Top Quark Physics at the Tevatron

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On behalf of CDF and D0 collaborations

Moriond EW, March 18-25, 2017

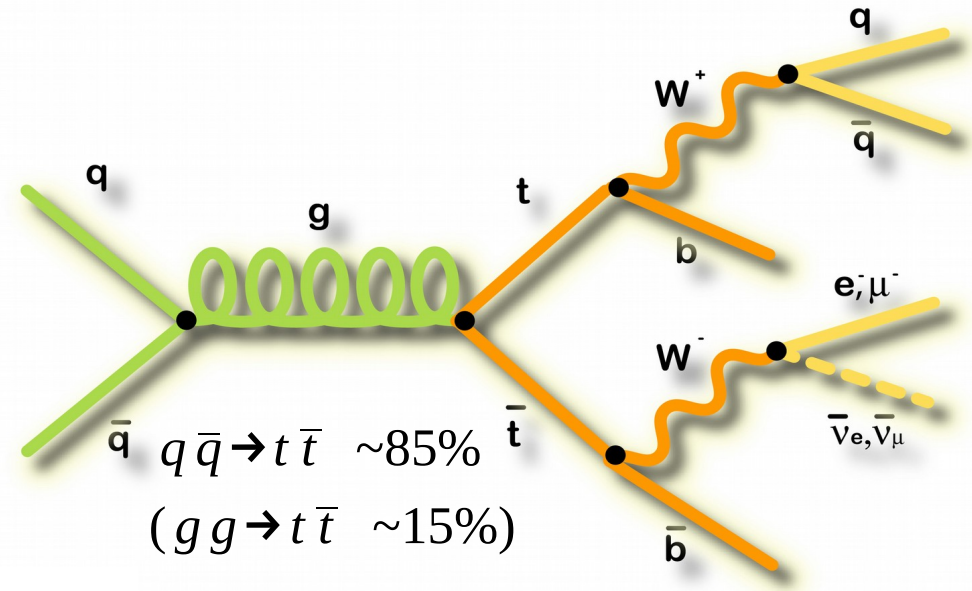
Outline

→ $t\bar{t}$ cross section

→ $t\bar{t}$ forward-backward asymmetry

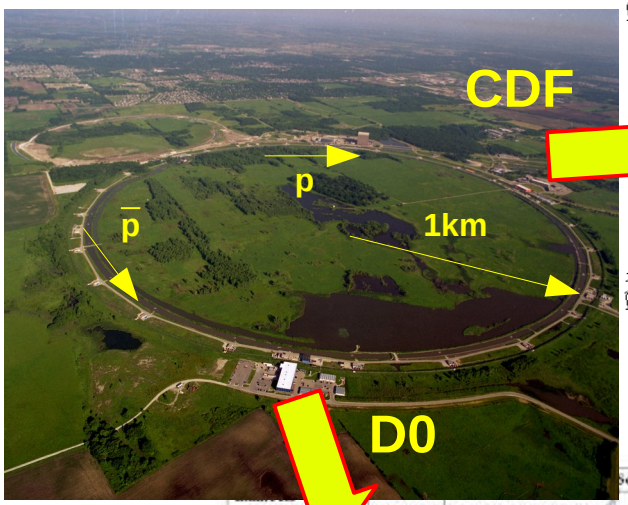
→ top quark polarization

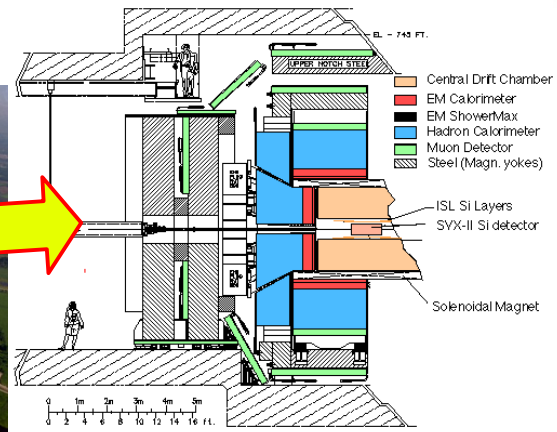
→ top quark mass



$q\bar{q} \rightarrow t\bar{t}$ ~85%

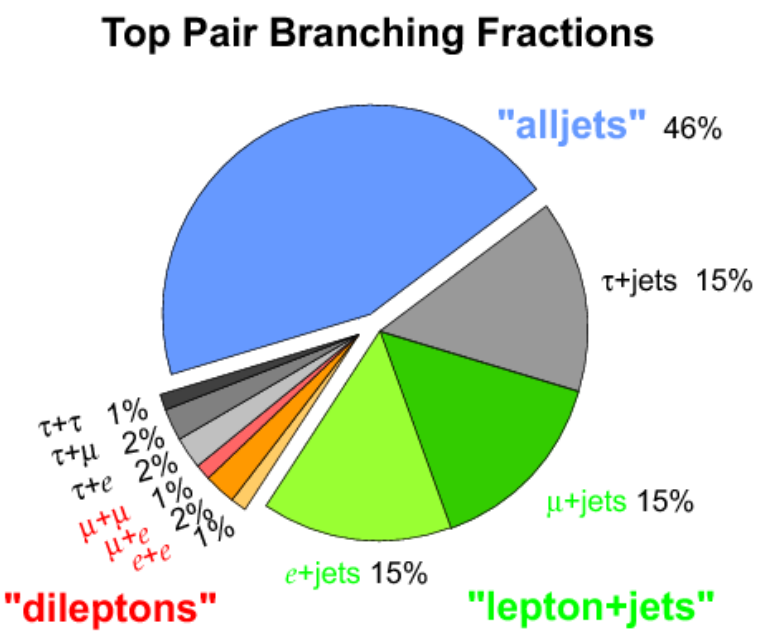
$(gg \rightarrow t\bar{t}$ ~15%)





