New approaches in determining $m_t$: alternative techniques and kinematic dependence

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Physics motivation

Why measure $M_t$ with high precision?

- Important for global EW fits (arXiv:1209.2716)
- Fate of universe depends on it! (arXiv:1205.6497)

- How to improve $m_t^{\text{observable}}$ understanding?
  - Check current understanding of $m_t^{\text{obs}}$ modelling in MC simulations
  - What is $m_t^{MC}$ measured with standard techniques? $m_t^{MC} \equiv m_t^{\text{pole}}$
  - Use non-standard techniques (different sensitivity to systematics)
How to improve $m_t^{\text{observable}}$ understanding?

- Check current understanding of $m_t^{\text{obs}}$ modelling in MC simulations
  - Dependence of $m_t^{\text{obs}}$ on event kinematics
    - Increase confidence in current $m_t^{\text{obs}}$ modelling in MC
      → compare MadGraph, PowHeg & MC@NLO
    - Sensitive to soft-QCD effects
      → underlying event, color reconnection, ...

- What is $m_t^{MC}$ measured with standard techniques? $m_t^{MC} \overset{?}{=} m_t^{\text{pole}}$
- Use non-standard techniques (different sensitivity to systematics)
Based on 2011 $\ell$+jets combined $m_t$+JES

- 2D-Ideogram method, arXiv:1209.2319
- See presentation of H. Stadie

$m_t^{2D} = 173.49 \pm 0.43_{\text{stat}} + \text{JES} \pm 0.98_{\text{syst}}$ GeV
Dependence of $m_t^{obs}$ on event kinematics (CMS-PAS-TOP-12-029)

- Measure $m_t^{1D}$, $m_t^{2D}$, JES ($\oplus$ stat $\oplus$ syst) in bins of kinematic variables
  - 2D-Idiogram method, arXiv:1209.2319
    - $m_t^{2D}$ & JES: 2D measurement
    - $m_t^{1D}$: no JES measured
- Results for 12 kinematic variables
- First binned $m_t^{obs}$ measurement
- Due to large $t\bar{t}$ dataset @ LHC
Dependence of $m_t^{obs}$ on event kinematics (CMS-PAS-TOP-12-029)

- Good agreement between Data and 'standard' MadGraph TuneZ2
- $m_t^{obs}$ not heavily affected by different tunes / generators
- Sensitivity limited by data statistics
  - 20 fb$^{-1}$ @ 8 TeV will help
**$\Delta m_t$ in the \(\ell+\text{jets}\) channel** (CMS-PAS-TOP-12-031)

- Check of CPT invariance in top sector: \( m_t \neq m_{\bar{t}} \)
- Lepton charge: split data in 2 samples: \( \Delta m_t = m_{t,\text{hadronic}} - m_{\bar{t},\text{hadronic}} \)
  - Measure \( m_t \) in each sample with 1D Ideogram method
  - \( m_t \) measurement differential in lepton charge
- Using entire 2012 dataset @ 8 TeV
\[ \Delta m_t = -272 \pm 196_{\text{stat}} \pm 122_{\text{syst}} \text{ MeV} \]

- Uncertainty statistics dominated
- Systematics reduce in the difference
- Compatible with zero (CPT conservation)

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimated effect (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>17 ( \pm ) 15</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>8 ( \pm ) 11</td>
</tr>
<tr>
<td>b vs. ( \bar{b} ) jet response</td>
<td>64 ( \pm ) 7</td>
</tr>
<tr>
<td>Signal fraction</td>
<td>45 \pm 2</td>
</tr>
<tr>
<td>Background charge asymmetry</td>
<td>12.43 ( \pm ) 0.03</td>
</tr>
<tr>
<td>Background composition</td>
<td>50 ( \pm ) 1</td>
</tr>
<tr>
<td>Pileup</td>
<td>17.4 ( \pm ) 0.4</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>20 ( \pm ) 8</td>
</tr>
<tr>
<td>b vs. ( \bar{b} ) tagging efficiency</td>
<td>43 ( \pm ) 6</td>
</tr>
<tr>
<td>Method calibration</td>
<td>15 ( \pm ) 54</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>12 ( \pm ) 3</td>
</tr>
<tr>
<td>Total</td>
<td>122</td>
</tr>
</tbody>
</table>
How to improve $m_t^{\text{observable}}$ understanding?

