Top quark mass and properties measurements with CMS

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Introduction

- Top quark is the heaviest particle in the Standard Model
- The question is: does it behave like the SM predicts?
  - Does it always decay to a W-boson and a b-quark?
  - Do Flavor Changing Neutral Current interactions occur?
  - Does it have $2/3e$ electrical charge?
- This presentation will show the latest results from CMS on the top quark mass and its properties in top quark pair decays.
Object reconstruction

- Event is reconstructed using the ParticleFlow reconstruction
- Jets are clustered using the ak5 algorithm
- Jet energy scale corrections are applied
- $E_T$ is calibrated for JES
- Leptons are reconstructed using ParticleFlow and have a particle based isolation definition
**Event selection** ($t\bar{t} \rightarrow b\bar{b}q\bar{q}\mu\nu\mu$)

- 1 isolated muon with $p_T > 30$ GeV, $|\eta| < 2.1$
- $\geq 4$ jets with $p_T > 30$ GeV, $|\eta| < 2.4$
- $\geq 2$ b-tagged jet

**Event reconstruction**

- 12 unique jet-quark assignments using the four leading jets
- b-tagging reduces combinatorics
- Solution: Kinematic fit of entire event (leptonic + hadronic decay)
  - two $m_W$-constraints and $m_t^{\text{hadronic}} = m_t^{\text{leptonic}}$
  - Fit probability $> 0.2$ to enhance purity
**$m_t$ in the muon+jets channel** (CMS-PAS-TOP-11-015)

**Ideogram method**

- Construct a likelihood to observe the data sample:

$$\mathcal{L}\left(\text{sample}|m_t,\text{JES}\right) = \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t,\text{JES}\right)^{w_{\text{event}}}$$

$$= \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{fit}}(i) P\left(m_{t,i}^{\text{fit}}, m_W^{\text{reco}}|m_t,\text{JES}\right)\right)^{\sum_{i=1}^{n} P_{\text{fit}}(i)}$$

- Used before at LEP ($m_W$) and Tevatron ($m_t$)
- Most precise LHC Measurement

**Systematics**

- Dominant systematics: b-JES and Factorisation scale
- Color reconnection, Underlying event effects under study

Results on data ($4.7 \, fb^{-1}$)

$$m_t = 172.6 \pm 0.6 (\text{stat}) \pm 1.2 (\text{syst}) \, \text{GeV}$$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta_{m_t}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.15</td>
</tr>
<tr>
<td>b-tagging</td>
<td>0.17</td>
</tr>
<tr>
<td>b-JES</td>
<td><strong>0.66</strong></td>
</tr>
<tr>
<td>$p_T$- and $\eta$-dependent JES</td>
<td>0.23</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.21</td>
</tr>
<tr>
<td>Missing transverse energy</td>
<td>0.08</td>
</tr>
<tr>
<td>Factorization scale</td>
<td>0.76</td>
</tr>
<tr>
<td>ME-PS matching threshold</td>
<td>0.25</td>
</tr>
<tr>
<td>Non-$t\bar{t}$ background</td>
<td>0.09</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.38</td>
</tr>
<tr>
<td>PDF</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td><strong>1.18</strong></td>
</tr>
</tbody>
</table>
Measurement of $m_t$ in the dileptonic channel ($ee/e\mu/\mu\mu$) (CMS-PAS-TOP-11-016)

Event selection ($t\bar{t} \rightarrow b\bar{b}l\nu_ell'\nu_{ell'}$)

- 2 leptons with $p_T > 20$ GeV, $|\eta| < 2.4$
- $\geq 2$ jets with $p_T > 30$ GeV, $|\eta| < 2.4$
- $E_T > 30$ GeV
- $ee/\mu\mu$-channels: reject $76 < m_{\ell\ell} < 106$ GeV
- $\geq 1$ b-tagged jet

