Measurements of the top quark pole mass at D0

EUROPEAN PHYSICAL SOCIETY HEP2017

EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

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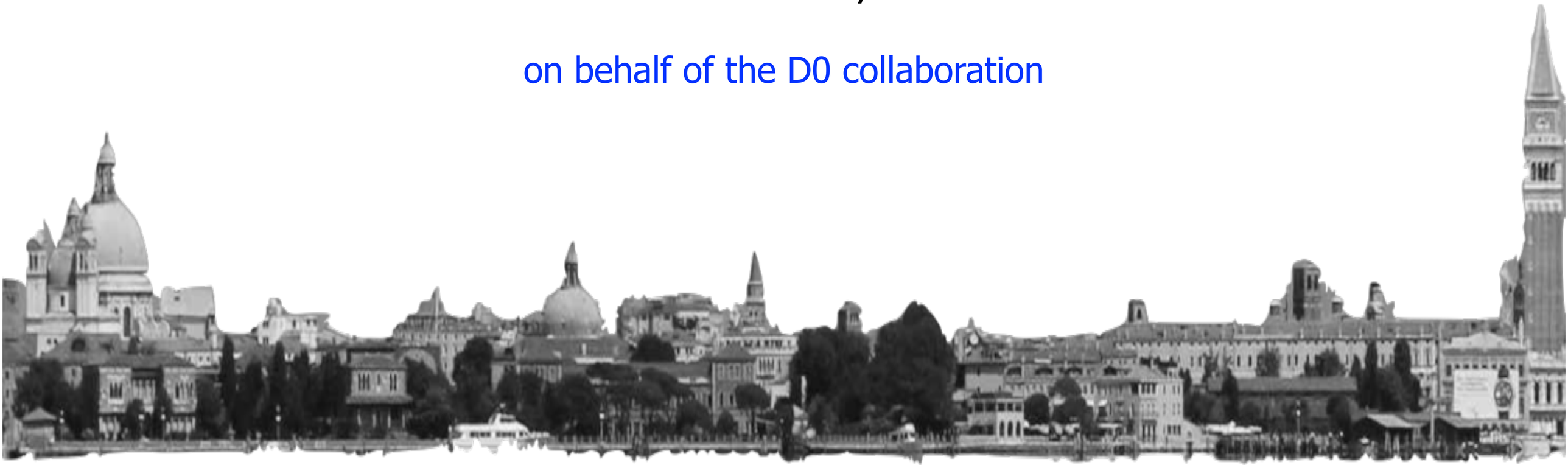
on behalf of the D0 collaboration