- Check current understanding of $m_t^{\text{obs}}$ modelling in MC simulations

- **What is** $m_t^{MC}$ **measured with standard techniques?** $m_t^{MC} \overset{?}{=} m_t^{\text{pole}}$
  - Perform measurements less dependent on $m_t^{MC}$
    - Extract mass from other measured quantities (e.g. $\sigma_{t\bar{t}}$)
    - Fully data-driven measurements

- Use non-standard techniques (different sensitivity to systematics)
Based on most precise $\sigma_{t\bar{t}}$ @ 7 TeV (CMS dilepton, arXiv:1208.2671)

Measure $\sigma_{t\bar{t}}$ for different $m_t$

Compare with theoretical $\sigma_{t\bar{t}}(m_t^{pole})$
  - Using latest NNLO calculation
  - $\alpha_s$ fixed to PDG value

Result with NNPDF

$$m_t^{pole} = 176.7^{+3.8}_{-3.4} \text{ GeV}$$

Compatible with direct measurements
Also: $\alpha_s$ from $t\bar{t}$ cross section (arXiv:1307.1907)

- Revert logic of $m_t^{pole}$ extraction
  - Fix $m_t^{pole}$ to direct $m_T^{Tevatron}$
- Compare measured $\sigma_{t\bar{t}}$ with theoretical $\sigma_{t\bar{t}}(\alpha_s)$
  - Using latest NNLO calculation

Result with NNPDF

$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

- First $\alpha_s$ at NNLO from hadron collider
Measuring $m_t^{endpoint}$ via kinematic endpoints (arXiv:1304.5783)

- Endpoint of 'transverse mass' variables sensitive to masses
  - $m_W$ measurement via $m_T(\ell, E_T^{\text{miss}})$
- $M_{T2}$-type variables designed to measure SUSY masses via endpoints.
  - Exploit analytic relations between $M_{T2}^{endpoint}$ and underlying masses

Endpoints are fitted using shapes independent of MC
- Measurement independent of $m_t^{MC}$
Measuring $m_t^{endpoint}$ via kinematic endpoints \textit{(arXiv:1304.5783)}

**Background**
Data-driven

**Signal**
Kinked-line $\otimes$ resolution

**Sum**
Signal + Background

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<table>
<thead>
<tr>
<th>Source</th>
<th>Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy resolution</td>
<td>0.5</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>+1.3</td>
</tr>
<tr>
<td>Fit range</td>
<td>0.6</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.5</td>
</tr>
<tr>
<td>B-tag &amp; $\ell$ efficiency</td>
<td>+0.1</td>
</tr>
<tr>
<td>QCD effects</td>
<td>0.6</td>
</tr>
</tbody>
</table>

- Doubly-constrained fit \((m_\nu = 0, m_W = 80.4 \text{ GeV})\)

**$m_t^{endpoint} = 173.9 \pm 0.9(\text{stat})^{+1.6}_{-2.0}(\text{syst}) \text{ GeV}**

- In agreement with other measurements
How to improve $m_t^{\text{observable}}$ understanding?

- Check current understanding of $m_t^{\text{obs}}$ modelling in MC simulations
- What is $m_t^{\text{MC}}$ measured with standard techniques? $m_t^{\text{MC}} \stackrel{?}{=} m_t^{\text{pole}}$
- Use non-standard techniques (different sensitivity to systematics)
Measure $m_t^{MC}$ via $b$-hadron lifetime (CMS-PAS-TOP-12-030)

$t \to bW$ decay

- Boost of $b$-quark correlated with $m_t$
- Decay length $L_{b-hadron}$ correlated with $m_t$
  - Use $L_{xy}$: transverse decay length of secondary vertex
- Same technique as CDF (arXiv:hep-ex/0612061)

CMS Simulation, $\sqrt{s}=8$ TeV

- $e+$jets, $\mu+$jets and dilepton $e\mu$ $t\bar{t}$ events
  - Per event, use $\max L_{xy}$ of jets ($|\eta| < 1.1, \frac{L_{xy}}{\sigma_{L_{xy}}} > 3$)
  - Median $L_{xy}$ ($\hat{L}_{xy}$) used to estimate $m_t^{MC}$
- Different sensitivity to systematics
  - Track-based
    → reduced jet energy scale uncertainty
  - Kinematics in lab frame
    → dependence on production model
Measure $m_t^{MC}$ via b-hadron lifetime (CMS-PAS-TOP-12-030)

**Data results**

$\hat{L}_{xy} = 0.682 \pm 0.004 \ cm$

$m_t^{MC} = 173.7 \pm 2.0 \ GeV$

$\hat{L}_{xy} = 0.6536 \pm 0.0013 \ cm$

$m_t^{MC} = 172.8 \pm 1.0 \ GeV$

$\hat{L}_{xy} = 0.6690 \pm 0.0013 \ cm$

$m_t^{MC} = 173.2 \pm 1.0 \ GeV$

- Only statistical uncertainties
Measure $m_t^{MC}$ via b-hadron lifetime (CMS-PAS-TOP-12-030)

