CMS Measurements of the Top Quark Mass and Width

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Outline
- Summary RunI Measurements
- 13 TeV measurements
- Alternative methods
- Top Width

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Top Mass: Motivation

- Fundamental parameter of the SM

- $m_{\text{top}}$ can be measured directly from the decay products (top quark decays well before hadronizing)

- $m_{\text{top}}$ is close to the EWSB scale, so top quark might play a special role

- Precise knowledge of $m_{\text{top}}$ crucial for testing the consistency of the SM:
  - participates in quantum loop radiative corrections to $m_W$ constraining $m_H$
  - $m_{\text{top}}$ related with $m_H$ and vacuum stability of SM
All decay channels are pursued
- provides consistency and precision

Lepton+Jets and All Jets channels
- in situ determination of jet energy scale factor (JSF)
- similar systematic uncertainties

Dilepton channel
- Different color flow
- Different main systematics:
  - b-fragmentation and QCD modeling

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**Top Mass: RunI Measurements (7 and 8 TeV)**

- CMS 2010, dilepton
  - JHEP 07 (2011) 049, 36 pb$^{-1}$
  - $175.50 \pm 4.60 \pm 4.60$ GeV (value ± stat ± syst)

- CMS 2011, dilepton
  - EPJC 72 (2012) 2202, 5.0 fb$^{-1}$
  - $172.50 \pm 0.43 \pm 1.43$ GeV (value ± stat ± syst)

- CMS 2011, all-jets
  - EPJC 74 (2014) 2758, 3.5 fb$^{-1}$
  - $173.49 \pm 0.69 \pm 1.21$ GeV (value ± stat ± syst)

- CMS 2011, lepton+jets
  - JHEP 12 (2012) 105, 5.0 fb$^{-1}$
  - $173.49 \pm 0.43 \pm 0.98$ GeV (value ± stat ± syst)

- CMS 2012, dilepton
  - This analysis, 19.7 fb$^{-1}$
  - $172.82 \pm 0.19 \pm 1.22$ GeV (value ± stat ± syst)

- CMS 2012, all-jets
  - This analysis, 18.2 fb$^{-1}$
  - $172.32 \pm 0.25 \pm 0.59$ GeV (value ± stat ± syst)

- CMS 2012, lepton+jets
  - This analysis, 19.7 fb$^{-1}$
  - $172.35 \pm 0.16 \pm 0.48$ GeV (value ± stat ± syst)

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

- Tevatron combination (2014)
  - arXiv:1407.2682
  - $174.34 \pm 0.37 \pm 0.52$ GeV (value ± stat ± syst)

- World combination 2014
  - ATLAS, CDF, CMS, D0
  - arXiv:1403.4427
  - $173.34 \pm 0.27 \pm 0.71$ GeV (value ± stat ± syst)

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Top Mass: Measurements @ 8 TeV

- **l+jets and all jets**: fit of the decay products to a $t\bar{t}$ hypothesis and joint maximum likelihood to estimate $m_{\text{top}}$ and JSF

- **Dilepton**: matrix weighting technique combined with an analytical algorithm to find solutions of the kinematic equations

- **Most precise measurements in each of the decay channels**

**Most precise measurements in each of the decay channels**

- Combination: $\frac{\delta m_{\text{top}}}{m_{\text{top}}} = 0.28\%$

- 0.44% for 2014 world combination

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PRD 93 (2016) 072004
Follows the 8 TeV measurement using $\mu$+jets events

Main systematics: JES and MC modeling

- CDF, lepton+jets
  - PRL 109 (2012) 152003, 8.7 fb$^{-1}$
  - $m_t = 172.85 \pm 1.10$ GeV

- D0 matrix element, lepton+jets
  - PRD 91 (2015) 112003, 9.7 fb$^{-1}$
  - $m_t = 174.98 \pm 0.76$ GeV

- ATLAS 2011, lepton+jets
  - EPJC 75 (2015) 330, 4.6 fb$^{-1}$
  - $m_t = 172.33 \pm 1.27$ GeV

- CMS 2011, lepton+jets
  - JHEP 12 (2012) 105, 5.0 fb$^{-1}$
  - $m_t = 173.49 \pm 1.07$ GeV

- CMS 2012, lepton+jets
  - PRD 93 (2016) 072004, 19.7 fb$^{-1}$
  - $m_t = 172.35 \pm 0.51$ GeV

