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Measurement of the top quark mass in the $t\bar{t} \to$ dilepton channel from $\sqrt{s} = 8$ TeV ATLAS data

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Abstract

The top quark mass is measured in the $t\bar{t} \to$ dilepton channel (lepton $= e, \mu$) using ATLAS data recorded in the year 2012 at the LHC. The data were taken at a proton–proton centre-of-mass energy of $\sqrt{s} = 8$ TeV and correspond to an integrated luminosity of about 20.2 fb^{-1}. Exploiting the template method, and using the distribution of invariant masses of lepton–b-jet pairs, the top quark mass is measured to be $m_{\text{top}} = 172.99 \pm 0.41$ (stat) ± 0.74 (syst) GeV, with a total uncertainty of 0.84 GeV. Finally, a combination with previous ATLAS m_{top} measurements from $\sqrt{s} = 7$ TeV data in the $t\bar{t} \to$ dilepton and $t\bar{t} \to$ lepton+jets channels results in $m_{\text{top}} = 172.84 \pm 0.34$ (stat) ± 0.61 (syst) GeV, with a total uncertainty of 0.70 GeV.

1 Introduction

The mass of the top quark (m_{top}) is an important parameter of the Standard Model (SM) of particle physics. Precise measurements of m_{top} provide crucial information for global fits of electroweak parameters [1–3] which help assess the internal consistency of the SM and to probe its extensions. In addition, the value of m_{top} affects the stability of the SM Higgs potential, which has cosmological implications [4–6]. Many measurements of m_{top} have been performed by the Tevatron and LHC collaborations. Combining a selection of those, the first Tevatron+LHC m_{top} result is m_{top} = 173.34 ±0.27 (stat) ±0.71 (syst) GeV, with a total uncertainty of 0.76 GeV [7]. Meanwhile, a number of new results have become available [8–13], some of which are more precise than the above combination. The latest ATLAS results in the $t\bar{t} \rightarrow$ lepton+jets and $t\bar{t} \rightarrow$ dilepton decay channels, both with electrons (e) and muons (μ) in the final state [14], are m_{top} = 172.33 ± 0.75 (stat) ± 1.02 (syst) GeV and m_{top} = 173.79 ± 0.54 (stat) ± 1.30 (syst) GeV, respectively.

This Letter presents a new measurement of m_{top} obtained in the $t\bar{t} \rightarrow$ dilepton decay channel using 2012 data taken at a proton–proton (pp) centre-of-mass energy of $\sqrt{s}$ = 8 TeV, with an integrated luminosity of about 20.2 fb^{-1}. The analysis exploits the decay $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$, which is realised when both W bosons decay into a charged lepton and its corresponding neutrino. In the analysis, the $t\bar{t}$ decay channels ee, $e\mu$ and $\mu\mu$ (including $\tau \rightarrow e, \mu$) are combined and referred to as the dilepton channel. Single-top-quark events with the same lepton final states are included in the signal. Given the larger data sample compared to Ref. [14], the event selection was optimised to achieve the smallest total uncertainty. The measurement is based on the implementation of the template method described in Ref. [14], which is calibrated using signal Monte Carlo (MC) samples. Consequently, the top quark mass measured in this way corresponds to the mass definition used in the MC program.

2 ATLAS detector

The ATLAS experiment [15] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each. Its bending power is in the range from 2.0 to 7.5 T m. It includes a system of precision tracking chambers and fast detectors for triggering. A three-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted

[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 $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

event rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted rate to 400 Hz on average depending on the data-taking conditions during 2012.

3 Data and MC samples

This analysis is based on pp collision data recorded in 2012 at $\sqrt{s}$ = 8 TeV. The integrated data luminosity amounts to 20.2 fb^{-1} with an uncertainty of 1.9% determined with the procedures described in Ref. [16].

The modelling of $t\bar{t}$ and single-top-quark signal events and of most background processes relies on MC simulations. For the simulation of signal events the Powheg-Box program [17–19] is used. The simulation of the top quark pair [20] and single-top-quark production in the Wt-channel [21] uses matrix elements at next-to-leading order (NLO) in the strong coupling constant α_S, with the NLO CT10 [22] parton distribution function (PDF) and the parameter $h_{\mathrm{damp}} = \infty$. The h_{damp} parameter sets the resummation scale, which controls the transition from the matrix element to the parton shower (PS) simulation. Given that the event selection described below requires leptonic decay products of two W bosons, single-top-quark events in the s-channel and t-channel are found not to contribute to the sample.

The Pythia (v6.425) program [23] with the P2011C [24] set of tuned parameters (tune) and the corresponding CTEQ6L1 PDF [25] are employed to provide the parton shower, hadronisation and underlying-event modelling. The uncertainties due to QCD initial- and final-state radiation (ISR/FSR) modelling are estimated with samples generated with the Powheg-Box program interfaced to the Pythia program for which the parameters of the generation are varied to span the ranges compatible with the results of measurements of $t\bar{t}$ production in association with jets [26–28].

For m_{top} hypothesis testing, the $t\bar{t}$ and single-top-quark event samples are generated for five values of m_{top} in the range 167.5 to 177.5 GeV in steps of 2.5 GeV. For each m_{top} value, the MC samples are normalised according to the best available cross-section calculations, which for m_{top} = 172.5 GeV are $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb [29–34] for $t\bar{t}$ production and $\sigma_{Wt} = 22.4 \pm 1.5$ pb [35] for single-top-quark production in the Wt-channel. The PDF+α_S-induced uncertainties in these cross-sections are calculated using the PDF4LHC prescription [36] with the MSTW2008 68% CL NNLO PDF [37, 38], CT10 NNLO PDF [22, 39] and NNPDF2.3 5f FFN PDF [40], and are added in quadrature with the uncertainties due to the choices of the factorisation and renormalisation scales.

