

Measurements of the top quark mass with the ATLAS detector

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The top quark mass is one of the fundamental parameters of the Standard Model. In these proceedings, recent measurements of the top quark mass in pp collisions at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV data in Run I of the Large Hadron Collider using the ATLAS detector are reviewed. A measurement using lepton+jets events is presented, where a multidimensional template fit is used to constrain the uncertainties on the energy measurements of jets. The measurement is combined with a measurement using dilepton events. In addition, novel measurements aiming to measure the mass in a well-defined scheme are presented. These measurements use precision theoretical QCD calculations for both inclusive $t\bar{t}$ production and $t\bar{t}$ production with an additional jet to extract the top quark mass in the pole mass scheme.

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1. Introduction

Since its discovery [1, 2], the determination of the top quark mass m_t , a fundamental parameter of the standard model (SM), has been one of the main goals of the CERN Large Hadron Collider (LHC) and of the Fermilab Tevatron Collider. Indeed, m_t and the masses of the W and Higgs bosons are related through radiative corrections that provide an internal consistency check of the SM [3]. Furthermore, m_t dominantly affects the stability of the SM Higgs potential [4, 5, 6]. Currently, with $m_t = 173.34 \pm 0.76$ GeV, a world-average combined precision of about 0.5% has been achieved [7]. Measurements of properties of the top quark other than m_t at ATLAS [8] are reviewed in Refs. [9, 10]. At the LHC, top quarks are mostly produced in pairs via the strong interaction. In the SM, the top quark decays to a W boson and a b quark nearly 100% of the time, resulting in $t\bar{t} \rightarrow W^+W^-b\bar{b}$. Thus, $t\bar{t}$ events are classified according to W boson decays as “dileptonic” ($\ell\ell$), “lepton+jets” (ℓ +jets), or “all-jets”. Single top production in the dominant t -channel proceeds predominantly through the $qg \rightarrow q't\bar{b}$ process.

2. Top quark mass in single top events

The first measurement of m_t in topologies enriched with t -channel single top events is performed using 20.3 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$ [11]. This analysis is complementary to traditional approaches using $t\bar{t}$ events due to factors like background composition or colour-connections, resulting in a different impact of systematic uncertainties. The selection requires a single isolated lepton (e or μ) with $p_T > 25 \text{ GeV}$ and ≥ 2 jets with one b -tag and $p_T > 30 \text{ GeV}$ within the well-instrumented region of the detector. Jets with $2.75 < |\eta| < 3.5$ and $p_T > 35$ are accepted as one forward jet is expected in $qg \rightarrow q't\bar{b}$. Missing transverse momentum $E_T^{\text{miss}} > 30 \text{ GeV}$ and topological requirements are imposed. The purity is increased to $\approx 50\%$ through a neural network constructed from 12 input variables. The extraction of m_t is performed with the template method, i.e., by fitting the data using template distributions obtained from MC and parametrised in m_t^{gen} . The $m_{\ell b}$ observable chosen for the templates is shown in Fig. 1(a). The best fit to data is given in Fig. 1(b) and provides $m_t = 172.2 \pm 0.7$ (stat) ± 2.0 (syst) GeV. Systematic uncertainties are dominated by the jet energy scale (JES) (1.5 GeV) as well as the parton showering (PS) and hadronisation (0.7 GeV).