$m_t$ with KINb method

- Solve kinematic equations multiple times per event
  - Each time, vary $p_T^{jet}$, $E_T$, direction and $p_T^{top}$ within resolutions
  - Only solutions accepted with $\Delta m_t < 3$ GeV
  - Pick combination with largest $N_{solutions}$
    - Gaussian fit on $M_{KINb}$ distribution $\rightarrow m_t^{reco}$
Fit templates to $m_t^{\text{reco}}$ in data
- Separately for $ee/\mu\mu$ and $e\mu$, and for 1 b-tag and $\geq 2$ b-tags
- Combined fit results for 2.3 $fb^{-1}$ of data

$m_t = 173.3 \pm 1.2 (\text{stat}) \pm 2.5 (\text{syst})$ GeV

- Most precise dilepton measurement ($\approx$ D0)
- Dominant systematics: Jet Energy Scale and Jet Energy Resolution

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta m_{\text{top}}$ (GeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>+1.90, -2.00, +1.08, -1.13</td>
</tr>
<tr>
<td>flavor-JES</td>
<td>± 0.30</td>
</tr>
<tr>
<td>JER</td>
<td>± 0.12</td>
</tr>
<tr>
<td>LES</td>
<td>± 0.18</td>
</tr>
<tr>
<td>Unclustered $E_T^{\text{miss}}$</td>
<td>± 0.43</td>
</tr>
<tr>
<td>Fit calibration</td>
<td>± 0.40</td>
</tr>
<tr>
<td>DY normalization</td>
<td>± 0.40</td>
</tr>
<tr>
<td>Factorization scale</td>
<td>± 0.41</td>
</tr>
<tr>
<td>Jet parton matching scale</td>
<td>± 0.65</td>
</tr>
<tr>
<td>Pile-up</td>
<td>± 0.19</td>
</tr>
<tr>
<td>$b$-tagging uncertainty</td>
<td>± 0.30</td>
</tr>
<tr>
<td>mis-tagging uncertainty</td>
<td>± 0.43</td>
</tr>
<tr>
<td>MC generator</td>
<td>± 0.14</td>
</tr>
<tr>
<td>PDF</td>
<td>± 0.39</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+2.52, -2.63</td>
</tr>
</tbody>
</table>
$m_t$ from $t\bar{t}$ cross section  (CMS-PAS-TOP-11-008)

- $\sigma_{t\bar{t}}$ from dilepton channel measurement.
- Event selection in $\sigma_{t\bar{t}} \rightarrow$ dependence on $m_t$
- Dependence parametrized by 3rd order polynomial in each dilepton channel
- Measure $\sigma_{t\bar{t}}$ for different $m_t$ assumptions

Compare with theoretical $\sigma_{t\bar{t}}(m_{t}^{pole})$

$$L(m_t) = \int f_{\exp}(\sigma_{t\bar{t}}|m_t)f_{\text{th}}(\sigma_{t\bar{t}}|m_t)\,d\sigma_{t\bar{t}}.$$
Combination of the different $m_t$ measurements

- Combination of the 2010 and 2011 mass measurements

\[ m_t = 172.6 \pm 0.4\,(stat) \pm 1.2\,(syst) \text{ GeV} \]

- Preparing LHC $m_t$ combination
- Working towards synchronization of systematic uncertainties between ATLAS – CMS
Measurement of $\Delta m_t$ in e/$\mu$+jets channel (CMS-TOP-11-019, arXiv:1204.2807, accepted by EPJC)

- Worlds best $\Delta m_t$ measurement
- Import check of CPT invariance
- Event selection
  - 1 isolated $\mu$ (e) $p_T > 25$ (30)GeV $|\eta| < 2.1$ (2.5)
  - $\geq 4$ jets with $p_T > 30$ GeV, $|\eta| < 2.4$
- $\ell$ charge: split data in 2 samples: $t$ and $\bar{t}$
  - $\Delta m_t = m_{t,\text{hadronic}} - m_{\bar{t},\text{hadronic}}$
  - Measure $m_t$ in each sample with Ideogram method

Systematics:

