Measurements of the top quark pole mass at D0

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on behalf of the D0 collaboration
Standard top-quark mass measurements

• standard methods: based on comparison of kinematics observables with MC generated at different top-quark masses
  - determination of the best-fit value of the MC top-quark mass parameter

• on-going theoretical works
  - to translate the MC top-quark mass into a mass in a well defined renormalization scheme (M. Butenschoen et al., arXiv:1608.01318):
    - currently for $e^+e^- \rightarrow t\bar{t}$:
      - in the MSR scheme: $m_t^{\text{MSR}(1\text{GeV})}$ equal to $m_t^{\text{MC}}$ within 220 MeV
      - $m_t^{\text{pole}}$ equal to $m_t^{\text{MC}}$ within 410 MeV
  - to assess the theoretical uncertainty on the computation of kinematic distributions using Shower MC

• note: the top-quark pole mass suffers from the renormalon ambiguity
  - ultimate ambiguity on the relation between the pole and MSbar mass: 110 MeV (M. Beneke et al., arXiv:1605.03609)
Experimental ‘alternative’ top-quark mass measurements

• experimental way to address the question of the top-quark mass definition:
  - use alternative methods to determine the top-quark mass:
    - with less inputs from MC
    - with different sensitivity to systematics
    - using theory computation with well defined mass
  - examples: from cross section, from single top events, using J/ψ events, from ttbar+jets, ...

• top-quark pole mass determination using the $t\bar{t}$ cross section at D0
  - using the inclusive $t\bar{t}$ cross section:
    - compare the experimental $t\bar{t}$ cross section measurement with the theory computation
    - these depend differently on the top-quark mass
  - using the differential $t\bar{t}$ cross section:
    - additional information coming from the shape of the distributions
    - possible since NNLO differential predictions are now available

• mass determination using the $t\bar{t}$ cross section
  - advantage: extract the top-quark mass in a well defined renormalization scheme, i.e the one used in the theory computation
  - drawback: less precise than direct measurements
The Tevatron and the D0 detector

- **pp collider**
- **Run I (1993-1996):**
  - $\sqrt{s} = 1.8$ TeV, $L \approx 120$ pb$^{-1}$
- **Run II (2002-2011):**
  - $\sqrt{s} = 1.96$ TeV, $L \approx 10$ fb$^{-1}$
Top-quark pole mass measurement using the inclusive $t\bar{t}$ cross section


- experimental input:
  - $t\bar{t}$ cross section in the dilepton and lepton+jets channel using the full D0 dataset (9.7 fb$^{-1}$)

- simultaneous fit of the b-ID MVA discriminant in the dilepton channel and a specific MVA in the lepton+jets channel
  - lepton+jets channel: events with at least 2 jets, W+jets background normalization fitted on data
  - dilepton: at least 1 jet (eµ channel) or at least 2 jets (ee and µµ channels)
  - multijet background determined using the matrix method
  - channels split by lepton flavor, number of jets, number of b-jets. Systematic uncertainties constrained in the fit
Top-quark pole mass measurement using the inclusive $t\bar{t}$ cross section

### Experimental Top-Quark Mass Dependence:
- Likelihood fit repeated for different mass points: the cross section changes by 0.7% for a change of 1 GeV in top-quark mass.
- Constant relative systematic uncertainty (scaled from the 172.5 GeV case).
- Parametrized with a fourth-order polynomial function.

\[ \frac{\Delta \sigma}{\sigma} = 7.6\% \]