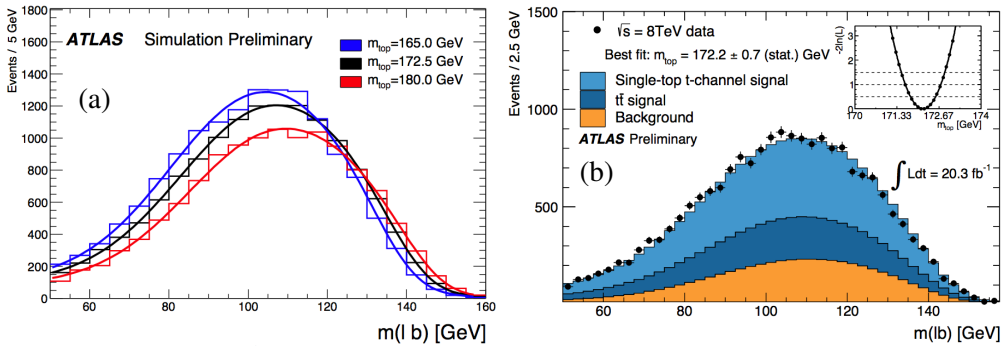


Figure 1: (a) Dependence of the $m_{\ell b}$ distribution of all processes involving top quarks on m_t using simulated MC samples, together with the fitted signal probability densities [11]. (b) The distribution in $m_{\ell b}$ in topologies enriched with single top events using 20.3 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$ [11]. The templates for the single top and $t\bar{t}$ predictions are scaled to the best-fit values in data, alongside with the background template.

3. All-hadronic channel

A measurement of m_t is performed in all-jets events with the highest $t\bar{t}$ branching ratio using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [12]. The analysis requires ≥ 5 jets with $p_T > 55 \text{ GeV}$ and a 6th jet with $p_T > 30 \text{ GeV}$, with two b -tags. A veto against isolated leptons (e or μ) and topological selections are imposed. The template method is applied to extract m_t . The dominant systematic uncertainty from the JES is reduced through the usage of the $R_{3/2} = m_{q'\bar{q}b}/m_{q'\bar{q}}$ observable, where $m_{q'\bar{q}b}$ ($m_{q'\bar{q}}$) is the invariant mass of the jet system matched to the $t \rightarrow q'\bar{q}b$ ($W \rightarrow q'\bar{q}$) decay. The correct assignment of jets to partons is identified through a kinematic likelihood fit. The dominant background from multijet (MJ) production is modelled from data using control regions in $p_T^{6^{\text{th}} \text{ jet}}$ and b -tag multiplicity. The best fit to data is shown in Fig. 2(a) and results in $m_t = 175.1 \pm 1.4 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ GeV}$. The dominant systematic uncertainties are JES (0.5 GeV), b quark JES (0.6 GeV), alongside PS and hadronisation (0.5 GeV).

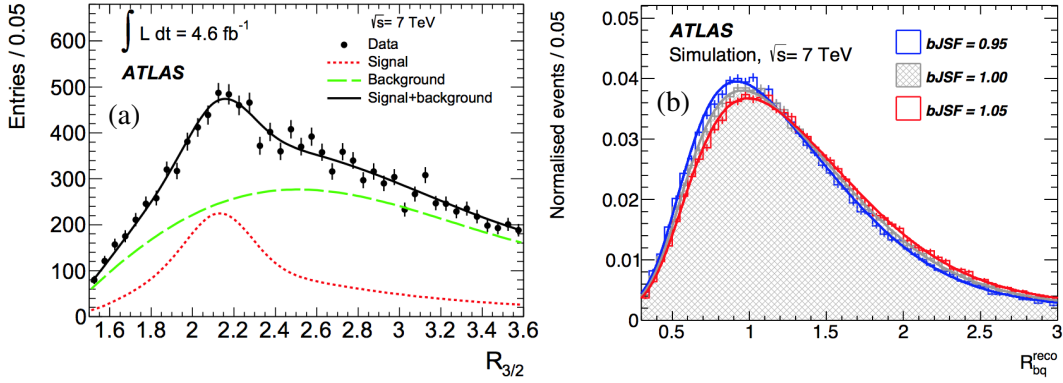


Figure 2: (a) The distribution in $R_{3/2}$ in the all-hadronic channel using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [12]. The signal and background templates are shown for the best-fit values in data. (b) The dependence of the templates in R_{bq} on the bJSF in the ℓ +jets channel, after reconstruction with a kinematic fit [13].

