Measurement of the Top Quark Mass with the Template Method in the ttbar->lepton+jets Channel using ATLAS Data

The Atlas Collaboration

Anthony Hawkins on behalf of the Best Group Ever
Backup
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Outline

• Introduction
• The ATLAS detector
• Event preselection
• Template method
• 1d-analysis
• 2d-analysis
• Systematics
• Results/Conclusion
• Precision measurements of the top and W mass provide a better constraint on the Higgs mass than the combination of many EW observable

• Plays an important role in many extensions of the SM

• Constrain gluon PDF at larger x

• Direct background in H -> W^+ W^-

• The mass of the top quark has been measured with high precision (< 1%) at CDF and D0:
  \[ m_t = 173 \pm 0.6(\text{stat}) \pm 0.8(\text{syst}) \text{ GeV} \]
  (arXiv:1107.5255)

\[ \sigma_{SM @ NNLO}^{t\bar{t}} = 167^{+17}_{-18} \text{ pb at } \sqrt{s} = 7\text{TeV} \]

\[ \text{for } m_{top} = 172.5 \text{ GeV} \]

\[ \sim 177k \text{ tt pairs expected in 1.04 fb}^{-1} \]
Magnet system:
B=2T in ID from solenoid B=0.5-1T from toroid

EM calorimeter:
|\eta|<3.2
PbLAr Accordion
\sigma/E = 10%/\sqrt{E} \oplus 0.7%

Hadronic calorimeter:
|\eta|<1.7 Fe/scintillator
1.3<|\eta|<4.9 Cu/WLar
\sigma/E_{\text{jet}} = 50%/\sqrt{E} \oplus 3%

Inner Detector:
|\eta|<2.5
Si pixels/strips
\sigma/p_{T} = 0.05% \times p_{T} (\text{GeV}) \oplus 1%

Trigger system:
3 levels to reduce 20MHZ collision rate to \sim 300Hz of events to tape

Muon Spectrometer:
|\eta|<2.7
Aircore toroids and gasbased muon chambers
\sigma/p_{T} = 2\% @ 50GeV to 10\% @ 1TeV (ID+MS)
Single lepton decay

$t\bar{t} \rightarrow W^+ b \ W^- \bar{b} \rightarrow q\bar{q} b \ l\nu \bar{b}$
Single lepton decay (1)
Single lepton decay (1)
Single lepton decay (2)

\[ t\bar{t} \rightarrow W^+b \ W^-\bar{b} \rightarrow q\bar{q}b \ l\nu \bar{b} \]

- \( \text{BR}(t \rightarrow Wb) \sim 1 \)
- \( \text{BR}(W \rightarrow l\nu) = 0.108 \) (for each \( l = e, \mu, \tau \))
- \( \text{BR}(W \rightarrow q\bar{q}) = 1 - 3 \times 0.108 = 0.676 \)
  \[ \implies \text{BR(DILEPT.)} = (3 \cdot 0.108)^2 \sim 11\% \]
  \[ \implies \text{BR(FULLY HAD.)} = 0.676^2 \sim 46\% \]
  \[ \implies \text{BR(SINGLE LEPT.)} \sim 43\% \]

* \( \tau \) channel not used here

Main backgrounds (common to 1d & 2d analysis):
- \( W^+ \) jets (major background)
- \( QCD \) multijet (fake high-\( p_T \) lepton & MET mis-measurement)
- \( Z^+ \) jets (missing one lepton & bad jet recons.)
- \( ZZ/WZ/WW \) (minor background)
- Single top (only for the 2d analysis)
Event preselection

Common requirements for 1d & 2d analysis:

<table>
<thead>
<tr>
<th>Cut</th>
<th>μ+jets</th>
<th>e+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Transverse Energy</td>
<td>$p_T &gt; 20$ GeV</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>Pseudorapidity</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 35$ GeV</td>
</tr>
<tr>
<td>Transverse Mass</td>
<td>$E_T^{\text{miss}} + m_T^W &gt; 60$ GeV</td>
<td>$m_T^W &gt; 25$ GeV</td>
</tr>
<tr>
<td>Isolation</td>
<td>$E_T (\Delta R =0.2)&lt;3.5$ GeV</td>
<td>$E_T (\Delta R=0.3)&lt;4$ GeV</td>
</tr>
<tr>
<td>Jets (Anti-$k_t$ R=0.4)</td>
<td>$\geq 4$ jets &amp; $p_T &gt; 25$ GeV &amp; $</td>
<td>\eta</td>
</tr>
</tbody>
</table>