The simulation of $W^{\pm}$ or Z boson production in association with jets is performed with the Alpgen (v2.13) program [41] interfaced to the Pythia6 program using the CTEQ6L1 PDF and the corresponding AUET2 tune [42]. Diboson production processes (WW, WZ and ZZ) are simulated using the Alpgen program interfaced to the Herwig (v6.520) program [43] with the AUET2 tune and to the Jimmy (v4.31) program [44]. All samples are simulated taking into account the effects of multiple soft pp interactions (pile-up) registered in the 2012 data. These interactions are modelled by overlaying simulated hits from events with exactly one inelastic (signal) collision per bunch crossing with hits from minimum-bias events that are produced with the Pythia (v8.160) program [45] using the A2M tune [46] and the MSTW2008 LO PDF. For this analysis, the observed values of the pile-up-related quantities $\langle\mu\rangle$, the mean number of interactions per bunch crossing, and n_{vtx}, the average number of vertices per event, are $\langle\mu\rangle$ = 20.7 and n_{vtx} = 9.2.

Finally, the samples undergo a simulation of the ATLAS detector [47] based on Geant4 [48], and are then processed through the same reconstruction software as the data. A number of samples used to assess systematic uncertainties are produced with a faster version of the simulation which, in addition to the full simulation of the tracking, uses smearing functions and interpolates particle behaviour and calorimeter response, based on resolution functions measured in full-simulation studies, to approximate the results of the full simulation.

4 Data selection and event reconstruction

Triggers based on isolated single electrons or muons with energy or momentum thresholds of 24 GeV are used. The detector objects resulting from the top quark pair decay are electron and muon candidates, jets and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). In the following, the term lepton is used for charged leptons (excluding τ leptons) exclusively.

Electron candidates [49] are required to have a transverse energy of $E_{\mathrm{T}} > 25$ GeV, a pseudorapidity of the corresponding EM cluster of $|\eta_{\mathrm{cluster}}| < 2.47$, with the transition region $1.37 < |\eta_{\mathrm{cluster}}| < 1.52$ between the barrel and the end-cap calorimeter excluded. The muon candidates [50] are required to have transverse momentum $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. To reduce the contamination by leptons from heavy-flavour decays inside jets or from photon conversions, referred to as non-prompt (NP) leptons, strict isolation criteria are applied to the amount of activity in the vicinity of the lepton candidate [49, 50].

Jets are built from topological clusters of calorimeter cells [51] with the anti-k_t jet clustering algorithm [52] using a radius parameter of $R = 0.4$. Jets are reconstructed using the local cluster weighting (LCW) and global sequential calibration (GSC) algorithms [53–55] and required to satisfy $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. Muons reconstructed within a $\Delta R = 0.4$ cone around the axis of a jet with $p_{\mathrm{T}} > 25$ GeV are not considered as charged-lepton candidates. In addition, jets within a $\Delta R = 0.2$ cone around an electron candidate are removed and finally electrons within a $\Delta R = 0.4$ cone around any of the remaining jets are discarded. The identification of jets containing b-hadrons, b-tagging, is used for event reconstruction and background suppression. In the following, irrespective of their origin, jets tagged by the b-tagging algorithm are referred to as b-tagged jets, whereas those not tagged are referred to as untagged jets. Similarly, whether they are tagged or not, jets originating from bottom quarks are referred to as b-jets and those from (u, d, c, s)-quarks or gluons as light jets. The working point of the neural-network-based MV1 b-tagging algorithm [56] corresponds to an average b-tagging efficiency of 70% for b-jets in simulated $t\bar{t}$ events and rejection factors of 5 for jets containing a c-hadron and 137 for jets containing only lighter-flavour hadrons. To match the b-tagging performance in the data, p_{T}- and η-dependent scale factors [56], obtained from dijet and $t\bar{t} \to$ dilepton events, are applied to MC jets depending on their true flavour. The reconstruction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is based on the vector sum of energy deposits in the calorimeters, projected onto the transverse plane. Muons are included in the $E_{\mathrm{T}}^{\mathrm{miss}}$ using their reconstructed momentum in the tracking detectors [57].

The contribution of events wrongly reconstructed as $t\bar{t} \to$ dilepton events due to the presence of objects misidentified as leptons (fake leptons), is estimated from data [58]. The technique employed uses fake-lepton and real-lepton efficiencies that depend on η and p_{T}, measured in a background-enhanced control region with low $E_{\mathrm{T}}^{\mathrm{miss}}$ and from events with dilepton masses around the Z peak [59].

The selection from Ref. [14] is applied as a pre-selection as follows:

1. Events are required to have a signal from the single-electron or single-muon trigger and at least one primary vertex with at least five associated tracks.

Selection	Pre-selection	Final selection
Data	36359	9426
$t\bar{t}$ signal	34300 ± 2700	9670 ± 770
Single-top-quark signal	1690 ± 110	363 ± 23
Fake leptons	240 ± 240	31 ± 31
Z+jets	212 ± 83	20.6 ± 8.5
$WW/WZ/ZZ$	57 ± 21	10.2 ± 3.8
Signal+background	36600 ± 2800	10100 ± 770
Expected background fraction	0.01 ± 0.01	0.01 ± 0.00
Data / (Signal+background)	0.99 ± 0.07	0.93 ± 0.07
Matching efficiency [%]	78.4 ± 0.2	95.3 ± 0.4
Selection purity [%]	51.6 ± 0.1	69.8 ± 0.3
Unmatched events [%]	34.2 ± 0.1	26.7 ± 0.1
Wrongly matched events [%]	14.2 ± 0.1	3.4 ± 0.0

Table 1: The observed numbers of events in data after the pre-selection and the final selection. In addition, the expected numbers of signal events for m_{top} = 172.5 GeV and background events corresponding to the integrated data luminosity are given. Two significant digits are used for the uncertainties of the predicted numbers of events explained in the text. The lower rows report the matching performance evaluated for m_{top} = 172.5 GeV, using one significant digit for the statistical uncertainties.

2. Exactly two oppositely charged leptons are required, with at least one of them matching the reconstructed object that fired the corresponding trigger.

3. In the same-lepton-flavour channels, ee and $\mu\mu$, $E_{\text{T}}^{\text{miss}} > 60$ GeV is required. In addition, the invariant mass of the lepton pair must satisfy $m_{\ell\ell} > 15$ GeV, and must not be compatible with the Z mass within 10 GeV.