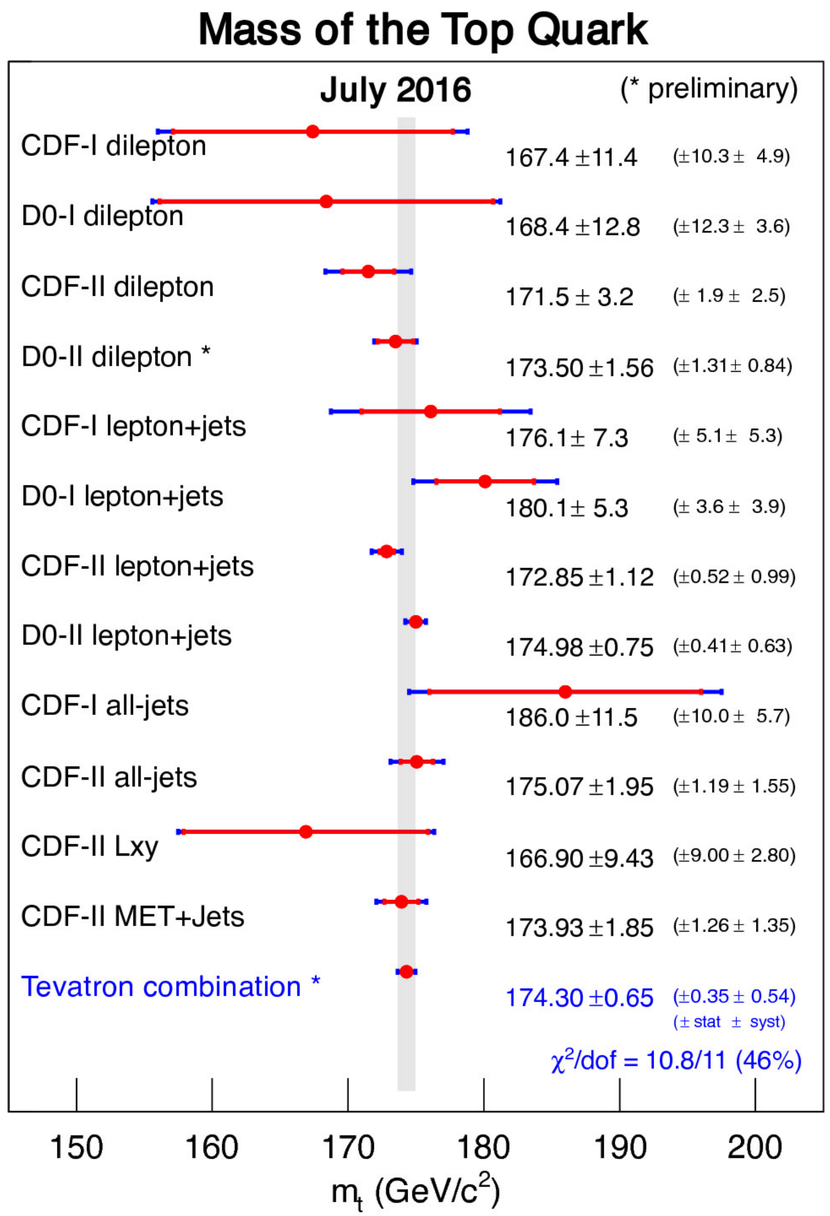


Standard top-quark mass measurements

- 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 ee → $t\bar{t}$:
      - in the MSR scheme: m_t^{MSR}(1GeV) equal to m_t^{MC} within 220 MeV
      - m_t^{pole} equal to m_t^{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, …

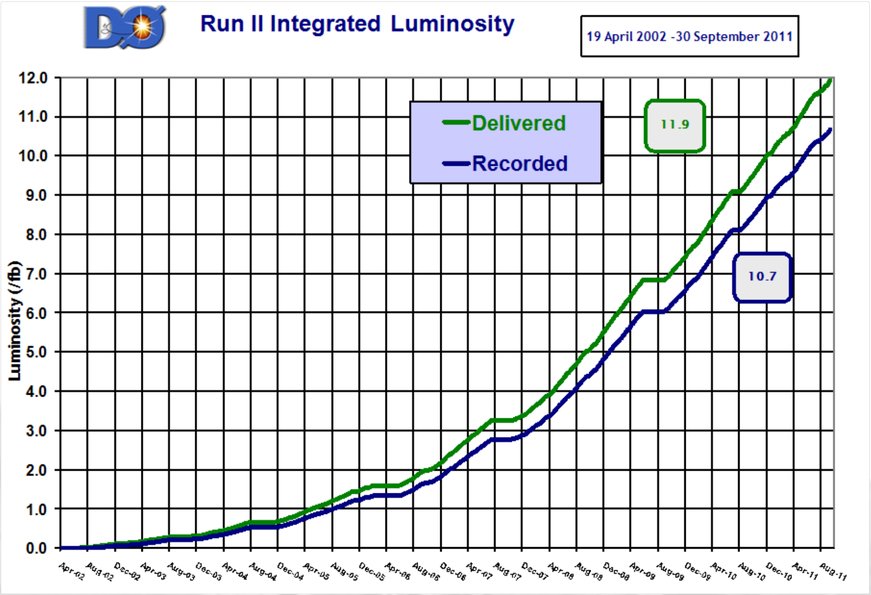
- top-quark pole mass determination using the $t\bar{t}$ cross section at D0
  - using the inclusive $t\bar{t}$ cross section:
    - compare the experimental $t\bar{t}$ cross section measurement with the theory computation
    - these depend differently on the top-quark mass