According to SM:

$B(t \rightarrow Wb) \sim 100\,\%$



Inclusive $t\bar{t}$ cross section (I)

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bckg}}{A \cdot L}$$

N_{data} → selected candidate events

N_{bckg} → estimated from MC
→ data fit of discriminant variable

L → integrated luminosity

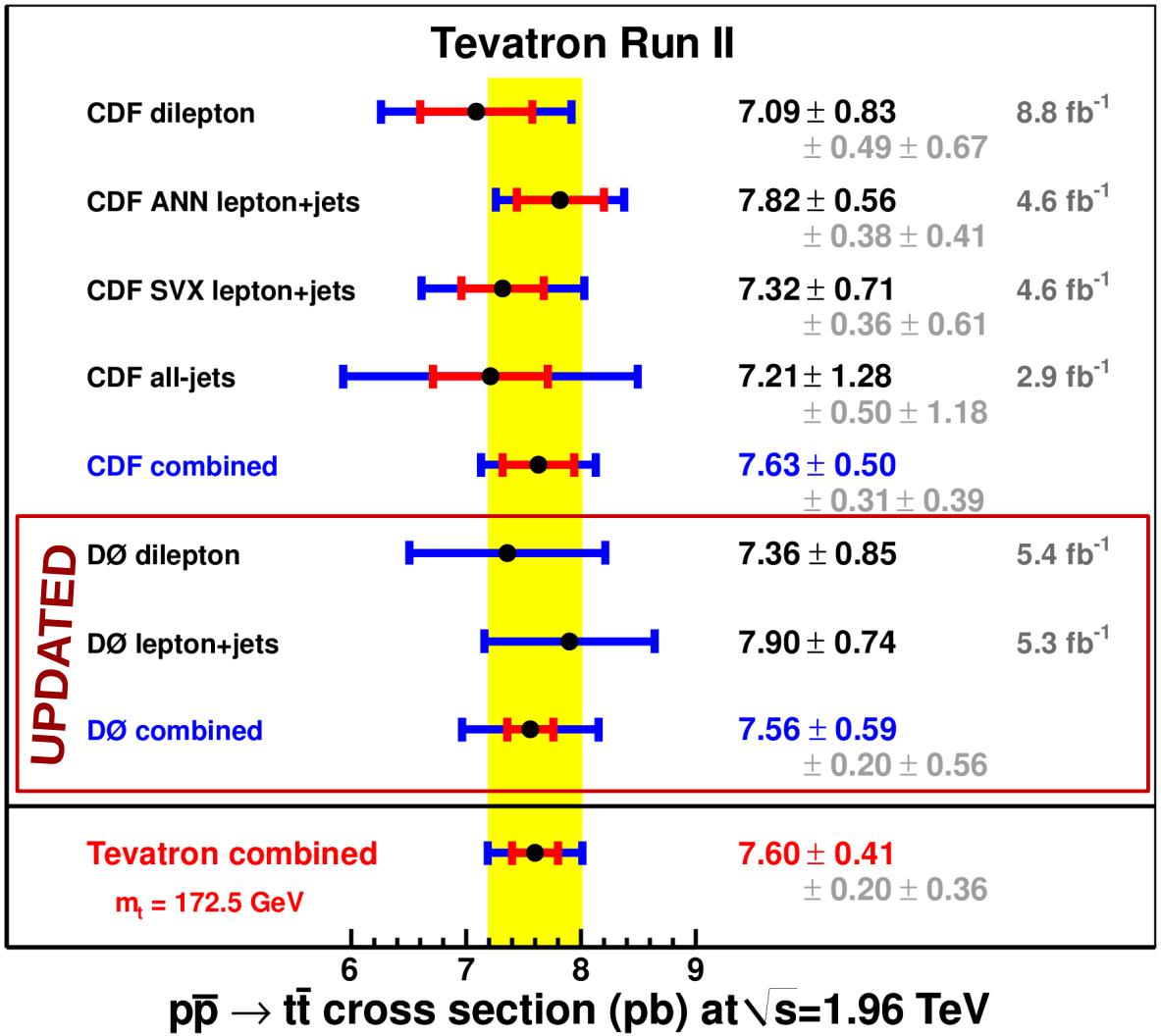
A → acceptance (inc. trig. select., b-tagging eff.)

Predictions:
fully resumed NNLO QCD
(m_t = 172.5 GeV):

$$\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27} \text{ (scale + pdf) pb}$$

Based on PRL 109, 132001 (2012)

