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Top Quark Mass

On behalf of the CMS collaboration
The top quark mass at LHC

22 years after its discovery at Tevatron we are still measuring the top quark mass:
- exploiting different channels (for completeness)
- recurring to different techniques (with different systematics)
- exploring its connection to the theory

Taking advantage of:

- LHC is a top factory
  - ≈5 million pairs per experiment in 2012, ≈30 million in 2016, each t decays ≈100% to W+b
  - single top EWK production ($\sigma_t \sim \sigma_{tt}/3$)
- Physics objects
  - isolated energetic e or $\mu$
  - energetic jets
  - b-tagged jets
  - momentum imbalance (MET)
  - boosted top jets
Why measure $M_t$?

1) Free parameter of SM
   - $t$ decays well before hadronizing $\Rightarrow$ measure $M_t$
     directly from decay products

   - We usually compare to Monte Carlo expectations,
     so what we really measure is $M_t^{MC}$ parameter

   - There are 'standard methods' and 'alternative methods' (based on specific features)

   - This is complemented by a pole mass measurement
Why measure $M_t$?

2) Participates in quantum loop radiative corrections to $M_W$ constraining $M_H$ → assessment of self-consistency within SM

3) $M_t$ is close to scale of EWSB, so $t$ might play a special role in it

4) $M_t$ related with $M_H$ and vacuum stability of SM (and of Universe): near criticality of $M_H$

$\text{arXiv:1307.3536}$

$\text{EPJC 74 (2014) 3046, arXiv:1407.3792}$
Latest results on $M_t$

There are several $M_t$ measurements made so far by CMS at 7 and 8 TeV.

We will discuss here only the most recent ones at 8 TeV ($19.7 \text{ fb}^{-1}$):

- single top $\mu$+jets
- boosted top
- pole mass
- “alternative” methods
Systematic uncertainties

Statistical uncertainties becoming smaller and smaller
⇒ systematic uncertainties become dominant

Different sources of systematics, related to:
- Experimental effects
- Signal modeling
- Background modeling
- Features of the method

For every source, measurements performed (usually with pseudo-experiments) with modified parameters:
change of $M_t$ ⇒ syst. uncertainty
Single top: $\mu + \text{jets}$

Template method $(m_{\mu\nu b})$

Selection:
- 1 $\mu$
- MET
- 2 jets (1 b-tagged)
- $m_{\mu\nu b}$ distributions as a proxy for $m_t^{\text{reco}}$
- $\mu$ charge $>0$ to improve S/B since $\sigma_t \sim 2 \sigma_t$
- light jet at large $\eta$ expected from single top

$q_{\mu}>0$ & $|\eta_{j}|>2.5 \Rightarrow$

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Single top: $\mu + \text{jets}$

Template method ($m_{\mu\nu b}$)

$m_{\mu\nu b}$ parametrization
Gaussian core ($\mu, \sigma$)+ tails:
- $t$: Crystal Ball
- $tt$: Crystal Ball
- non-$t$: Novosibirsk

Calibration for the mass parameter $\mu$

Fit

$M_t = 172.95 \pm 0.77 \text{(stat)} + 0.97 - 0.93 \text{(syst)} \text{ GeV}$

$M_t = 172.95 \pm 1.24 \text{ GeV} \quad (\pm 0.72\%)$

Main systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>0.68</td>
</tr>
<tr>
<td>bkgd</td>
<td>0.39</td>
</tr>
<tr>
<td>fit calibration</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Boosted top: $e/\mu + \text{jets}$

*Template method* ($m_{\text{jet}}$)

**Selection:**
- 1 $e$ or $\mu$
- $\geq 2$ narrow jets ($\geq 1$ b-tagged)
- $\geq 2$ wide jets
- MET

The $M_t$-sensitive quantity is the leading-jet mass

Distributions are translated (unfolded) from reconstruction to particle-level (fiducial)

\[ \frac{d\sigma}{dM} \]

\[ p_T > 500 \text{ GeV} \]

\[ \sigma_{\text{fid,obs}} \approx (0.7 - 0.8)\sigma_{\text{fid,th}} \]