- **CMS 2015 prel., lepton+jets**
  - TOP-16-022 (2017), 2.2 fb$^{-1}$
  - $m_t = 172.62 \pm 0.80$ GeV

- CMS Run 1 combination
  - PRD 93 (2016) 072004
  - $m_t = 172.44 \pm 0.49$ GeV

- World combination
  - ATLAS, CDF, CMS, D0
  - $m_t = 173.34 \pm 0.76$ GeV

Still not as precise as Run I measurement

- new generators used in Run II still being tested/tuned (see details in E. Yazgan's talk)

But in excellent agreement with other measurements
World combination reaching a precision of 0.5 GeV (<0.3%)

- arXiv:1403.4427

Precision limited by understanding of hadronization modeling

Different ways to improve

- Use cleaner observables
- Avoid jets

- Use theoretically calculable observables sensitive to the mass $\sigma(tt)$, $m(llb)$

Constrain modeling systematics

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### Top Mass: Current Status

- World combination reaching a precision of 0.5 GeV (<0.3%)
  - arXiv:1403.4427

- Precision limited by understanding of hadronization modeling

- Different ways to improve
  - Use cleaner observables
  - Avoid jets
  - Use theoretically calculable observables sensitive to the mass $\sigma(tt)$, $m(llb)$
  - Constrain modeling systematics

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#### ATLAS+CMS Preliminary LHCTopWG

<table>
<thead>
<tr>
<th>Experiment</th>
<th>m$_{top}$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, $l+jets$ (*)</td>
<td>172.33 ± 1.27 (0.75 ± 1.02) GeV</td>
<td>7 TeV [8]</td>
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<tr>
<td>ATLAS, dilepton (*)</td>
<td>173.79 ± 1.41 (0.54 ± 1.30) GeV</td>
<td>7 TeV [8]</td>
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<tr>
<td>CMS, $l+jets$</td>
<td>175.1 ± 1.8 (1.4 ± 1.2) GeV</td>
<td>7 TeV [9]</td>
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<tr>
<td>CMS, single top</td>
<td>172.2 ± 2.1 (0.7 ± 2.0) GeV</td>
<td>8 TeV [10]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.99 ± 0.85 (0.41 ± 0.74) GeV</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>173.72 ± 1.15 (0.55 ± 1.01) GeV</td>
<td>8 TeV [12]</td>
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<tr>
<td>ATLAS comb. (June 2016)</td>
<td>172.84 ± 0.70 (0.34 ± 0.61) GeV</td>
<td>7+8 TeV [11]</td>
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<tr>
<td>CMS, $l+jets$, dil.</td>
<td>172.35 ± 0.51 (0.16 ± 0.48) GeV</td>
<td>8 TeV [13]</td>
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<tr>
<td>CMS, dilepton</td>
<td>172.82 ± 1.23 (0.19 ± 1.22) GeV</td>
<td>8 TeV [13]</td>
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<tr>
<td>CMS, all jets</td>
<td>172.32 ± 0.64 (0.25 ± 0.59) GeV</td>
<td>8 TeV [13]</td>
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<tr>
<td>CMS, single top</td>
<td>172.95 ± 1.22 (0.77 ± 0.95) GeV</td>
<td>8 TeV [14]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>172.44 ± 0.48 (0.13 ± 0.47) GeV</td>
<td>7+8 TeV [13]</td>
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(*) Superseded by results shown below the line

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| m$_{top}$ [GeV] | Ref.
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<td>165</td>
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</table>
Lepton + J/ψ Events or Secondary Vertex @ 8 TeV

- Extract $m_{\text{top}}$ from the invariant mass of J/ψ + lepton
- Events in the main leptonic top quark decay where the b-quark decays via $b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$
- Statistically limited (for now): 3.0 GeV
- But no use of jets: syst. unc. < 1 GeV
- Limited by top $p_T$ modeling, QCD scales

More general version of J/ψ analysis
- Invariant mass of lepton and secondary vertex used as observable (in bins of SV track multiplicity)
- Gain in statistics but limited by fragmentation

$\begin{align*}
\text{Extract } m_{\text{top}} \text{ from the invariant mass of J/ψ + lepton} \\
\text{Events in the main leptonic top quark decay where the b-quark decays via } b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X \\
\text{Statistically limited (for now): } 3.0 \text{ GeV} \\
\text{But no use of jets: syst. unc. } < 1 \text{ GeV} \\
\text{Limited by top } p_T \text{ modeling, } QCD \text{ scales} \\
\end{align*}$
Dilepton channel

The transverse momentum of the lepton pair from the decay of the top quark pair is chosen to extract the top quark mass.