September 2012

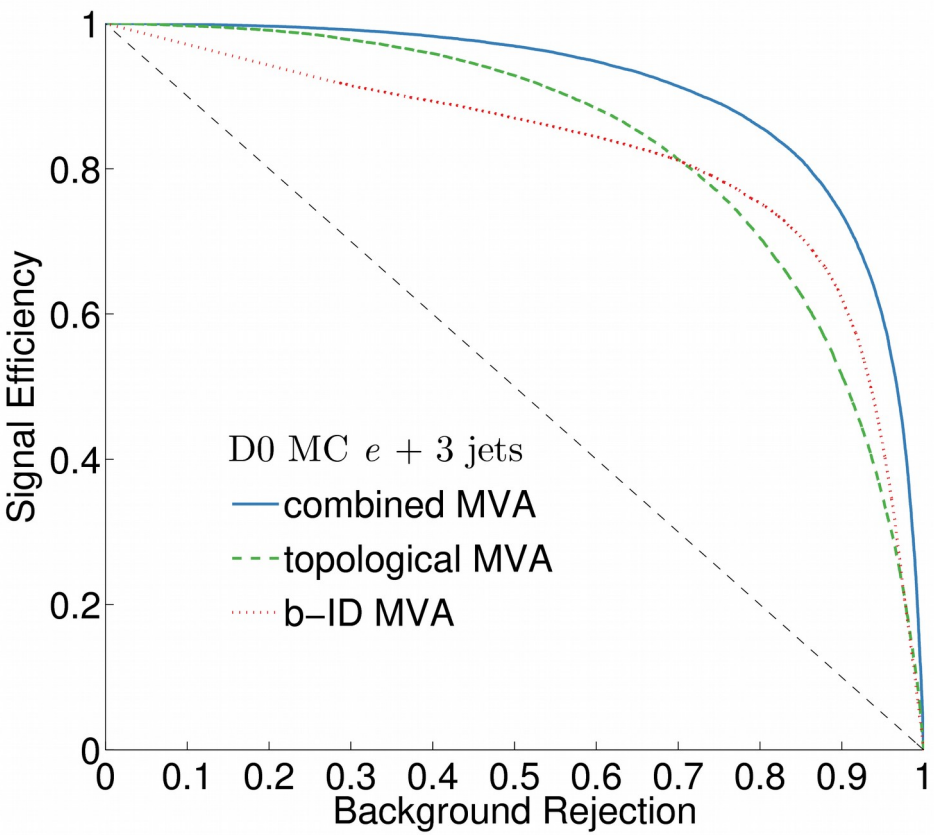


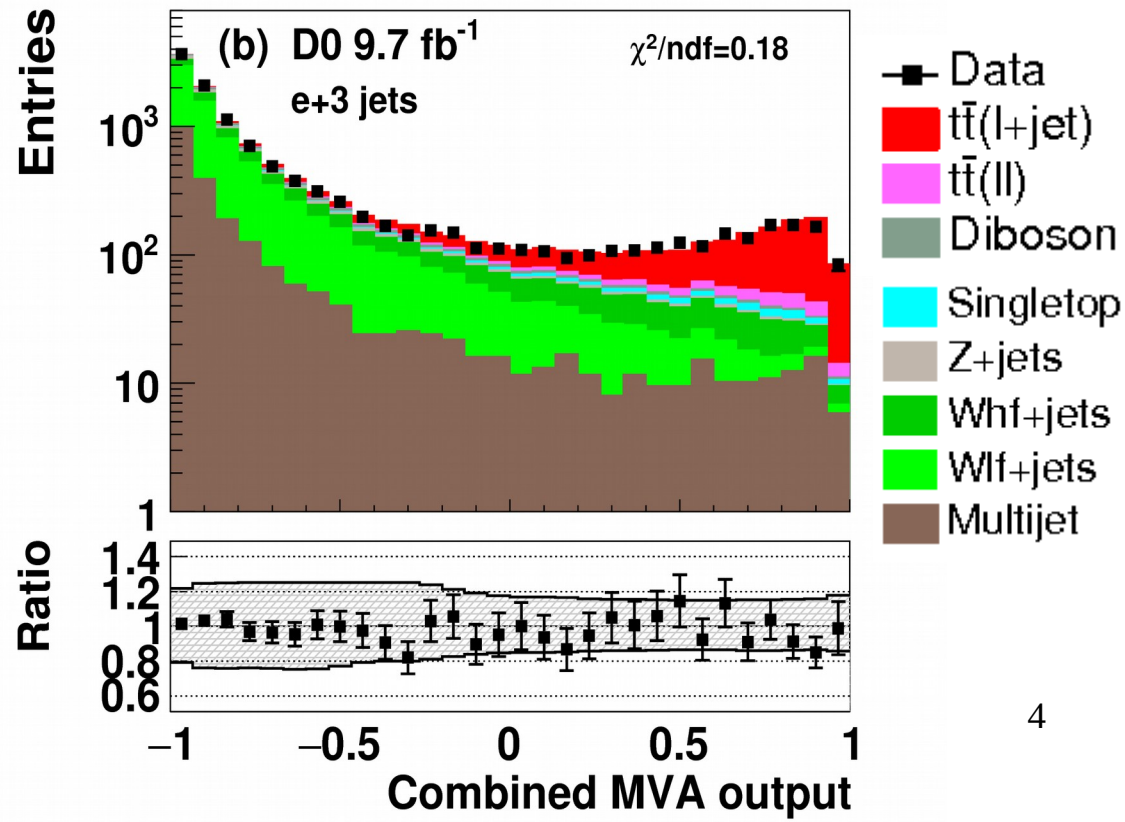
Inclusive $t\bar{t}$ cross section (II)

→ using full statistics in both, l+jets and dilepton channels
→ different multivariate techniques (MVA) used to separate signal from background
→ MVA used to identify *b*-jets

L+jets channel:

→ sample divided into 6 subsamples by lepton type (e, μ) & number of jets (2, 3, ≥4)
→ Signal and backgound separation – using combined MVA
  → includes ~20 kinematic variables (jets p_T, H_T, missing E_T,…) – topological MVA
  → use also maximum output value of the MVA *b*-jet discriminant of all jets $j_{\text{b-ID}}^{\max}$





Inclusive $t\bar{t}$ cross section (III)

