Extraction of the top quark mass in ATLAS: Theory meets experiment

Ludovic Scyboz

IMPRS Kolloquium

MPP

26th April 2018
<table>
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<th>Introduction</th>
<th>Mass measurements</th>
<th>The template method</th>
<th>Backup</th>
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Introduction
Top quark discovery

- Bottom quark discovered in 1977 at Fermilab
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- Missing isospin partner
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- Top quark discovered 18 years later at CDF and DØ!

LHC $\simeq 80$M top pairs produced
A top factory

80M top pairs!
Precision $m_t$ measurements: motivation

- Top mass $m_t$: parameter in SM
- Heaviest elementary particle
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- Top mass $m_t$: parameter in SM
- Heaviest elementary particle
  - Radiative corrections to Higgs effective potential
  - Electroweak parameter fits ($m_W, \theta_W$)
  - Important background in BSM searches
Theorists and experimentalists

Why is my friend acting so passive-aggressive towards me?
Mass measurements
Mass reconstruction

- Decayed particle: reconstruct 4-momentum from decay products
Mass reconstruction

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  - $J/\Psi \rightarrow \mu^+ \mu^-$
Mass reconstruction

- Decayed particle: reconstruct 4-momentum from decay products
  - $J/\psi \rightarrow \mu^+ \mu^-$
  - $Z \rightarrow \mu^+ \mu^-$

ATLAS
s = 8 TeV, 11.4 fb⁻¹
$|y(J/\psi)| < 1.05$
Mass reconstruction

- Decayed particle: reconstruct 4-momentum from decay products
  - $J/\Psi \rightarrow \mu^+ \mu^-$
  - $Z \rightarrow \mu^+ \mu^-$
  - $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ \rightarrow 4\ell$
  - ...

![Graph showing mass reconstruction](image)
Mass reconstruction

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- Tradeoff

$$\Gamma(\text{decay}) \leftrightarrow \frac{S}{B}, \text{ resolution, ...}$$
Decayed particle: reconstruct 4-momentum from decay products
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Tradeoff

$\Gamma(\text{decay}) \leftrightarrow \frac{S}{B}$, resolution, ...

$\rightarrow$ Top decay reconstruction

**ATLAS**

$s = 8$ TeV, 11.4 fb$^{-1}$

$|y(J/\psi)| < 1.05$

- Data

Entries / 0.04 GeV

---

8/23 – $m_t$ extraction @ ATLAS – Ludovic Scyboz
Top pair production: event topology

- Top decay: $\Gamma(t \to Wb) = 0.998$
  - $\Gamma(W \to q \bar{q}') = 0.67$
  - $\Gamma(W \to \ell \nu_\ell) = 0.33$
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  - All-hadronic
    + Largest branching fraction
    - QCD background
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- **Event selection:**
  - **All-hadronic**
    - Largest branching fraction
      - QCD background
  - $\ell + \text{jets}$
    - Full reconstruction possible
      - Jet energy scale uncertainty

\[\sim 46\%\]
\[\sim 29\%\]
\[\sim 4.5\%\]
Top pair production: event topology

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- Event selection:
  - All-hadronic
    + Largest branching fraction
      - QCD background
  - $\ell +$ jets
    + Full reconstruction possible
      - Jet energy scale uncertainty
  - Dilepton
    + Clean signature
      - No full reconstruction

$\sim 46\%$ for all-hadronic, $\sim 29\%$ for dilepton.
Event selection

**All-hadronic**

\[ t\bar{t} \rightarrow qqqqbb \]

≥ 4 light jets
0 id. leptons

**ℓ + jets**

\[ t\bar{t} \rightarrow ℓνqqbb \]

≥ 2 light jets
1 id. lepton
MET

**Dilepton**

\[ t\bar{t} \rightarrow ℓ⁺ℓ⁻νbb \]