**TOP2017**
Boosted top: $e/\mu + \text{jets}$

*Template method* ($m_{\text{jet}}$)

**Normalized differential cross section**
(Madgraph+Pythia)

**Uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>20</td>
</tr>
<tr>
<td>PDF</td>
<td>20</td>
</tr>
<tr>
<td>$m_R,m_F$ scales</td>
<td>10</td>
</tr>
<tr>
<td>Parton shower</td>
<td>20</td>
</tr>
<tr>
<td>Choice of $m_t$</td>
<td>5</td>
</tr>
</tbody>
</table>

**Fit**

$M_t = 170.8 \pm 6.0 \text{(stat)} \pm 2.8 \text{(syst)} \pm 4.6 \text{(model)} \pm 4.0 \text{(theory)}$ GeV

$M_t = 170.8 \pm 9.0$ GeV \hspace{1cm} (\pm 5.3\%)

Method works but need more data, better modeling and higher-order calculations

*TOP2017*
What mass are we measuring?

The mass measured so far is the $M_t^{MC}$ (typically LO or NLO) and is affected by perturbative/non-perturbative sub-1% uncertainties.

The increasing level of accuracy requires to relate this to theory-based quantities like:

- the \textit{pole mass}, universal but theoretically ambiguous by amounts $O(\Lambda_{QCD})$ due to soft gluon radiation (\textit{infrared renormalon problem})

- \textit{Lagrangian masses}, theoretically unambiguous but not universal, like the \textit{MS mass} which is defined only in perturbation theory
Pole mass

$M_{t}^{\text{pole}}$ can be derived from $\sigma_{tt}$ cross section measurements compared to NNLO (but need to assume $M_{t}^{\text{MC}}$)

Syst. dominated by PDF and lumi
1% precision, but could reach 0.5%
(CMS-PAS-FTR-16-006)

$M_{t}^{\text{pole}}=173.8\pm1.7\ldots1.8$ GeV
The precision of the standard measurements depends strongly on the hadronization modeling.

To improve it we can use cleaner observables, i.e. avoid jets.

$M_t$ can be derived from observables other than the reconstructed mass, like for instance:
- lepton + $J/\Psi$ mass
- lepton + secondary vertex mass
- mass observables: $M_{b\ell}$, $M_{bbT2}$, $M_{b\ell\nu}$
Lepton+J/Ψ

The $M_t$-sensitive quantity is the lepton+J/Ψ mass

Limited by statistics, top $p_T$ modeling and QCD scales

$M_t = 175.3 \pm 3.0\,(\text{stat}) \pm 0.9\,(\text{syst})$ GeV

JHEP 12 (2016) 123

Lepton+sec.vertex

The $M_t$-sensitive quantity is the lepton+S.V. mass in bins of track multiplicity

Limited by b-fragmentation and top $p_T$ modeling

$M_t = 173.68 \pm 0.20\,(\text{stat})^{+1.58}_{-0.97}\,(\text{syst})$ GeV

PRD 93 (2016) 092006
Mass observables: $2e/\mu + \text{jets}$

The $M_t$-sensitive quantities $M_x$ are:

$$M_{b\ell}, \quad M_{b\ell}^{bb}, \quad M_{b\ell\nu}$$

3D ($M_x, M_t, JSF$) non-parametrical modeling of these distributions

Systematics dominated by JES, $b$ fragmentation and top $p_T$ reweighting

$$M_t = 172.22 \pm 0.18 \text{ (stat)} + 0.89 - 0.93 \text{ (syst)} \text{ GeV}$$
Mt combinations

The individual measurements are then combined into experiment/world averages to gain in precision

Results computed with the Best Linear Unbiased Estimator, accounting for correlations $\rho$ in the systematics ($\rho$ signs are relevant for large systematics)
7+8 TeV combination