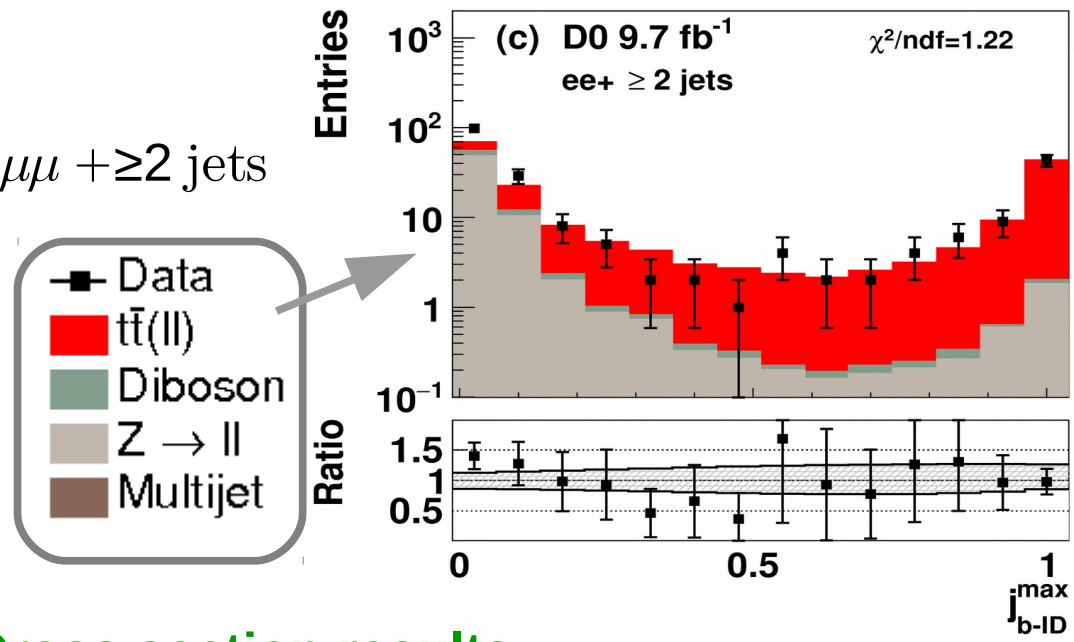
dilepton channel:

→ sample divided into 4 subsamples:

$e\mu$ +1 jet, $e\mu$ +≥2 jets, ee +≥2 jets, $\mu\mu$ +≥2 jets

→ Signal and backgound separation

→ using $j_{\text{b-Id}}^{\max}$ is sufficiently good



Source of uncertainty	$\delta_{\ell+\text{jets}}$, pb	$\delta_{\ell\ell}$, pb	$\delta_{\text{comb.}}$, pb	Shift, pb
Signal modeling				
Signal generator	±0.21	±0.05	±0.17	+0.08
Hadronization	±0.26	±0.33	±0.25	+0.12
Color reconnection	±0.08	±0.05	±0.09	+0.02
ISR/FSR variation	±0.08	±0.04	±0.06	−0.05
PDF	±0.04	±0.03	±0.02	−0.01
Detector modeling				
Jet modeling & ID	±0.11	±0.08	±0.04	+0.07
b-jet modeling & ID	±0.27	±0.26	±0.23	−0.15
Lepton modeling & ID	±0.20	±0.26	±0.17	−0.11
Trigger efficiency	±0.32	±0.08	±0.16	+0.01
Luminosity	±0.30	±0.30	±0.27	+0.10
Sample Composition				
MC cross sections	±0.07	±0.13	±0.09	+0.01
Multijet contribution	±0.11	±0.02	±0.10	+0.10
W + jets scale factor	±0.21	±0.01	±0.15	−0.50
Z/γ^* + jets scale factor	±0.07	±0.11	±0.12	+0.12
MC statistics	±0.01	±0.01	±0.02	+0.00
Total systematic uncertainty (quadratic sum)	±0.70	±0.64	±0.60	
Total systematic uncertainty (central COLLIE)	±0.67	±0.73	±0.55	

Cross section results:

→ obtained by simultaneous fit

→ using systematics as nuisance parameters

→ dominant systematics from hadronization

→ **relative precision 7.6%**

L+jets: $\sigma_{t\bar{t}} = 7.33 \pm 0.14\,(\text{stat})^{+0.71}_{-0.61}\,(\text{syst})$ pb

Dilepton: $\sigma_{t\bar{t}} = 7.58 \pm 0.35\,(\text{stat})^{+0.69}_{-0.58}\,(\text{syst})$ pb

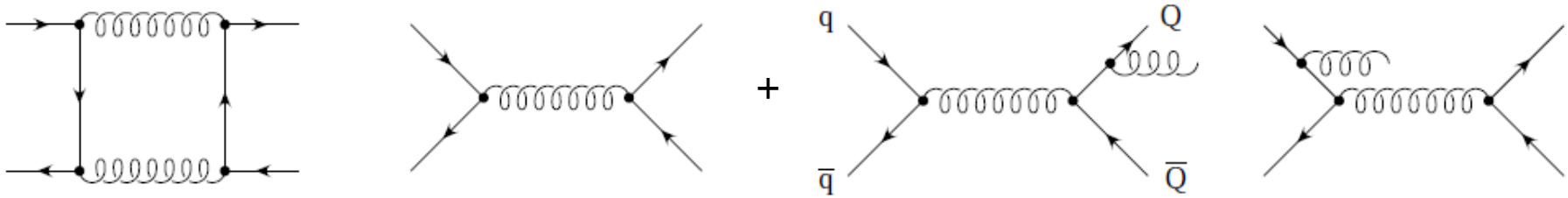
Combined: $\sigma_{t\bar{t}} = 7.26 \pm 0.13\,(\text{stat})^{+0.57}_{-0.50}\,(\text{syst})$ pb

PRD 94, 092004 (2016)

$t\bar{t}$ forward-backward asymmetry (I)