4. In the $e\mu$ channel the scalar sum of p_{T} of the two selected leptons and all jets is required to be larger than 130 GeV.

5. The presence of at least two jets with $p_{\text{T}} > 25$ GeV and $|\eta| < 2.5$ is required, and at least one of these jets has to be b-tagged.

The observed numbers of events in the data after this pre-selection, together with the expected numbers of signal and background events corresponding to the integrated data luminosity, are given in Table 1. Assuming a top quark mass of m_{top} = 172.5 GeV, the predicted number of events is consistent with the one observed in the data within uncertainties. For all predictions, the uncertainties are estimated as the sum in quadrature of the statistical uncertainty, a 1.9% uncertainty in the integrated luminosity, and a number of additional components. For the signal, these are a 5.4% uncertainty in the $t\bar{t}$ cross-section, or a 6.0% uncertainty in the single-top-quark cross-section, as given in Sect. 3. Finally, global 4.1%, 2.2% and 2.8% uncertainties are added, corresponding to the envelopes of the results from the eigenvector variations of the jet energy scale (JES), the relative b-to-light-jet energy scale (bJES) and the b-tagging scale factors, respectively. The background uncertainties contain jet-multiplicity-dependent uncertainties of about 40% in the normalisation of the Z+jets background and a 100% uncertainty in the normalisation of fake-lepton background.

The two jets carrying the highest MV1 weight are taken as the two b-jets originating from the decays of the two top quarks, and the two leptons are taken as the leptons from the leptonic W decays. From the two possible assignments of the two pairs, the combination leading to the lowest average invariant

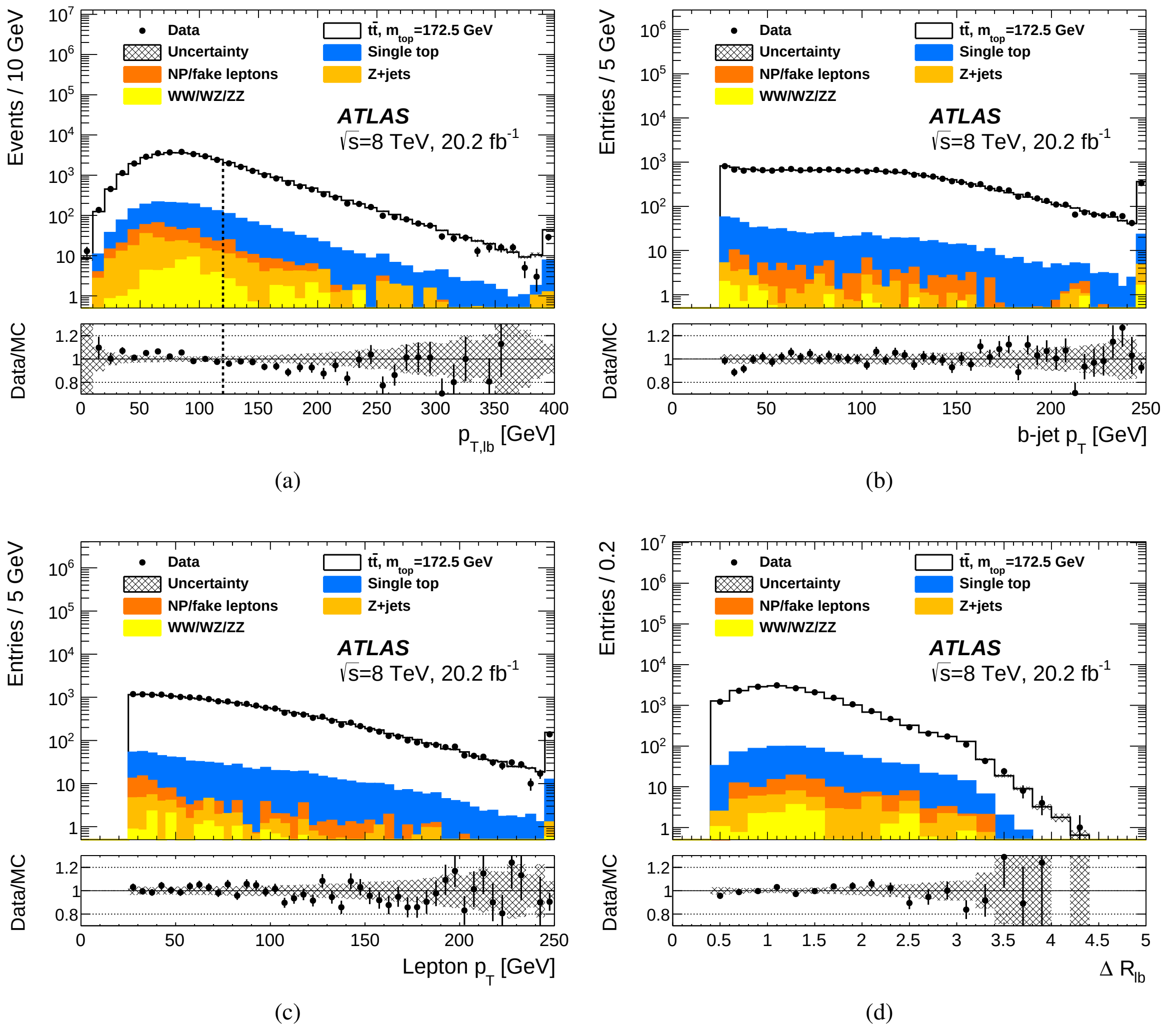


Figure 1: Kinematic distributions obtained from the objects assigned to the two lepton–b-jet pairs for (a) the pre-selection, or (b)–(d) the final selection. The average p_{T} of the two lepton–b-jet pairs, denoted by $p_{\mathrm{T},\ell b}$, is shown in (a). The $p_{\mathrm{T},\ell b}$ requirement for the final selection is indicated by the vertical dashed line. The remaining distributions show the p_{T} of the b-jets in (b), the p_{T} of the leptons in (c), and the $\Delta R_{\ell b}$ of the lepton and the b-jet for the two lepton–b-jet pairs in (d). The rightmost bin contains the overflow, if present. For all distributions, the number of predicted events is normalised to the one observed in the data. The hatched area corresponds to the statistical uncertainties in the prediction, the uncertainty bars to the statistical uncertainties in the data. For each figure, the ratio of data and prediction is also presented.