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimated effect (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>$0.04 \pm 0.08$</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>$0.04 \pm 0.06$</td>
</tr>
<tr>
<td>b vs. $\bar{b}$ jet response</td>
<td>$0.10 \pm 0.10$</td>
</tr>
<tr>
<td>Signal fraction</td>
<td>$0.02 \pm 0.01$</td>
</tr>
<tr>
<td>Difference in $W^+/W^-$ production</td>
<td>$0.014 \pm 0.002$</td>
</tr>
<tr>
<td>Background composition</td>
<td>$0.09 \pm 0.07$</td>
</tr>
<tr>
<td>Pileup</td>
<td>$0.10 \pm 0.05$</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>$0.03 \pm 0.02$</td>
</tr>
<tr>
<td>b vs. $\bar{b}$ tagging efficiency</td>
<td>$0.08 \pm 0.03$</td>
</tr>
<tr>
<td>Method calibration</td>
<td>$0.11 \pm 0.14$</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>$0.088$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.27$</td>
</tr>
</tbody>
</table>

$\Delta m_t = -0.44 \pm 0.46 $ (stat) $\pm 0.27$ (syst) GeV
Measurement of other top quark properties

W boson polarization in the $\mu+\text{jets}$ channel (CMS-PAS-TOP-11-020)

- Kinematic fit of entire event $\rightarrow$ improve $\cos(\theta^*)$ reconstruction
- Measure the $F_0$, $F_L$ and $F_R$ helicity fractions using a fit to the $\cos(\theta^*)$ distribution

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta^*} = \frac{3}{8} (1-\cos \theta^*)^2 F_L + \frac{3}{8} (1+\cos \theta^*)^2 F_R + \frac{3}{4} \sin^2 \theta^* F_0$$

- $F_0 + F_L + F_R = 1$
- SM coupling: $F_0 = 0.7$ $F_L = 0.3$ and $F_R = 0$

| $F_0$ | $0.567 \pm 0.074$ (stat) $\pm 0.047$ (syst) |
| $F_L$ | $0.393 \pm 0.045$ (stat) $\pm 0.029$ (syst) |
| $F_R$ | $0.040 \pm 0.035$ (stat) $\pm 0.044$ (syst) |

- Dominant systematics: Background normalization and factorization scale
- Limits on anomalous couplings

$$\mathcal{L}_{\text{Wtb}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L p_L + V_R p_R) t W^- \mu - \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu q^\nu (g_L p_L + g_R p_R) t W^- \mu$$

Michael Maes (IIHE - VUB)
Search for FCNC in Top Quark decays (CMS-PAS-TOP-11-028)

- World best limit
- Search for $t\bar{t} \rightarrow Zq + Wb \rightarrow \ell^+\ell^-j + \ell^\pm \nu b$ ($\ell = e, \mu$)
- Baseline event selection:
  - thee leptons $p_T^{\ell} > 20$ GeV ($\ell = e, \mu$)
  - $60 < m_{\ell^+\ell^-} < 120$ GeV (ee/$\mu\mu$)
- HTs cut based selection
  - $\text{HTs} = \sum p_{T\ell} + \sum E_{Tj} + E_T > 250$ GeV
  - $10 < m_{Wb}, m_{Zq} < 250$ GeV
- cross-checked with b-tag based selection
- Background estimation:
  - Di-boson and singleTop backgrounds from simulation
  - DY and $t\bar{t}$ backgrounds data-driven

- Expected SM background: $16.2 \pm 3.9$ (stat.) $\pm 2.6$ (syst) events.
- Observed 11 events
- Branching limit for for $4.6 fb^{-1}$ of data:

$$\text{Br}(t \rightarrow Zq) < 0.34\% \text{ at 95\% CL}$$
Measurement of other top quark properties

- Probing heavy flavor content in the dilepton channel
- Likelihood fit on the b-tag multiplicity

\[ \mathcal{L} = \prod_\ell \prod_{\text{jets} \geq 2} \prod_k \mathcal{P}_{\text{poisson}}[N_{\text{jet}}(k), \hat{N}_{\text{jet}}(k)] \prod_x \mathcal{G}_{\text{bkg}}(x, x, \sigma_x) \]

- Jet-mismatching rate estimated on data

- Combined channel fit:
  \[ R = 0.98 \pm 0.04 \]
  \[ R > 0.85 \text{ at } 95\% \text{ CL} \]

