



## Top-quark mass measurements using the ATLAS detector at the LHC

Kaven Yau Wong, Physikalisches Institut, Universität Bonn, On behalf of the ATLAS Collaboration

---

### Abstract

The most recent results of the top-quark mass measurements with the ATLAS detector using data collected from proton-proton collisions at the Large Hadron Collider are presented. Although several decay modes of the top-quark pairs have been used in ATLAS for top-quark mass measurements, only the latest results are presented (single lepton and dilepton channels). The top-quark pole mass from the  $t\bar{t}$  cross-section measurement in the dilepton channel and the top-antitop quark mass difference measurement in the single-lepton channel are also shown. The systematic uncertainties associated to these measurements are discussed in some detail.

*Keywords:* top quark, mass, pole mass,  $t\bar{t}$ , mass difference, ATLAS

---

### 1. Introduction

The top quark is the heaviest elementary particle in the Standard Model and its mass is a fundamental parameter in quantum chromodynamics. Its value must be determined experimentally and its precise measurement has a large impact in the computation of electroweak corrections.

The ATLAS detector [1] is a general purpose detector located at the Large Hadron Collider (LHC) [2]. Over the last years, the ATLAS Collaboration has measured the top-quark mass with increasing precision, with the following most recent analyses:

- Top-quark mass measurement in the  $t\bar{t}$  single lepton channel [3];
- Top-quark mass measurement in the  $t\bar{t}$  dilepton channel [4];
- Top-quark pole mass from the  $t\bar{t}$  cross-section measurement in the dilepton channel [5];
- Top-antitop mass difference in the  $t\bar{t}$  single lepton channel [6].

Almost all the analyses use the template method to extract the variable of interest from data, where the templates are built with the help of Monte-Carlo simulations.

### 2. Top-quark mass measurement in the $t\bar{t}$ single lepton channel

The analysis [3] is performed using data at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV, which amounts to an integrated luminosity of  $4.7 \text{ fb}^{-1}$ .

A three-dimensional template technique is used, where the  $m_{\text{top}}^{\text{reco}}$ , the jet scale factor (JSF) and the  $b$ -jet scale factor ( $b$ JSF) are measured simultaneously by fitting the distribution of three observables reconstructed using a kinematic likelihood fit: the top-quark mass, the  $W$ -boson mass and the ratio between the average transverse momentum of the  $b$ -tagged jets and the average transverse momentum of the two jets of the  $W$ -boson hadronic decay,  $R_{lb}^{\text{reco}}$  (see Figure 1).

The reconstructed top-quark mass is expected to be sensitive to the top-quark mass, the JSF and the  $b$ JSF, while the reconstructed  $W$ -boson mass is expected to only depend on the JSF. Finally, the reconstructed  $R_{lb}$  is expected to depend on the  $b$ JSF and the top-quark mass.

Applying the three-dimensional template technique to data, the top-quark mass is measured to be:

$$m_{\text{top}} = 172.31 \pm 0.75(\text{stat}) \pm 1.35(\text{syst}) \text{ GeV}, \quad (1)$$

where the statistical uncertainty also includes the uncertainty from the JSF and  $b$ JSF measurements.