mass of the two lepton–b-jet pairs ($m_{\ell b}$) is retained. To estimate the performance of this algorithm in MC simulated samples, the reconstruction-level objects are matched to the closest generator-level object based on a maximum allowed ΔR, being 0.1 for leptons and 0.3 for jets. A matched object is defined as a reconstruction-level object that falls within ΔR of any generator-level object of that type, and a correct match means that this generator-level object is the one it originated from. Due to acceptance losses and reconstruction inefficiency, not all reconstruction-level objects can successfully be matched to their generator-level counterparts, resulting in unmatched events. The matching efficiency is the fraction of correctly matched events among all the matched events, and the selection purity is the fraction of correctly matched events among all events, regardless of whether they could be matched or not. The corresponding numbers for $m_{\mathrm{top}} = 172.5$ GeV are reported in Table 1.

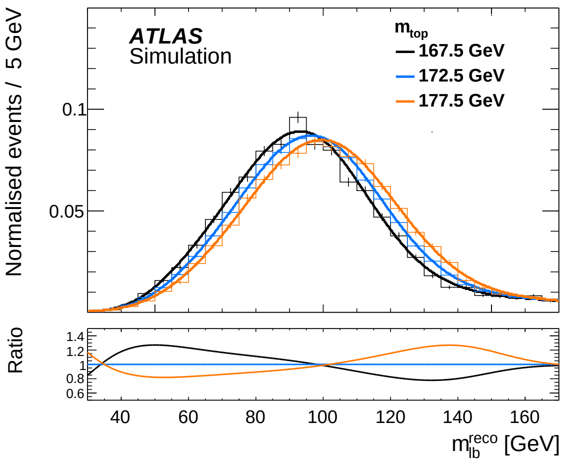
Starting from this pre-selection, an optimisation of the total uncertainty in m_{top} is performed. A phase-space restriction based on the average p_{T} of the two lepton–b-jet pairs ($p_{\mathrm{T},\ell b}$) is used to obtain the smallest total uncertainty in m_{top}. The corresponding $p_{\mathrm{T},\ell b}$ distribution is shown in Fig. 1(a). The smallest uncertainty in m_{top} corresponds to $p_{\mathrm{T},\ell b} > 120$ GeV. The difference in shape between data and prediction is covered by the systematic uncertainty as detailed in Sect. 6. This restriction is found to also increase the fraction of correctly matched events in the $t\bar{t}$ sample, and reduces the number of unmatched or wrongly matched events.

To perform the template parameterisation described in Sect. 5, an additional selection criterion is applied, restricting the reconstructed $m_{\ell b}$ value ($m_{\ell b}^{\mathrm{reco}}$) to the range 30 GeV $< m_{\ell b}^{\mathrm{reco}} <$ 170 GeV. Applying both restrictions, the numbers of predicted and observed events resulting from the final selection are reported in Table 1. Using this optimisation, the matching efficiency and the sample purity are much improved as reported in the bottom rows of Table 1, while retaining about 26% of the events. Using this selection, and the objects assigned to the two lepton–b-jet pairs, the kinematic distributions in the data are well described by the predictions, as shown in Fig. 1 for the transverse momenta of b-jets and leptons, and for the $\Delta R_{\ell \mathrm{b}}$ of the two lepton–b-jet pairs.

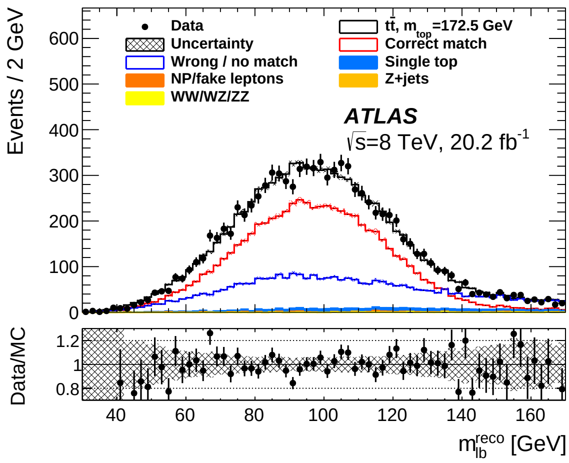
5 Template fit and results in the data

The implementation of the template method used in this analysis is described in Ref. [14]. For this analysis, the templates are simulated distributions of $m_{\ell b}^{\mathrm{reco}}$, constructed for a number of discrete values of m_{top}. Appropriate functions are fitted to these templates, interpolating between different input m_{top}. The remaining parameters of the functions are fixed by a simultaneous fit to all templates, imposing linear dependences of the parameters on m_{top}. The resulting template fit function has m_{top} as the only free parameter and an unbinned likelihood maximisation gives the value of m_{top} that best describes the data. Statistically independent signal templates, comprising $t\bar{t}$ and single-top-quark events, are constructed as a function of the top quark mass used in the MC generator. Within the statistical uncertainties, the sum of a Gaussian distribution and a Landau function gives a good description of the shape of the $m_{\ell b}^{\mathrm{reco}}$ distribution as shown in Fig. 2(a) for three values of m_{top}. With this signal choice, the background distribution is independent of m_{top}, and a Landau function is fitted to it. The sum of the signal template at $m_{\mathrm{top}} = 172.5$ GeV and the background is compared to data in Fig. 2(b). It gives a good description of the data except for differences that can be accounted for by a different top quark mass. In this distribution, the correctly matched events are concentrated in the central part, whereas the remainder is less peaked and accounts for most of the tails.

