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Top quark mass and properties with the ATLAS detector

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The top-quark mass is one of the key fundamental parameters of the Standard Model that must be determined experimentally. Its value has an important effect on many precision measurements and tests of the Standard Model. The Tevatron and LHC experiments have developed an extensive program to determine the top quark mass using a variety of methods. In this contribution, the top quark mass measurements by the ATLAS experiment are reviewed. These include measurements in two broad categories: the direct measurements, where the mass is determined from a comparison with Monte Carlo templates, and determinations that compare differential cross-section measurements to first-principle calculations. The exceptionally large dataset collected by the ATLAS detector during Run 2 of the LHC also enables precision testing of theoretical predictions using an extensive sample of top quark events. New results on top-quark properties including tests of lepton-flavour universality are also shown.

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1. Introduction

The top quark is the heaviest known elementary particle and its mass is an important free parameter of the Standard Model (SM). Its mass enters into the prediction of the top-quark Yukawa coupling, affects the dynamics of other elementary particles via loop diagrams, and influences the stability of the electroweak vacuum. At present, the Large Hadron Collider (LHC) [1] is the only machine allowing precise measurements of the top-quark mass and properties, which are essential for fully establishing the role of the top quark in the SM. During Run 2 of the LHC the ATLAS experiment [2] collected a large dataset of pp collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 140 fb^{-1}. These proceedings summarise recent ATLAS results based on the full Run 2 dataset for top-quark mass measurements and tests of lepton-flavour universality in top-quark decays.

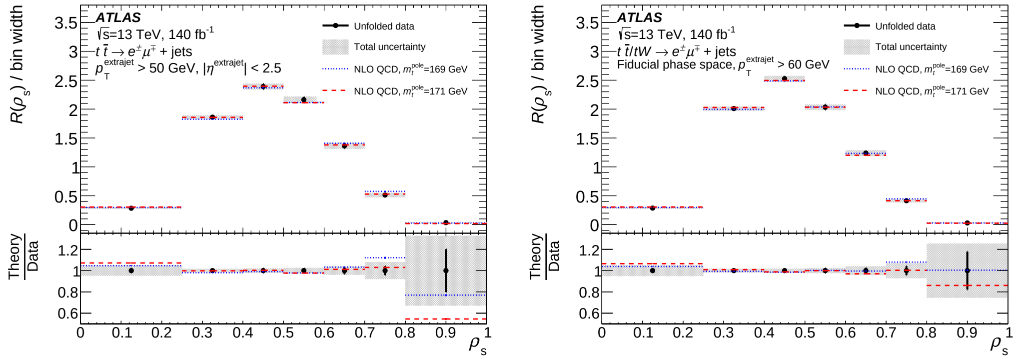
2. Top quark mass measurements

Measurements of the top-quark mass are generally split into so-called 'direct' and 'indirect' measurements. Direct measurements, which typically have smaller uncertainties, are based on fits to the observed distributions of top-quark decay products and use predictions from Monte Carlo (MC) generators, i.e. they determine the value of the MC top-quark mass parameter. In contrast, indirect measurements from total or differential cross-sections rely on the dependence of theoretical predictions on the top-quark mass parameter in the SM Lagrangian, which allows the results to be interpreted in a well-defined renormalisation scheme, often the pole mass scheme. The results of the direct measurements are also generally identified with the top-quark pole mass, but with an ambiguity of a few hundred MeV in this identification [3].

2.1 Measurement of the top-quark pole mass in dilepton $t\bar{t} + 1$ jet events

A measurement of the top-quark pole mass m_t^{pole} using $t\bar{t}$ events with an additional jet is presented in Ref. [4]. The $t\bar{t}$ + 1-jet differential cross-section as a function of the inverse invariant mass of the $t\bar{t}$ + 1-jet system has sensitivity to m_t^{pole} near the $t\bar{t}$ production threshold, which is enhanced by the presence of the jet produced in association with the $t\bar{t}$ pair. The measured normalised cross-section is compared to fixed-order (FO) calculations at next-to-leading-order (NLO) accuracy in the strong coupling to extract m_t^{pole}. In this analysis, events are selected to have an electron and a muon of opposite charge, two b-tagged jets, an additional jet with high transverse momentum (p_{T}) and high missing transverse momentum. The data are corrected to the level of stable top quarks using Iterative Bayesian Unfolding and compared to FO calculation of the $2 \to 3$ process $pp \to t\bar{t}$ + 1-jet at NLO QCD [5]. The data are also corrected to parton level phase space defined by leptons, neutrinos and jets, which allows comparison with a FO NLO QCD calculation for the $2 \to 7$ process $pp \to b\bar{b}l^{+}\nu l^{-}\bar{\nu}j$ that includes top-quark decay and off-shell effects [6]. The results for the differential cross-sections at parton level are shown in Figure 1. The top-quark mass is extracted from the unfolded differential cross-section using a χ^2 fit to FO NLO predictions. The result obtained with the $2 \to 3$ approach, considered the main result, is: $m_t^{\mathrm{pole}} = 170.7 \pm 0.3(\mathrm{stat.}) \pm 1.4(\mathrm{syst.}) \pm 0.3(\mathrm{scale}) \pm 0.2(\mathrm{PDF} \oplus \alpha_{\mathrm{S}})$ GeV. The m_t^{pole} extracted from the $2 \to 7$ measurement is compatible with the $2 \to 3$ result within theoretical uncertainties:

$m_t^{\text{pole}} = 171.69 \pm 0.41(\text{stat.}) \pm 1.68(\text{syst.})^{+0.66}_{-1.34}(\text{scale})^{+0.49}_{-0.46}(\text{PDF} \oplus \alpha_S)$ GeV. The results of this analysis are in good agreement with other top-quark mass results and have similar precision.



(a) (b)

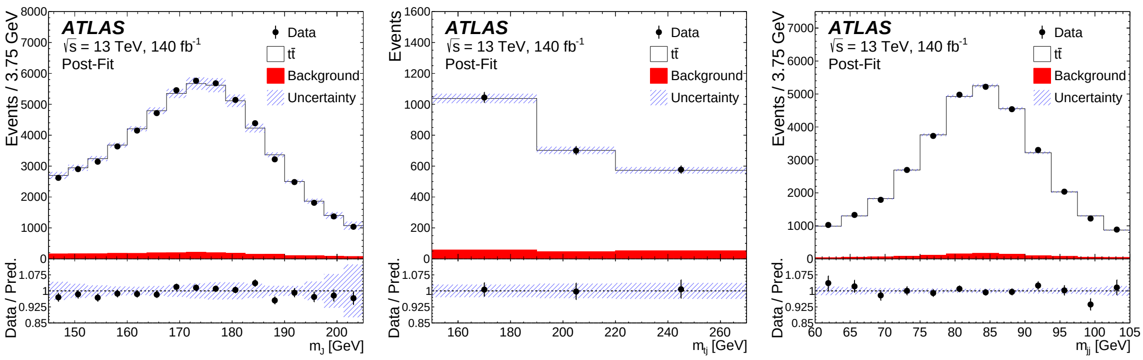
Figure 1: The measured normalised differential cross-section $R(\rho_S) = \frac{1}{\sigma_{t\bar{t}+1-\text{jet}}} \cdot \frac{d\sigma_{t\bar{t}+1-\text{jet}}}{d\rho_S}$ unfolded to the $2 \to 3$ parton level (a) and the $2 \to 7$ parton level (b). Theoretical predictions at FO NLO QCD for two exemplary m_t^{pole} values are also shown [4].

2.2 Measurement of the top quark mass using $t\bar{t}$ events with a high p_T top quark

The mass of the top quark is measured using $t\bar{t}$ events with high transverse momentum top quarks, as reported in Ref. [7]. The analysis targets events with an electron or muon, originating from a semileptonically decaying top quark, and jets in the final state. The second top quark decays hadronically and has sufficient transverse momentum to be reconstructed as a single large-radius jet (‘top-jet’). The mean of the invariant mass of the selected large-radius jet $\overline{m_J}$ is the observable sensitive to m_t and two additional observables are defined to control and reduce the systematic uncertainties. The second observable, the invariant mass of the two non b-tagged constituent jets with the largest p_T inside the top-jet (m_{jj}), aims at identifying jets from the $W \to q\bar{q}'$ decay and is sensitive to the jet energy scale (JES). The final observable, the invariant mass of the semileptonically decaying top quark and the closest additional jet (m_{tj}), is designed to select events with additional QCD radiation from the b-quark and is sensitive to the recoil effects in the top quark decay. The top quark mass is obtained from a profile-likelihood fit to $\overline{m_J}$, m_{jj} and m_{tj} and its measured value is $m_t = 172.95 \pm 0.27(\text{stat.}) \pm 0.46(\text{syst.})$ GeV. The inclusion of the m_{jj} distribution reduces the JES uncertainty by more than 1 GeV and initial- and final-state radiation uncertainty by more than 0.5 GeV. The inclusion of the m_{tj} variable reduces the recoil uncertainty by 0.3 GeV. The post-fit distributions of m_J, m_{jj} and m_{tj} are shown in Figure 2. The combination of the boosted selection, improved understanding of the flavour dependence of the jet energy response and the fit strategy lead to the most precise ATLAS measurement from a single channel.