→ **at NLO, the SM predicts asymmetry** in $t\bar{t}$ production

→ asymmetry comes from events with **$q\bar{q}$ initial states**, **gg is symmetric**



positive asymmetry negative asymmetry

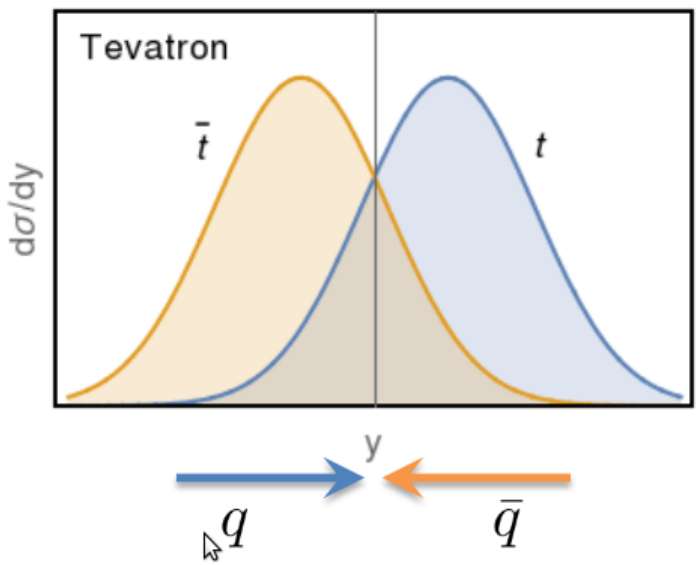
→ **Definition:**

$$\Delta y = y_t - y_{\bar{t}}$$

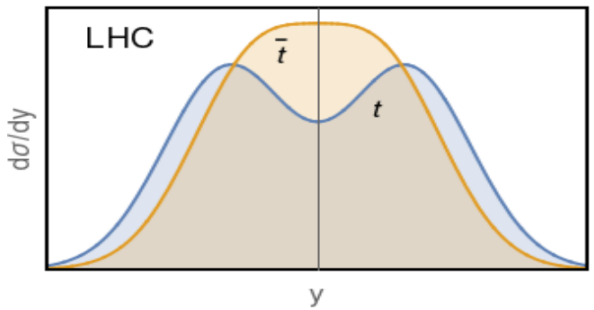
y_t – top-quark rapidity

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$p\bar{p}$ collisions



LHC: pp collisions

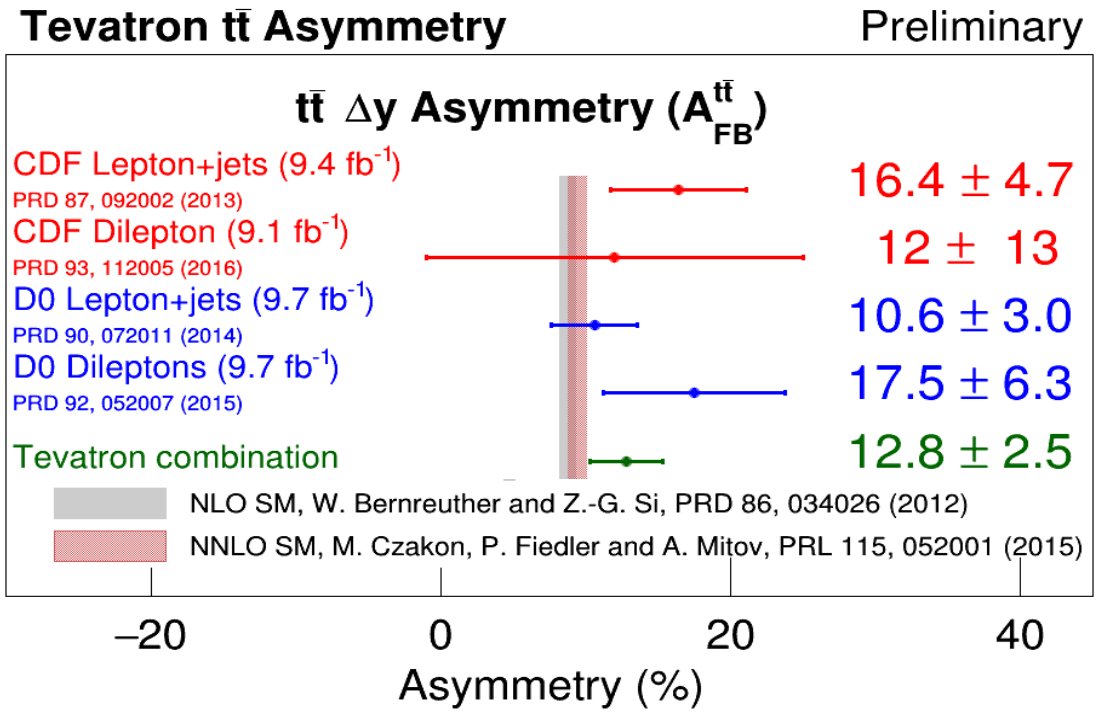


$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$t\bar{t}$ forward-backward asymmetry (II)

