Top mass reconstruction in ATLAS

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Abstract. The top-quark mass is a fundamental parameter of the Standard Model. After the discovery of the top quark, the measurements of its properties were of substantial interest. Within the framework of the SM, the top-quark mass can be used in combination with other electroweak precision measurements to constrain the mass of the yet unobserved Higgs boson. In the new era of the Large Hadron Collider (LHC), the first top quarks have been produced in Europe in proton-proton collisions at a center-of-mass energy of 7 TeV. The top-quark mass measurement of ATLAS in the so called lepton+jets channel with 35 pb⁻¹ integrated luminosity is presented. In this early data-taking period the largest uncertainty on this measurement comes from the knowledge of the jet energy scale. It is shown how this uncertainty is determined and which methods are used for measuring the top-quark mass.

1. Introduction
After the discovery of the top-quark in 1995, much work has been devoted to precisely measure its mass. The present world average value is

\[ m_{\text{top}} = (173.3 \pm 1.1) \text{ GeV} \]

¹ Until now the most precise measurements are based on the \( t\bar{t} \rightarrow \text{lepton+jets} \) channel with lepton = e, μ, where one of the W bosons decays leptonically and the other hadronically. The largest systematic uncertainty results from the limited accuracy of the jet energy scale (JES). Especially in first ATLAS data this will be the dominating contribution to the total systematic uncertainty. In ATLAS three complementary methods in the \( t\bar{t} \rightarrow \text{lepton+jets} \) channel are exploited and a brief summary is given here. A detailed description can be found in [2].

- a 2-dimensional template analysis (2d-analysis) that simultaneously determines \( m_{\text{top}} \) and a global Jet energy Scale Factor (JSF).
- a 1-dimensional template analysis (1d-kinfit analysis) exploiting a kinematical likelihood fit to all decay products.
- a 1-dimensional template analysis (1d-\( R_{32} \) analysis) which is based on the measurement of the mass ratio:

\[ R_{32} \equiv \frac{m_{\text{reco}}^{\text{top}}}{m_{\text{reco}}^{W}}. \]

\( m_{\text{reco}}^{\text{top}} \) and \( m_{\text{reco}}^{W} \) are the per event reconstructed invariant masses of the top-quark and the W boson, respectively.

With the presently available luminosity and the current understanding of the ATLAS data the 1d-\( R_{32} \) analysis yields the smallest expected uncertainty and is chosen as the present baseline and presented in the following two sections.

¹ Natural units are used throughout, i.e. \( c = \hbar = 1 \).

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2. Data sample, object definitions and event selection

The data used were collected with the ATLAS detector [3] at the LHC. The integrated luminosity of the data sample amounts to $L_{\text{int}} = 35.3$ pb$^{-1}$ with an uncertainty of 3.4% [4]. The sources of background considered are: $t\bar{t}$ events in all other decay channels, single top-quark production processes, di-boson processes, $W/Z+$jets processes, and finally QCD multijet production, which is the only source of background which is directly determined from data [5].

The $t\bar{t}$ signal samples were generated with the MC@NLO program [6, 7]. The single top-quark production events are simulated with the MC@NLO code, the di-boson processes with the HERWIG program [8], and the $W/Z+$jets events with the ALPGEN [9] generator.

In addition to the selection listed above, two requirements specific to the 1d-$R_{32}$ analysis are imposed. If the jet-triplet assigned to the hadronic top-quark contains two $b$-tagged jets the event is rejected. Furthermore, the reconstructed mass of the $W$ boson jet candidates must be

\[ m_{W}^{T} \geq 25 \text{ GeV} \]

The SM top-quark decays into a $W$ boson and a $b$-quark in almost 100% of the cases. The event is expected to contain a charged lepton, missing transverse energy ($E_{T}^{\text{miss}}$) from the undetected neutrino and four jets with high transverse momentum, two of which are $b$-jets. Both lepton channels are kept separate throughout the analysis and the $t\bar{t} \to e+jets$ ($t\bar{t} \to \mu+jets$) channel is referred to as electron (muon) channel. Events are selected by applying the following requirements to the reconstructed objects:

- **Trigger:** It is required that an electron or muon must have fired the ATLAS trigger. The triggers used are fully efficient for leptons with $p_T > 20$ GeV.