- Dominant systematics: b-tagging efficiency and factorisation scale
Constraints on the Top Quark charge

- Discriminate between 2/3e (SM) and 4/3 (exotic) charge hypothesis
- W boson charge reconstructed from lepton charge
- b quark charge reconstructed from
  - momentum weighted charge of charged particles in the jet
  - soft muon from B-decay

\[ A = \frac{1}{D_S} \frac{N_{SM} - N_{XM} - <N_{BG}>}{D_B} \]

\[ N_{SM} = (P_{signal} \cdot (1 - f_{BG}) + P_{BG} \cdot f_{BG}) \cdot N \]

\[ N_{XM} = ((1 - P_{signal}) \cdot (1 - f_{BG}) + (1 - P_{BG}) \cdot f_{BG}) \cdot N \]

- \( A = 1 \) (SM), \( A \neq 1 \) (exotic)
- charge 4/3e excluded at 99.9% CL with 4.6 fb\(^{-1}\)

\[ A_{meas} = 0.97 \pm 0.12(\text{stat}) \pm 0.31(\text{syst}) \]
CMS is advancing in the exploration of the top properties

- Large $t\bar{t}$ dataset collected at $\sqrt{s} = 7$ TeV
- CMS obtained the most precise results on
  - $\Delta m_t = m_t - m_{\bar{t}}$
  - limit on FCNC

Top mass measurements at CMS increase in precision

For top mass measurements systematics dominated by jet energy scale
- Large dataset can help to reduce this

CMS conducted measurements in the phase-space where the top quark is sensitive to new physics like FCNC, anomalous couplings, exotic top quark charge and heavy flavor content.
- No deviation from the SM observed so far
- The search is not yet over!
Back-up
# KINb method (CMS)

<table>
<thead>
<tr>
<th>Process</th>
<th>Pre-selection</th>
<th>KINb</th>
<th>$= 1\ b$-tag</th>
<th>$\geq 2\ b$-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-bosons</td>
<td>$73 \pm 14$</td>
<td>$55 \pm 10$</td>
<td>$18 \pm 4$</td>
<td>$4 \pm 1$</td>
</tr>
<tr>
<td>Single top</td>
<td>$247 \pm 92$</td>
<td>$182 \pm 68$</td>
<td>$88 \pm 33$</td>
<td>$76 \pm 29$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$22 \pm 10$</td>
<td>$16 \pm 8$</td>
<td>$8 \pm 6$</td>
<td>-</td>
</tr>
<tr>
<td>$Z/\gamma^{\ast}\rightarrow \ell\ell$</td>
<td>$1091 \pm 97$</td>
<td>$756 \pm 71$</td>
<td>$238 \pm 29$</td>
<td>$47 \pm 11$</td>
</tr>
<tr>
<td>Other $t\bar{t}$</td>
<td>$32 \pm 4$</td>
<td>$28 \pm 3$</td>
<td>$11 \pm 2$</td>
<td>$14 \pm 2$</td>
</tr>
<tr>
<td>$t\bar{t}$ dileptons</td>
<td>$5057 \pm 463$</td>
<td>$4209 \pm 385$</td>
<td>$1379 \pm 127$</td>
<td>$2623 \pm 240$</td>
</tr>
<tr>
<td><strong>total expected</strong></td>
<td>$6522 \pm 482$</td>
<td>$5246 \pm 398$</td>
<td>$1742 \pm 134$</td>
<td>$2765 \pm 242$</td>
</tr>
<tr>
<td><strong>data</strong></td>
<td>$6358$</td>
<td>$5047$</td>
<td>$1692$</td>
<td>$2620$</td>
</tr>
</tbody>
</table>

**Graphs:**
- **Left:** $m_{top}=173.3^{+1.24}_{-1.23}$ GeV/c$^2$
- **Middle left:** $-$log$(-L/L_{max})$ for $1\ b$-tag and $\geq 2\ b$-tags.
- **Middle right:** Events with $ee/\mu\mu$.
- **Right:** Events with $ee/\mu\mu$. 

