Top quark mass measurements in ATLAS

Teresa Barillari, MPP Munich
Shanghai LHCP 2017
15 May 2017 – 20 May 2017
Introduction

- The top-quark mass, $m_{\text{top}}$, is a fundamental parameter of the Standard Model (SM).
- Precise determinations of the SM parameters allow to challenge consistency tests of the SM and to look for signs of new physics beyond the SM (BSM).
- Plots show experimental results for: (left) the $W$ mass ($m_W$) and top-quark pole mass ($m_{\text{top}}^{\text{pole}}$) with 1σ uncertainties in comparison with the SM and the MSSM prediction; (central) ellipses for the 1σ uncertainties in the mass of the Higgs, $m_h$, $m_{\text{top}}^{\text{pole}}$ plane confronted with the SM vacuum expectations; (right) ATLAS results on cross-section measurements compared and in agreement with the SM predictions.

JHEP 1312 (2013) 084
The top quark is the heaviest known elementary particle, \( m_{\text{top}} \approx 173 \text{ GeV} \) (left top plot)

- It decays before hadronization (lifetime \( \tau \approx 5 \times 10^{-25} \text{ s} \))

- Main top decay: \( t \rightarrow Wb \)

- The final states for the leading \( t \bar{t} \)-production process can be divided in three classes:
  - All-jets (46.2%):
    \[ t \bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b q'' \bar{q}''' \bar{b} \]
  - Lepton+jets (43.5%):
    \[ t \bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow q \bar{q}' b l \bar{\nu}_l \bar{b} + \bar{\nu}_l b q \bar{q}' \bar{b} \]
  - Dilepton (10.3%):
    \[ t \bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \bar{\nu}_l b l' \bar{\nu}_l b' \]

---

**Top Pair Branching Fractions**

- "alljets" 46%
- \( \tau + \mu \) 15%
- \( \tau + e \) 15%
- \( \mu + \mu \) 2%
- \( \mu + e \) 15%
- \( e + e \) 15%
- \( e + \mu \) 2%
- \( e + \tau \) 2%

- "dileptons" 10.3%
Top Quark Mass Measurements

Different definitions of $m_{\text{top}}$:

- The top-quark Monte Carlo (MC) mass, $m_{\text{top}}^{\text{MC}}$, parameter measured from comparison to MC events with top-quark decay products.
- The top-quark pole mass, $m_{\text{top}}^{\text{pole}}$, parameter, is the classic rest mass that enters the top propagator.
- The running top-quark mass, $\overline{M}_S$ mass, parameter defined in a low-scale short distance scheme.

Typical $m_{\text{top}}^{\text{MC}}$ or just $m_{\text{top}}$ analyses reconstruct top quark candidates in data and MC often using kinematic fits and likelihood fits based on templates, in one ($m_{\text{top}}$) or more (JES, bJES) parameters.

Though $m_{\text{top}} \neq m_{\text{top}}^{\text{pole}}$.

“The uncertainty on the translation from the $m_{\text{top}}^{\text{MC}}$ definition to a theoretically well defined short distance mass definition at low scale is currently estimated to be of the order of 1 GeV” arxiv:1405.4781, arXiv:1408.6080, Nucl. Phys. Proc. Suppl. 185 (2008):220-226

Cross-section based methods measure a theoretically well defined mass e.g. the $m_{\text{top}}^{\text{pole}}$, though with not competitive precision $\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 5\% \rightarrow \Delta m_{\text{top}}/m_{\text{top}} \sim 1\%$.

In the following the latest $m_{\text{top}}$ and $m_{\text{top}}^{\text{pole}}$ ATLAS results will be presented.
Dilepton top-quark mass at 8 TeV