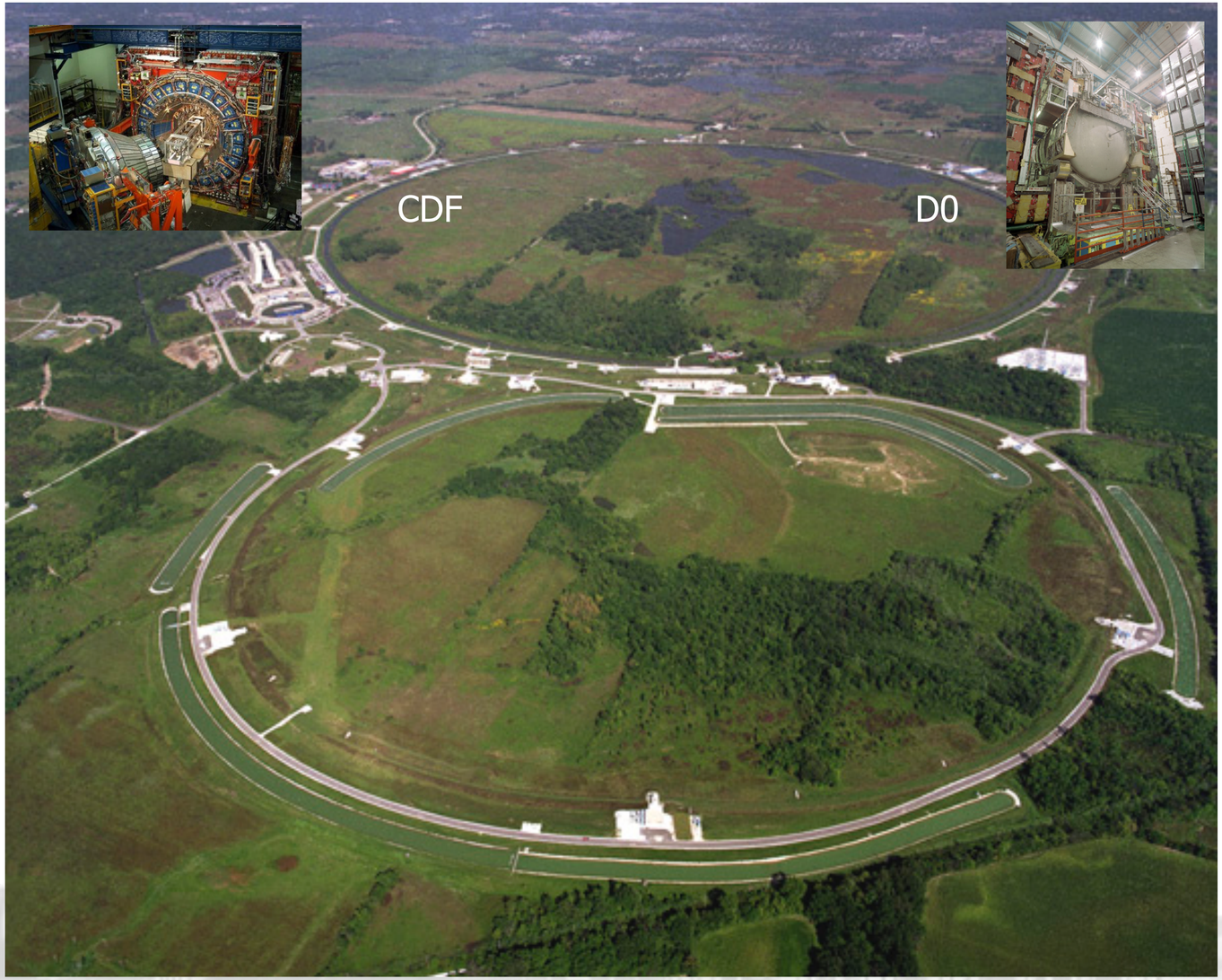
  - using the differential $t\bar{t}$ cross section:
    - additional information coming from the shape of the distributions
    - possible since NNLO differential predictions are now available

- 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

- $p\bar{p}$ collider
- Run I (1993-1996):
  - $\sqrt{s}$ = 1.8 TeV, L≈120 pb^{-1}
- Run II (2002-2011):
  - $\sqrt{s}$ = 1.96 TeV, L≈10 fb^{-1}