≥ 0 id. leptons
MET

≥ 2 id. leptons

\[ \geq 4 \text{ light jets} \]
\[ = 1 \text{ id. lepton} \]
\[ = 2 \text{ id. leptons} \]
The template method
1. Choose distributions sensitive to the top-quark mass
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2. Generate distributions for different input $m_t^{in}$:

$$m_t^{in} \in [165.0, 172.5, 180.0] \text{ GeV}$$
General idea

1. Choose distributions sensitive to the top-quark mass

2. Generate distributions for different input $m_t^{in}$:

   $m_t^{in} \in [165.0, 172.5, 180.0]$ GeV

3. Fit the data to extract $m_t^{in}$
1. Choose $m_{lb}^2 = (p_\ell + p_b)^2$

Simple example: dilepton channel @ 8 TeV


1. Choose $m_{\ell b}^2 = (p_\ell + p_b)^2$

2. Generate distributions for different input $m_t^{in}$:

   $m_t^{in} \in [167.5, 172.5, 177.5] \text{ GeV}$
Simple example: dilepton channel @ 8 TeV


1. Choose $m_{lb}^2 = (p_\ell + p_b)^2$

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   $m_t^{in} \in [167.5, 172.5, 177.5] \text{ GeV}$

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Simple example: dilepton channel @ 8 TeV


1. Choose $m_{lb}^2 = (p_\ell + p_b)^2$

2. Generate distributions for different input $m_t^{\text{in}}$:

   $m_t^{\text{in}} \in [167.5, 172.5, 177.5] \text{ GeV}$

3. Fit the data

   $m_t = 172.99 \pm 0.41(\text{stat}) \text{ GeV}$
A more complex example: $\ell + \text{jets} @ 7 \text{ TeV}$


Jet energy scale (JES)

- From 7 TeV analysis:

- JES, b-JES are the largest systematic uncert.

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<th>$e+$jets</th>
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Jet energy calibration

- Jets energy measured by hadron calorimeter deposits
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- Not 100% effective → correction factors
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  - MC simulation: $\text{JES} = \frac{E_{\text{MC}}}{E_{\text{meas}}}$
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![Graph showing jet energy calibration results](image)
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\[ R_{\text{DATA}}/R_{\text{MC}} \]

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\[ R_{\text{MC}} = \frac{E_{\text{MC}}}{E_{\text{MC}}} \]

\[ E_{\text{DATA}} \]

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- Different correction for light–/b–jets
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- Different correction for light−/b−jets
  - Jet scale factor (JSF)
  - b−jet scale factor (bJSF)
A more complex example: $\ell + \text{jets} @ 8 \text{ TeV}$


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Idea: Add distributions sensitive to JSF, b-JSF

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\( \ell + \text{jets} @ 8 \text{ TeV} \)


- 3 parameters to fit: \( m_t^{\text{in}} \), JSF, bJSF
- 3 distributions sensitive to them:
  - Reco. top mass \( m_t^{\text{reco}} \propto m_t^{\text{in}}, \text{JSF}, \text{bJSF} \)
  - Reco. \( W \) mass \( m_W^{\text{reco}} \propto \text{JSF} \)
  - \( R_{bq} = \frac{p_T,b_1+p_T,b_2}{p_T,j_1+p_T,j_2} \propto m_t^{\text{in}}, \text{bJSF} \)
\( \ell + \text{jets} \, @ \, 8 \, \text{TeV} \)


- 3 parameters to fit: \( m_{t}^{\text{in}} \), JSF, bJSF
- 3 distributions sensitive to them:
  - Reco. top mass \( m_{t}^{\text{reco}} \propto m_{t}^{\text{in}}, \text{JSF}, \text{bJSF} \)
  - Reco. W mass \( m_{W}^{\text{reco}} \propto \text{JSF} \)
  - \( R_{bq} = \frac{p_{T,b_{1}} + p_{T,b_{2}}}{p_{T,j_{1}} + p_{T,j_{2}}} \propto m_{t}^{\text{in}}, \text{bJSF} \)

(a) \( m_{\text{top}}^{\text{reco}} \) as a function of \( m_{\text{top}} \)
(b) \( m_{W}^{\text{reco}} \) as a function of JSF
(c) \( m_{W}^{\text{reco}} \) as a function of JSF
(d) \( R_{bq}^{\text{reco}} \) as a function of bJSF
$\ell + \text{jets} @ 8 \text{ TeV}: \text{fit results}$