4. Lepton+jets channel

ATLAS' most precise single measurement of m_t is done in ℓ +jets events using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [13]. The selection is similar to that in Sect. 2, however, ≥ 4 jets within $|\eta| < 2.5$ are required, with one or two b -tags. Like in the all-jets analysis from Sect. 3, the correct assignment of jets to partons is identified through a kinematic fit, and m_t is extracted with a template method. The uncertainty from JES is reduced through a novel approach which simultaneously fits m_t together with the overall JES factor (JSF) and with the ratio of the energy scales for b quark jets to that of u, d, c, s quark and gluon jets (bJSF). The $m_{q'\bar{q}}$ observable is used to extract JSF, while bJSF is constrained through the $R_{bq} = (p_T^b + p_T^{\bar{b}})/(p_T^{q'} + p_T^{\bar{q}})$ observable shown in Fig. 2(b) in events with two b -tags, and $R_{bq} = 2p_T^{b\text{-tag}}/(p_T^{q'} + p_T^{\bar{q}})$ for one b -tag. Thus, the uncertainty from b quark JES is diminished from $\approx 1 \text{ GeV}$ to 0.06 GeV and other uncertainties are reduced, albeit at the cost of an additional statistical component of 0.67 GeV . The reconstructed m_t for the best fit to data is shown in Fig. 3(a), and the final result reads $m_t = 172.33 \pm 0.75 \text{ (stat + JSF + bJSF)} \pm 1.02 \text{ (syst)} \text{ GeV}$. The dominant systematic uncertainty remains JES (0.58 GeV), followed by b -tagging (0.50 GeV) as the dependence of the b -tagging uncertainty on p_T^{jet} impacts the R_{bq} observable.

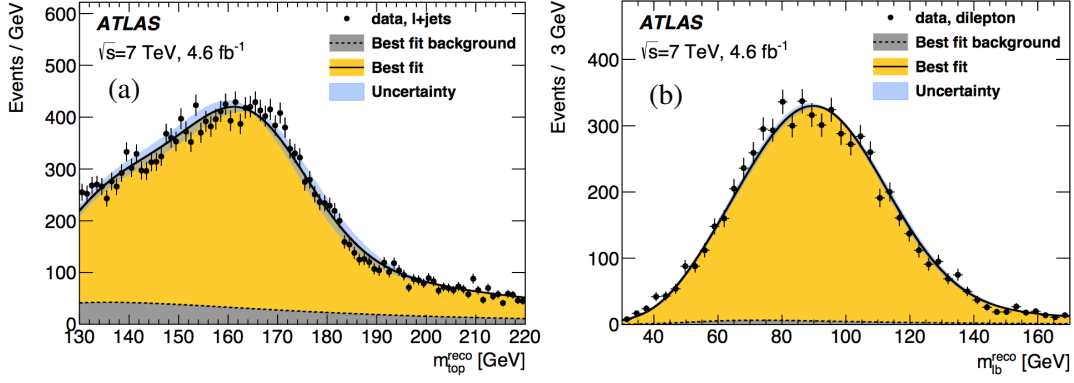


Figure 3: (a) The distribution in reconstructed m_t in the ℓ +jets channel using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [13]. Also shown are the templates for the $t\bar{t}$ prediction scaled to the best-fit values measured in data, alongside with the background template. The shaded band indicates the uncertainty of the template fit. (b) Same as (a), but for the $\ell\ell$ channel [13].

5. Dilepton channel

A measurement of m_t is performed in the $\ell\ell$ channel using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [13]. The selection is similar to that in the ℓ +jets analysis from Sect. 4, however, two isolated leptons (e or μ) of opposite charge and ≥ 2 jets are required. Like for the m_t measurement using single top events from Sect. 2, templates in $m_{\ell b}$ are used to extract m_t . The best fit to data is shown in Fig. 3(b), and results in $m_t = 173.79 \pm 0.54(\text{stat}) \pm 1.30(\text{syst}) \text{ GeV}$. The dominant systematic uncertainties are the overall JES (0.75 GeV) and the b quark JES (0.68 GeV), followed by modelling of the PS and hadronisation (0.53 GeV) and initial/final state radiation (0.47 GeV).