- \( m_{\text{top}} \) measurement from dilepton channel

Events preselection:
- Exactly two oppositely charged central leptons (\( \ell \))
- In the same-lepton-flavor channels an \( E_T^{\text{Miss}} > 60 \) GeV is required, with an invariant mass of the lepton pair \( m_{\ell\ell} > 15 \) GeV
- In the e\( \mu \) channel the scalar sum of \( p_T \) of the two \( \ell \) and all jets is required to be > 130 GeV
- Two jets with \( p_T > 25 \) GeV and \(|\eta| < 2.5\), one of this is a b-tagged jet
- Keep events with two b-tagged jets and two \( \ell \)
- The combination with the lowest average invariant mass of the two \( \ell \)-b-jet pairs, \( m_{\ell b}^{\text{reco}} \), with 30 GeV < \( m_{\ell b}^{\text{reco}} \) < 170 GeV is retained
- A cut on the average \( p_T \) of the two \( \ell \)-b-jet pairs \( p_{T\ell b} > 120 \) GeV is applied to optimize the final \( m_{\text{top}} \) uncertainty
The analysis uses a template fit to $m_{\text{reco}^{\ell \ell b}}$.

An unbinned likelihood maximisation gives the $m_{\text{top}}$ value that best describes the data:

$$m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat.)} \pm 0.72 \text{ (syst.) GeV}$$

Biggest systematic uncertainties come from jet energy scale (JES) and relative b-to-light-jet energy scale (bJES).

Result is $\sim 40\%$ more precise than $m_{\text{top}}$ measured at 7 TeV.

It is the the most precise single result in this decay channel to date.

Combining this result with the ATLAS $m_{\text{top}}$ measurements in the $t\bar{t} \rightarrow \ell \ell + \text{jets}$ and $t\bar{t} \rightarrow \text{dilepton channel}$ at 7 TeV gives:

$$m_{\text{top}} = 172.84 \pm 0.34 \text{ (stat.)} \pm 0.61 \text{ (syst.) GeV}$$

The result is limited by the calibration of the JES and by the MC modeling of signal events.
**All-jets top-quark mass at 8 TeV**

- $m_{\text{top}}$ measurement from all-jets channel is challenging because of the large multi-jets background arising from various QCD processes.

- Events selection:
  - No leptons $\geq$ jets with $p_T > 60$ GeV and $|\eta| < 2.5$, two of them b-tagged
  - Small $E_T^{\text{Miss}} < 60$ GeV
  - Topological cuts applied to reduce background: large distance of b-tagged jets; small distance of W, b pairs from best kinematic solution

- The jet assignment is accomplished by $\chi^2$ fit to the $t\bar{t}$ system,

- A data-driven method is used to determine the large multi-jets background with regions defined by number of b-tags and proximity of W,b pairs.
All-jets top-quark mass measurement at 8 TeV

- The $m_{\text{top}}$ measurement is extracted by using a template fit to the ratio of the three-jet to the dijet mass, $R_{3/2}$, with a binned minimum-$\chi^2$ approach.
- $m_{\text{top}} = 173.72 \pm 0.55 \text{ (stat.)} \pm 1.01 \text{ (syst.)} \text{GeV}$
- Biggest systematic uncertainties come from JES, hadronisation modeling, and bJES.
- This measurement agrees with the previous Tevatron and LHC $m_{\text{top}}$ measurements.
- Result $\sim 40\%$ more precise that $m_{\text{top}}$ measured @ 7 TeV

$t\bar{t} \rightarrow W^+ bW^- \bar{b} \rightarrow \ell^\pm \ell^\pm \nu \bar{\nu} b\bar{b}$

arXiv:1702.07546
**Top-quark Pole Mass Measurements: Dilepton 7 & 8 TeV**

- $m_{\text{top}}^{\text{pole}}$ measurement from total cross-section in the dilepton channel @ 7 and 8 TeV
- Production $\sigma_{t\bar{t}}$ measurement performed using $t\bar{t}$ events with opposite-charge $e\mu$ pair in the final state and exactly one or two b-tagged jets
- Main background: $Wt$
- $\sigma_{t\bar{t}} = 182.9 \pm 7.1$ pb (7 TeV)
- $\sigma_{t\bar{t}} = 242.4 \pm 10.3$ pb (8 TeV)
Extraction of $m_{\text{top}}^{\text{pole}}$ using a Bayesian likelihood approach, assumed $m_{\text{top}} = 172.5$ GeV

Used different PDF + $\alpha_s$ sets

Results obtained using PDF4LHC show small dependency of $\sigma_{t\bar{t}}$ on the assumed value of $m_t$ arising from variations in the acceptance and $Wt$ background