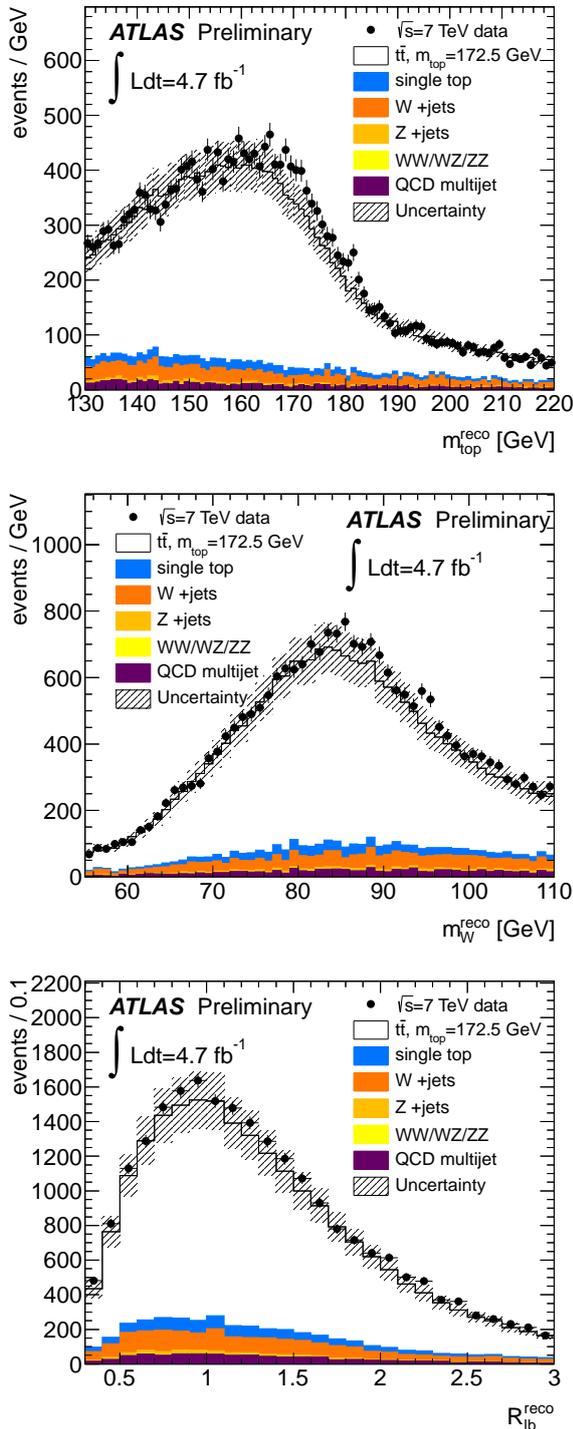


Figure 1: Data-MC comparison for  $m_{\text{top}}^{\text{reco}}$  (top),  $m_W^{\text{reco}}$  (middle) and  $R_{lb}^{\text{reco}}$  (bottom). Each point is obtained from the result of the per-event kinematic likelihood fit. The hashed area is the total uncertainty.

By comparing a two-dimensional template analysis (where the  $b$ -jet energy scale is fixed) to the three-dimensional template analysis (where the  $b$ -jet energy scale is allowed to vary), it is shown that the three-dimensional template technique significantly reduces the  $b$ -jet energy scale uncertainty from 0.92 GeV to 0.08 GeV and the hadronization uncertainty from 1.30 GeV to 0.27 GeV. There is a drawback, however, since the  $b$ -tagging efficiency and mistag rate uncertainty increases from 0.17 GeV to 0.81 GeV. But the overall effect is a total systematic uncertainty improvement of 33%, reducing from 2.02 GeV to the final 1.35 GeV quoted in this measurement.

### 3. Top-quark mass measurement in the $t\bar{t}$ dilepton channel

The dilepton channel does not allow a direct mass reconstruction, but has the advantage that it offers a very clean signal and a very good signal-to-background ratio. The analysis [4] is performed using  $4.7 \text{ fb}^{-1}$  of 7 TeV data.

The template method is used to measure the top-quark mass using the  $m_{lb}$  variable, defined as the average invariant mass of the two lepton- $b$ -jet systems in the dileptonic channel. Since the correct pairing between the two leptons and the two  $b$ -jets is not known, the values of  $m_{lb}$  for both combinations are computed and the smallest value is taken. This algorithm gives the correct pairing 77% of the times.

The  $m_{lb}$  distribution of the signal is modelled as the sum of a Gaussian function and a Landau function for the signal, while the background is modelled as a Landau function. It is to be noted that the background is very small, contributing only 3% to the total number of events. The template fit function for different input top-quark masses is shown in Figure 2.

