statistical errors. Pull distributions are produced using these samples. In addition, stress tests are performed to demonstrate that the unfolding procedure is independent of the input distribution. All these tests demonstrate that the analysis procedure is unbiased and correctly estimates the statistical uncertainties.

The assigned theoretical uncertainty to the measured top-quark pole mass is cross-checked in two alternative ways, following the approach applied to the measurement based

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on the data set at 7 TeV centre-of-mass energy [11]:

- The value of the top-quark mass is evaluated based on an LO calculation and compared to the default, which is based on an NLO calculation. The difference is found to be 0.3 GeV and is covered by the assigned uncertainties due to the scale choice.

- An expansion of $\mathcal{R}$ in powers of α_S is performed and the theoretical uncertainty is re-evaluated performing scale variations on the new expression for $\mathcal{R}$. In this way, potential cancellations are avoided which may occur when expanding the numerator and the denominator or $\mathcal{R}$ separately as a function of α_S and can lead to a too optimistic uncertainty. Only the case of m_t^{pole} is considered in this test and the result obtained (+0.4, -0.2) is found to be compatible with that expressed in table 2,

All the above considerations and cross-checks suggest that the error assigned to unknown higher orders gives a reliable estimation of its value.

The scale variation has a larger impact in the $\overline{\text{MS}}$ mass scheme, as already observed in ref. [17].

The top-quark pole mass result obtained from data unfolded to parton level and reported in eq. (9.1) is compatible with previous measurements of the pole mass [8–14], as is shown in figure 4. Compared with the result obtained by ATLAS with the same method at 7 TeV [11] the statistical and systematic uncertainties of the new result are reduced by more than a factor of two.

The $\overline{\text{MS}}$ mass result is translated to the pole-mass scheme using the NLO QCD relationship [18] between the top-quark masses in the two schemes.[9] When converting $m_t(m_t)$ to m_t^{pole} the obtained value is $m_t^{\text{pole}} \approx 170.9$ GeV, which is in good agreement with the direct extraction of the pole mass. The measurements of m_t^{pole} and $m_t(m_t)$ are therefore fully compatible.

10 Conclusions

In this paper, the normalised differential cross section, $\mathcal{R}$, of top-quark pair production in association with an energetic jet is presented as a function of the inverse of the invariant mass of the $t\bar{t}+1$-jet system $\rho_s = 2m_0/m_{t\bar{t}+1\text{-jet}}$. The measurement is performed using pp collision data at a centre-of-mass energy of 8 TeV collected by the ATLAS experiment at the LHC in 2012. The data sample corresponds to an integrated luminosity of 20.2 fb^{-1}. The distribution of $\mathcal{R}$ observed in the semileptonic final state is unfolded to the parton and particle levels. The result from data unfolded to parton level is compared with the NLO

[9]The QCD relation between the two schemes is known to four loops, but here the series is truncated at two loops to match the precision of the $t\bar{t}+1$-jet cross section that was used to extract the mass in both schemes. The relationship between the two masses then takes the simple form:

$$m_t^{\text{pole}} = m_t(m_t)\left(1 + \frac{4}{3}\,\frac{\alpha_s\,(\mu = m_t)}{\pi}\right) + \mathcal{O}(\alpha_s^2).$$

The pole mass result quoted in the text is obtained for $\alpha_s(163\text{ GeV}) \sim 0.116$.

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QCD predictions in two different renormalisation schemes. The top-quark running mass in the $\overline{\text{MS}}$ scheme yields the following value:

$$m_t(m_t) = 162.9 \pm 0.5 \text{ (stat)} \pm 1.0 \text{ (syst)} \; {}^{+2.1}_{-1.2} \text{ (theo)} \; \text{GeV}.$$

The top-quark mass extracted in the pole-mass scheme yields

$$m_t^{\text{pole}} = 171.1 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)} \; {}^{+0.7}_{-0.3} \text{ (theo) GeV}$$

with a total uncertainty of $\Delta m_t^{\text{pole}} = {}^{+1.2}_{-1.1}$ GeV.

The result for $m_t(m_t)$ suffers from a larger theoretical uncertainty as compared with the pole mass. This is due to a larger dependence on the renormalisation and factorisation scales of the $\overline{\text{MS}}$ scheme in the most sensitive region close to the $t\bar{t} + 1$-jet threshold.

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