Clean but overwhelmed by $\mu_R$, $\mu_F$ scale unc.

Based on LO Madgraph (Run I MC)

Expected to improve using NLO+PS

After the calibration with simulated events

$$m_t = 171.7 \pm 1.1 \text{ (stat.)} \pm 0.5 \text{ (exp.)} \pm 2.5 \text{ (th.)} \pm 0.8 \text{ (}$p_T(\text{t})$)$ \text{ GeV}$

Signal modeling is the dominant systematic uncertainty.
Analyses targeting alternative topologies can give further insights, e.g. pure EW production.

**Single top t-channel**

Fit to the reconstructed $m_{\text{top}}$ of the top candidates.

**JES is the main systematic uncertainty.**
Top Mass: Combination Alternative Measurements

- Only few alternative methods shown here
- Others are available
- All measurements combined using BLUE
  - 0.4% precision, comparable with the combination of standard methods
  - Similar exp. unc. but larger theoretical
- When combining with standard methods not large improvement due to correlations between the main syst. uncertainty

How to increase the impact
- Decrease the size of the correlations using less sensitive techniques
- Decrease the size of the correlated terms data-based constraints
Top Pole Mass

- Extract $m_{\text{top}}$ from production cross section
- Calculate mass dependence at NNLO
- 1% precision, not yet competitive with direct measurements
  
  $$m_{t}^{\text{pole}} = 173.8^{+1.7}_{-1.8} \text{ GeV}$$

  PDF set: NNPDF3.0 (consistent results with CT14 and MMHT2014)

- Could reach 0.5% precision with 5% and 2% theory and experimental unc., respectively (CMS-PAS-FTR-16-006).

- Main systematics: PDF, luminosity

- 13 TeV l+jets x-sect measurement (details in T. Arndt's talk) yields $170.6 \pm 2.7$ GeV (using CT14 PDF)
Top Width

- Less tested of the top quark properties!
- Dilepton channel
- Reconstructed mass of the decay products (lepton and b) is used as observable to probe variations in $\Gamma_t$
- Observable compared to the simulated expectations for different $\Gamma_t$ scenarios using a likelihood technique
- MC modeling main systematic uncertainty

For a SM-like top quark hypothesis:
- Observed limit: $0.6 \leq \Gamma_t \leq 2.5$ GeV, expected limit: $0.6 \leq \Gamma_t \leq 2.4$ GeV
- $\Gamma_t$ (NLO) = 1.35 GeV

$\Gamma_t = 1.36 \pm 0.02$ (stat) $+0.14-0.11$ (syst)
Summary

In Run I, CMS measured $m_{\text{top}}$ in all decay channels with different complementary methods. The combination produced the most precise measurement to date.

Level of precision reached in $m_{\text{top}}$ ($<0.3\%$) impressive but comes from many years of continuous improvements.

Combination of alternative methods yields similar precision as standard methods.

First measurement at 13 TeV already available.

Outlook: ultimate precision of $0(10^2)$ MeV expected when merging measurements and experiments, accounting for correlations, and improving the MC modeling.

The first direct bounds on $\Gamma_t$ at the LHC has been achieved.

Most precise performed to date.
Thank you for your attention!

Back-up

Slides
Select events in the main leptonic top quark decay where the b-quark decays via $b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$

Extract $m_{\text{top}}$ from the invariant mass of $J/\psi + \text{lepton}$

Very small BR ⇒ statistically limited (for now)
- 666 events ⇒ stat. unc. of 3.0 GeV

But no use of jets to build observable
- Avoid JES/bJES
- Systematic uncertainty < 1 GeV
- Limited by top $p_T$ modeling, QCD scales

$m_t = (173.5 \pm 3.0) \text{ GeV}$
Lepton + Secondary Vertices @ 8 TeV

- More general version of J/ψ analysis
- Sensitivity to $m_{\text{top}}$ from leptons (e/μ) and via decay lengths of charged hadrons (from b-quark decay)
- Stronger sensitivity to $m_{\text{top}}$ without inclusion of jets
- Semileptonic and dileptonic channels
- Invariant mass of lepton and secondary vertex used as observable (in bins of SV-track multiplicity)

![Graph showing invariant mass distribution](image)

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

- Experimental uncertainties <500 MeV
- Dominant systematic: top quark $p_T$ and b-quark fragmentation