Applying the template fit to data gives the value (see Figure 3):

$$m_{\text{top}} = 173.09 \pm 0.64(\text{stat}) \pm 1.50(\text{syst}) \text{ GeV}, \quad (2)$$

where the systematic uncertainty is dominated by the jet energy scale (0.89 GeV) and the  $b$ -jet energy scale (0.71 GeV).

### 4. Top-quark pole mass from the $t\bar{t}$ cross-section measurement in the dilepton channel

The ATLAS collaboration has performed a  $t\bar{t}$  cross-section measurement in the dilepton channel using

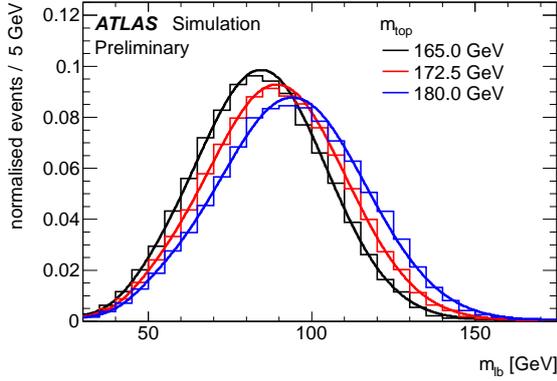


Figure 2:  $m_{t\bar{t}}$  template fit function for different input top-quark masses. The plot shows the sensitivity of  $m_{t\bar{t}}$  to the top-quark mass.

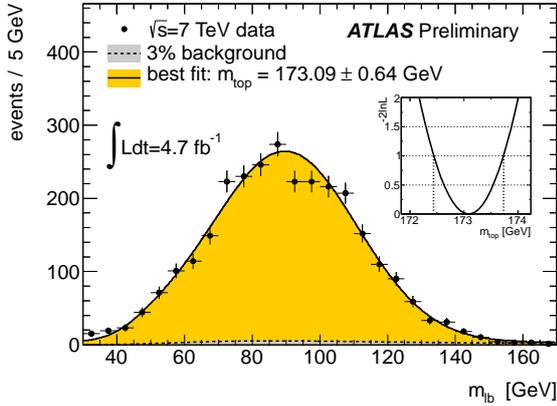


Figure 3: Top-quark mass measured by fitting the template function to data. Only the statistical uncertainty is quoted.

7 TeV and 8 TeV data, amounting to integrated luminosities of  $4.6 \text{ fb}^{-1}$  and  $20.3 \text{ fb}^{-1}$  respectively [5].

With the top-quark mass measurements reaching precisions of the order 1 GeV, one should remember that the values of these reconstructed top-quark masses are different from the value of the top-quark pole mass. This difference has been estimated to be of the order of 1 GeV [7].

The top-quark pole mass, *i.e.*, the mass of the top quark as a free particle, can be computed from the  $t\bar{t}$  cross section. The idea is to exploit the strong dependence of the  $t\bar{t}$  cross section on the top-quark pole mass. This dependence is obtained for both centre-of-mass energies using different parton density function (PDF) models, as shown in Figure 4. Notice that the measured

cross section does not depend on the assumed input Monte-Carlo top-quark mass, ensuring that the method used to measure the  $t\bar{t}$  cross section is independent from the value of the top-quark pole mass. This requirement is important in order to extract the top-quark pole mass from the measured value of the  $t\bar{t}$  cross section.

The dependence of the  $t\bar{t}$  cross section on the top-quark pole mass is parametrized as:

$$\sigma_{t\bar{t}}^{\text{theo}}(m_{\text{top}}^{\text{pole}}) = \sigma(m_{\text{top}}^{\text{ref}}) \left( \frac{m_{\text{top}}^{\text{ref}}}{m_{\text{top}}^{\text{pole}}} \right)^4 (1 + a_1 x + a_2 x^2), \quad (3)$$

where  $m_{\text{top}}^{\text{ref}} = 172.5 \text{ GeV}$ ,  $x = (m_{\text{top}}^{\text{pole}} - m_{\text{top}}^{\text{ref}}) / m_{\text{top}}^{\text{ref}}$ , and  $\sigma(m_{\text{top}}^{\text{ref}})$ ,  $a_1$  and  $a_2$  being free parameters.