Specific requirements, depending on the analysis (1d or 2d), will be further described.
Template method

- Choice of observables $x_i$ which are sensitive to $m_{top}$
- Create MC -Samples for different $m_{top}$: 160, 170, 172.5, 175, 180, 190 GeV
- Find continuous parametrization of shape of $x_i$ as function of $m_{top}$ (and other parameters)
- Estimate $m_{top}$ from DATA distribution

<table>
<thead>
<tr>
<th>1-d</th>
<th>2-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1 = R_{32} = \frac{m_{top}^{reco}}{m_W^{reco}}$</td>
<td>$x_1 = m_{top}^{reco}$</td>
</tr>
<tr>
<td>- Fitting $m_{top}$, $n_{bckg}$</td>
<td>- Fitting $m_{top}$, JSF, $n_{bckg}$</td>
</tr>
<tr>
<td>- In this ratio the dependency on the JES scale is reduced significantly</td>
<td>- JSF as a fitting parameter</td>
</tr>
</tbody>
</table>
1D Template

• Selection of the top associated jets: kinematic likelihood relating the objects to the $t\bar{t}$ decay products predicted by Monte Carlo (MC@NLO)

• Maximum likelihood built from the 4 jet combinations per each event

• Use the reconstructed four vectors objects (jets and leptons) and Missing Transverse Momentum

• The maximized value of the likelihood discriminates mismatches and correct matching (cut at $-\ln L=50$)

*Transfer function* between reconstructed objects and MC generator level matched objects

*B* Breit Wigner functions modeling the top and W masses.

*Wbtag* Weights containing b-tagging information
1D Template

- Combination of single top and t \bar{t} contribution for each choice of \( m_{top} \)
- Parametrization of R\(_{32} \) templates by a ratio of two gaussians (for the two mass distributions) summed to a Landau (modeling the tail contribution)
- Linear assumption on the parameters dependance to \( m_{top} \)
- Overall \( \chi^2 \) minimization of R\(_{32} \) at all mass points
- Template fit with binned likelihood for signal yield and top mass

\[
L(R_{32}|m_{top}) = L_{shape}(R_{32}|m_{top}) \times L_{bkg}(R_{32})
\]

\[
L_{shape}(R_{32}|m_{top}) = \prod_{i=1}^{N_{bins}} \frac{\lambda_i^{N_i}}{N_i!} \cdot e^{-\lambda_i}, \quad L_{bkg}(R_{32}) = \exp \left\{ -\frac{(n_{bkg} - n_{bkg}^{pred})^2}{2\sigma_{n_{bkg}^{pred}}^2} \right\}
\]

\[
\lambda_i = (N - n_{bkg}) \cdot P_{sig}(R_{32}|m_{top})_i + n_{bkg} \cdot P_{bkg}(R_{32})_i
\]

- Performance of this algorithm tested with pseudo-experiments
  - Poisson statistics for signal events
  - Background fluctuations around expected values (S.M. predictions)
  - Linearity between input and estimates

\[
\begin{align*}
m_{top} &= 172.9 \pm 1.5 \\
m_{top} &= 175.5 \pm 1.1
\end{align*}
\]

\[
m_{top} = 174.4 \pm 0.9 \text{ GeV}
\]
2D Template

- Construct jet triplet, 1 b-jet & 2 light jets
- Build $m_{\text{top}}^{\text{reco}}$ with b-jet (unscaled) and light jets(scaled)
- Build $m_{W}^{\text{reco}}$ with unscaled light jets

Construct templates with JSF varied from 0.9-1.1 and $m_{\text{top}}$ from 160-190 GeV

- Parameterize likelihood functions with the templates.
Parametrization found to have good linearity for JSF and $m_{\text{top}}$

Maximized likelihood with data and found

- $e+\text{jets}$: $m_{\text{top}} = 174.3 \pm 0.8_{\text{stat}} \pm 2.3_{\text{syst}}$ GeV
- $\mu+\text{jets}$: $m_{\text{top}} = 175.0 \pm 0.7_{\text{stat}} \pm 2.6_{\text{syst}}$ GeV
Systematic Uncertainties

- vary parameters ±1σ
- run pseudo-experiments with changed parameters
- add in quadrature, no correlation

Largest contributions:

• Jet energy scale:
  • Impact smaller than JES itself:
    • minimized in R32 observable for 1d fit.
    • constrained in 2d fit.