**September 2017**

- **CMS 2010, dilepton**
  JHEP 07 (2011) 049, 36 pb
  $m_t = 175.50 \pm 4.60 \pm 4.60$ GeV

- **CMS 2011, dilepton**
  EPJC 72 (2012) 2202, 5.0 fb
  $m_t = 172.50 \pm 0.43 \pm 1.43$ GeV

- **CMS 2011, all-jets**
  EPJC 74 (2014) 2758, 3.5 fb
  $m_t = 173.49 \pm 0.69 \pm 1.21$ GeV

- **CMS 2011, lepton+jets**
  JHEP 12 (2012) 105, 5.0 fb
  $m_t = 173.49 \pm 0.43 \pm 0.98$ GeV

- **CMS 2012, dilepton**
  PRD 93 (2016) 072004, 19.7 fb
  $m_t = 172.82 \pm 0.19 \pm 1.22$ GeV

- **CMS 2012, all-jets**
  PRD 93 (2016) 072004, 18.2 fb
  $m_t = 172.32 \pm 0.25 \pm 0.59$ GeV

- **CMS 2012, lepton+jets**
  PRD 93 (2016) 072004, 19.7 fb
  $m_t = 172.35 \pm 0.16 \pm 0.48$ GeV

- **CMS legacy**
  PRD 93 (2016) 072004
  $m_t = 172.44 \pm 0.13 \pm 0.47$ GeV

- **CMS 2016, lepton+jets**
  TOP-17-007 (2017), 35.9 fb
  $m_t = 172.25 \pm 0.08 \pm 0.62$ GeV

- **Tevatron combination**
  $m_t = 174.34 \pm 0.37 \pm 0.52$ GeV

- **World combination**
  ATLAS, CDF, CMS, D0
  $m_t = 173.34 \pm 0.27 \pm 0.71$ GeV
  (value = stat. ± syst.)

**PRD 93 (2016) 072004**

- Several decay channels pursued (some with in situ JSF)
- Different main systematics
- Combination to check consistency and increase precision

**September 2015 value:**

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

$m_t = 172.44 \pm 0.49$ GeV (±0.28%)
7+8 TeV alternative methods

CMS-PAS-TOP-15-012

Slightly less precise (0.4%) than the standard measurements

Independent verification with different systematics

\[ M_t = 172.58 \pm 0.21 \text{ (stat)} \pm 0.72 \text{ (syst)} \text{ GeV} \]
March 2014 value:

\[ M_t = 173.34 \pm 0.36 \text{(stat)} \pm 0.67 \text{(syst)} \text{ GeV} \]

\[ M_t = 173.34 \pm 0.76 \text{ GeV} \quad (\pm 0.44\%) \]

Tevatron 2016 combination

\[ 174.30 \pm 0.65 \text{ GeV} \]

\[ \text{arXiv:1608.01881} \]
@13 TeV: e/μ + 4 jets

*Ideogram method*

2D fit ($m^\text{reco}_{t}$, $m^\text{reco}_{w}$)

*w. in situ JSF* (35.9 fb$^{-1}$)

Kinematic fit to the $tt\rightarrow WbWb$ hypothesis

Possible combinations treated separately:

- correct:
- wrong:
- unmatched

Selection:

- 1 e or μ
- ≥4 jets (2 b-tagged)
@13 TeV: $\mu + 4$ jets

Ideogram method ($m_{t}^{\text{reco}}, m_{W}^{\text{reco}}$) w. in situ JSF

See E. Yazgan’s talk

Main systematics

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<td>flavor JEC</td>
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</tr>
<tr>
<td>color reconn.</td>
<td>0.31</td>
</tr>
<tr>
<td>ME generator</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Multiple permutations weighted by $P_{\text{gof}}=\exp(-\chi^{2}/2)$

$P_{\text{gof}}=\exp(-\chi^{2}/2)>0.2$ to favor the correct combin.