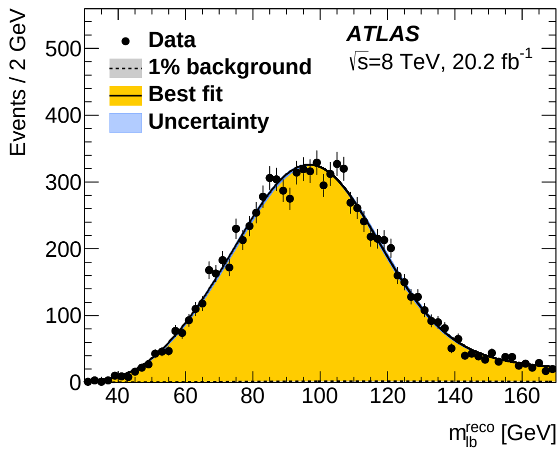
In this analysis the expected statistical precision as well as all systematic uncertainties are obtained from pseudo-experiments generated from MC simulated samples mimicking ATLAS data. To verify the internal consistency of the method, 1000 pseudo-experiments per mass point are performed, correcting for oversampling [60]. Within uncertainties, and for all m_{top} values, the residuals and pull means are consistent with zero and the pull widths are consistent with unity, i.e. the estimator is unbiased and uncertainties are calculated properly. The expected statistical uncertainty is obtained from the distribution of the statistical uncertainty in the fitted m_{top} of the pseudo-experiments. For $m_{\mathrm{top}} = 172.5$ GeV and the data luminosity it amounts to 0.41 ± 0.03 GeV, where the quoted precision is statistical. The $m_{\ell b}^{\mathrm{reco}}$ distribution in the data is shown in Fig. 2(c) together with the corresponding fitted probability density functions for the



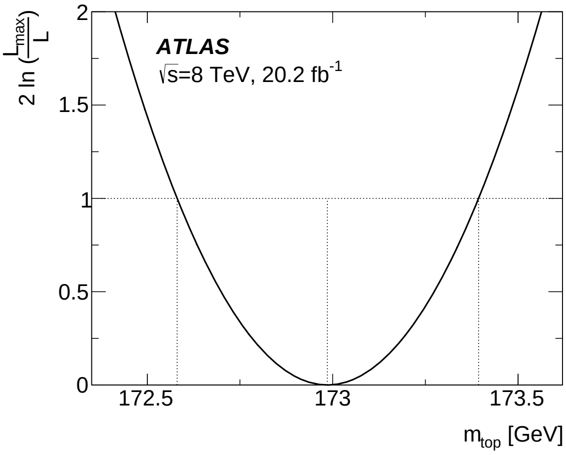
(a) Signal templates in simulation



(b) $m_{\ell b}^{\mathrm{reco}}$ in data and simulation



(c) Fit to $m_{\ell b}^{\mathrm{reco}}$ in data



(d) Logarithm of the likelihood

Figure 2: Simulated signal templates (histograms) for different values of m_{top} together with the template fits (curves) are given in (a). The $m_{\ell b}^{\mathrm{reco}}$ distribution observed in data in comparison to the prediction is shown in (b). Both figures show statistical uncertainties only. In (b) the background contributions are too small to be distinguished. The $m_{\ell b}^{\mathrm{reco}}$ distribution is shown in (c) for data with statistical uncertainties together with the fitted probability density functions for the background alone (barely visible at the bottom of the figure) and for the sum of signal and background. The uncertainty band corresponds to the total uncertainty in m_{top}. Finally, the corresponding logarithm of the likelihood as a function of m_{top} is displayed in (d).

background alone and for the sum of signal and background. The value obtained fixing the background contribution to its prediction is $m_{\text{top}} = 172.99 \pm 0.41$ (stat) GeV. The statistical uncertainty in m_{top} is taken from the parabolic approximation of the logarithm of the likelihood as shown in Fig. 2(d). The observed and predicted values of the statistical uncertainty agree.

6 Uncertainties affecting the m_{top} determination

The same systematic uncertainty sources as in Ref. [14] are investigated. Their impact on the analysis is mostly evaluated from pairs of samples expressing a particular systematic uncertainty, by constructing the corresponding templates and measuring the average difference in m_{top} of the pair from 1000 pseudo-experiments. To facilitate a combination with other results, every systematic uncertainty is assigned a statistical uncertainty, taking into account the statistical correlation of the considered samples. Following Ref. [61], the resulting uncertainty components are given in Table 2 irrespective of their statistical significance. The uncertainty sources are constructed so as to be uncorrelated with each another and thus the total uncertainty squared is calculated as the sum in quadrature of all components. The various sources of systematic uncertainties and the evaluation of their effect on m_{top} are briefly described in the following. The values are given in Table 2.

Method: The mean value of the differences between the fitted and generated m_{top} for the MC samples at various input top quark masses is assigned as the method calibration uncertainty. This also covers effects from limited numbers of MC simulated events in the templates.
Signal Monte Carlo generator: The difference in m_{top} between the event sample produced with the MC@NLO program [62,63] and the default Powheg sample, both generated at $m_{\text{top}} = 172.5$ GeV and using the Herwig program for parton shower, hadronisation and underlying event, is quoted as a systematic uncertainty.
Hadronisation: The difference in m_{top} between samples produced with the Powheg-Box program and showered with either the Pythia6 program using the P2011C tune or the Herwig and Jimmy programs using the ATLAS AUET2 tune [42] is quoted as a systematic uncertainty. This includes different approaches in parton-shower modelling and hadronisation, namely the Lund string model [64, 65] and the cluster model [66]. The difference in shape between data and prediction observed for the $p_{\text{T},\ell b}$ distribution shown in Fig. 1(a) is much reduced when using the Powheg+Herwig sample and therefore covered by this uncertainty. As a check to assess the maximum possible difference in m_{top} caused by the mismodelling of the $p_{\text{T},\ell b}$ distribution, the predicted distribution is reweighted to the data distribution and the fit is repeated. The observed difference in m_{top} from the nominal sample is about 0.2 GeV, well below the statistical uncertainty in the data. Consequently, no additional uncertainty is applied. Finally, the calibration of the JES and bJES, discussed below, is also partially based on a comparison of jet energy responses in event samples produced with the Herwig++ [67] and Pythia6 programs. However, it was verified [68] that the amount of double-counting of JES and hadronisation effects for the $t\bar{t} \rightarrow$ lepton+jets channel is small.
Initial- and final-state QCD radiation (ISR/FSR): The uncertainty due to this effect is evaluated by comparing two dedicated samples generated with the Powheg-Box and Pythia6 programs that differ in several parameters, namely: the QCD scale Λ_{QCD}, the transverse momentum scale for space-like parton-shower evolution Q^2_{max} and the h_{damp} parameter [69]. Half the observed difference between the up variation and the down variation is quoted as a systematic uncertainty. For comparison, using the signal samples generated at $m_{\text{top}} = 172.5$ GeV, and only changing the h_{damp} parameter but using a much larger range, i.e. from ∞ to m_{top}, the measured m_{top} is lowered by 0.23 ± 0.13 GeV, where the uncertainty is

