Recent top mass results from CMS

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Introduction

Recent measurements of $m_t$

- **TOP-14-022**
  Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV submitted to PRD, arXiv:1509.04044

- **TOP-15-002**
  Measurement of the top-quark mass from the $b$ jet energy spectrum

- **TOP-14-011**
  Measurement of the top-quark mass using the BEST-assisted $R$ distribution in the muon + jets channel

Additional studies

- **TOP-14-022**
  $m_t$ as function of kinematic observables

- Hadronization uncertainties in CMS incl. Sherpa Lund vs Cluster model
Paper contents

- Updated measurement in lepton+jets at 8 TeV using “hybrid” ideogram method incl. $m_t$ as function of kinematics
- Updated measurement in all-jets at 8 TeV using “hybrid” ideogram method
- Updated measurement in dilepton at 8 TeV using AMWT method
- Updated CMS combination 7 + 8 TeV including anti-correlation studies
- Select $t\bar{t}$ lepton+jets events (exactly 1 $e$ or $\mu$, 4 jets, exactly 2 $b$ tagged)
- Kinematic fit to $t\bar{t}$ hypothesis ($m_W = 80.4$ GeV, $m_t = m_{\bar{t}}$), require $P_{gof} > 0.2$
- Jet scale factor (JSF) extracted from $W$ mass peak ("2D" method)
Found anti-correlated uncertainties between 1D and 2D fits
- JEC, JER, pileup, radiation, top $p_T$, ...

Reason: Flat JSF overcorrects for uncertainties that mostly affect the light jets (due to flavor- and/or $p_T$-dependency)

Methods for improvement:
- Use $p_T$-dependent JSF (CDF)
- BLUE combination of 1D and 2D (ATLAS)
- Weigh down JSF constraint
- Add external JES constraint (D0, CMS)

Trade-off between JEC and other unc., minimum in-between
In-situ JSF and external constraint from $\gamma/Z$+jet have equal precision $\rightarrow$ equal weights

Most precise result from hybrid fit (JSF+JEC)

$$m_{t}^{\text{hyb}} = 172.35 \pm 0.16 \, (\text{stat+JSF}) \pm 0.48 \, (\text{syst}) \, \text{GeV}$$

Dominant uncertainty: flavor-dependent JEC

*cross-checked with $Z+b$ measurement*
Select $t\bar{t}$ all-jets events (6 jets, exactly 2 $b$ tagged)
- Kinematic fit to $t\bar{t}$ hypothesis, require $P_{gof} > 0.1, \Delta R_{b\bar{b}} > 2.0$
- QCD multijet background obtained from control sample (PAS: event mixing)
- Jet scale factor (JSF) extracted from $W$ mass peak
- In-situ JSF gets large background uncertainty
  - hybrid fit closer to 1D
  - 2D fit compatible within systematic uncertainties
    (only stat. $2\Delta \log \mathcal{L} = \{1, 4\}$ contours are shown)
- Most precise result from hybrid fit (JSF+JEC)
  \[ m_t^{\text{hyb}} = 172.32 \pm 0.25 \text{ (stat+JSF)} \pm 0.59 \text{ (syst)} \text{ GeV} \]
- Dominant uncertainties:
  JEC, flavor-dependent JEC, background
Select $t\bar{t}$ dilepton events
- 2 opposite-sign leptons
- at least 2 b-tagged jets
- for $ee$ and $\mu\mu$: MET $> 40$ GeV, $76 < m_{\ell\ell} < 106$ GeV

AMWT method
- Solve kinematic equations for $100 < m_t < 600$ GeV $\rightarrow$ up to 8 solutions for neutrino momenta
- Repeat $500 \times$ with object energies smeared within detector resolutions
- Calculate matrix element weight for $E_\ell$ in top frame
- Solution with highest average weight $\rightarrow m_t^{\text{AMWT}}$
Result obtained from binned likelihood

\[ m_t = 172.82 \pm 0.19 \text{ (stat)} \pm 1.22 \text{ (syst)} \text{ GeV} \]

Dominant uncertainties

- 0.75 GeV scale variation \( (\mu_R, \mu_F) \)
- 0.69 GeV b fragmentation
- Measurements combined with BLUE
- Pileup uncertainty uncorrelated between 7 and 8 TeV
- Anti-correlations are minimized by hybrid fits \( \rightarrow \) no negative correlations assigned
- Use constraint \( \rho < \sigma_i/\sigma_j \rightarrow \) avoid negative coefficients, slightly larger uncertainty

![Graphs showing \( \delta m_t \) distributions for dilepton, all-jets, and lepton+jets channels at 8 TeV, with blue combination coefficients for 2010-2012 data.]

2010 dilepton < 0.05 %
2011 dilepton 1.1 %
2011 all-jets 0.2 %
2011 lepton+jets 6.6 %
2012 dilepton 3.1 %
2012 all-jets 16.6 %
2012 lepton+jets 72.5 %

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**TOP-14-022**

**Result**

**CMS**

- **CMS combination, lepton+jets**
  - This analysis
  - $172.45 \pm 0.15 \pm 0.47$ GeV (value ± stat ± syst)

- **CMS combination, all-jets**
  - This analysis
  - $172.42 \pm 0.24 \pm 0.59$ GeV (value ± stat ± syst)

- **CMS combination, dilepton**
  - This analysis
  - $172.71 \pm 0.20 \pm 1.07$ GeV (value ± stat ± syst)

- **CMS combination**
  - $172.44 \pm 0.13 \pm 0.47$ GeV (value ± stat ± syst)

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$m_t = 172.44 \pm 0.13 \text{ (stat)} \pm 0.47 \text{ (syst)}$ GeV with $\chi^2/\text{ndf} = 2.5/6$

