Top quark mass measurements at the ATLAS experiment

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On behalf of the ATLAS collaboration

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- Introduction
- 1D and 2D Template Methods
- Top Mass from Cross-Section
- All-hadronic Measurement
- Summary and Combined Result
The mass of the top quark has been measured with high precision (<1%) at CDF and D0.

It is an important quantity for standard model precision fits.

The top quark plays an important role in many extensions of the standard model.
This Presentation

- Several measurements using 2010 and 2011 data
- Three use the lepton+jets decay channel of the top pair
- One additional measurement in the all-hadronic channel

<table>
<thead>
<tr>
<th>Method</th>
<th>Year</th>
<th>$\mathcal{L}_{\text{int.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D template fit</td>
<td>2011</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>2D template fit</td>
<td>2011</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>$m_{\text{top}}$ from $\sigma_{\text{top}}$</td>
<td>2010</td>
<td>35 pb$^{-1}$</td>
</tr>
<tr>
<td>All hadronic</td>
<td>2011</td>
<td>2 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- Combination of the two template measurements
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Description of the 2D Method

- Simultaneously determine $m_{\text{top}}$ and a jet scale factor (JSF) with shape fits of invariant mass of top and $W$ candidate
  - Build 2-jet mass of all untagged jets
  - Combine each 2-jet mass with each $b$-tagged jet, keep the combination with the highest $p_T$
  - Use well known mass and width of $W$ to constrain $\alpha$

\[
\chi^2(\alpha_1, \alpha_2) = \left[ \frac{E_1(1 - \alpha_1)}{\sigma_1} \right]^2 + \left[ \frac{E_2(1 - \alpha_2)}{\sigma_2} \right]^2 + \left[ \frac{M_{12}(\alpha_1, \alpha_2) - m_W}{\Gamma_W} \right]^2
\]
Signal and Background Parametrisations

- Knowledge of $\alpha_{1,2}$ only propagated to $m_{\text{top}}$
- Retains full sensitivity to JSF in $m_W$ but mediates effect of JES for $m_{\text{top}}$
Description of the 1D Method

- Do a template fit to a variable which is less sensitive to JES
  - Use of $R_{32} = \frac{m_{\text{reco}}}{m_{\text{reco}}^{W}}$
  - The jet pair/triplet is chosen with a kinematic fit using the full event topology as well as b-tagging information.
Systematic uncertainties

- Systematics are evaluated by changing the quantity by $\pm 1\sigma$

- Pseudoexperiments are performed to estimate each uncertainty

- Dominating uncertainties
  - Jet energy scales
  - Signal MC generator
  - Modelling of initial and final state radiation

<table>
<thead>
<tr>
<th>Systematic</th>
<th>1d analysis $\Delta m_{\text{top}}$ [GeV]</th>
<th>2d analysis $\Delta m_{\text{top}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSF</td>
<td>n.a.</td>
<td>0.59</td>
</tr>
<tr>
<td>Method Calibration</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>Signal MC Generator</td>
<td>0.81</td>
<td>0.39</td>
</tr>
<tr>
<td>Hadronisation</td>
<td>0.33</td>
<td>0.20</td>
</tr>
<tr>
<td>Pileup</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.06</td>
<td>0.42</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>0.47</td>
<td>0.32</td>
</tr>
<tr>
<td>ISR and FSR (signal)</td>
<td>1.45</td>
<td>1.04</td>
</tr>
<tr>
<td>Proton PDFs</td>
<td>0.22</td>
<td>0.10</td>
</tr>
<tr>
<td>W+jets background normalization</td>
<td>0.16</td>
<td>0.34</td>
</tr>
<tr>
<td>W+jets background shape</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>QCD background normalization</td>
<td>0.07</td>
<td>0.25</td>
</tr>
<tr>
<td>QCD background shape</td>
<td>0.14</td>
<td>0.38</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.21</td>
<td>0.63</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>1.09</td>
<td>1.61</td>
</tr>
<tr>
<td>$b$-tagging efficiency and mistag rate</td>
<td>0.21</td>
<td>0.31</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.34</td>
<td>0.07</td>
</tr>
<tr>
<td>Jet reconstruction efficiency</td>
<td>0.08</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Missing transverse energy</td>
<td>&lt;0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>2.46</td>
<td>2.31</td>
</tr>
</tbody>
</table>
Both channels in good agreement with each other

JSF modelled with an accuracy of 1%

| electron | $m_{\text{top}}$ [GeV] | JSF | $\rho$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>muon</td>
<td>$174.3 \pm 1.0_{\text{stat}} \pm 2.2_{\text{syst}}$</td>
<td>$0.985 \pm 0.008$</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>$175.0 \pm 0.9_{\text{stat}} \pm 2.5_{\text{syst}}$</td>
<td>$0.986 \pm 0.006$</td>
<td>-0.6</td>
</tr>
</tbody>
</table>
Results - 1D Template