- **Primary vertex:** A primary vertex with at least five charged particles assigned to it is required.

- **Electrons:** Electron candidates are defined by the following criteria: $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$, $p_T > 20$ GeV, and the electron must be isolated, see [5]. No high-$p_T$ and isolated muon must be present$^2$.

- **Muons:** Muon candidates are defined by the following criteria: $|\eta| < 2.5$, $p_T > 20$ GeV, and as in the case of electrons, muons must be isolated, and the separation to the closest jet with $p_T > 20$ GeV has to be larger than $\Delta R = 0.4$. No high-$p_T$ and isolated electron must be present.

- **Missing transverse energy $E_{T}^{\text{miss}}$:** The $E_{T}^{\text{miss}}$ is calculated from the vector sum of the transverse energy of muons and all calorimeter cells. A requirement of $E_{T}^{\text{miss}} > 35$ GeV (20 GeV) is used in the electron (muon) channels to help separate events with and without leptonic $W$ boson decays.

- **$W$ boson transverse mass $m_{W}^{T}$:** In the electron channel $m_{W}^{T} > 25$ GeV is required, where $m_{W}^{T}$ is calculated from the momentum vectors of the charged lepton candidate and the missing transverse energy. In the muon channel a triangular region in the $E_{T}^{\text{miss}} - m_{W}^{T}$ plane is excluded by requiring $E_{T}^{\text{miss}} + m_{W}^{T} > 60$ GeV.

- **Jets:** Jet candidates are reconstructed with the anti-$k_t$ algorithm [10, 11] with a distance parameter of 0.4. The jets are calibrated to the hadronic energy scale. Jet candidates must have $|\eta| < 2.5$ and $p_T > 25$ GeV. Events must contain at least four jets. At least one jet is required to be $b$-tagged by the SV0 [5] algorithm. Events containing a jet with $p_T > 20$ GeV which fails basic jet quality criteria are rejected. Jets are removed from the event if they are closer than $\Delta R = 0.2$ to any selected electron.

In addition to the selection listed above, two requirements specific to the 1d-$R_{32}$ analysis are imposed. If the jet-triplet assigned to the hadronic top-quark contains two $b$-tagged jets the event is rejected. Furthermore, the reconstructed mass of the $W$ boson jet candidates must be

$^2$ In the ATLAS right-handed coordinate system the $x$-axis points towards the center of the LHC ring, the $y$-axis points upwards and the $z$-axis points in the direction of the counter-clockwise running proton beam. The polar angle $\theta$ and the azimuthal angle $\phi$ are defined with respect to this $z$-axis and $x$-axis, respectively. The pseudo rapidity is defined as $y = -\ln(\tan(\theta/2))$ and the radial distance in $(\eta, \phi)$ space is $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

$^3$ Transverse mass is given by: $M_T \equiv (E_T^{\text{lepton}} + E_{T}^{\text{miss}})^2 - (p_T^{\text{lepton}} + E_{T}^{\text{miss}})^2$.
Figure 1. The signal templates (a), together with their respective fits for four $m_{\text{top}}$ values are shown (only the electron channel). The background template (b) is shown with their respective fits (only the electron channel).

within a window of $60 \text{ GeV} < m_{\text{reco}}^{W} < 100 \text{ GeV}$. Consequently, the numbers of events used by the complementary analyses are correspondingly larger than in the baseline method. With this selection the expected background contribution is $15\%$ ($16\%$) for the electron (muon) channel, and the corresponding signal-to-background ratio ($S/B$) is $5.8$ ($5.2$).

3. Results from the $1d-R_{32}$ analysis
The $R_{32}$ method uses the ratio of the reconstructed 2-jet and 3-jet invariant masses and is therefore inherently more stable against JES variations.

