Measurement of the top-quark mass using 7 TeV proton-proton collisions with the ATLAS detector

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Abstract. The top quark is the heaviest known elementary particle. Its mass is intriguingly close to the electroweak symmetry breaking scale. Therefore its accurate determination is an important aspect of the LHC physics program. A summary of the present measurements of the top-quark mass with the ATLAS detector is presented here. The data used in those analyses amounts up to 4.7 fb of proton-proton collisions at 7 TeV with the Large Hadron Collider. The top-quark mass has been measured in different event topologies, namely all-hadronic, lepton plus jets and dilepton channel. The kinematic approach to measure the top-quark mass uses template methods for the all-hadronic and lepton plus jets channels, and the $m_{T2}$ variable, that relates the transverse mass of the two leptons, is used in the dilepton channel.

1. Top-quark mass introduction

The top quark was discovered in 1995 at Tevatron in Chicago, USA [1][2]. It plays an important role due to its large contribution to radiative corrections and high sensitivity to physics beyond the standard model (SM). The top-quark mass is a fundamental parameter of the SM. After its discovery many methods have been developed to measure its mass with a high precision (< 1 GeV). Nowadays, the most precise top-quark mass measurement has been provided by the combination of the CDF and D0 experiments: $m_{top} = 173.2 \pm 0.9$ GeV [3].

The LHC (Large Hadron Collider) [4] operated at pp centre of mass energy of $\sqrt{s} = 7$ TeV in 2011. During this period ATLAS (A Toroidal LHC Apparatus) [5] collected an integrated luminosity of data with all detector subsystems operational of 4.7 fb. The top quark at LHC is mainly produced in pairs through gluon-gluon fusion processes. Once produced, the top quark decays almost exclusively to a W boson and a b-quark (BR>99%). Its lifetime is of the order of $10^{-25}$ s, therefore the top quark decays before hadronizing. Here, measurements from using the invariant mass of the top-quark decay products are reported. The $t\bar{t}$ events can be divided in three channels depending of the final state objects: all-hadronic channel, lepton plus jets channel and the dilepton channel (lepton=e,μ).

2. ATLAS object reconstruction and selection for top mass analysis

To achieve a good reconstruction of the objects involved in the top-mass measurements (electrons, muons, jets and missing transverse energy ($E_T^{miss}$)) the detector has to be fully operational. All the analyses have used the standard ATLAS reconstruction and selection. Electron candidates are defined as a deposit of energy in the electromagnetic (EM) calorimeter associated with a reconstructed track of the Inner detector (ID). The candidates are selected if they have a transverse energy $E_T^{e}>25$ GeV and pseudorapidity $|\eta|<2.5$ excluding the region of $1.37<|\eta|<1.52$. Stringent selection cuts in the
calorimeter and tracker are required to provide a good separation between electrons and jets (fake electrons). Moreover electron isolation is necessary to suppress the QCD multi-jet background. The muon candidate is reconstructed with an algorithm that combines track segment from muon chambers and from the ID and refitted them as a single track with a tight quality. The muon candidates are required to have $p_T>20$ GeV and $|\eta|<2.5$. An isolation cut is used to suppress the background origination from heavy quarks flavour decay. Moreover an overlap between muon and jet is also applied to avoid wrong muon identification. The $E_T^{miss}$ is defined as the event momentum imbalance in the transverse plane of the beam axis, in this plane the momentum conservation is expected. An imbalance indicates the transit of undetectable particles, as for example neutrinos. The $E_T^{miss}$ has been computed with the information of all objects in the event: electrons, muons, jets, soft jets and calorimeter cell out term (this term takes into account the energy not associated with any object). The jets are clustered using Anti-Kt algorithm with $R=0.4$ as cone size. The constituents of the calorimeter jets are clusters of calorimeter cells. The EM shower energy deposit in the calorimeter is accounted correctly. In addition, a calibration at hadronic scale must be applied. This calibration includes corrections depending of the E and $\eta$ of the jet at EM scale as well as jet energy scale (JES) corrections based on Monte Carlo (MC) studies that have been validated with data. The jets are selected with $p_T>25$ GeV and $|\eta|<2.5$ respect to the primary vertex. In order to reduce the impact of the pile-up, a cut in the probability that the jet stems from the hard scatter vertex is applied. Furthermore a jet quality criterion is imposed to remove jets not associated to the real energy deposits (hardware problems or cosmic-ray showers). Jets originating form b-quarks are identified using different b-tagging algorithms with a tagging efficiency higher than 70%.

3. ATLAS top-mass analyses

Basically two techniques have been used to perform the mass measurements in ATLAS: the templates methods and the calibration curves. The template methods obtain the top-mass value confronting simulated distributions with their real countpartners. On the other hand, the calibration curves extract the top-mass from a curve that describes the dependence of an experimental observable versus $m_{top}$. The top-mass measurement obtained for both methods corresponds to the mass definition used in the MC generator. The difference between the MC mass and the pole mass of the top quark is expected of order of 1 GeV [6]. The ATLAS analysis has been developed in different channel topologies:

3.1. All-hadronic channel

The top-mass measurement in the all-hadronic channel has been done with a template method using 2.04/fb [7]. The selection of full hadronic events is based on a $\chi^2$ equation that measures the compatibility of the jets with a particular assignment of the $t\bar{t}$ decay products:

$$\chi^2 = \frac{(m_{j_1j_2} - m_W)}{\sigma_W^2} + \frac{(m_{j_1j_2b} - m_j)}{\sigma_j^2} + \frac{(m_{j_1j_2b2} - m_j)}{\sigma_j^2} + \frac{(m_{j_1j_2b3} - m_j)}{\sigma_j^2}$$  \hspace{1cm} (1)