### Experimental

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu$+jets</th>
<th>$e$+jets</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>0.30 ± 0.01</td>
<td>0.30 ± 0.01</td>
<td>0.30 ± 0.01</td>
</tr>
<tr>
<td>Multijet normalization ($\ell$+jets)</td>
<td>0.50 ± 0.01</td>
<td>0.67 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td>W+jets normalization ($\ell$+jets)</td>
<td>1.42 ± 0.01</td>
<td>1.33 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td>DY normalization ($\ell\ell$)</td>
<td>-</td>
<td>-</td>
<td>0.38 ± 0.06</td>
</tr>
<tr>
<td>Other backgrounds normalization</td>
<td>0.05 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.15 ± 0.07</td>
</tr>
<tr>
<td>W+jets background shapes ($\ell$+jets)</td>
<td>0.40 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>-</td>
</tr>
<tr>
<td>Single top background shapes</td>
<td>0.20 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.30 ± 0.06</td>
</tr>
<tr>
<td>DY background shapes ($\ell\ell$)</td>
<td>-</td>
<td>-</td>
<td>0.04 ± 0.06</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.42 ± 0.01</td>
<td>0.50 ± 0.01</td>
<td>0.21 ± 0.01</td>
</tr>
</tbody>
</table>

### Theory

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu$+jets</th>
<th>$e$+jets</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$-scale</td>
<td>0.47 ± 0.13</td>
<td>0.20 ± 0.03</td>
<td>0.11 ± 0.08</td>
</tr>
<tr>
<td>ME-PS matching scale</td>
<td>0.73 ± 0.01</td>
<td>0.87 ± 0.03</td>
<td>0.44 ± 0.08</td>
</tr>
<tr>
<td>PDF</td>
<td>0.26 ± 0.15</td>
<td>0.26 ± 0.15</td>
<td>0.26 ± 0.15</td>
</tr>
<tr>
<td>Hadronization model</td>
<td>0.95 ± 0.13</td>
<td>0.95 ± 0.13</td>
<td>0.67 ± 0.10</td>
</tr>
<tr>
<td>B-hadron composition</td>
<td>0.39 ± 0.01</td>
<td>0.39 ± 0.01</td>
<td>0.39 ± 0.01</td>
</tr>
<tr>
<td>B-hadron lifetime</td>
<td>0.29 ± 0.18</td>
<td>0.29 ± 0.18</td>
<td>0.29 ± 0.18</td>
</tr>
<tr>
<td>Top quark $p_T$ modeling</td>
<td>3.27 ± 0.48</td>
<td>3.07 ± 0.45</td>
<td>2.36 ± 0.35</td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.27 ± 0.51</td>
<td>0.25 ± 0.48</td>
<td>0.19 ± 0.37</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>0.36 ± 0.51</td>
<td>0.34 ± 0.48</td>
<td>0.26 ± 0.37</td>
</tr>
</tbody>
</table>

**Final results**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_t$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon+jets</td>
<td>173.2 ± 1.0_{stat} ± 1.6_{syst} ± 3.3_{pT(t)}</td>
</tr>
<tr>
<td>electron+jets</td>
<td>172.8 ± 1.0_{stat} ± 1.7_{syst} ± 3.1_{pT(t)}</td>
</tr>
<tr>
<td>electron-muon</td>
<td>173.7 ± 2.0_{stat} ± 1.4_{syst} ± 2.4_{pT(t)}</td>
</tr>
</tbody>
</table>

**Combination of all channels**

$m_t^{MC} = 173.5 ± 1.5_{stat} ± 1.3_{syst} ± 2.6_{pT(top)}$
Conclusion

- Several techniques explored to improve our $m_t$ understanding
  - Cross-checks of $m_t^{obs}$ modelling in MC
    - Kinematic dependence of $m_t^{obs}$
    - Also: very precise $\Delta m_t$ measurement
  - Measurements independent of $m_t^{MC}$
    - From $\sigma_{t\bar{t}}$ and kinematic endpoints
  - Conducted alternative measurements of $m_t^{MC}$
    - Different sensitivity to systematics
  
  → Everything in agreement with standard $m_t^{obs}$ measurements, and modelled well by MC simulations

- Outlook
  - Large 2012 dataset
    - Improvement of differential $m_t^{obs}$ studies
    - Non-standard techniques become possible
  - Stay tuned!
Back-up
### Endpoint method

### Full results, with/without constraints

<table>
<thead>
<tr>
<th>Fit quantity</th>
<th>None</th>
<th>$m_v = 0$</th>
<th>$m_v = 0$ and $M_W = 80.4$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_v^2$ (GeV$^2$)</td>
<td>$-556 \pm 473 \pm 622$</td>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>$M_W$ (GeV)</td>
<td>$72 \pm 7 \pm 9$</td>
<td>$80.7 \pm 1.1 \pm 0.6$</td>
<td>(80.4)</td>
</tr>
<tr>
<td>$M_t$ (GeV)</td>
<td>$163 \pm 10 \pm 11$</td>
<td>$174.0 \pm 0.9^{+1.5}_{-2.0}$</td>
<td>$173.9 \pm 0.9^{+1.6}_{-2.0}$</td>
</tr>
</tbody>
</table>