3. Testing lepton flavour universality in top-quark decays

Top-quark production and decay can be a useful tool to test generic assumptions of the SM, such as lepton flavour universality (LFU). SM predicts equal lepton couplings to electroweak bosons



(a) (b) (c)

Figure 2: The post-fit expectations for the m_J (a), m_{jj} (b), and m_{tj} (c) compared with the data. The fit does not contain the distribution of m_J, but only the value of $\overline{m_J}$ [7].

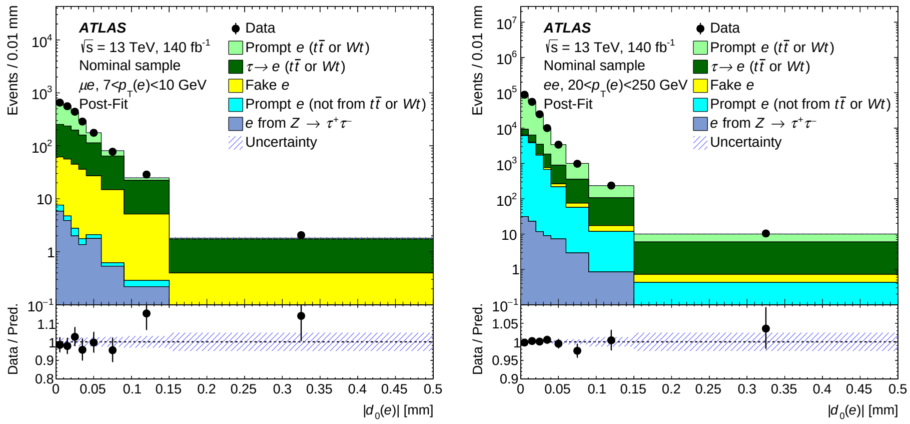
and any violation of LFU would be evidence of physics beyond the SM. Top-quark pair-production yields a clean source of W-bosons which can be used to test LFU by measuring the ratio of W-boson decay rates into different charged leptons, $l, l' = e, \mu, \tau$: $R_W(l/l') = B(W \to l\nu_l)/B(W \to l'\nu_{l'})$.

3.1 Test of LFU in W-boson decays into electrons and τ-leptons

Ref. [8] presents a measurement of the ratio of the branching fractions, $R_{\tau/e} = B(W \to \tau\nu)/B(W \to e\nu)$ is performed using a sample of W bosons originating from top-quark decays to final states containing τ-leptons, decaying leptonically, or electrons. Having electrons in both final states results in substantial reduction of the systematic uncertainties in the ratio $R_{\tau/e}$. A sample of $t\bar{t}$ events with both top quarks decaying leptonically is selected for the measurement, and the tag-and-probe approach is used. The *tag* electron or muon is used to select events and the *probe* electron is used to determine whether the electron is *prompt* (produced in the decay $W \to e\bar{\nu}_e$) or originates from a τ-lepton decay (i.e. is produced via decay $W \to \tau\bar{\nu}_\tau \to e\bar{\nu}_e\nu_\tau\bar{\nu}_\tau$). Prompt electrons and electrons from τ-lepton decays are distinguished using the differences in the impact parameter (d_0) distributions and p_{T} spectra of the electrons: electrons originating from τ-lepton decays generally have lower p_{T} and larger d_0. The d_0 distribution of prompt electrons is calibrated using the $Z \to ee$ decay events, which considerably reduces the uncertainties related to the d_0 shape. The ratio $R_{\tau/e}$ is measured using a two-dimensional binned template profile likelihood fit to the p_{T} and $|d_0|$ distributions of the probe electron. Figure 3 shows the d_0 distribution in two exemplary p_{T} bins after the fit. The measured ratio of branching fractions $R_{\tau/e} = 0.975 \pm 0.012(\text{stat.}) \pm 0.020(\text{syst.})$ is consistent with the SM assumption of lepton flavour universality in W-boson decays.

