Measurements of the top quark mass with the ATLAS detector

Max-Planck-Institut für Physik München (MPP)
on behalf of the ATLAS Collaboration

TERESA BARILLARI

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Overview

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- Direct and indirect top-quark mass measurements
- Direct top-quark mass measurements in ATLAS
- Indirect top-quark mass measurements in ATLAS
- Conclusions
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: (left) the \( W \) mass, \( m_W \), and top-quark pole mass, \( m_{\text{top}}^{\text{pole}} \), with \( 1\sigma \) uncertainties in comparison with the SM and the MSSM prediction; (central) \( m_{\text{top}}^{\text{pole}} / m_H \), mass of the Higgs, plane confronted with the SM vacuum expectations. Ellipses show 68%, 95% and 99% contours based on the experimental uncertainties on \( m_{\text{top}}^{\text{pole}} \) and \( m_H \); (right) ATLAS results on cross-section measurements compared and still in agreement with the SM predictions. Not all measurements are statistically significant.
Top quark production

- The top quark is the heaviest known elementary particle, $m_{\text{top}} \approx 173$ GeV (left top plot).
- It decays before hadronization (lifetime $\tau \approx 5 \times 10^{-25}$ s).
- Main top decay: $t \rightarrow Wb$.
- Leading $t\bar{t}$-production process final states divided in three classes:
  - **All-jets (46.2%)**: $t\bar{t} \rightarrow W^+bW^−b \rightarrow q\bar{q}'bq''\bar{q}''\bar{b}$
  - **Lepton+jets (43.5%)**: $t\bar{t} \rightarrow W^+bW^−b \rightarrow q\bar{q}'b\ell\ell'b + \ell\nu\ell'bq\bar{q}'b$
  - **Dilepton (10.3%)**: $t\bar{t} \rightarrow W^+bW^−b \rightarrow \ell\nu\ell'\ell'b$
- LHC is a top quark factory.
  - $\sigma_{t\bar{t}} (14.0 \text{ TeV}) = 800 \text{ pb}$, 2 $t\bar{t}$ events per second.
- Total cross section for $t\bar{t}$-production about a factor of 100 larger at LHC than at Tevatron.
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 entering the top propagator
- The running top-quark mass, \( m_{\text{top}}^{\overline{MS}} \), mass, parameter defined in a low-scale short distance scheme

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

Though \( m_{\text{top}} \) (direct measurement) \( \neq m_{\text{top}}^{\text{pole}} \) (indirect measurement).


Although it may be much smaller, perhaps \(< 100 \text{ MeV} \) (arXiv:1712.02796, arXiv:1608.01318).

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

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

- Direct: $m_{\text{top}}$ measurement from $t\bar{t}$ dilepton channel
- After a preselection, keep events with two central ($|\eta| < 2.5$) $b$-tagged jets ($b$-jet) and two oppositely charged central leptons ($\ell$)'
- The combination with the lowest average invariant mass of the two $\ell$-$b$-jet pairs, $m_{\ell b}^{\text{reco}}$, with $30 \text{ GeV} < m_{\ell b}^{\text{reco}} < 170 \text{ GeV}$ is retained
- A cut on the average $p_T$ of the two $\ell$-$b$-jet pairs $p_T^{\ell b} > 120 \text{ GeV}$ is applied to optimize the final $m_{\text{top}}$ uncertainty
- The analysis uses a template fit to $m_{\ell b}^{\text{reco}}$
- An unbinned likelihood maximization gives the $m_{\text{top}}$ value that best describes the data
- $m_{\text{top}} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst)} \text{ GeV}$
- Biggest systematic uncertainties: jet energy scale (JES) and relative $b$-to-light-jet energy scale (bJES)
- Most precise result in this decay channel to date
**All-jets $m_{\text{top}}$ measurement at 8 TeV**

- **Direct**: $m_{\text{top}}$ measurement from $t\bar{t}$ all-jets channel
- Challenging measurement because of the large multi-jets background
- Basic selection: no leptons, $\geq 6$ central ($|\eta| < 2.5$) jets two of them $b$-jets, $E_T^{\text{Miss}} < 60$ GeV, topological cuts applied to reduce background
- Jet assignment made 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 $b$-jet and proximity of $W,b$ pairs
- $m_{\text{top}}$ measurement extracted 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
- $m_{\text{top}} = 173.72 \pm 0.55\text{ (stat)} \pm 1.01\text{ (syst)}$ GeV
- Biggest systematic uncertainties: hadronisation modeling, JES, and bJES
- Measurement $\sim 40\%$ more precise than $m_{\text{top}}$ at 7 TeV

$t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'bq''\bar{q}''\bar{b}$

arXiv:1702.07546

**Graphs and Figures**

- ATLAS measurement of $m_{\text{top}}$ with data, signal, background, and total fit.
- Chi-square fits and contours for $m_{\text{top}}$.
- Data and signal fits at 8 TeV.