<table>
<thead>
<tr>
<th>Top Quark Mass [GeV]</th>
<th>Cross Section $\sigma(t\bar{t})$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>$9.70 \pm 0.16 \text{ (stat.)}^{+0.73}_{-0.67} \text{ (syst.)}$</td>
</tr>
<tr>
<td>160</td>
<td>$8.25 \pm 0.14 \text{ (stat.)}^{+0.63}_{-0.57} \text{ (syst.)}$</td>
</tr>
<tr>
<td>165</td>
<td>$7.46 \pm 0.13 \text{ (stat.)}^{+0.58}_{-0.51} \text{ (syst.)}$</td>
</tr>
<tr>
<td>170</td>
<td>$7.55 \pm 0.13 \text{ (stat.)}^{+0.58}_{-0.55} \text{ (syst.)}$</td>
</tr>
<tr>
<td>172.5</td>
<td>$7.26 \pm 0.12 \text{ (stat.)}^{+0.57}_{-0.50} \text{ (syst.)}$</td>
</tr>
<tr>
<td>175</td>
<td>$7.28 \pm 0.12 \text{ (stat.)}^{+0.54}_{-0.49} \text{ (syst.)}$</td>
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<tr>
<td>180</td>
<td>$6.86 \pm 0.12 \text{ (stat.)}^{+0.53}_{-0.47} \text{ (syst.)}$</td>
</tr>
<tr>
<td>185</td>
<td>$6.50 \pm 0.11 \text{ (stat.)}^{+0.50}_{-0.43} \text{ (syst.)}$</td>
</tr>
<tr>
<td>190</td>
<td>$6.70 \pm 0.11 \text{ (stat.)}^{+0.60}_{-0.47} \text{ (syst.)}$</td>
</tr>
</tbody>
</table>

### Theoretical Input:
- NNLO+NNLL $t\bar{t}$ cross section computed with top++ (M. Czakon and A. Mitov, Comp. Phys. Com. 185 2930 (2014)).
- Theoretical uncertainties: scale variations $\oplus$ PDF uncertainties (MSTW2008 NNLO).
Top-quark pole mass result using the inclusive $t\bar{t}$ cross section

- most probable value of the top-quark pole mass:
  - extracted from the maximum of a normalized joint-likelihood function

\[ L(m_t) = \int f_{\text{exp}}(\sigma|m_t) \left( f_{\text{scale}}(\sigma|m_t) \otimes f_{\text{PDF}}(\sigma|m_t) \right) \, d\sigma \]

- result:
  - precision: 1.9%
  - dominated by experimental uncertainties

\[ m_t = 172.8 \pm 1.1 \, \text{(theo.)}^{+3.3}_{-3.1} \, \text{(exp.)} \, \text{GeV} \]
\[ m_t = 172.8^{+3.4}_{-3.2} \, \text{(tot.)} \, \text{GeV} \]

- same method was used in the past to extract the MSbar mass
  - using 5.4 fb$^{-1}$: $m_t^{\text{MS}} = 160.0^{+5.1}_{-4.5} \, \text{GeV}$
  
Top-quark pole mass measurement using the differential $t\bar{t}$ cross section

- **experimental input:**
  - differential $t\bar{t}$ cross section in the lepton+jets channel using the full D0 dataset ($9.7 \text{ fb}^{-1}$)
  - simultaneous fit of $t\bar{t}$ cross section and the heavy flavor $W$+jets using the b-ID MVA discriminant to determine the sample composition in the 2-jets, 3-jets and 4-jets channels
  - $t\bar{t}$ kinematic reconstruction using $\chi^2$ to find the best jet permutations
  - unfolding to parton level using regularized matrix inversion

- $t\bar{t}$ are produced mostly at rest

- **MVA discriminant** to determine the sample composition in the 2-jets, 3-jets and 4-jets channels

- Phys. Rev. D 90, 092006 (2014)
• theoretical input:
  - NNLO calculations from Czakon, Mitov et al (JHEP1605, 034 (2016) ) with the same binning as the experimental measurement
  - using fixed non-dynamic scales equal to $m_t$, scale uncertainties range from 5% to 10-20%
  - four different PDFs (MSTW2008, CT10, NNPDF23, HERAPDF15)
method:
- $\chi^2$ to compare the measured differential cross section with the theoretical calculation:

$$\chi^2 = \sum_{i,j} (x_i^{\text{true}} - x_i^{\text{theo}}) \cdot V_{xx}^{-1} \cdot (x_j^{\text{true}} - x_j^{\text{theo}})$$