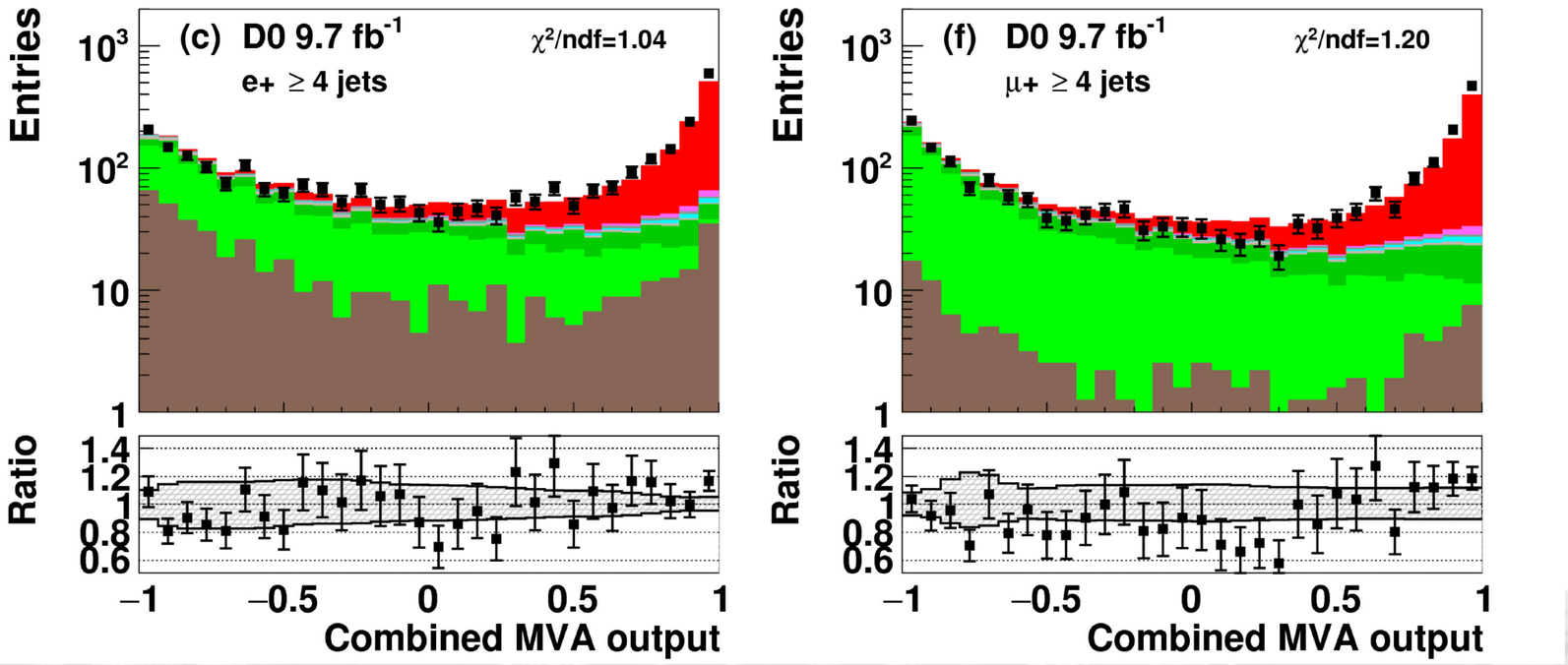


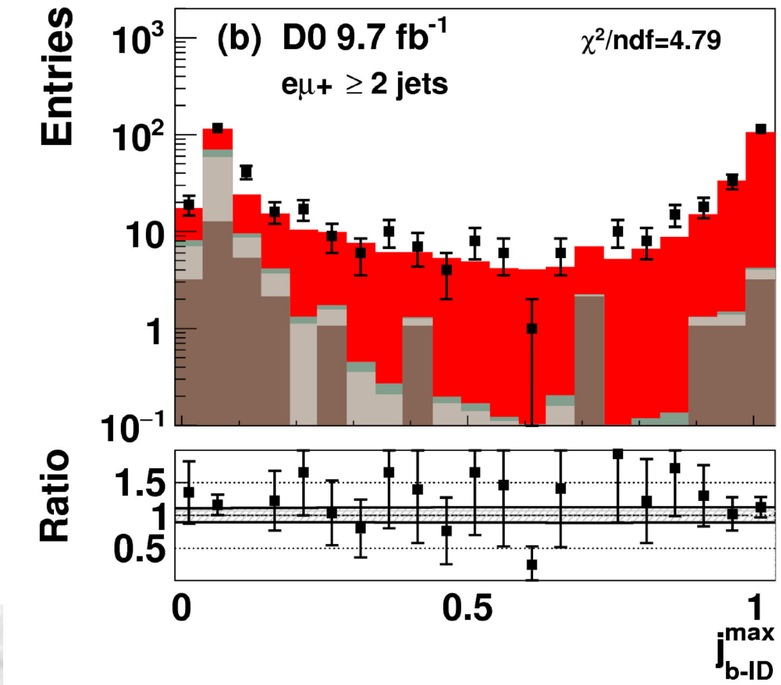
Top-quark pole mass measurement using the inclusive $t\bar{t}$ cross section

Phys. Rev. D 94, 092004 (2016)

- 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

Phys. Rev. D 94, 092004 (2016)

- experimental top-quark mass dependence:
  - likelihood fit repeated for different mass point: 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

Top quark mass [GeV]	Cross section $\sigma(t\bar{t})$ [pb]
150	$9.70 \pm 0.16\,(\text{stat.})^{+0.73}_{-0.67}\,(\text{syst.})$
160	$8.25 \pm 0.14\,(\text{stat.})^{+0.63}_{-0.57}\,(\text{syst.})$
165	$7.46 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.51}\,(\text{syst.})$
170	$7.55 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.55}\,(\text{syst.})$
172.5	$7.26 \pm 0.12\,(\text{stat.})^{+0.57}_{-0.50}\,(\text{syst.})$
175	$7.28 \pm 0.12\,(\text{stat.})^{+0.54}_{-0.49}\,(\text{syst.})$
180	$6.86 \pm 0.12\,(\text{stat.})^{+0.53}_{-0.47}\,(\text{syst.})$
185	$6.50 \pm 0.11\,(\text{stat.})^{+0.50}_{-0.43}\,(\text{syst.})$
190	$6.70 \pm 0.11\,(\text{stat.})^{+0.60}_{-0.47}\,(\text{syst.})$

$\Delta\sigma/\sigma = 7.6\%$

- 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

Phys. Rev. D 94, 092004 (2016)

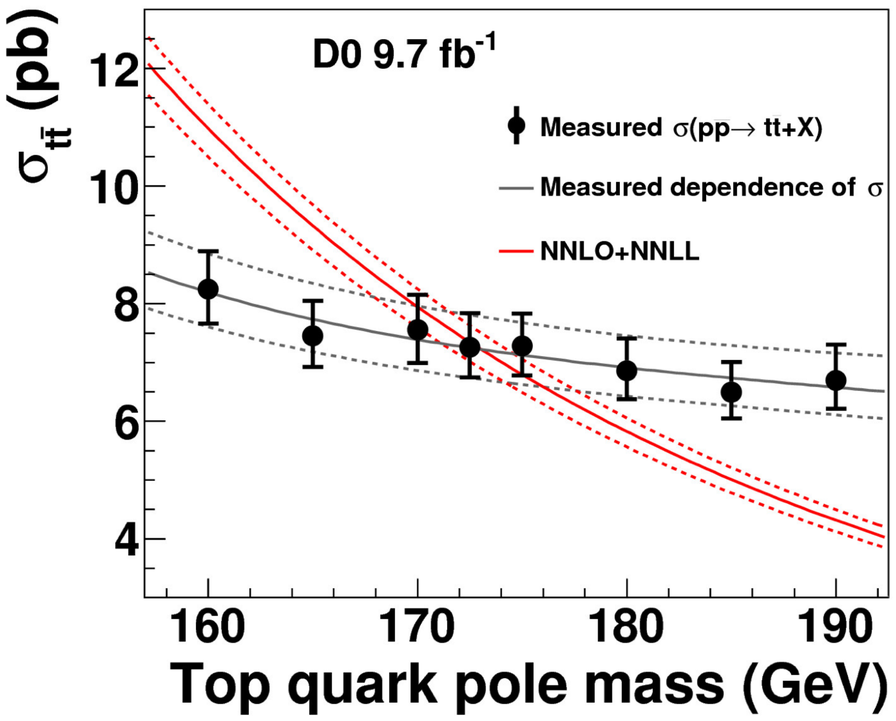
- most probable value of the top-quark pole mass:
  - extracted from the maximum of a normalized joint-likelihood function