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TOP-15-002  $m_t$ from b-jet energy spectrum

- Select $t\bar{t}$ dilepton $e\mu$ events (2 opposite sign leptons, 1 or 2 b-tagged jets)
- $E_b$ peak position sensitive to $m_t$ [PRD 88 (2013) 057701]
- Biased by selection and reconstruction effects $\rightarrow$ MC calibration needed
Result from fit to $\log(E)$

$$m_t = 172.29 \pm 1.17 \text{ (stat)} \pm 2.66 \text{ (syst)} \text{ GeV}$$

- Dominant uncertainties
  - 1.17 GeV statistics
  - 0.74 GeV JEC (pre-final 2012)
  - 0.91 GeV ME generator
  - 0.91 GeV top $p_T$

- Used $Z+b$ jet calibration JME-13-001
  - central value compatible with 1
  - uncertainty reduced by 60%
Select $t\bar{t}$ lepton+jets events (exactly 1 $\mu$, $\geq 4$ jets, $\geq 2$ $b$ tagged)

- Estimation of comb. background using Bi-Event Subtraction Technique (BEST)

Result from fit to $R = m_{jjb}/m_{jj}$: $m_t = 172.61 \pm 0.57 \text{ (stat)} \pm 0.90 \text{ (syst)} \text{ GeV}$
TOP-14-022  

**lepton+jets**  
$m_t$ as function of kinematic observables

- Measure $m_t$ on subsets depending on kinematic observables
- Subtract value of inclusive measurements
- Compare data to models, difference should be flat

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**CMS**  
Lepton+jets, 19.7 fb$^{-1}$ (8 TeV)

**Data**
- 2D
- Hybrid
- 1D

**Models**
- Data
- MG+MS, Pythia Z2*
- MG, Pythia P11
- MG, Pythia P11 no CR
- Powheg, Pythia Z2*
- Powheg, Herwig 6
- MC@NLO, Herwig 6
- Sherpa

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**CMS**  
Lepton+jets, 19.7 fb$^{-1}$ (8 TeV)

**Graphs**
- $m_{t,\text{had}}$ vs $p_T^{\text{had}}$
- $m_{t,\text{cal}}$ vs $m_{t,\text{had}}$

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lepton+jets  $m_t$ as function of kinematic observables

- Included 8 observables: $p_{T,t}$, $p_{T,b}$, $|\eta_b|$, $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, $\Delta R_{q\bar{q}}$, $\Delta R_{b\bar{b}}$, number of jets
- Quantified overall agreement by
  \[ \chi^2 = \sum \frac{(\text{data} - \text{sim})^2}{\sigma^2_{\text{data}} + \sigma^2_{\text{sim}}} \]
- Summed $\chi^2$ for different generators

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$\chi^2$</th>
<th>$\sigma$</th>
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</thead>
<tbody>
<tr>
<td>MG + Pythia 6 Z2*</td>
<td>17.55</td>
<td>0.10</td>
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<td>MG + Pythia 6 P11</td>
<td>37.68</td>
<td>1.73</td>
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<tr>
<td>MG + Pythia 6 P11noCR</td>
<td>31.57</td>
<td>1.15</td>
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<td>Powheg + Pythia 6 Z2*</td>
<td>19.70</td>
<td>0.20</td>
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<td>Powheg + Herwig 6</td>
<td>76.48</td>
<td>4.84</td>
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<td>MC@NLO + Herwig 6</td>
<td>20.47</td>
<td>0.24</td>
</tr>
<tr>
<td>Sherpa</td>
<td>46.79</td>
<td>2.56</td>
</tr>
</tbody>
</table>
Hadronization model → particle-level comparison in Sherpa

\[ m_{jjb} \approx m_t \text{ (from jets w/o neutrinos)} \]

Mass distribution for reconstructed top after \( m_W \) cut

Difference in BR \( B \rightarrow \ell \nu X \)

- Sherpa Lund: 0.247
- Sherpa Cluster: 0.287
- PDG: 0.239 – 0.268

Hadronization model...

- has small effect on IR-safe observables
- affects analyses by jet composition (particle types and momenta)
Hadronization uncertainties in CMS

**JEC: Flavor**

- Pythia 6 vs. Herwig++ for each jet flavor

**b fragmentation**

- Retune to LEP data using Professor framework
- Take full difference between $Z2^*$ and $Z2^*$rbLEP

**B hadron decays**

- Neutrinos in b jets → lower response
- Vary BR to cover PDG values for $B^+/0$

**Ask our data:** JME-13-001 Direct measurement of b jet response using $Z + b$ events
Conclusions

- Very good agreement of default MC MadGraph+Pythia 6 Z2* with CMS Run1 data
  - $m_t$ in dependence of kinematics, differential cross sections, jet multiplicity
  - Exception: top $p_T \rightarrow$ included as uncertainty

- Very precise final 2012 JEC + detailed breakdown of hadronization uncertainties

- Obtained a set of most precise measurements in each analysis channel, yielding a combined Run1 result of

  $$m_t = 172.44 \pm 0.13 \text{ (stat)} \pm 0.47 \text{ (syst)} \text{ GeV}$$

- Alternative mass extractions in good agreement with main result
Additional material
New NLO tools for Run2

- For $m_t$: accurate description of decay products more important than $n^{th}$ extra jet
- Currently ME corrections “off” recommended for NLO matching?

“Gedanken” experiment in $e^+e^-$ at $\sqrt{s} = 350 \text{ GeV}$

- Select dilepton events, look at additional jets
- No contribution from UE and ISR
- Large effect from ME corrections that are implemented in Pythia and Herwig for top decays

→ need clarification from theory on correct procedure for NLO matching + ME corrections