**Observables/Reference:**
- $m_{top}$ [GeV/c$^2$] for $ee/\mu\mu$.
Ideogram method (CMS)

Construct a likelihood to observe the data sample:

\[
\mathcal{L} \left( \text{sample} | m_t, \text{JES} \right) = \prod_{\text{events}} \mathcal{L} \left( \text{event} | m_t, \text{JES} \right)^{w_{\text{event}}}
\]

\[
= \prod_{\text{events}} \left( \sum_{i=1}^{n} P_{\text{fit}}(i) P \left( m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} | m_t, \text{JES} \right) \right)^{\sum_{i=1}^{n} P_{\text{fit}}(i)}
\]

With:

\[
P \left( m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} | m_t, \text{JES} \right) = P \left( m_{t,i}^{\text{fit}} | m_t, \text{JES} \right) \cdot P \left( m_{W,i}^{\text{reco}} | m_t, \text{JES} \right)
\]

\[
= \sum_{j} f_{j} P_{j} \left( m_{t,i}^{\text{fit}} | m_t, \text{JES} \right) \cdot P_{j} \left( m_{W,i}^{\text{reco}} | m_t, \text{JES} \right)
\]

\[ j \] runs over all possible jet combination cases:

- correct permutations
- wrong permutations
- unmatched permutations

Shapes of \( P_{j}(m_{t,i}^{\text{fit}} | m_t, \text{JES}) \) and \( P_{j}(m_{W,i}^{\text{reco}} | m_t, \text{JES}) \) from simulation
Measurement of other top quark properties

Ideogram method (CMS)
Search for FCNC in Top Quark pair decays

- b-tagging based event selection
  - Jets required to be associated to the same vertex as Z-boson
  - At least two jets and one b-jet
  - Jet selected with $m_{Zj}$ closest to $m_t$
  - $|m_{Zj} - m_t| < 25\text{GeV}$
  - $|m_{Wj} - m_t| < 35\text{GeV}$

- Estimation of DY and $t\bar{t}$ background
  - Compare sample with two or three jets and loose requirements on $HT_s$, $m_{Wj}$ and $m_{Zj}$ to the same sample with looser lepton isolation cuts
  - Samples are related by efficiency of events with nominal lepton isolation and the probability of jets faking a lepton
  - Composition of true and false three-lepton events is found using true and fake lepton efficiencies
  - Subtract di-boson contribution and account for acceptance to turn it into an estimation of the DY and $t\bar{t}$ background

- Dominant systematics: $t\bar{t}$ cross section, Jet Energy scale and b-tagging efficiency
Jet missasignment estimate

- Use the invariant mass of jet-lepton pairs.
- Jet-lepton mass can be subdivided in correct and wrong (e.g. radiation jet) jet assignment categories.
- Estimate shape for wrong jet assignments using two data-driven methods
  - "Swapping": swap jet with a jet from another event
  - "randomly rotating": randomly rotate the momentum vector of the selected leptons

This gives an estimate of the fraction of correctly assigned jets and hence the number of top quark pair events in the selected sample
b jet charge determination

- Use the presence of a soft muon in the b jet due to the decay of a B meson (carries the charge of the B)
- Soft muon charge can be diluted by
  - Neutral B oscillations
  - Cascade decay of the B to a muon through a charm hadron (D)

\[ \epsilon D = \frac{N_{\text{correct}} - N_{\text{wrong}}}{N_{\text{correct}} - N_{\text{wrong}}} \]

- \( \epsilon \): signal eff of charge assignment requirement
- D: dilution factor
- \( p_T^{rel} > 0.85 \text{GeV} \rightarrow \) Maximize \( \epsilon D \)

Alternative: momentum weighted charge of all charged particles in the jet

\[ JC = \frac{\sum_{\text{tracks}} (\vec{p}_i \cdot \vec{j})^{0.7} \cdot q}{\sum_{\text{tracks}} (\vec{p}_i \cdot \vec{j})^{0.7}} \]

- Better signal efficiency and lower dilution
- Very sensitive to systematics, hence not the chosen method