These terms constrain the W mass and the top mass with a $\sigma_W = 10.2$ GeV and $\sigma_j = 17.4$ GeV respectively. Both resolutions have been determined using MC information. Only the events with a $\chi^2$ lower than 8 are kept for the measurement. In addition, some extra cuts as number of b-jets equal to two and the rejection of events with $E_T^{miss}$ contribution are required to get a purer sample. One of the most important systematic errors for the top-mass measurement is the not well know energy of the jets (JES). To minimize this effect, a ratio of the known W mass and the W mass candidate is calculated event by event and the light jets are corrected by this scale factor. Finally the top-mass is obtained by fitting templates of the three-jet mass combination. The templates for signal have been obtained from five MC $t\bar{t}$ samples generated with a $m_{top}$ between 160-190 GeV. Background contribution has been estimated from data. The final reconstructed mass can be observed in figure 1. This yields a top-quark mass of $m_{top} = 174.9 \pm 2.1$ (stat)$\pm 3.8$ (sys) GeV. The systematic errors have been analyzed in detail (table 1).
3.2. Dilepton channel

A measurement of the top quark mass using the transverse mass variable $m_{T2}$ has been performed using 4.7/fb [8]. The $m_{T2}(m_{\text{invisible}}) = \min[\max[m_T(m_{\text{invisible}},p_T^{(1)}),m_T(m_{\text{invisible}},p_T^{(2)})]]$ represents a lower bound on the parent’s particle mass and is useful in pair production events with two undetected particles. The b-jets from top quarks are selected by requiring a $p_T > 45$ GeV and $m_{T2} < 200$ GeV. The top decay objects assignment has been done using the multivariate optimization analyses. The dependence of the mean $m_{T2}$ versus eight MC samples generated at different $m_{\text{top}}$ have been used to build the calibration curve. Finally, the mean value of $m_{T2}$ distribution measured in data, figure 2, is used to obtain the $m_{\text{top}}$ from the calibration curve. This yields a $m_{\text{top}} = 175.2 \pm 1.6{\text{(stat)}} \pm 2.8{\text{(syst)}}$ GeV. The systematic error sources that contribute to the measurement are summarized in table 2.

3.3. Lepton+jets channel

In this channel, two templates methods have been developed to measure $m_{\text{top}}$ using 1.04/fb. The 1d-analysis [9] uses a mass ratio between the reconstructed top-mass and the hadronic W mass ($R_{32} = m_{\text{top}}/m_w$). The selection of the top decay objects is done using a kinematic fit that exploits the full event topology as well as b-tagging information. The $R_{32}$, that is sensitive to the top mass variations and helps in the JES reduction, is used to derive the templates at different top masses. The top mass measurement obtained from 1d template is $m_{\text{top}} = 174.4 \pm 0.9{\text{(stat)}} \pm 2.8{\text{(syst)}}$.

The 2d-analysis [9] determines simultaneously the $m_{\text{top}}$ and the jet scale factor (JSF) using the $m_{\text{top}}$ and $m_w$ distributions. The JSF, calculated using the differences between the predicted $m_w$ and the

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**Figure 1.** Distribution of $m_{\text{top}}$ observed in data (points). The top-quark signal is superimposed on the distribution from multijet background [7].

**Figure 2.** The $m_{T2}$ distribution of the selected events [8].

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| Source                  | Uncertainty | Source                  | Uncertainty |
|-------------------------|-------------|-------------------------|-------------|
| Method                  | 0.4         | Jet energy scale        | 2.1         |
| Template statistics     | 0.9         | b-jet energy scale      | 1.4         |
| MC generator            | 0.5         | b-tag efficiency SF     | 0.3         |
| ISR/FSR                 | 1.7         | Jet energy resolution   | 0.3         |
| PDF                     | 0.6         | Jet reco. efficiency    | 0.2         |
| Backg. Modelling        | 1.9         |                         |             |
| Total systematic uncertainty | 3.8     |                         |             |

**Table 1.** Table of systematic uncertainty contributions in the measurement of $m_{\text{top}}$ in all hadronic channel [7].

| Source                      | Uncertainty |
|-----------------------------|-------------|
| $t\bar{t}$ generator model  | -1.3/+1.3   |
| Parton shower               | -0.9/+0.9   |
| Color reconnection          | -1.2/+1.2   |
| ISR/FSR                     | -0.5/+0.5   |
| PDF                         | -0.1/0.1    |
| Calibration Curve           | -0.3/+0.3   |
| Fake modelling              | -0.3/0.3    |
| Underlying event            | -0.2/0.2    |
| Total Syst. uncertainty     | -3.3/+3.5   |

**Table 2.** Table of systematic uncertainty contributions in the measurement of $m_{\text{top}}$ in the dilepton channel [8].
observed in data, reduces the impact of the JES in the measurement. The top jet triplet candidate is constructed from any b-jet together with any light-jet pair with $m_W$ within 50-110 GeV. The jet triplet with maximum $p_T$ is chosen as top quark candidate. The selected W light-jet pair is calibrated at parton level using a $\chi^2$ equation and the corrections are applied only to the $m_{top}$ parameter to reduce the JES. The templates are constructed as a function of top-quark mass in the range of 160 GeV - 190 GeV and the input value for the JSF is in the range of 0.9-1.1. The unbinned likelihood fit is used to perform a top-mass measurement $m_{top}=174.5\pm0.6$ (stat)$\pm2.3$ (sys). Detailed systematic information can be found in table 3. Figure 3 shows the top-mass measurement in the e+jets channel.

![Figure 3](image)

**Figure 3.** The correlation of the measured top-quark mass, and the jet energy scale factor (JSF) for the e+jets channel [9].

### 4. Conclusions
A summary of the present top-mass measurement in ATLAS for the different channels has been reported.

### References

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