**References**

T. Barillari Measurements of the top-quark mass with the ATLAS detector ICHEP 2018
Lepton+jets $m_{\text{top}}$ measurement at 8 TeV

- **Direct:** $m_{\text{top}}$ measurement from $t\bar{t}$ lepton+jets channel
- **Basic selection:**
  - $\geq 1$ lepton, $\geq 4$ central ($|\eta| < 2.5$) jets two of them b-jets
  - In $t\bar{t} \rightarrow \mu +$ jets ($t\bar{t} \rightarrow e +$ jets) events, use $E_{T}^{\text{Miss}} > 20$ (30) GeV and $E_{T}^{\text{Miss}} + m_{T}^{W} > 60$ (30) GeV
- **Event kinematic reconstruction** based on a likelihood fit performed with the KLFitter package
- **Measurement of** $m_{\text{top}}$ based on an optimization of the selection based on a boosted decision tree (BDT)
- **Use 3-dimensional template fit** to determine $m_{\text{top}}$ with the jet energy scale factor (JES) and the relative b-to-light-jet energy scale factor (bJES)
- $m_{\text{top}} = 172.08 \pm 0.39 \text{ (stat)} \pm 82 \text{ (syst)} \text{ GeV}$
- **Biggest systematic uncertainties:** JES, and bJES
- **Combining this** $m_{\text{top}}$ with the dilepton $m_{\text{top}}$ at 7 and 8 TeV, and lepton+jets at 7 TeV:
  - $m_{\text{top}} = 172.51 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)} \text{ GeV}$

ATLAS-CONF-2017-071

(a) Reconstructed top quark mass

(b) Reconstructed $W$ boson mass
**$m_{\text{top}}$ measurement in $t\bar{t} + 1\text{jet}$ events at 7 TeV**

- Indirect: $m_{\text{top}}$ measurement from comparison of NLO prediction with the normalized differential cross-section in $t\bar{t} + 1\text{jet}$ events at 7 TeV
- Select semileptonic $t\bar{t}$ events with two $b$-jets
  - Mass jets pair ($m_{jj}$) consistent with $W$ boson:
    \[ 0.9 < \alpha = m_W/m_{jj} < 1.25 \]
    \[ (m_{W}^{\text{ref}} = 80.4 \text{ GeV}), \text{ and correct with } \alpha \]
  - Further requirement $m_{\text{top}}^{\text{lep}}/m_{t}^{\text{hadro}} > 0.9$
- $m_{\text{top}}$ obtained from fit to the normalized diff. cross-section $\mathcal{R}(m_{\text{top}}^{\text{pole}}, \rho_s)$ for $t\bar{t} + 1\text{jet}$ production as a function of the inverse of the invariant mass of the $t\bar{t} + 1\text{jet}$ system, $\rho_s$.
- Most sensitive bin $0.675 \leq \rho_s < 1$
- Prediction of $t\bar{t} + 1\text{jet}$ at NLO+PS using
  $m_{\text{top}} = 170, 175, 180 \text{ GeV}$ is compared with $m_{\text{top}}^{\text{pole}}$
  extracted from best fit
  \[ m_{\text{top}}^{\text{pole}} = 173.7 \pm 1.5(\text{stat}) \pm 1.4(\text{syst})^{+1.0}_{-0.5}(\text{th}) \text{ GeV} \]
Indirect: \( m_{\text{top}} \) from measurement of cross-sections with oppositely charged dilepton (e\( \mu \)) final states at 8 TeV

Select dileptonic \( t\bar{t} \) events with two \( b \)-jets

Eight differential cross-section distributions are measured for \( t\bar{t} \to e\mu\nu\nu bb \):

- \( p_T^\ell, |\eta^\ell|, p_T^{e\mu}, m^{e\mu}, p_T^e + p_T^\mu, E^e + E^\mu, p_T, |y^{e\mu}|, \) and \( \Delta \phi^{e\mu} \)

Various techniques for extracting \( m_{\text{top}} \) explored

Results are compared to the predictions of various NLO and LO \( t\bar{t} \) generators, and to fixed-order perturbative QCD predictions from the MCFM program

Most precise \( m_{\text{top}} \) extracted from simultaneous fit of fixed-order predictions to all eight measured differential distributions simultaneously

\[
m_{\text{top}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{th}) \text{ GeV}
\]

Dominant theoretical uncertainty from QCD scales
**Direct and indirect summary $m_{\text{top}}$ measurements**

- Left figure shows summary of ATLAS and CMS direct $m_{\text{top}}$ measurements, compared with the LHC and Tevatron+LHC $m_{\text{top}}$ combinations. Top right plot shows summary of ATLAS latest direct $m_{\text{top}}$ measurements. Bottom right plot shows latest ATLAS indirect $m_{\text{top}}$ determinations.