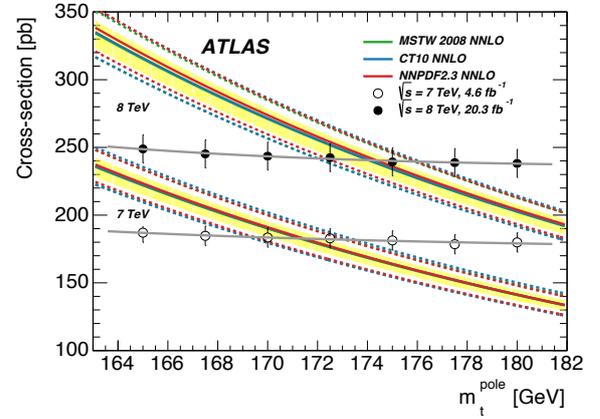


Figure 4: Predicted NNLO+NNLL  $t\bar{t}$  production cross-sections at  $\sqrt{s} = 7 \text{ TeV}$  and  $\sqrt{s} = 8 \text{ TeV}$  as a function of  $m_{\text{top}}^{\text{pole}}$  using different PDF sets. The total uncertainty is shown in dashed lines, while the yellow band shows the QCD scale uncertainty.

Once the parameters are computed, the pole mass is extracted by maximizing the likelihood:

$$\mathcal{L} = \int G(\sigma'_{t\bar{t}} | \sigma_{t\bar{t}}, \rho_{\text{exp}}) G(\sigma'_{t\bar{t}} | \sigma_{t\bar{t}}^{\text{theo}}, \rho_{\text{theo}}^{\pm}) d\sigma'_{t\bar{t}}, \quad (4)$$

where  $\mathcal{L}$ ,  $\sigma_{t\bar{t}}$  and  $\sigma_{t\bar{t}}^{\text{theo}}$  depend on  $m_{\text{top}}^{\text{pole}}$ . The function  $G(x|\mu, \rho)$  is a Gaussian probability density in the variable  $x$  with mean  $\mu$  and standard deviation  $\rho$ .

The top-quark pole mass measurements using different PDF sets and the two different cross sections are shown in Table 1. By combining both measurements, the top-quark pole mass is found to be:

$$m_{\text{top}}^{\text{pole}} = 172.9_{-2.6}^{+2.5} \text{ GeV}. \quad (5)$$

PDF	$m_{\text{top}}^{\text{pole}}$ (GeV) from $\sigma_{t\bar{t}}$	
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
CT10 NNLO	$171.5 \pm 2.6$	$174.2 \pm 2.6$
MSTW 68% NNLO	$171.4 \pm 2.4$	$174.0 \pm 2.5$
NNPDF2.3 5f FFN	$171.4 \pm 2.3$	$174.2 \pm 2.4$

Table 1:  $m_{\text{top}}^{\text{pole}}$  measurements using different PDF sets.

## 5. Top-antitop mass difference in the $t\bar{t}$ single lepton channel

The analysis [6] is performed in the  $t\bar{t}$  single-lepton channel using data at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV, which amounts to an integrated luminosity of  $4.7 \text{ fb}^{-1}$ .

A kinematic fit is used to fully reconstruct the top quark pair in each event, where the mass values of the top quark and the antitop quark are obtained from this fit. Therefore, the difference between the top quark and antitop-quark masses can be defined as:

$$\Delta m_m^{\text{fit}} = q_\ell \cdot (m_{b\ell\nu}^{\text{fit}} - m_{bjj}^{\text{fit}}), \quad (6)$$

where  $q_\ell$  is the charge of the lepton. As one of the top quarks in the  $t\bar{t}$  pair decays hadronically and the other one decays leptonically,  $m_{b\ell\nu}^{\text{fit}}$  is the fitted mass of the leptonic decay while  $m_{bjj}^{\text{fit}}$  is the fitted mass of the hadronic decay.