Hybrid Fit

$M_{t}=172.25\pm0.08(\text{stat}+\text{JSF})\pm0.62(\text{syst})$ GeV

$M_{t}=172.25\pm0.63$ GeV (±0.36%)

JSF = 0.996±0.008

TOP2017
Conclusions

- Level of precision reached (<0.3%) in measuring $M_t$ impressive but comes from 22 years of continuous improvements
- Even better precision expected from Run2; single top events and boosted top can contribute
- Inclusion of alternative methods will improve precision
- Test of the consistency of the SM, vacuum stability and new physics

Important to work on reducing systematics e.g. those related to theory and signal modeling
Outlook

Run1 legacy measurements of $M_t$ being completed
⇒ published soon

Ultimate precision of few hundreds MeV expected merging measurements/experiments, accounting for correlations and taking advantage of improvements in MC modelling

Differences between $M_{t}^{MC}$ and theoretical definitions (pole mass, Lagrangian mass): important issue to deal with
Backup
Methods for measuring $M_t$

1) *Template method:* distributions of variables sensitive to $M_t$, e.g., reconstructed $M_t^{reco}$ from $\chi^2$ fit to WbWb

Pdf’s derived for MC events assuming different $M_t^{MC}$; parametrized vs $M_t$

Likelihood from pdf’s; outcome calibrated for biases (pull-mean and pull-width of pseudo-experiments)

$M_W$ templates for in-situ calibration of JES

Possible to add constraints on b-jet JES

Relatively simple, fast, but non optimal statistical uncertainty
Methods for measuring $M_t$

2) **Ideogram method**: modification of template method using multiple permutations with different weights

Starts from kinematical reconstruction, then computes event likelihood as a function of $M_t$

Different pdf’s used for different jet-quark assignments

Event likelihoods (ideograms) are given by

$$P_{\text{gof}} = \exp(-\chi^2/2)$$

$$w_{\text{event}} = \sum P_{\text{gof}}(i)$$

$$P_{\text{sig}}^{\text{cp}}(m_t^{\text{fit}}|M_t,\text{JSF})$$

$$\mathcal{L}(\text{sample}|m_t,\text{JSF}) = \prod \mathcal{L}(\text{event}|m_t,\text{JSF})^{w_{\text{event}}}$$

![Diagram showing distribution of $m_t$ and $m_{t,\text{CP}}$ with different JES values]
Gaussian process regression technique

GP shape determined by:
• a set of training points
• smoothing parameters
• 35 binned distributions (7 bins for $M_t$, 5 for JSF, 75 for $M_x$)
• Gaussian = values in each point are Gaussian distributions
Mass observables: $M_{T2}^{bb}$

$$M_T = \sqrt{m_\ell^2 + m_\nu^2 + 2(E_\ell E_\nu - \vec{p}_T \cdot \vec{p}_T)} ,$$

$$M_{T2} = \min_{\vec{p}_T^{a} + \vec{p}_T^{b} = \vec{p}_T^{\text{miss}}} \left[ \max\{M_T^{a}, M_T^{b}\} \right] ,$$

Impose the constraint on the invisible particle momenta + preserve the kinematic endpoint
Systematic uncertainties

Experimental \textit{(i.e. imperfect knowledge of)}:
- Jet Energy Scale (JES)
- b-Jet Energy Scale (bJES)
- jet energy resolution and reconstruction
- MET scale
- b-tagging scale factor
- lepton energy scale and reconstruction
- pileup
- trigger

Background modeling \textit{(i.e. uncertainty on)}:
- MC normalization and shape
- normalization and shapes of data-driven backgrounds

Signal modeling \textit{(i.e. imperfect knowledge of theory regarding)}:
- MC generator
- hadronization
- amount of ISR/FSR
- flavor-dependent hadronization
- b-quark fragmentation and BRs
- renormaliz./factoriz. scales
- PDF’s
- Color reconnection
- Underlying event

Features of the method \textit{(i.e. dependence on)}:
- parametrization of pdf’s
- calibration
- MC statistics

Agreement between ATLAS and CMS is essential

\textbf{TOP2017}