→ **TEVATRON combination** → Using BLUE technique

→ CDF, D0 used full statistics



Weight

0.25

0.01

0.64

0.11

χ^2 / NDF: 1.74 / 3

1.3σ from NNLO prediction

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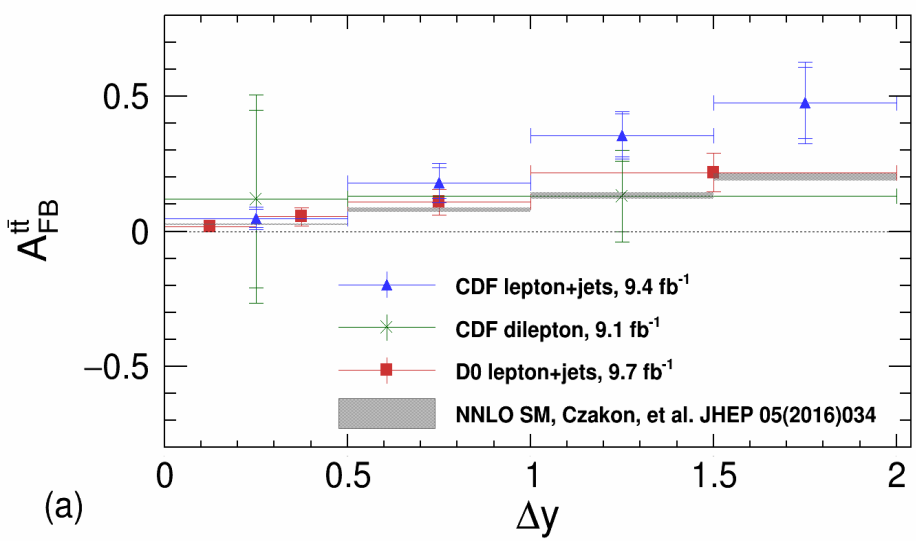
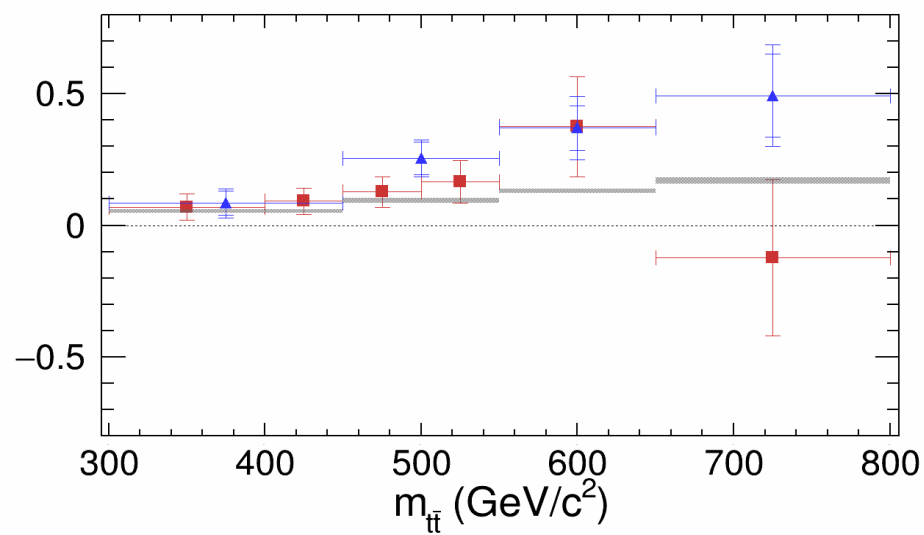




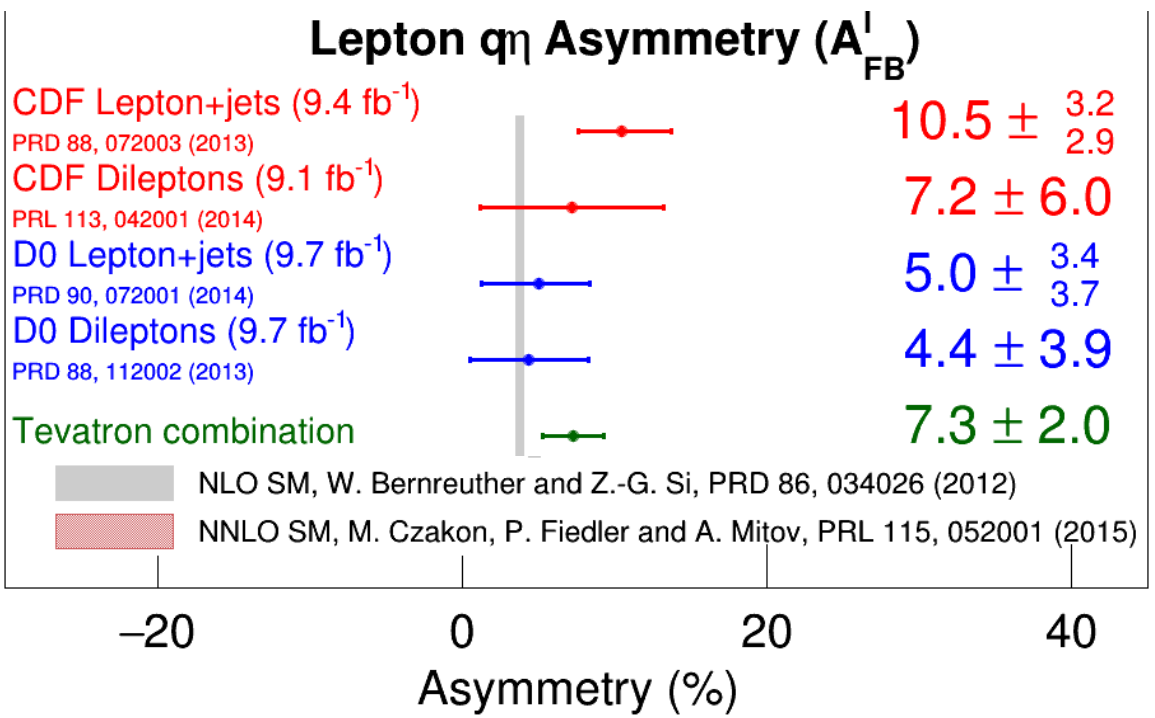
Lepton based $t\bar{t}$ asymmetry (I)

→ **Advantage:** no need to reconstruct the $t\bar{t}$ final state.
sensitive to top quark polarization
→ lepton direction is measured with high precision + good charge determination
→ asymmetry is smaller than $t\bar{t}$ forward-backward one