$$L(m_t) = \int f_{\rm exp}(\sigma|m_t)\ [f_{\rm scale}(\sigma|m_t) \otimes f_{\rm PDF}(\sigma|m_t)]\ d\sigma$$

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

$$m_t = 172.8 \pm 1.1\,({\rm theo.})\,^{+3.3}_{-3.1}\,({\rm exp.})\,{\rm GeV}$$

$$m_t = 172.8^{+3.4}_{-3.2}\,({\rm tot.})\,{\rm GeV}$$

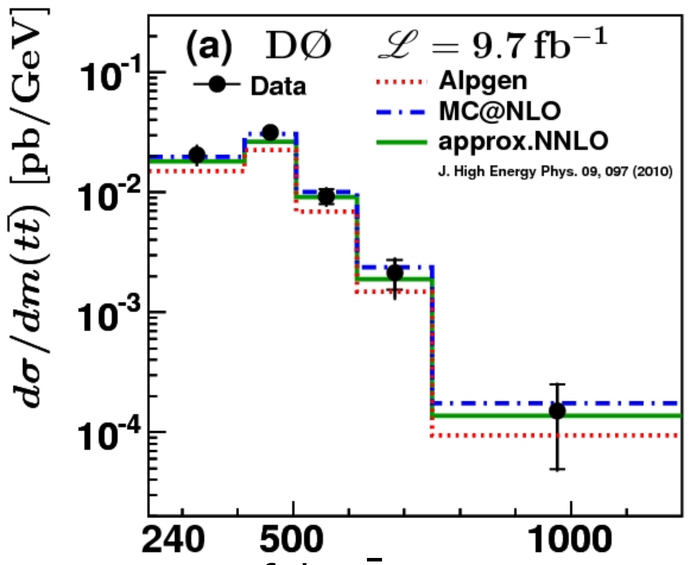


- same method was used in the past to extract the MSbar mass
  - using 5.4 fb^{-1}: $m_t^{\overline{\rm MS}} = 160.0^{+5.1}_{-4.5}$ GeV

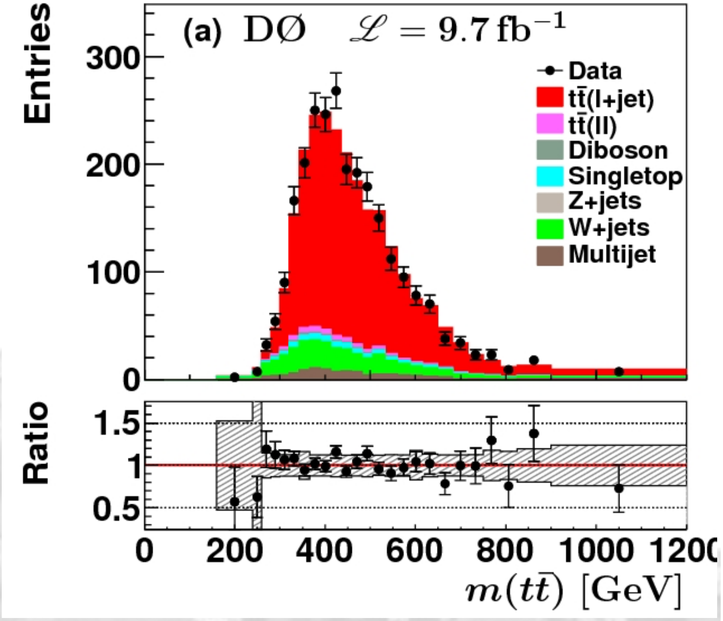
Phys. Lett. B 703, 422 (2011)