• b-jet energy scale
  • Differences in fragmentation and hadronization of jets from light-quarks and b-quarks

• ISR and FSR
  • pseudo-experiments with dedicated signal samples where Pythia shower parameters are varied.

<table>
<thead>
<tr>
<th></th>
<th>1d template</th>
<th>2d template</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>0.71%</td>
<td>0.38%</td>
</tr>
<tr>
<td>b-jet energy scale</td>
<td>0.67%</td>
<td>0.91%</td>
</tr>
<tr>
<td>ISR and FSR</td>
<td>0.81%</td>
<td>0.58%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.43%</td>
<td>1.32%</td>
</tr>
</tbody>
</table>
Conclusion

• Top mass measured using 2 different methods

• Both mitigating the impact of the 3 largest systematics

\[ m_t = 174.5 \pm 0.6 \text{(stat)} \pm 2.3 \text{(syst)} \text{ GeV} \]

(2d analysis)
Back-up slides
# Full systematics

<table>
<thead>
<tr>
<th></th>
<th>1d-analysis</th>
<th>2d-analysis</th>
<th>Combinations</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e+jets</td>
<td>µ+jets</td>
<td>e+jets</td>
<td>µ+jets</td>
</tr>
<tr>
<td>Measured value of ( m_{\text{top}} )</td>
<td>172.93</td>
<td>175.54</td>
<td>174.30</td>
<td>175.01</td>
</tr>
<tr>
<td>Data statistics</td>
<td>1.46</td>
<td>1.13</td>
<td>0.83</td>
<td>0.74</td>
</tr>
<tr>
<td>Jet energy scale factor</td>
<td>na</td>
<td>na</td>
<td>0.59</td>
<td>0.51</td>
</tr>
<tr>
<td>Method calibration</td>
<td>0.07</td>
<td>&lt; 0.05</td>
<td>0.10</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Signal MC generator</td>
<td>0.81</td>
<td>0.69</td>
<td>0.39</td>
<td>0.22</td>
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<tr>
<td>Hadronisation</td>
<td>0.33</td>
<td>0.52</td>
<td>0.20</td>
<td>0.06</td>
</tr>
<tr>
<td>Pileup</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.06</td>
<td>0.10</td>
<td>0.42</td>
<td>0.96</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>0.47</td>
<td>0.74</td>
<td>0.32</td>
<td>1.04</td>
</tr>
<tr>
<td>ISR and FSR (signal only)</td>
<td>1.45</td>
<td>1.40</td>
<td>1.04</td>
<td>0.95</td>
</tr>
<tr>
<td>Proton PDF</td>
<td>0.22</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>W+jets background normalisation</td>
<td>0.16</td>
<td>0.19</td>
<td>0.34</td>
<td>0.44</td>
</tr>
<tr>
<td>W+jets background shape</td>
<td>0.11</td>
<td>0.74</td>
<td>0.42</td>
<td>0.96</td>
</tr>
<tr>
<td>QCD multijet background normalisation</td>
<td>0.07</td>
<td>&lt; 0.05</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
<td>QCD multijet background shape</td>
<td>0.14</td>
<td>0.12</td>
<td>0.38</td>
<td>0.30</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.21</td>
<td>1.25</td>
<td>0.63</td>
<td>0.71</td>
</tr>
<tr>
<td>b-jet energy scale</td>
<td>1.09</td>
<td>1.21</td>
<td>1.61</td>
<td>1.53</td>
</tr>
<tr>
<td>b-tagging efficiency and mistag rate</td>
<td>0.21</td>
<td>0.13</td>
<td>0.31</td>
<td>0.26</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.34</td>
<td>0.38</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Jet reconstruction efficiency</td>
<td>0.08</td>
<td>0.11</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Missing transverse momentum</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>2.46</td>
<td>2.56</td>
<td>2.31</td>
<td>2.57</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>2.86</td>
<td>2.80</td>
<td>2.46</td>
<td>2.68</td>
</tr>
</tbody>
</table>