- Determine values for the three parameters in a simultaneous fit

\[
\begin{align*}
    m_t &= 172.08 \pm 0.39(\text{stat}) \text{ GeV} \\
    \text{JSF} &= 1.005 \pm 0.001(\text{stat}) \\
    b\text{JSF} &= 1.008 \pm 0.005(\text{stat})
\end{align*}
\]
ATLAS Top mass results

Successive combination

\[ m_{\text{top}}^{\text{dil}} \ (8 \text{ TeV}) \]
\[ + m_{\text{top}}^{\text{l+jets}} \ (8 \text{ TeV}) \]
\[ + m_{\text{top}}^{\text{l+jets}} \ (7 \text{ TeV})^* \]
\[ + m_{\text{top}}^{\text{dil}} \ (7 \text{ TeV}) \]

**ATLAS Preliminary**

\[ m_{\text{top}} \pm \text{stat.} \pm \text{syst.} \]
\[ 172.99 \pm 0.41 \pm 0.74 \]
\[ 172.56 \pm 0.28 \pm 0.48 \]
\[ 172.51 \pm 0.27 \pm 0.42 \]
\[ 172.50 \pm 0.27 \pm 0.42 \]

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**Notes:**
- *ATLAS Combination
- stat. uncertainty
- total uncertainty

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21/23 – \( m_t \) extraction @ ATLAS – Ludovic Scyboz
Conclusions

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  - Top mass = one of the most important parameters of the SM
  - The LHC is a very good top quark producer
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Thank you!
# Results summary

<table>
<thead>
<tr>
<th>Pseudo-data</th>
<th>Calibration</th>
<th>$m_{lb}$</th>
<th>$m_{T^2}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>LO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>+0.51 ± 0.06</td>
<td>+0.48 ± 0.04</td>
<td>0.17</td>
</tr>
<tr>
<td>NLO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>LO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>−1.80 ± 0.06</td>
<td>−1.67 ± 0.04</td>
<td>3.25</td>
</tr>
<tr>
<td>NLO$^{\text{NLOdec}}_{\text{NWA}}$</td>
<td>LO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>−1.38 ± 0.07</td>
<td>−1.24 ± 0.05</td>
<td>2.65</td>
</tr>
<tr>
<td>NLO$^{\text{full}}_{\text{NWA}}$</td>
<td>LO$^{\text{full}}$</td>
<td>−1.52 ± 0.07</td>
<td>−1.62 ± 0.05</td>
<td>1.35</td>
</tr>
<tr>
<td>NLO$^{\text{full}}_{\text{NWA}}$</td>
<td>NLO$^{\text{NLOdec}}_{\text{NWA}}$</td>
<td>+0.83 ± 0.07</td>
<td>+0.60 ± 0.06</td>
<td>6.22</td>
</tr>
<tr>
<td>NLO$^{\text{full}}_{\text{NWA}}$</td>
<td>NLO$^{\text{PS}}$</td>
<td>+2.55 ± 0.07</td>
<td>+2.38 ± 0.06</td>
<td>3.40</td>
</tr>
<tr>
<td>NLO$^{\text{PS}}_{\text{NWA}}$</td>
<td>NLO$^{\text{LOdec}}_{\text{NWA}}$</td>
<td>−3.43 ± 0.07</td>
<td>−3.62 ± 0.06</td>
<td>4.25</td>
</tr>
<tr>
<td>NLO$^{\text{PS}}_{\text{NWA}}$</td>
<td>NLO$^{\text{NLOdec}}_{\text{NWA}}$</td>
<td>−1.60 ± 0.07</td>
<td>−1.67 ± 0.06</td>
<td>0.58</td>
</tr>
<tr>
<td>NLO$^{\text{PS}}_{\text{NWA}}$</td>
<td>NLO$^{\text{PS}}(\mu_{t\bar{t}})$</td>
<td>−0.07 ± 0.07</td>
<td>−0.05 ± 0.06</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table: Summary of the offsets observed when analysing pseudo-data listed in the first column with template fit functions calibrated based on various theoretical predictions as given in the second column.