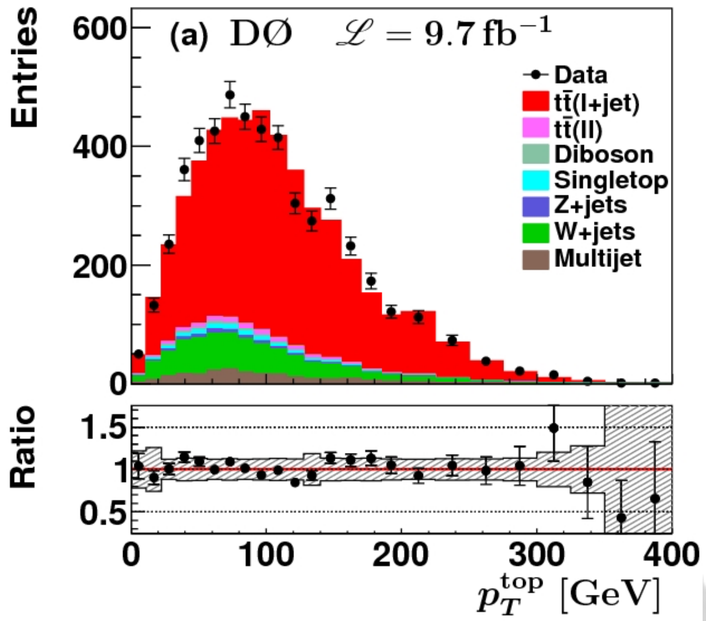
Top-quark pole mass measurement using the differential $t\bar{t}$ cross section

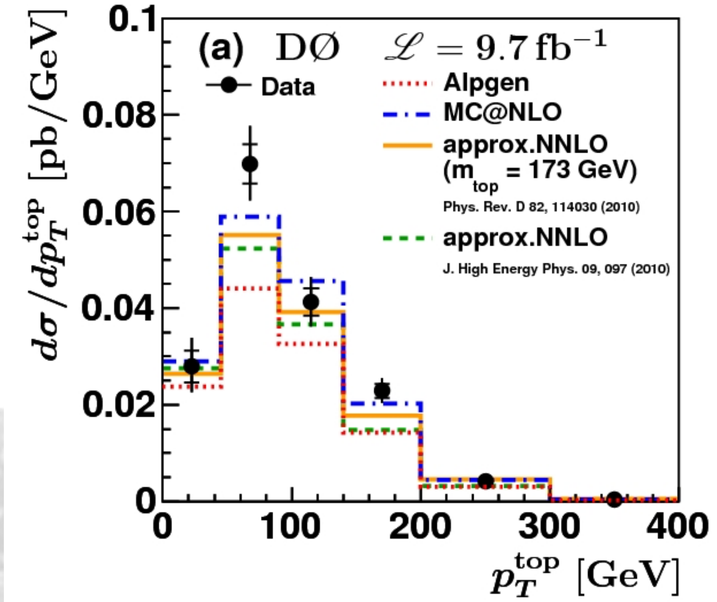
- experimental input:
  - differential $t\bar{t}$ cross section in the lepton+jets channel using the full D0 dataset (9.7 fb^{-1})
  - simultaneous fit of $t\bar{t}$ cross section and the heavy flavor W+jets using the b-ID MVA discriminant to determine the sample composition in the 2-jets, 3-jets and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



at Tevatron most of the $t\bar{t}$ are produced mostly at rest





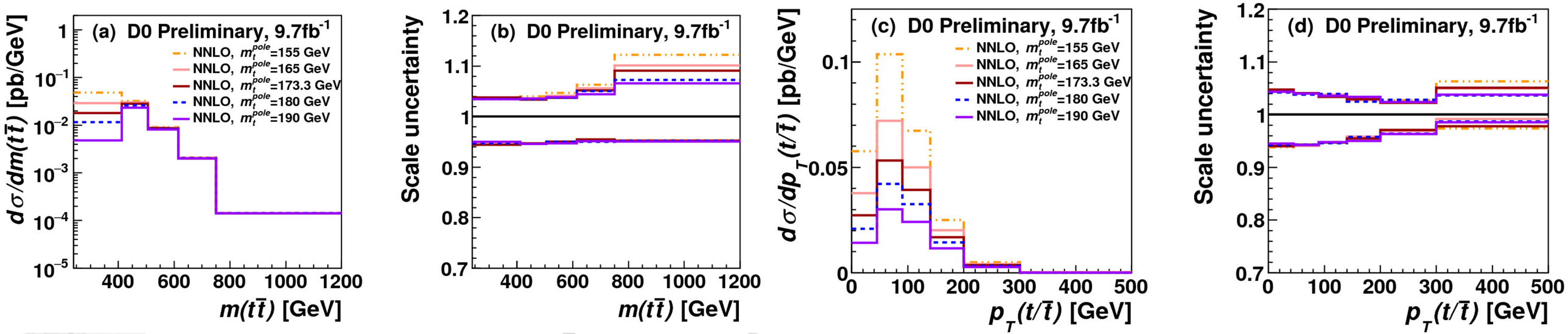


Phys. Rev. D 90, 092006 (2014)

Top-quark pole mass measurement using the differential $t\bar{t}$ cross section

D0 Note 6473-CONF

- 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)