- $V_{xx}$ experimental covariant matrix (including the reduction of the luminosity uncertainty from 6.1% to 4.3%)
- parabolic fit to the $\chi^2$ distribution to determine the minimum
- spread of the extractions for the 3 global PDF used as PDF uncertainty on $m_t^{\text{pole}}$
Top-quark pole mass results using the differential $t\bar{t}$ cross section

- **combined result:**
  - $\chi^2$ using the 2D covariant matrix $m_{t\bar{t}}$ vs $p_{t\bar{t}}$ (small global correlation of 0.12)
  - main sensitivity is coming from $p_{t\bar{t}}$ (though the normalization)
  - consistent average increase from using NLO to using NNLO
  - contribution from experimental uncertainty slightly higher than the one from theory

<table>
<thead>
<tr>
<th>Order &amp; PDF</th>
<th>$m(t\bar{t})$</th>
<th>$m_{t\bar{t}}^\text{pole}$ [GeV]</th>
<th>$p_{t\bar{t}}$</th>
<th>$m(t\bar{t}) \oplus p_{t\bar{t}}$</th>
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<tbody>
<tr>
<td>NLO:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MSTW2008</td>
<td>169.3 ± 5.7</td>
<td>166.8 ± 2.9</td>
<td>167.4 ± 2.5</td>
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</tr>
<tr>
<td>CT10</td>
<td>169.4 ± 5.9</td>
<td>167.0 ± 2.9</td>
<td>167.5 ± 2.6</td>
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</tr>
<tr>
<td>NNPDF2.3</td>
<td>169.0 ± 6.0</td>
<td>166.4 ± 2.9</td>
<td>167.1 ± 2.5</td>
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<tr>
<td>HERAPDF1.5</td>
<td>167.2 ± 6.4</td>
<td>166.0 ± 2.9</td>
<td>165.1 ± 2.7</td>
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- **lower results than using the inclusive cross section:**
  - 9% higher total cross section measured using the differential results (but 30% larger cross-section error, so not significant)
  - theory input not using NNLL (2% lower total cross section)
• measurement of the top-quark pole mass
  - complementary to standard measurement based on MC

• D0 top-quark pole measurements
  - using the inclusive $t\bar{t}$ cross section: $m_{t}^{\text{pole}} = 172.8 \pm 3.3$ GeV
  - using for the first the differential $t\bar{t}$ cross section: $m_{t}^{\text{pole}} = 169.1 \pm 2.5$ GeV

• further developments
  - at the LHC with more precise experimental inputs
  - on-going improvements from the theoretical calculations (including NNLL, including the top decays, ...)

(b) D0 Preliminary, 9.7fb$^{-1}$

- $m_{t}^{\text{pole}}$ extractions
  - NLO vs. $d\sigma/dX$
    - [This article] $167.3 \pm 2.6$
  - NNLO vs. $d\sigma/dX$
    - [This article] $169.1 \pm 2.5$
  - D0 (NNLO+NNLL $\sigma_{\text{tot}}$)
    - [arXiv:1605.06168] $172.8 \pm 3.3$
  - ATLAS $(t\bar{t}+fj)$
    - [JHEP 10 (2015)] $173.7 \pm 2.2$
  - CMS (NNLO+NNLL $\sigma_{\text{tot}}$)
    - [PLB 728 (2014)] $176.7 \pm 2.9$

Direct techniques

- Tevatron average
  - [arXiv:1608.01881] $174.30 \pm 0.65$
- ATLAS average
  - [arXiv:1606.02179] $172.84 \pm 0.70$
- CMS combination
  - [PRD 93 (2016)] $172.44 \pm 0.49$

Top quark mass [GeV]