3.1. Main concept
In the following the main elements of this method are described: the template parametrizations and the likelihood construction. For each of the events selected the hadronic top-quark mass is reconstructed. Among all selected jets, the three whose 4-vector sum yields the highest transverse momentum are identified as the decay products of the hadronically decaying top-quark. If this jet-triplet contains exactly one $b$-tagged jet the other two jets are assigned to the $W$ boson. If the jet-triplet contains no $b$-tagged jets, the association of jets to the $W$ boson is performed by choosing the pair of jets with the smallest $\Delta R$ in the reconstructed top-quark candidate rest-frame. The signal templates are constructed from Monte Carlo samples for different $m_{\text{top}}$ assumptions $[160, 170, 172.5, 180, 190] \text{ GeV}$. The signal templates are described by the sum of a ratio of two Gaussians and a Landau function, the latter represents mainly wrong jet-triplet assignments. In Figure 1(a) the sensitivity to $m_{\text{top}}$ is visualized by showing the superposition of the signal templates and their fits for four $m_{\text{top}}$ values in the electron channel. For the background the $m_{\text{top}}$ independent parts are treated together and their $R_{32}$ distribution is described by a Landau function. In Figure 1(b) the background template and its fit is shown for the electron channel. The functions choosen describe the templates adequately and also for the muon channel the templates are equally well described.
These parametrizations (PDFs) are used in an extended unbinned likelihood fit to the data:

\[
\mathcal{L}(R_{32}|m_{\text{top}}) = \mathcal{L}_{\text{shape}}(R_{32}|m_{\text{top}}) \times \mathcal{L}_{n_s+n_b} \times \mathcal{L}_{\text{bkg}},
\]

\[
\mathcal{L}_{\text{shape}}(R_{32}|m_{\text{top}}) = \prod_{i=1}^{N} \frac{n_s \cdot P_{\text{sig}}(R_{32}|m_{\text{top}})_i + n_b \cdot P_{\text{bkg}}(R_{32})_i}{n_s + n_b},
\]

\[
\mathcal{L}_{n_s+n_b} = \frac{e^{-(n_s+n_b)} \cdot (n_s + n_b)^N}{N!},
\]

\[
\mathcal{L}_{\text{bkg}} = \exp\left\{ -\frac{(n_b - n_{b,\text{pred}})^2}{2\sigma_{n_{b,\text{pred}}}^2} \right\}.
\]

The likelihood function (eq. 2) contains three terms. \(\mathcal{L}_{\text{shape}}\) accounts for the shape of the \(R_{32}\) distribution and its dependence on the top-quark mass \(m_{\text{top}}\). \(\mathcal{L}_{n_s+n_b}\) determines the relative contribution of signal \((n_s)\) and background \((n_b)\) events to all observed events, \(N\), and \(\mathcal{L}_{\text{bkg}}\) constrains the normalization of background events within the background prediction of \(n_{b,\text{pred}}\) events. The validity of this approach is verified with the pseudo-experiment technique. A good linearity is found between the input top-quark mass \((m_{\text{in}})\) used to perform the pseudo-experiments, and the result of the fits, averaged over 50 pseudo-experiments.

### 3.2. Evaluation of systematic uncertainties

To evaluate systematic uncertainties pseudo-experiments are performed and the systematic difference is evaluated with respect to the standard analysis. Neglecting possible correlations, the total uncertainty is calculated as the quadratic sum of all individual contributions.

The sources of systematic uncertainties considered are the following:

**Method calibration:** The limited statistics of the Monte Carlo samples leading to a systematic uncertainty for the template fits.

**Signal Monte Carlo generator:** The systematic uncertainty related to the choice of the generator which influences the signal template shapes, compared are MC@NLO and POWHEG samples [12].

**Hadronization:** Choice of hadronization model (Lund-String [13] or the Cluster model [8]).

**Pileup:** Systematic uncertainty from the imperfect description of pile-up in MC compared to data.

**Initial (ISR) and final state (FSR) QCD radiation:** Systematic uncertainty from different amounts of ISR and FSR altering the observed jet multiplicity. Dedicated ACERMC [14, 15] signal samples with modified QCD parameter \(\Lambda\) are used.

**Proton parton density function:** The signal samples are generated using the CTEQ66 [16] proton parton density function. The impact of the uncertainties of the proton parton density functions on \(R_{32}\) are evaluated.