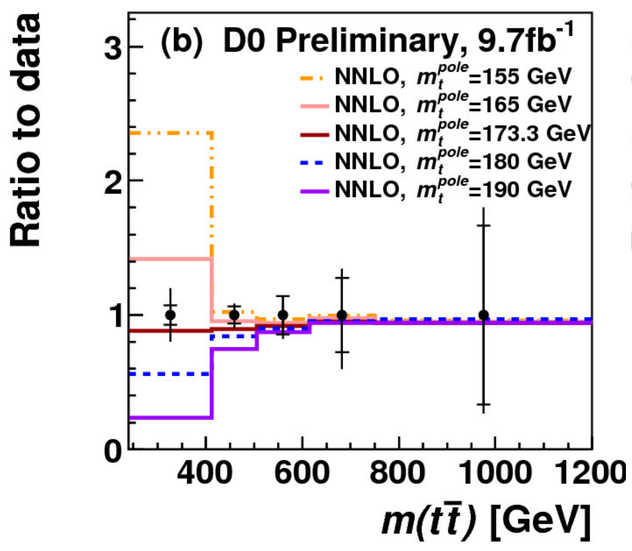
Top-quark pole mass measurement using the differential $t\bar{t}$ cross section

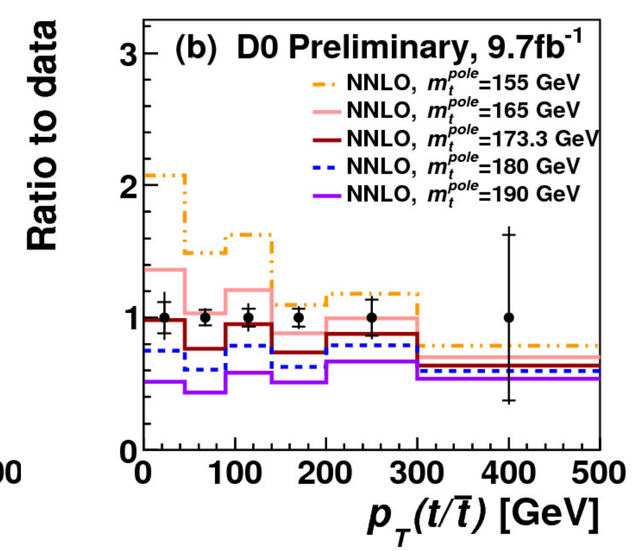
D0 Note 6473-CONF

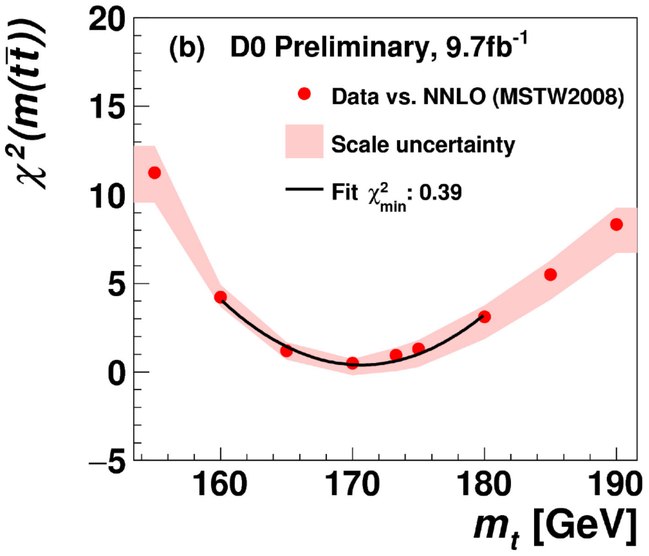
- method:
  - χ^2 to compare the measured differential cross section with the theoretical calculation:

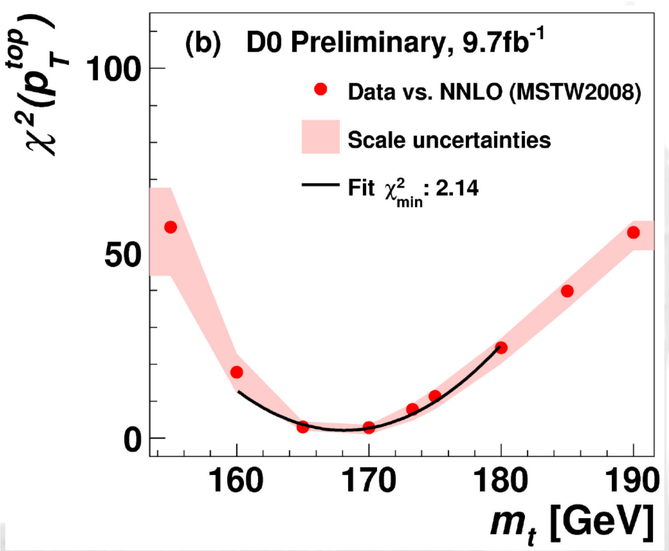
$$\chi^2 = \sum_{i,j} (x_i^{\text{true}} - x_i^{\text{theo}}) \cdot \mathbf{V}^{-1}_{\mathbf{xx;\ i,j}} \cdot (x_j^{\text{true}} - x_j^{\text{theo}})$$