6. Combination in lepton+jets and dilepton channels

The m_t values measured in the ℓ +jets and $\ell\ell$ channels from respective Sects. 4 and 5 are combined using the best linear unbiased estimator, taking into account the signs of the correlation coefficients between the channels for the sources of systematic uncertainty considered [13]. With this approach, the $\ell\ell$ channel can benefit from the constraint on JSF and bJSF in the ℓ +jets channel, which in turn benefits from the smaller statistical uncertainty and the reduced dependence of m_t on the b -tagging uncertainty in the $\ell\ell$ channel. The combination results in $m_t = 172.99 \pm 0.48(\text{stat}) \pm 0.78(\text{syst}) \text{ GeV}$, corresponding to a relative uncertainty of 0.53%.

7. Top quark mass from $\sigma_{t\bar{t}}$

The *direct* measurements of m_t presented in Sects. 2-6 provide the most precise experimental determination of m_t . However, they measure the m_t parameter as implemented in MC generators, which is related to the theoretically sound definition in the pole mass scheme m_t^{pole} with an uncertainty of $\leq 1 \text{ GeV}$ [14]. The world's most precise *indirect* measurement of m_t^{pole} from $\sigma_{t\bar{t}}$ is performed using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ and 20.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ [15]. This analysis exploits the dependence of $\sigma_{t\bar{t}}$ on m_t^{pole} which is now known with $\approx 3\%$ precision at NNLO with NNLL corrections [16], and extracts m_t^{pole} using the measurement of $\sigma_{t\bar{t}}$ in $e^\pm\mu^\mp$ final states. The

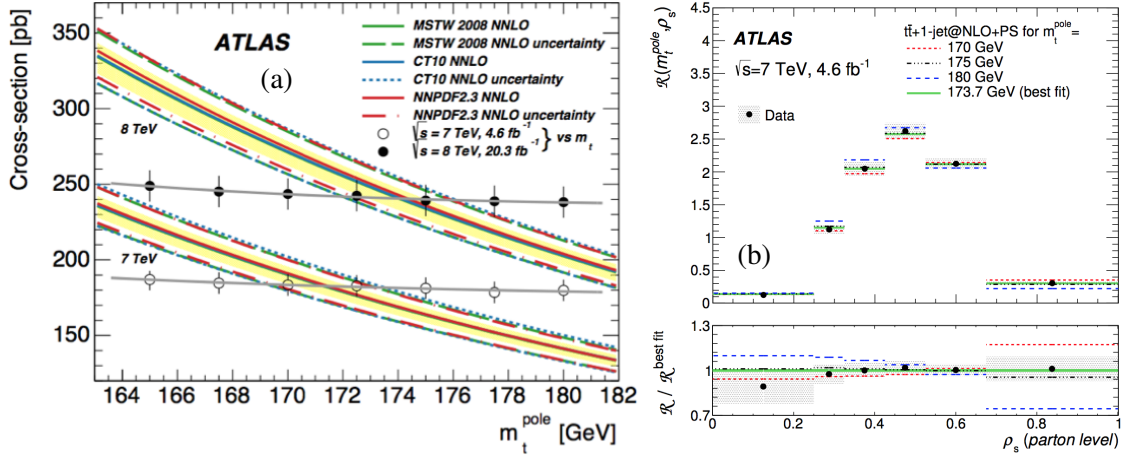


Figure 4: **(a)** Predicted NNLO+NNLL $t\bar{t}$ production cross sections at $\sqrt{s} = 7$ and 8 TeV as a function of m_t^{pole} [15]. The shaded band indicates the QCD scale uncertainty. The measurements of $\sigma_{t\bar{t}}$ are also shown. **(b)** The distribution $\mathcal{R} \equiv 1/\sigma_{t\bar{t}+1\text{jet}} \cdot d\sigma_{t\bar{t}+1\text{jet}}/d\rho_s$ at parton level, after corrections for detector, PS, and hadronisation effects, and after background subtraction at $\sqrt{s} = 7$ TeV [17]. The uncertainty on the data points includes the statistical component only.