**W/Z+jets background normalization:** The influence of the limited knowledge of the normalization is taken into account by altering the Monte Carlo predicted background fraction by \(\pm 100\%\).

**W/Z+jets background shape:** The impact of the variation of the shape of the \(W/Z\)+jets background contribution based on changes observed on stable particle jets while re-weighting Monte Carlo model parameters.

**QCD background normalization:** The QCD normalization is varied by \(\pm 100\%\).

**QCD background shape:** As suggested in [5] two shape variations per decay channel are applied and the fit is repeated.

**Jet energy scale:** Impact on \(R_{32}\) of jet energy scale variations (average JES uncertainty about \(\pm 4\%\)).
Figure 2. The measured $R_{32}$ distribution for the electron (a) and muon (b) channels. In addition the background PDF and the total PDF are shown for the measured top-quark mass, i.e. for the top-quark mass corresponding to the minimum of the likelihood function as shown in the inset (only statistical uncertainty given).

Relative b-jet to light jet energy scale: Impact on $R_{32}$ of a varied b-jet energy scale of 2.5%.

b-tagging efficiency and mistag rate: The b-tagging efficiency and mistag rates in data and Monte Carlo simulation are not identical. The uncertainty on those b-tagging scale factors which describe these differences are taken into account.

Jet energy resolution: The uncertainty of the jet energy resolution is evaluated by smearing each reconstructed jet in simulation and re-doing the event selection and fitting.

Jet reconstruction efficiency: The jet reconstruction efficiency in data and Monte Carlo are found to agree within an accuracy of 2%. To account for this difference, jets are randomly removed from the events.

The three biggest contributions to the systematic uncertainty are the ISR/FSR uncertainties (about 2.5 GeV), the b-jet energy scale (2.5 GeV) and the jet energy scale (about 2 GeV). The W/Z+jets background normalization contributes of the order of 1.5 GeV. The other uncertainties are of the order or below 1 GeV. The numbers given represent a mean value of both channels. The total systematic uncertainty is 4.8 GeV in the electron channel and 5.0 GeV in the muon channel.

3.3. Top-quark mass measurement

Figure 2 shows the results of the $R_{32}$ analysis when performed on data. For both channels the fit function adequately coincides with the distribution observed in the data. The results from both channels are statistically consistent with each other, and they are also in agreement with the present world average for $m_{\text{top}}$. The values measured of the top-quark mass are:

- $m_{\text{top}} = (173.8 \pm 6.7 \pm 4.8) \text{ GeV}$ electron channel
- $m_{\text{top}} = (166.7 \pm 5.0 \pm 5.0) \text{ GeV}$ muon channel
- $m_{\text{top}} = (169.3 \pm 4.0 \pm 4.9) \text{ GeV}$ combined
4. Results from the 2d-analysis

In the 2d-analysis, similarly to [17], both $m_{\text{top}}$ and a global Jet Energy Scale Factor (JSF) are determined simultaneously by using the $m_{\text{top}}^{\text{reco}}$ and $m_{W}^{\text{reco}}$ distributions. This analysis performs an in-situ jet rescaling and the systematic uncertainty on $m_{\text{top}}$ stemming from the JES is reduced and partly transformed into an additional statistical uncertainty on $m_{\text{top}}$ due to the 2-d fit, see [18]. For this a global JSF (averaged over $\eta$ and $p_T$) is obtained, which is mainly based on the observed differences between the predicted $m_{W}^{\text{reco}}$ distribution and the data. The well known values of $m_{W}$ and $\Gamma_{W}$ are used to improve on the experimental resolution of $m_{\text{top}}^{\text{reco}}$. For the events fulfilling the common requirements listed in Section 2 a kinematic fit using the hadronic $W$ boson decay candidates is performed. For each event the two jets of each light jet pair with a reconstructed $m_{W}^{\text{reco}}$ within 30 GeV ($\approx 3\sigma$) around the peak position of the $m_{W}^{\text{reco}}$ distribution are input to the following $\chi^2$:

$$
\chi^2 = \left[ \frac{E_{j1}(1 - \alpha_1)}{\sigma_1} \right]^2 + \left[ \frac{E_{j2}(1 - \alpha_2)}{\sigma_2} \right]^2 + \left[ \frac{M_{jj}(\alpha_1, \alpha_2) - m_{W}}{\Gamma_{W}} \right]^2
$$