	$\sqrt{s}$ = 7 TeV		$\sqrt{s}$ = 8 TeV	Correlations			Combinations		
	$m_{top}^{\ell+jets}$ [GeV]	m_{top}^{dil} [GeV]	m_{top}^{dil} [GeV]	ρ_{01}	ρ_{02}	ρ_{12}	$m_{top}^{7\,TeV}$ [GeV]	m_{top}^{dil} [GeV]	m_{top}^{all} [GeV]
Results	172.33	173.79	172.99				172.99	173.04	172.84
Statistics	0.75	0.54	0.41	0	0	0	0.48	0.38	0.34
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07	0	0	0	0.07	0.05	0.05
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15	+1.00	+1.00	+1.00	0.24	0.10	0.14
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09	+1.00	+1.00	+1.00	0.34	0.24	0.23
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07	−1.00	−1.00	+1.00	0.04	0.24	0.08
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14	−1.00	−1.00	+1.00	0.06	0.10	0.02
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14	−1.00	−1.00	+1.00	0.01	0.03	0.01
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00	+0.57	−0.29	+0.03	0.17	0.04	0.08
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	+1.00	+0.23	+0.23	0.07	0.03	0.04
W/Z+jets shape	0.29 ± 0.00	0.00 ± 0.00	0	0			0.16	0.00	0.09
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00	+0.23	+0.20	−0.08	0.03	0.07	0.05
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04	−0.23	+0.06	+0.35	0.41	0.52	0.41
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01	+1.00	+1.00	+1.00	0.34	0.32	0.25
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05	−1.00	0	0	0.03	0.08	0.08
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00	+1.00	+1.00	+1.00	0.10	0.01	0.04
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	−1.00	+1.00	−1.00	0.00	0.02	0.02
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02	−0.77	0	0	0.25	0.03	0.15
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01	−0.34	−0.52	+0.96	0.05	0.14	0.09
E_T^{miss}	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01	−0.15	+0.25	−0.24	0.08	0.01	0.05
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01	0	0	0	0.01	0.05	0.03
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29				0.77	0.74	0.61
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29	−0.07	0.00	0.51	0.91	0.84	0.70

Table 2: The three measured values of m_{top} together with their statistical and systematic uncertainty components are shown on the left. The middle part reports the estimated correlations ρ_{ij} per pair of measurements, with 0, 1 and 2 denoting the ℓ+jets and dilepton measurements at $\sqrt{s}$ = 7 TeV (from Ref. [14]) and the dilepton measurement at $\sqrt{s}$ = 8 TeV, respectively. Finally, the right part lists the m_{top} results for the combinations of the two measurements at $\sqrt{s}$ = 7 TeV, the two measurements in the dilepton channel and all measurements. For the individual measurements, the systematic uncertainty in m_{top} and its associated statistical uncertainty is given for each source of uncertainty. Assigned correlations are given as integer values, determined correlations as real values. The last line refers to the sum in quadrature of the statistical and systematic uncertainty components or the total correlations, respectively.

statistical.

Underlying event (UE): The difference in UE modelling is assessed by comparing POWHEG samples based on the same partonic events generated with the CT10 PDFs. The difference in $m_{\rm top}$ for a sample with the Perugia 2012 tune (P2012) and a sample with the P2012 mpiHi tune [24] is assigned as a systematic uncertainty.

Colour reconnection (CR): This systematic uncertainty is estimated using samples with the same partonic events as for the UE uncertainty evaluation, but with the P2012 tune and the P2012 loCR tune [24] for PS and hadronisation. The difference in $m_{\rm top}$ is quoted as a systematic uncertainty.

Parton distribution function (PDF): The PDF systematic uncertainty is the sum in quadrature of three contributions. These are: the sum in quadrature of the differences in $m_{\rm top}$ for the 26 eigenvector variations of the CTEQ PDF [25] and two differences in $m_{\rm top}$ obtained from reweighting the central CT10 PDF set to the MSTW2008 PDF [37] and the NNPDF23 PDF [40].

Background normalisation: The normalisations are varied simultaneously for the MC-based and the data-driven background estimates according to the above mentioned uncertainties.

Background shapes: Given the negligible uncertainty in the dilepton channel observed in Ref. [14], no shape uncertainty is evaluated for the MC-based background. For the data-driven background the shape uncertainty is obtained from the estimate of fake-lepton events using the matrix method [58].

Jet energy scale (JES): Mean jet energies are measured with a relative precision of about 1% to 4%, typically falling with jet $p_{\rm T}$ and rising with jet $|\eta|$ [70, 71]. The large number of subcomponents of the total JES uncertainty are reduced by a matrix diagonalisation of the full JES covariance matrix. For each of the resulting 25 significant nuisance parameters [54] the corresponding uncertainty in $m_{\rm top}$ is calculated. The total JES-induced uncertainty in $m_{\rm top}$ is obtained by the sum in quadrature of the results for the subcomponents.

Relative *b*-to-light-jet energy scale (bJES): The bJES is an additional uncertainty for the remaining differences between b-jets and light jets after the global JES is applied and therefore the corresponding uncertainty is uncorrelated with the JES uncertainty. Jets containing b-hadrons are assigned an additional uncertainty of 0.2% to 1.2%, with lowest uncertainties for high-$p_{\rm T}$ b-jets [54].

Jet energy resolution (JER): The JER uncertainty is determined by the sum in quadrature of the $m_{\rm top}$ differences between the varied samples and the nominal sample or, where applicable, half the fitted difference between the up variation and the down variation of the components of the eigenvector decomposition.