3.2 Test of LFU in W-boson decays into electrons and muons

The ratio of branching fractions of the W boson to muons and electrons, $R_W^{\mu/e} = B(W \to \mu\nu)/B(W \to e\nu)$ has been measured in Ref. [9], probing the universality of lepton couplings. The W bosons are produced in top-quark decays in $t\bar{t}$ events, and the final state containing two opposite charge leptons and one or two b-tagged jets is considered. The ratio $R_W^{\mu/e}$ is derived from a comparison of the $t\bar{t}$ production cross-section measured in ee, $e\mu$ and $\mu\mu$ dilepton final



(a) (b)

Figure 3: The post-fit distributions of d_0 in $7 < p_{\mathrm{T}}(e) < 10$ GeV bin for the μe channel (a) and in $20 < p_{\mathrm{T}}(e) < 250$ GeV bin for the ee channel (b) compared with the data [8].

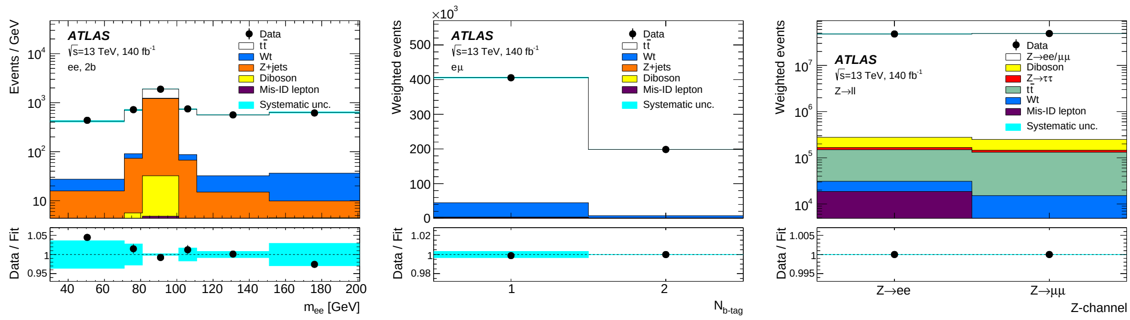
states. The uncertainties related to the identification of electrons and muons are reduced by simultaneously measuring $R_Z^{\mu\mu/ee} = B(Z \to \mu\mu)/B(Z \to ee)$ and redefining the parameter of interest as $R_{WZ}^{\mu/e} = R_W^{\mu/e}/\sqrt{R_Z^{\mu\mu/ee}}$. The final result is then obtained using the precise value of $R_Z^{\mu\mu/ee}$ measured at LEP and SLD experiments [10]. To reduce physics modelling uncertainties, a reweighting procedure was applied to muons, which allows to equalise the kinematic acceptance in ee and $\mu\mu$ $t\bar{t}$ events. To minimise selection efficiency uncertainties due to the modelling of additional jets, the b-jet reconstruction and tagging efficiency was determined from data, simultaneously with the $t\bar{t}$ cross-section measurement. The lepton isolation efficiency was also measured directly in data, separately in $Z \to ll$ and $t\bar{t} \to ll$ events. This analysis performs a maximum likelihood fit to the event counts in the $e\mu$ channel and for the $Z \to ll$ events and to the dilepton invariant mass distributions. Some of the fitted distributions are shown in Figure 4. Using the measured $R_{WZ}^{\mu/e}$ and the precise value of $R_Z^{\mu\mu/ee}$ from e^+e^- colliders, the ratio $R_W^{\mu/e}$ is determined to be

$$R_W^{\mu/e} = 0.9995 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0014(\text{ext.}), \tag{1}$$

where the three uncertainties correspond to data statistics, experimental systematics and the external measurement of $R_Z^{\mu\mu/ee}$. The result is consistent with the SM assumption of lepton flavour universality and with previous measurements and is more precise than the previous world average.

4. Conclusion

A review of recent ATLAS measurements of the top-quark mass and properties using full LHC Run 2 data was presented. In a new m_t^{pole} measurement using $t\bar{t} + 1$ jet events, improved theoretical predictions have been employed, in particular a calculation including non-resonant and off-shell effects. A recent direct m_t measurement using boosted top quarks achieved a substantial reduction of systematic uncertainties related to jets and additional radiation by incorporating two auxiliary



(a) (b) (c)

Figure 4: Results of the fit to data, showing the invariant mass distribution for the two b-jet samples in the ee channel (a), b-jet multiplicity in the $e\mu$ channel (b), and number of events in the inclusive $Z \to ll$ selection (c) [9].

observables sensitive to these effects into the fit. The R_W measurements in $t\bar{t}$ events, performed to test lepton universality, made extensive use of data-driven techniques to calibrate reconstructed distributions, thereby reducing systematic uncertainties and, in the case of the $R_W^{\mu/e}$ measurement, achieving unprecedented precision.

Further studies of the top-quark mass and properties benefiting from the large dataset being collected during Run 3 of the LHC will allow us to deepen our understanding of top-quark physics.

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