This fit determines the best light jet combination in the event and the corresponding parton scale factors ($\alpha$) for their jet energies. The jet-triplet assigned to the hadronic top-quark decay is then obtained by adding the $b$-tagged jet which maximizes the $p_T$ of the jet-triplet. From these jets the two observables $m_{W}^{\text{reco}}$ and $m_{\text{top}}^{\text{reco}}$ are constructed. The $m_{W}^{\text{reco}}$ is calculated using the reconstructed light jet 4-vectors (i.e. not applying the $\alpha$) of the combination with the smallest $\chi^2$. In contrast, $m_{\text{top}}^{\text{reco}}$ is calculated from these light jet 4-vectors scaled to the parton level (i.e. applying the $\alpha$) and the above determined $b$-tagged jet. After the $\chi^2$ fit, the observed numbers of events are 134 (210) in the electron (muon) channel. The respective predicted numbers of signal events are 112.

For the muon channel the observed $m_{\text{top}}^{\text{reco}}$ distribution and the corresponding fit are shown in Figure 3.

The results for the two channels and their combination are:

- $m_{\text{top}} = (168.3 \pm 6.2 \pm 4.3)$ GeV electron channel
- $m_{\text{top}} = (163.5 \pm 6.7 \pm 4.6)$ GeV muon channel
- $m_{\text{top}} = (166.1 \pm 4.6 \pm 4.4)$ GeV combined

The measured JSF is $1.08^{+0.04}_{-0.06} (1.01^{+0.05}_{-0.05})$ in the electron (muon) channel, uncertainties quoted are statistical. This analysis has a reduced JES systematic of 0.7 GeV but a reduced statistical precision. The other important uncertainties, i.e. those from the relative $b$-jet to light jet energy scale and ISR/FSR variations, are about the same size as for the baseline analysis.

5. Results from the 1d-kinfit analysis

This analysis explores a kinematical likelihood fitter to relate the observed objects to parton level predictions. The entire reconstructed objects are input to the kinematical fitter. In this procedure the measured jets relate to the quark decay products of the $W$ boson and the top-quarks, and the $E_T^{\text{miss}}$ is identified with the transverse momentum components of the neutrino. The kinematical likelihood is defined as:

$$
L = \text{BW}(\hat{E}_{\text{jet},1}, \hat{E}_{\text{jet},2}|m_{W}, \Gamma_{W}) \cdot \text{BW}(\hat{E}_\ell, \hat{E}_\nu|m_{W}, \Gamma_{W})
$$
The likelihood profile as a function of the top-quark mass (in the electron channel).

\[ \text{BW}(\hat{E}_{\text{jet},1}, \hat{E}_{\text{jet},2}, \hat{E}_{\text{jet},3}|m_{\text{top}}^{\text{reco}}, \Gamma_{\text{top}}) \cdot \text{BW}(\hat{E}_{\ell}, \hat{E}_{\text{jet},4}|m_{\text{top}}^{\text{reco}}, \Gamma_{\text{top}}) \cdot \]

\[ \text{TF}(E_{x}^{\text{miss}}|\hat{p}_{x,\nu}) \cdot \text{TF}(E_{y}^{\text{miss}}|\hat{p}_{y,\nu}) \cdot \text{TF}(E_{z}|\hat{E}_{\ell}) \cdot \]

\[ \prod_{i=1}^{4} \text{TF}(E_{\text{jet},i}|\hat{E}_{\text{jet},i}) \cdot \prod_{i=1}^{4} \text{TF}(\eta_{\text{jet},i}|\hat{\eta}_{\text{jet},i}) \cdot \prod_{i=1}^{4} \text{TF}(\phi_{\text{jet},i}|\hat{\phi}_{\text{jet},i}) \cdot \delta(\text{b-tagged jet} | b\text{-quark}). \]