  - V_{xx} experimental covariant matrix (including the reduction of the luminosity uncertainty from 6.1% to 4.3%)
  - parabolic fit to the χ^2 distribution to determine the minimum
  - spread of the extractions for the 3 global PDF used as PDF uncertainty on m_t^{pole}









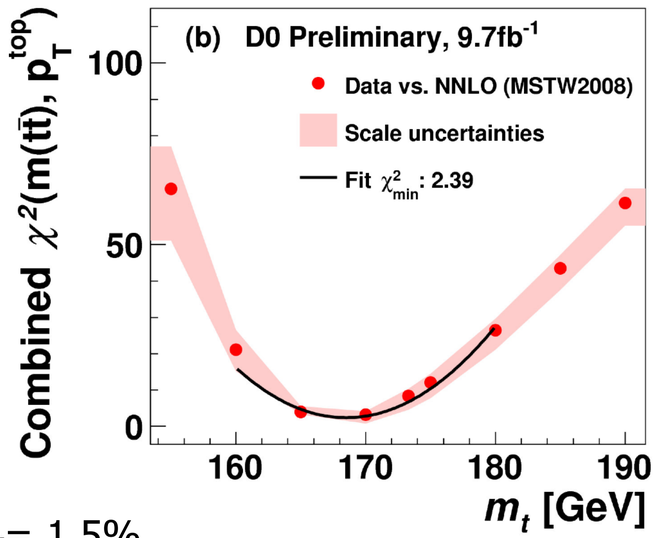
Top-quark pole mass results using the differential $t\bar{t}$ cross section

D0 Note 6473-CONF

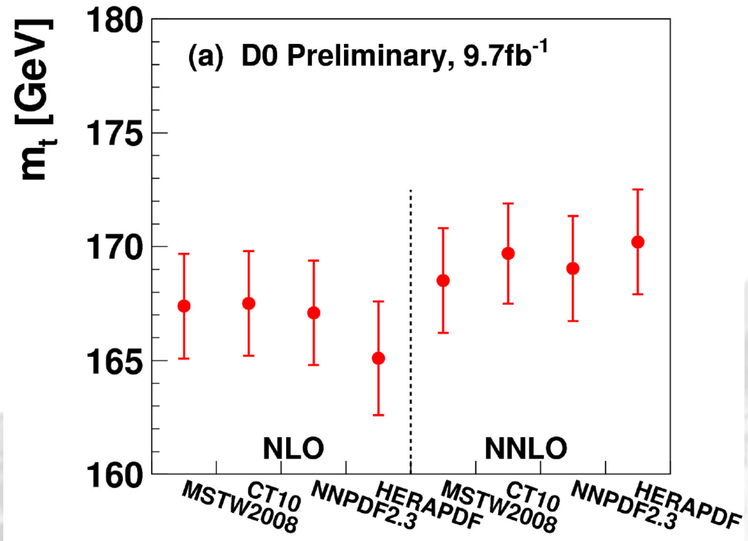
- combined result:
  - χ^2 using the 2D covariant matrix $m_{t\bar{t}}$ vs p_t^{top} (small global correlation of 0.12)
  - main sensitivity is coming from p_t^{top} (though the normalization)
  - consistent average increase from using NLO to using NNLO
  - contribution from experimental uncertainty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

Order & PDF	$m(t\bar{t})$	m_t^{pole} [GeV] p_T^{top}	$m(t\bar{t}) \oplus p_T^{top}$
NLO:			
MSTW2008	169.3 ± 5.7	166.8 ± 2.9	167.4 ± 2.5
CT10	169.4 ± 5.9	167.9 ± 3.0	167.5 ± 2.6
NNPDF2.3	169.0 ± 6.0	166.4 ± 2.9	167.1 ± 2.5
HERAPDF1.5	167.2 ± 6.4	166.0 ± 2.9	165.1 ± 2.7
NNLO:			
MSTW2008	170.7 ± 5.6	168.0 ± 2.5	168.5 ± 2.3
CT10	171.5 ± 5.5	169.4 ± 2.4	169.7 ± 2.2
NNPDF2.3	171.1 ± 5.6	168.5 ± 2.5	169.0 ± 2.3
HERAPDF1.5	172.6 ± 5.6	170.3 ± 2.6	170.2 ± 2.3

Order & PDF	$m_t^{pole} \pm \delta_{tot.}$ [GeV] $m(t\bar{t}) \oplus p_T^{top}$	δ_{exp} [GeV] $m(t\bar{t}) \oplus p_T^{top}$	δ_{theo}^{scale} [GeV] $m(t\bar{t}) \oplus p_T^{top}$
NNLO			
MSTW2008	168.5 ± 2.3	± 2.2	± 0.7
CT10	169.7 ± 2.2	± 2.0	± 0.9
NNPDF2.3	169.0 ± 2.3	± 2.1	± 0.8
HERAPDF1.5	170.2 ± 2.3	± 2.2	± 0.7



$\Delta m_t/m_t = 1.5\%$



- 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)

Conclusion

- 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^{pole} = 172.8 ± 3.3 GeV

  - using for the the first the differential $t\bar{t}$ cross section: m_t^{pole} = 169.1 ± 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, …)