### ATLAS+CMS Preliminary

<table>
<thead>
<tr>
<th>$m_{\text{top}}$ summary, $\sqrt{s} = 7-13$ TeV</th>
<th>September 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC top WG</td>
<td></td>
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<tr>
<td>World Comb. Mar 2014, [7]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, I+jets (*)</td>
<td>172.31 ± 1.55 (0.75 ± 1.35)</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>173.08 ± 1.63 (0.64 ± 1.50)</td>
</tr>
<tr>
<td>CMS, I+jets</td>
<td>173.49 ± 1.06 (0.43 ± 0.97)</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.50 ± 1.52 (0.43 ± 1.46)</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>173.49 ± 1.41 (0.69 ± 1.23)</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>173.29 ± 0.95 (0.35 ± 0.88)</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>173.34 ± 0.76 (0.36 ± 0.67)</td>
</tr>
<tr>
<td>ATLAS, I+jets</td>
<td>172.33 ± 1.27 (0.75 ± 1.02)</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>173.79 ± 1.41 (0.54 ± 1.30)</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>175.1 ± 1.8 (1.4 ± 1.2)</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>172.2 ± 2.1 (0.7 ± 2.0)</td>
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<tr>
<td>ATLAS, dilepton</td>
<td>172.99 ± 0.85 (0.41 ± 0.74)</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>173.72 ± 1.15 (0.55 ± 1.01)</td>
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<td>ATLAS, I+jets (Sep 2017)</td>
<td>172.08 ± 0.91 (0.38 ± 0.82)</td>
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<td>ATLAS comb. (Sep 2017)</td>
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<tr>
<td>CMS, I+jets</td>
<td>172.35 ± 0.51 (0.16 ± 0.48)</td>
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<tr>
<td>CMS, dilepton</td>
<td>172.82 ± 1.23 (0.19 ± 1.22)</td>
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<tr>
<td>CMS, all jets</td>
<td>172.32 ± 0.64 (0.25 ± 0.59)</td>
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<tr>
<td>CMS, single top</td>
<td>172.95 ± 1.22 (0.77 ± 0.95)</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>172.44 ± 0.48 (0.13 ± 0.47)</td>
</tr>
<tr>
<td>CMS, I+jets</td>
<td>172.25 ± 0.63 (0.08 ± 0.62)</td>
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(*) Superseded by results shown below the line.

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### ATLAS

- **D0 inclusive $\sigma(t\bar{t})$**: 172.8 ± 3.3 GeV
- **ATLAS inclusive $\sigma(t\bar{t})$**: 172.9 ± 2.6 GeV
- **CMS inclusive $\sigma(t\bar{t})$**: 173.8 ± 1.8 GeV
- **ATLAS differential $\sigma(t\bar{t}+1j)$**: 173.7 ± 2.2 GeV
- **ATLAS leptonic (8 dist.)**: 173.2 ± 1.6 GeV

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T. Barillari  Measurements of the top-quark mass with the ATLAS detector  ICHEP 2018  11
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 ATLAS results of $m_{\text{top}}$ and $m_{\text{top}}^{\text{pole}}$ performed using Run1 data at LHC.

Most precise $m_{\text{top}}^{\text{pole}}$ @ 8 TeV measured in dilepton

$$m_{\text{top}}^{\text{pole}} = 173.2 \pm 0.9\,\text{(stat)} \pm 0.8\,\text{(syst)} \pm 1.2\,\text{(th)}\,\text{GeV}$$

Most precise single $m_{\text{top}}$ measurement in the dilepton channel

$$m_{\text{top}} = 172.99 \pm 0.41\,\text{(stat)} \pm 0.74\,\text{(syst)}\,\text{GeV}$$

Most recent $m_{\text{top}}$ measurement in all-jets and in lepton+jets channel @ 8 TeV:

$$m_{\text{top}} = 173.72 \pm 0.55\,\text{(stat)} \pm 1.01\,\text{(syst)}\,\text{GeV}$$

$$m_{\text{top}} = 172.08 \pm 0.39\,\text{(stat)} \pm 82\,\text{(syst)}\,\text{GeV}$$

Combining the lepton + jets and dilepton $m_{\text{top}}$ result @ 8 TeV and @ 7 TeV

$$m_{\text{top}} = 172.51 \pm 0.27\,\text{(stat)} \pm 0.42\,\text{(syst)}\,\text{GeV}$$

With this precision the relation between $m_{\text{top}}$ definition of the experimental analysis and the $m_{\text{top}}^{\text{pole}}$ is becoming relevant.

$m_{\text{top}}$ measurements dominated by systematic uncertainties.

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