The parton level objects are marked with a hat like \( \hat{E}_{\text{jet},1} \), \( m_{W} \) is the known W boson mass, and \( m_{\text{top}}^{\text{reco}} \) is the estimator for the top-quark mass, i.e. the per event result. For a given event a likelihood is calculated for each possible assignment. The permutation selected maximizes the negative log likelihood. The transfer functions (TF) are derived from the signal Monte Carlo. These functions are obtained for energies and angles of light jets and b-jets, the energy of the charged lepton, and the two components of the \( E_{x}^{\text{miss}} \). In addition, the kinematical likelihood exploits the known values of \( m_{W} \) and \( \Gamma_{W} \) to constrain the reconstructed leptonic and hadronic W boson masses and constrains the reconstructed leptonic and hadronic top-quark masses to be identical. The inclusion of the b-tagging information as a delta distribution restricts the number of permutations investigated per event. With this analysis the correlation of all objects is utilized leading to a narrower \( m_{\text{top}}^{\text{reco}} \) distribution than what is achieved by the baseline analysis, resulting in a significantly reduced expected statistical uncertainty of \( m_{\text{top}} \). However, the analysis is subject to a stronger JES sensitivity than the other two analyses described above.

The analysis is performed for the events fulfilling the common requirements listed in Section 2. The observed numbers of events after the kinematical likelihood fit are 157 (247) in the electron (muon) channel. The respective predicted numbers of signal events are 131.3 ± 0.9 and 190.4 ± 1.0, and the S/B amounts to 3.8 and 4.3, in the electron and muon channel. Again, pseudo-experiments verified that the mean values and widths of the pull distributions are consistent with the expectations of zero and one. The result of a likelihood fit as a function of the top-quark mass is reported in Figure 4. The maximum of the likelihood profile determines the measured \( m_{\text{top}} \), and the 68% area around that value gives the statistical uncertainty. The results for the two channels and their combination, performed as for the baseline analysis above, are:

\[ m_{\text{top}} = (179.0 \pm 4.3 \pm 7.5) \text{ GeV} \quad \text{electron channel} \]

\[ m_{\text{top}} = (172.0 \pm 3.5 \pm 7.5) \text{ GeV} \quad \text{muon channel} \]
\[ m_{\text{top}} = (174.8 \pm 2.7 \pm 7.5) \text{ GeV} \text{ combined} \]

As expected the statistical precision is significantly improved in comparison to the presented baseline method. The dominating uncertainty stems from the JES and amounts to about 6.6 GeV. The other important uncertainties, i.e. those from the relative \( b \)-jet to light jet energy scale and ISR/FSR variations are about the same size as for the baseline analysis.

6. Comparison of the three top-quark mass measurements

The results for all analyses, and for each lepton channel are consistent within uncertainties. For all analyses, the muon channel has a slightly smaller expected statistical uncertainty. The systematic uncertainty is similar for both channels. The expected statistical uncertainty is smallest for the 1d-kinfit analysis, followed by the 1d-\( R_{32} \) analysis, with the 2d-analysis having the least precise statistical component. At the present level of understanding of the JES, the order of precision of systematic uncertainty is reverted. The fact that the complementary methods lead to consistent results gives confidence in their stability.

7. Summary

The top-quark mass has been measured directly via three complementary implementations of the template method in the \( t\bar{t} \rightarrow \text{lepton+jets} \) channel based on first \( pp \)-collision data at \( \sqrt{s} = 7 \) TeV from ATLAS. The integrated luminosity used is about \( \mathcal{L}_{\text{int}} = 35 \text{ pb}^{-1} \). All analyses lead to consistent results within their uncertainties. The measured ATLAS value presented here is obtained from a one dimensional template analysis exploiting a new variable \( R_{32} \), defined as the event-by-event ratio of \( m_{\text{top}}^{\text{reco}} \) and \( m_{W}^{\text{reco}} \). The main sources of uncertainty stem from the jet energy scale uncertainty for light jets and \( b \)-jets, and from the modelling of initial and final state radiation. Combining both channels the top-quark mass is measured with a total uncertainty of 6.3 GeV to be

\[ m_{\text{top}} = (169.3 \pm 4.0 \pm 4.9) \text{ GeV}, \]

where the first uncertainty is statistical, and the second one systematic.

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