The distribution of  $\Delta m_m^{\text{fit}}$  is parametrized as the sum of two Gaussians for the signal, and as a single Gaussian function for the background. The signal templates are shown in Figure 5.

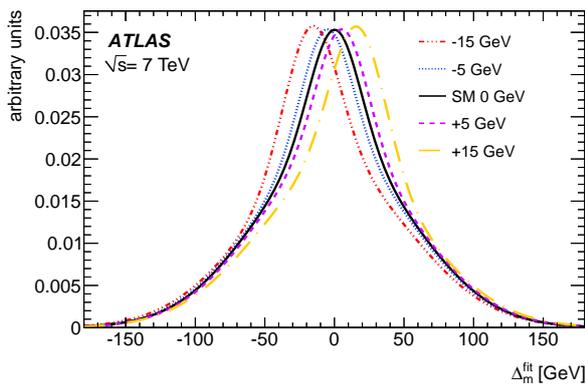
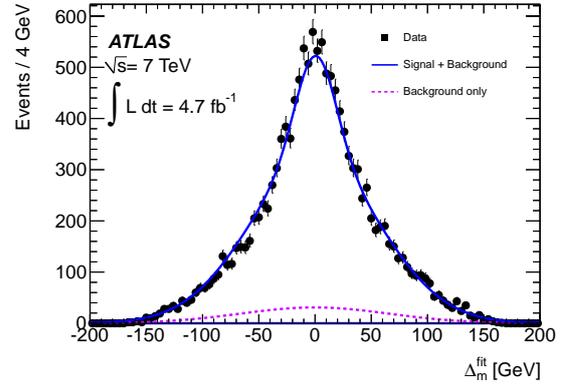
Figure 5: Signal template for the  $\Delta m_m^{\text{fit}}$  distribution. The distribution is modelled as the sum of two Gaussian functions.

Figure 6: Reconstructed top-antitop mass difference distribution in data, fitted with the template (signal and background).

Applying the template fit to data (see Figure 6), the measured mass difference between the top quark and the antitop quark is:

$$\Delta m_{t\bar{t}} = 0.67 \pm 0.61(\text{stat}) \pm 0.41(\text{syst}) \text{ GeV}. \quad (7)$$

The systematic uncertainty is completely dominated by the  $b$ -fragmentation model. This uncertainty addresses differences in the detector response to jets originating from  $b$  and  $\bar{b}$  quarks. In order to evaluate this effect, events were generated using POWHEG and interfaced with PYTHIA. These events were then compared with the same generated events, but the  $b$ -hadron decays were simulated with EVTGEN instead. Using this procedure, the  $b$ -fragmentation model uncertainty is estimated to be 0.34 GeV.

## Acknowledgment

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme ERC Grant Agreement n. 617185.

## References

- [1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (08) (2008) S08003.
- [2] L. Evans and P. Bryant (editors), LHC Machine, JINST 3 (08) (2008) S08001.
- [3] ATLAS Collaboration, Measurement of the Top Quark Mass from  $\sqrt{s} = 7$  TeV ATLAS Data using a 3-dimensional Template Fit (ATLAS-CONF-2013-046). URL <http://cds.cern.ch/record/1547327>
- [4] ATLAS Collaboration, Measurement of the Top Quark Mass in Dileptonic Top Quark Pair Decays with  $\sqrt{s} = 7$  TeV ATLAS Data (ATLAS-CONF-2013-077). URL <http://cds.cern.ch/record/1562935>

- [5] ATLAS Collaboration, Measurement of the  $t\bar{t}$  production cross-section using  $e\mu$  events with  $b$ -tagged jets in  $pp$  collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS detector (CERN-PH-EP-2014-124). arXiv:1406.5375.
- [6] ATLAS Collaboration, Measurement of the mass difference between top and anti-top quarks in  $pp$  collisions at using the ATLAS detector, Phys. Lett. B 728 (2014) 363 – 379.
- [7] A. Hoang, I. Stewart, Top Mass Measurements from Jets and the Tevatron Top-Quark Mass, Nucl. Phys. B (Proc. Suppl.) 185 (2008) 220–226.