input measurement of $\sigma_{t\bar{t}}$ achieves an unprecedented relative uncertainty of $\approx 4\%$ through widely applying data-driven techniques and extracting $\sigma_{t\bar{t}}$ simultaneously with the b -tagging efficiency, which would otherwise represent the largest source of experimental uncertainty. The resulting distributions of extracted $\sigma_{t\bar{t}}(m_t^{\text{pole}})$ for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV are given in Fig. 4(a), and show a very small dependence on m_t^{pole} due to minimal use of MC simulations in the analysis. The m_t^{pole} parameter is extracted using a maximal likelihood fit of the experimental result and the theoretical calculations [16]. The final results are given by $m_t^{\text{pole}} = 171.4 \pm 2.6$ GeV at $\sqrt{s} = 7$ TeV, $m_t^{\text{pole}} = 174.1 \pm 2.6$ GeV at $\sqrt{s} = 8$ TeV, and $m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV in combination. The dominant sources of systematic uncertainty on the experimental side are the luminosity (0.9 GeV) and the beam energy (0.6 GeV), while the choice of parton distribution functions and α_s (1.7 GeV) and the choice of factorisation and renormalisation scales (1.2 GeV) dominate the theory side.

8. Top quark mass from $\sigma_{t\bar{t}+1 \text{ jet}}$

The world's first measurement of m_t^{pole} from the production cross section of a $t\bar{t}$ system in association with a jet $\sigma_{t\bar{t}+1 \text{ jet}}$ is performed in the ℓ +jets channel using 4.6 fb^{-1} of data at $\sqrt{s} = 7$ TeV [17]. The sensitivity to m_t^{pole} is established through the radiation rate of a high- p_T gluon off the $t\bar{t}$ system, which is proportional to m_t^{pole} . More precisely, the differential production cross section $\mathcal{R}(m_t^{\text{pole}}, \rho_s) \equiv 1/\sigma_{t\bar{t}+1\text{jet}} \cdot d\sigma_{t\bar{t}+1\text{jet}}/d\rho_s$ is compared to NLO calculations [18], where $\rho_s \equiv 2m_0/\sqrt{s_{t\bar{t}+1\text{jet}}}$, and the arbitrary constant m_0 is set to 170 GeV in this analysis. The selection is similar to the ℓ +jets analysis in Sect. 4, however, two b -tagged jets are required in each event. The reconstruction of the $t\bar{t}$ system is performed through a χ^2 kinematic fit. To reduce the total uncertainty, $p_T > 50$ GeV is required for the extra jet. The distribution in ρ_s is corrected for detector, PS, hadronisation effects, and the presence of background. The resulting distribution at parton level is given in Fig. 4(b). The extraction of m_t^{pole} is performed through a χ^2 fit of

the observed and expected values in each bin of the ρ_s distribution for the m_t^{pole} parameter, and yields $m_t^{\text{pole}} = 173.1 \pm 1.50(\text{stat}) \pm 1.43(\text{syst})_{-0.49}^{+0.93}$ GeV. The dominant experimental systematic uncertainties are the contributions from the modelling of initial and final state radiation (0.72 GeV) and from the JES (0.94 GeV). The theory uncertainty is dominated by the choice of factorisation and renormalisation scales.

9. Conclusions

I presented recent measurements of the top quark mass, a fundamental parameter of the SM, by the ATLAS Collaboration. ATLAS' most precise determination of $m_t = 172.99 \pm 0.48(\text{stat}) \pm 0.78(\text{syst})$ GeV is attained in the combination of the ℓ +jets and $\ell\ell$ channels. Innovative techniques have been put in place, like the first measurement of m_t in single top events, the first *in situ* calibration of the b quark JES, and the world's most precise measurements of m_t^{pole} from $\sigma_{t\bar{t}}$ and $\sigma_{t\bar{t}+1 \text{ jet}}$.

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