Jet reconstruction efficiency (JRE): The JRE uncertainty is evaluated by randomly removing 2% of the jets with $p_{\rm T} < 30$ GeV from the MC simulated events prior to the event selection to reflect the precision with which the data-to-MC JRE ratio is known [53]. The $m_{\rm top}$ difference with respect to the nominal sample is taken as a systematic uncertainty.

Jet vertex fraction (JVF): When summing the scalar $p_{\rm T}$ of all tracks in a jet, the JVF is the fraction contributed by tracks originating at the primary vertex. The uncertainty is evaluated by varying the requirement on the JVF within its uncertainty [72].

***b*-tagging:** Mismodelling of the b-tagging efficiency and mistag rate is accounted for by the application of scale factors which depend on jet $p_{\rm T}$ and jet η to MC simulated events [56]. The eigenvector decomposition [56, 73] accounts for the uncertainties in the b-tagging, c/τ-tagging and mistagging scale factors. The final b-tagging uncertainty is the sum in quadrature of these uncorrelated components.

Lepton uncertainties: The lepton uncertainties measured in $J/\psi \to \ell\ell$ and $Z \to \ell\ell$ events are related to the electron energy or muon momentum scales and resolutions, and the trigger and identification efficiencies [49, 50, 74]. For each component, the corresponding uncertainty is propagated to the analysis including the recalculation of the $E_{\rm T}^{\rm miss}$.

Missing transverse momentum ($E_{\rm T}^{\rm miss}$): The remaining contribution to the $E_{\rm T}^{\rm miss}$ uncertainty stems from the uncertainties in calorimeter cell energies associated with low-$p_{\rm T}$ jets (7 GeV $< p_{\rm T} <$ 20 GeV), without any corresponding reconstructed physics object or from pile-up interactions. Their impact is accounted for as described in Ref. [57].

Pile-up: Besides the component treated in the JES, the residual dependence of the fitted m_{top} on the amount of pile-up activity and a possible MC mismodelling is determined. The m_{top} dependence as functions of n_{vtx} and $\langle\mu\rangle$ is found to be consistent in data and simulation. The corresponding uncertainty evaluated from the remaining difference is small.

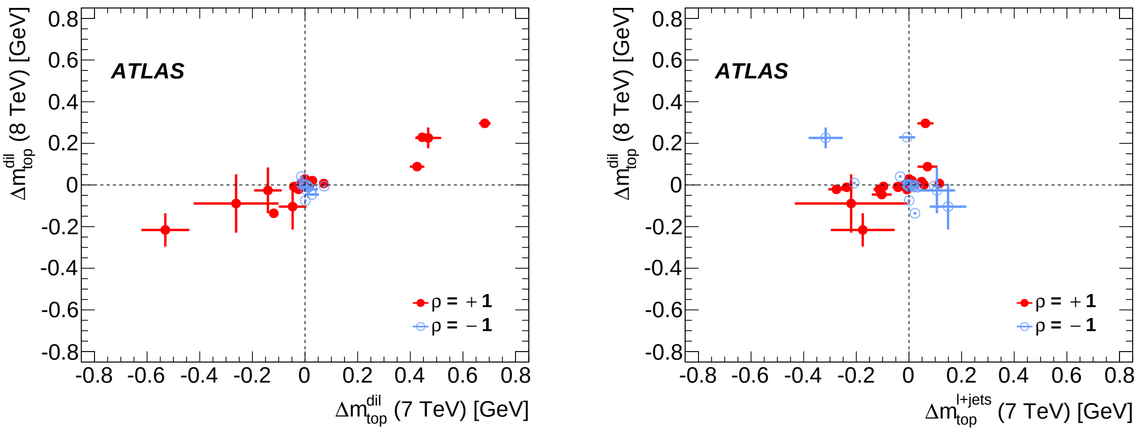
The systematic uncertainties quoted in Table 2 carry statistical uncertainties. The statistical precision of a single sample fit is about 100 MeV. The statistical correlation of the samples is calculated from the fraction of shared events. Pairs of samples with only a change in a single parameter have high correlation and correspondingly low statistical uncertainty in the difference in m_{top}, while a pair of statistically independent samples results in a larger uncertainty.

In summary, the result in the dilepton channel at $\sqrt{s}$ = 8 TeV of m_{top} = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV is about 40% more precise than the one obtained from the $\sqrt{s}$ = 7 TeV data and the most precise single result in this decay channel to date. The increased precision is partly driven by a better knowledge of the JES and bJES. In addition, the applied optimisation procedure significantly reduces the total systematic uncertainty, mostly due to a lower impact of the JES and theory modelling uncertainties.

7 Combination with previous ATLAS measurements

The combination of the m_{top} results follows the approach developed for the combination of the $\sqrt{s}$ = 7 TeV measurements in Ref. [14] including the evaluation of the correlations. For combining the measurements from data at different centre-of-mass energies a mapping of uncertainty categories is performed. Complex cases are the uncertainty components involving eigenvector decompositions such as the JES, the JER and the b-tagging scale factor uncertainties. The $\sqrt{s}$ = 7 and 8 TeV measurements are treated as uncorrelated for the nuisance parameters of the JER and the b-tagging, c/τ-tagging and mistagging uncertainties. A correlated treatment of the estimators for the flavour-tagging nuisance parameters results in an insignificant change in the combination. The total JES uncertainty consists of about 20 eigenvector components, which partly differ for the analyses of $\sqrt{s}$ = 7 and 8 TeV data, which make use of the EM+JES and the LCW+GSC [70] jet calibrations, respectively. For the combination, a mapping between uncertainty components at the different centre-of-mass energies is employed to identify the corresponding ones. The combination was found to be stable against variations of the assumptions for ambiguous cases.