$m_{\text{top}}^{\text{pole}} = 171.4 \pm 2.6$ GeV (7 TeV)

$m_{\text{top}}^{\text{pole}} = 174.1 \pm 2.6$ GeV (8 TeV)

Combining 7 and 8 TeV measurements:

$m_{\text{top}}^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV

Results compatible with $m_{\text{top}}$ extracted using different techniques

$m_{\text{top}}^{\text{pole}}$ from diff. cross-section $t\bar{t} + 1\text{jet}$ events at 7 TeV (arXiv:1507.01769v1)

$m_{\text{top}}^{\text{pole}} = 173.7 \pm 1.5(\text{stat.}) \pm 1.4(\text{syst.})^{+1.0}_{-0.5}(\text{theory})$ GeV
Figure shows the latest results, and the previous results that are now superseded. The results are compared with the ATLAS, CMS, Tevatron and Tevatron+LHC $m_{\text{top}}$ combinations.

### ATLAS+CMS Preliminary LHC$\text{topWG}$

$m_{\text{top}}$ summary, $\sqrt{s} = 7$-8 TeV  May 2017

<table>
<thead>
<tr>
<th>Source</th>
<th>$m_{\text{top}}$ (GeV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, $l+jets$ (*)</td>
<td>172.33 ± 1.27 (0.75 ± 1.02)</td>
<td>7 TeV [8]</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>173.79 ± 1.41 (0.54 ± 1.30)</td>
<td>7 TeV [8]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>175.1 ± 1.8 (1.4 ± 1.2)</td>
<td>7 TeV [9]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>172.2 ± 2.1 (0.7 ± 2.0)</td>
<td>8 TeV [10]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>172.99 ± 0.85 (0.41 ± 0.74)</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>173.72 ± 1.15 (0.55 ± 1.01)</td>
<td>8 TeV [12]</td>
</tr>
<tr>
<td>ATLAS comb. (June 2016)</td>
<td>172.84 ± 0.70 (0.34 ± 0.61)</td>
<td>7+8 TeV [11]</td>
</tr>
<tr>
<td>CMS, $l+jets$</td>
<td>172.35 ± 0.51 (0.16 ± 0.48)</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.82 ± 1.23 (0.19 ± 1.22)</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>172.32 ± 0.64 (0.25 ± 0.59)</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>CMS, single top</td>
<td>172.95 ± 1.22 (0.77 ± 0.95)</td>
<td>8 TeV [14]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>172.44 ± 0.48 (0.13 ± 0.47)</td>
<td>7+8 TeV [13]</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line
Conclusions

- Precise measurements of \( m_{\text{top}} \) are fundamental to provide inputs to test the self-consistency of the SM and search physics BSM.

- Presented latest results of \( m_{\text{top}} \) and \( m_{\text{top}}^{\text{pole}} \) measurements performed by the ATLAS experiments using Run1 data at LHC:
  \[
  m_{\text{top}}^{\text{pole}} = 172.9^{+2.5}_{-2.6} \text{ GeV}
  \]

- Most precise \( m_{\text{top}} \) measurement in the dilepton channel
  \[
  m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat.)} \pm 0.72 \text{ (syst.) GeV}
  \]

- Most recent \( m_{\text{top}} \) measurement in the all-jets channel
  \[
  m_{\text{top}} = 173.72 \pm 0.55 \text{ (stat.)} \pm 1.01 \text{ (syst.) GeV}
  \]

- \( m_{\text{top}} \) measurements dominated by systematic uncertainties.

- Combining the dilepton \( m_{\text{top}} \) result @ 8 TeV with the \( m_{\text{top}} \) measurements in the \( t\bar{t} \rightarrow \text{lepton + jets} \) and \( t\bar{t} \rightarrow \text{dilepton channel} \) @ 7 TeV:
  \[
  m_{\text{top}} = 172.84 \pm 0.34 \text{ (stat.)} \pm 0.61 \text{ (syst.) GeV}
  \]

- More analyses are undergoing.

- We will continue looking at more interesting measurements done using Run2 data at LHC with the challenge to bring the systematics uncertainties down.