- Good description of likelihood
- Results in agreement with each other

\[ m_{\text{top}} = 172.9 \pm 1.5_{\text{stat}} \pm 2.5_{\text{syst}} \text{ GeV} \]

\[ m_{\text{top}} = 175.5 \pm 1.1_{\text{stat}} \pm 2.6_{\text{syst}} \text{ GeV} \]
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Description of the Method

- The top cross-section depends on the top mass
- Theory prediction has different dependence than measurement

- Repeat cross-section measurement with multiple top mass hypotheses
- Parametrize experimental and theory curves
- Extract well-defined pole mass instead of “MC generator mass”
Results

- Build uncorrelated likelihood
  \[ f(m_{\text{top}}) \propto \int f_{\text{th}}(\sigma \mid m_{\text{top}}) f_{\exp}(\sigma \mid m_{\text{top}}) d\sigma \]
- The maximum of this likelihood determines the extracted \( m_{\text{top}}^{\text{pole}} \)
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All-hadronic measurement

- Cut-based selection of candidate events
- $\chi^2$-Fit to select correct pairs of jets
- Background from event mixing

- Additional cut on the $\chi^2$ to be lesser than 6
- Top peak clearly visible despite large multijet background before cuts
Event Mixing

- Use 5-jet data events and add a lower-$p_T$ jet to the event
- Several validations, here with 4-jet to 5-jet
- Good description in the control regions
Template fit to extract top mass

Fit result yields
\[ m_{\text{top}} = 174.9 \pm 2.1_{\text{stat.}} \pm 3.8_{\text{syst.}} \text{ GeV} \]

Dominating uncertainties are JES, Radiation and Modelling of the Background
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Combination & Outlook

- Combine presented template measurement with each other
- Result compatible with other measurements
- ATLAS measurements take full list of systematics into account

- We need to improve our understanding of the systematic uncertainties (ongoing!)
- Stay tuned for new results from ATLAS
Backup
Template Methods - Control Plots

- ATLAS 1D and 2D Template Methods
- Top Mass from Cross-Section
- Summary and Combined Result

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ATLAS Top Mass 22
2D template - Verification of the fit

**ATLAS Preliminary (simulation)**

Mean = -0.02 ± 0.23
\[\chi^2 / \text{NDF} = 0.6\]

**ATLAS Preliminary (simulation)**

Mean = -0.08 ± 0.17
\[\chi^2 / \text{NDF} = 1.8\]

**Mass pull width**

Mean = 0.96 ± 0.01
\[\chi^2 / \text{NDF} = 0.9\]

**Mass pull width**

Mean = 0.98 ± 0.01
\[\chi^2 / \text{NDF} = 0.8\]
2D template - Correlation between JSF and top mass

Correlation coefficient is -0.6 in both channels
Invariant Mass of $W$ Candidates

- $W$ peak visible
- Knowledge of $\alpha_{1,2}$ not propagated to $W$ mass
- Allows to obtain full sensitivity to the JSF

![Graphs showing invariant mass distributions for $e + jets$ and $\mu + jets$](image)
Invariant Mass of the Top Candidates

- Depends on $m_{\text{top}}$ and JSF
- Knowledge of $\alpha_{1,2}$ propagated to mediate effect of JES
Measurement of the Cross-Section

- Multivariate analysis using lepton, jet and b-tagging information
- Result has precision of 13% @ $m_{\text{top}} = 172.5 \text{ GeV}$

- Repeat analysis for different mass hypothesis between 140 GeV and 210 GeV of the MC generator (MC@NLO)
- Assume that relative uncertainty is independent of the top mass

![Graph showing data and fit comparison](image-url)

**ATLAS Preliminary**

Data 2010, $\int L = 35 \text{ pb}^{-1}$

**L+jets w/ b-tagging**

- Multivariate: $186 \pm 10 \pm 6$
- Top mass profile fit: $156 \pm 8 \pm 5$
- Top mass standard fit: $183 \pm 14 \pm 6$
- Counting: $156 \pm 10 \pm 6$

($\text{stat}\pm\text{(syst)}\pm\text{(lumi)}$)
Systematics of the method

- There are additional uncertainties on top of the ones from the cross-section measurement.

- The theory has uncertainties due to PDFs and scales, they are added linearly.

- Assumption on the scale of the relative uncertainty.

- Identifying the MC mass with the pole mass, it is added linearly.

| Systematic                           | $|\Delta m_{\text{top}}|$ [GeV] |
|--------------------------------------|----------------------------------|
| Theory                              | $+2.4$                           |
| Scale of $\Delta \sigma_{\text{top}}$ | $-4.0$                           |
| $m_{\text{top}}^{\text{MC}} \equiv m_{\text{top}}^{\text{pole}}$ ($\pm 1$ GeV) | $\pm 2.2$                       |
| $m_{\text{top}}^{\text{MC}} \equiv m_{\text{top}}^{\text{pole}}$ ($\pm 2$ GeV) | $\pm 0.8$                       |
| $m_{\text{top}}^{\text{MC}} \equiv m_{\text{top}}^{\text{pole}}$ ($\pm 5$ GeV) | $-2.3$                           |
|                                      | $+1.9$                           |