The combination is performed using the best linear unbiased estimate (BLUE) method [75, 76], implying Gaussian probability density functions for all uncertainties, using the implementation described in Ref. [77]. The central values, the list of uncertainty components and the correlations ρ of the estimators for each uncertainty component have to be provided. For the statistical, method calibration, MC-based background shape at $\sqrt{s}$ = 7 TeV, and pile-up uncertainties in m_{top} the measurements are assumed to be uncorrelated. For the remaining uncertainties in m_{top}, when using $\pm 1\sigma$ variations of a systematic effect, e.g. when changing the bJES by $\pm 1\sigma$, there are two possibilities. When simultaneously applying a variation for a systematic uncertainty, e.g. $+1\sigma$ for the bJES to a pair of analyses, e.g. the dilepton measurements at $\sqrt{s}$ = 7 and 8 TeV, both analyses can result in a larger or smaller m_{top} value than what is obtained for the nominal case (full correlation, $\rho = +1$), or one analysis can obtain a larger and the other



(a) $\sqrt{s}$ = 7 TeV versus $\sqrt{s}$ = 8 TeV dilepton

(b) $\sqrt{s}$ = 7 TeV ℓ+jets versus $\sqrt{s}$ = 8 TeV dilepton

Figure 3: The pairwise differences in m_{top} when simultaneously varying both analyses for a systematic uncertainty. Each cross indicates the statistical precisions of the systematic uncertainty. The red full points indicate $\rho = 1$, the blue open points $\rho = -1$.

a smaller value (full anti-correlation, $\rho = -1$). Consequently, an uncertainty from a source only consisting of a single variation, such as the uncertainty related to the choice of MC generator for signal events, results in a correlation of $\rho = \pm 1$. The estimator correlations for composite uncertainties are evaluated by adding the covariance terms of the subcomponents i with $\rho_i = \pm 1$ and dividing by the total uncertainties for that source. The resulting estimator correlation per uncertainty is quoted in Table 2 and used in the combination.

The evaluated uncertainties in m_{top} for the uncertainty components for the two dilepton analyses, denoted by $\Delta m_{\mathrm{top}}^{\mathrm{dil}}$, are shown in Fig. 3(a). Each point represents a systematic uncertainty together with a cross, indicating the respective statistical precision of the systematic uncertainty in the two analyses. The red full points indicate $\rho = 1$, the blue open points $\rho = -1$. Given the similarity of the analyses, a positive estimator correlation is observed for most uncertainty components of the two measurements in the dilepton channel. The corresponding distribution for the ℓ+jets measurement at $\sqrt{s}$ = 7 TeV and the dilepton measurement at $\sqrt{s}$ = 8 TeV is given in Fig. 3(b). In this figure, the estimates are anti-correlated for several significant uncertainties. This is caused by the in-situ measurement of the jet energy scale factor (JSF) and relative b-to-light-jet energy scale factor (bJSF) in the three-dimensional ℓ+jets analysis, detailed in Ref. [14]. The resulting total correlation for this pair is very low as shown in Table 2. The combination strongly profits from this.

The central values of the three measurements, their uncertainty components, the determined correlations per pair of measurements and the results of the combinations are given in Table 2. The pairwise differences in the three measurements are 0.75σ for the $\sqrt{s}$ = 7 TeV measurements, 0.43σ for the ℓ+jets measurement at $\sqrt{s}$ = 7 TeV and the dilepton measurement at $\sqrt{s}$ = 8 TeV and 0.66σ for the two dilepton measurements. For all three cases σ denotes the one standard deviation of the respective m_{top} difference. The combined result in the dilepton channel alone is $m_{\mathrm{top}}^{\mathrm{dil}}$ = 173.04 ± 0.38 (stat) ± 0.74 (syst) GeV = 173.04 ± 0.84 GeV, providing no significant improvement with respect to the more precise result at $\sqrt{s}$ = 8 TeV which carries a BLUE combination weight of 0.94. This is a mere consequence of the measurement correlation of 0.51, which is close to the ratio of uncertainties (see Ref. [76]). The χ^2 probability of the combination is 51%. The stability of the combination is assessed from the results of 1000 combinations for which all input uncertainties are varied within their statistical uncertainties, which for some cases also result in different correlations (see Fig. 3). The corresponding distributions of the central values and uncertainties of the combinations are approximately Gaussian, with a width of 0.03 GeV and of 0.04 GeV, respectively.

The combination of all three measurements provides a 17% improvement with respect to the most precise single input measurement. The combined result is $m_{\text{top}}^{\text{all}} = 172.84 \pm 0.34\ (\text{stat}) \pm 0.61\ (\text{syst})\ \text{GeV} = 172.84 \pm 0.70\ \text{GeV}$. The χ^2 probability of the combination is 73% and the BLUE combination weights of the ℓ+jets and dilepton measurements at $\sqrt{s} = 7$ TeV and the dilepton measurement at $\sqrt{s} = 8$ TeV are 0.30, 0.07 and 0.63, respectively. Again, the central value and the combined total uncertainty are both stable at the level of 0.03 GeV.

8 Conclusion

The top quark mass is measured in the $t\bar{t} \to$ dilepton channel from about 20.2 fb^{-1} of $\sqrt{s} = 8$ TeV proton–proton collision data recorded by the ATLAS detector at the LHC. Compared to the latest ATLAS measurement in this decay channel, the event selection is refined exploiting the average p_{T} of the lepton–b-jet pairs to enhance the fraction of correctly reconstructed events, thereby reducing the systematic uncertainties. Using the optimal point in terms of total uncertainty observed in a phase-space scan of this variable as an additional event selection criterion, the measured value of m_{top} is

$$m_{\text{top}} = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV},$$

with a total uncertainty of 0.84 GeV. The precision is mainly limited by systematic uncertainties, mostly by the calibration of the jet energy scale, and to a lesser extent by the calibration of the relative b-to-light-jet energy scale and by the Monte Carlo modelling of signal events.

This measurement is combined with the ATLAS measurements in the $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ dilepton decay channels from $\sqrt{s} = 7$ TeV data. The correlations of the measurements are evaluated for all sources of the systematic uncertainty. Using a dedicated mapping of uncertainty categories, the combination of the three measurements results in

$$m_{\text{top}} = 172.84 \pm 0.34\ (\text{stat}) \pm 0.61\ (\text{syst})\ \text{GeV},$$

with a total uncertainty of 0.70 GeV, i.e. a relative precision of 0.4%. The result is mostly limited by the calibration of the jet energy scales and by the Monte Carlo modelling of signal events.

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