→ **Definition:**

$$A^{l}_{FB} = \frac{N(qy_l>0) - N(qy_l<0)}{N(qy_l>0) + N(qy_l<0)}$$

q – lepton charge
y_l – lepton rapidity



Weight

0.40
0.11
0.27
0.23

χ^2 / NDF: 2.17 / 3

1.6σ from NLO prediction

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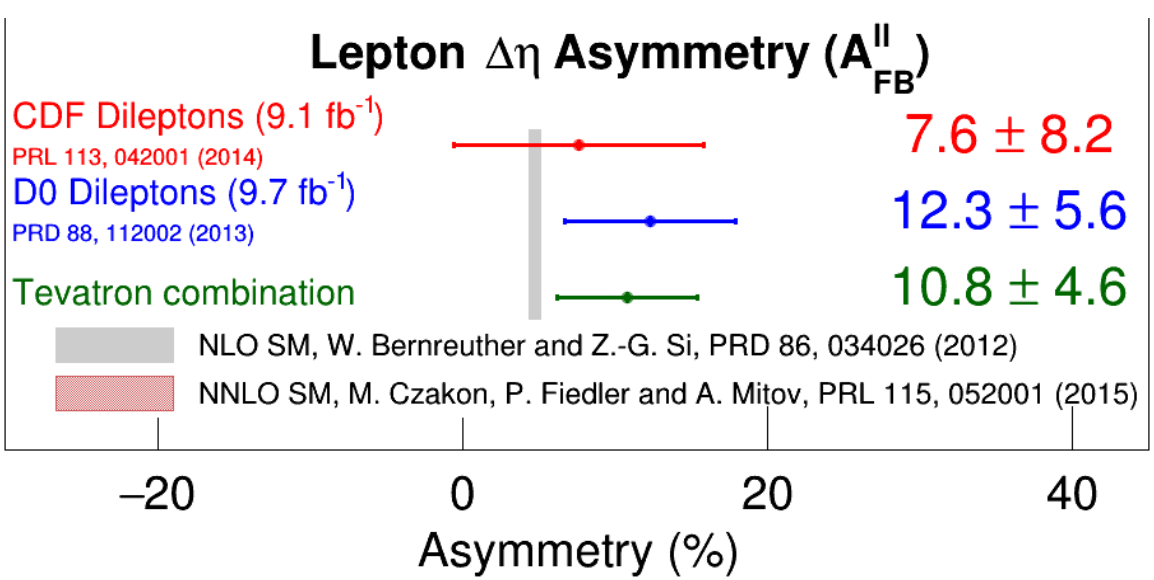
Lepton based $t\bar{t}$ asymmetry (II)

→ **Advantage:** no need to reconstruct the $t\bar{t}$ final state.
sensitive to top quark polarization
→ lepton direction is measured with high precision + good charge determination
→ asymmetry is smaller than $t\bar{t}$ forward-backward one

→ **Definition:**

Dilepton events: $\Delta\eta = \eta_{l^+} - \eta_{l^-}$, η_l – lepton pseudorapidity

$$A_{FB}^{\Delta\eta} = \frac{N(\Delta\eta>0) - N(\Delta\eta<0)}{N(\Delta\eta>0) + N(\Delta\eta<0)}$$



Weight

0.32

0.68

χ^2 / NDF: 0.22 / 1

1.3σ from NLO prediction

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Top quark polarization (I)

→ at Tevatron – top quark produced almost unpolarized
→ beyond SM models predict enhanced polarization

Polarization $P_{\hat{n}}$:

→ measured in top quark rest frame
→ angular distribution of decay products is used

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}}=\frac{1}{2}\left(1+P_{\hat{n}}\,\kappa_i\cos\theta_{i,\hat{n}}\right)$$

κ_i – analyzing power ~1 for leptons

→ one need to choose quantization axis $\hat{n}$:

- Beam axis – given by direction of proton
- Helicity axis – given by direction of parent t ($\bar{t}$) quark
- Transverse axis – perpendicular to production plane (cross product of beam and helicity axes)

Top quark polarization (II)

D0 measurement:

→ using L+jet channel, full statistics

→ **world's first measurement using transverse axis**

PRD 96, 011101(R) (2017)

Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Beam—D0 comb.	$+0.081 \pm 0.048$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.035$	$+0.011$

→ l+3jets, l+4jets samples

→ lepton angles obtained from kinematic reconstruction

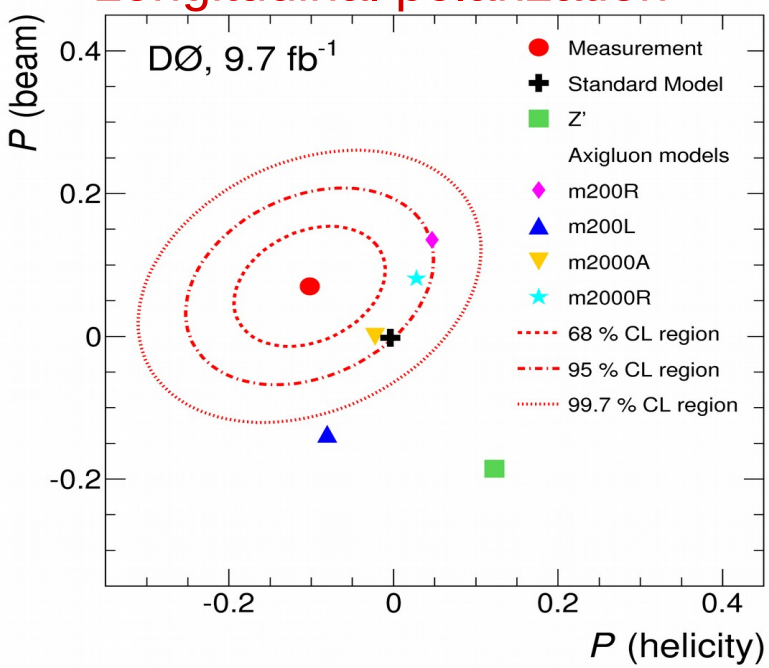
→ templates with P=+1, P=-1

→ polarization extracted from relative fractions of the templates

→ result obtained along the beam axis combined with one from dilepton

→ results consistent with SM and 0

Longitudinal polarization



Top quark mass

How do we measure it? → Several methods to choose:

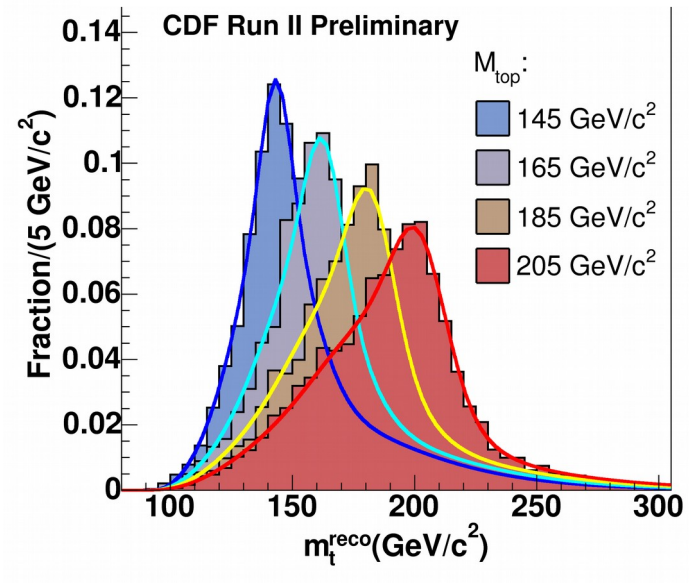
Template method:

→ use **variable sensitive to top mass** (e.g. m_t^{reco} from decay products)

→ constrain JES (by another variable)

→ likelihood fit to various templates

→ fast, but worse stat. uncertainties



Matrix element method:

→ evaluate **event-by-event probability** based on the full event kinematics

→ signal probability:

$$P_{t\bar{t}}(\vec{x}, m_t) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \sum_{j-p} \int \sum_{flavors} dq_1 dq_2 \frac{d\sigma(q\bar{q} \to t\bar{t} \to \vec{y})}{dy} \cdot f(q_1) f(q_2) \cdot W(\vec{x}; \vec{y}) \cdot dy$$

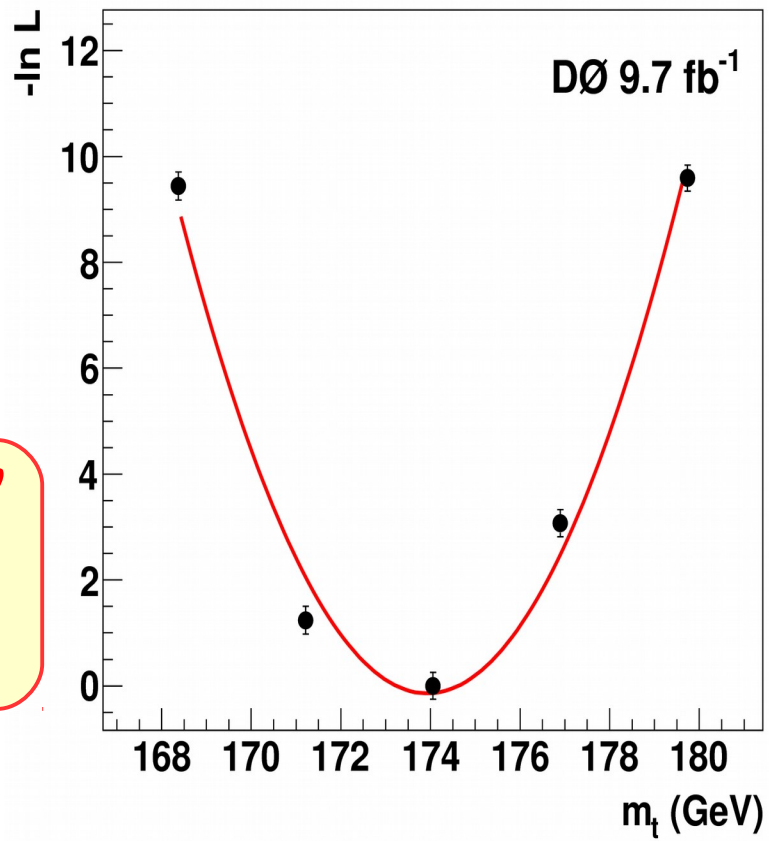
LO Matrix element **PDFs** **resolution**

→ mass extracted from global likelihood

Top quark mass (I)

New D0 measurement:

→ dilepton channel, using full statistics
→ using matrix element method
→ jet energy scaled by kJES obtained "in situ" in previous measurement
→ to extract mass: likelihood fit to data



$$173.93 \pm 1.61(stat) \pm 0.88(syst)\ GeV$$

$$\delta m_t / m_t = 1.0\%$$

PRD 94, 032004 (2016)

Previous dilepton measurement: **Phys.Lett. B 752, 18 (2016)**

$\mathcal{M}_t = 173.32 \pm 1.60\ GeV \quad \delta m_t / m_t = 0.92\%$ (neutrino weighting technique)

Combination of dilepton measurements: **D0 note 6484-CONF**

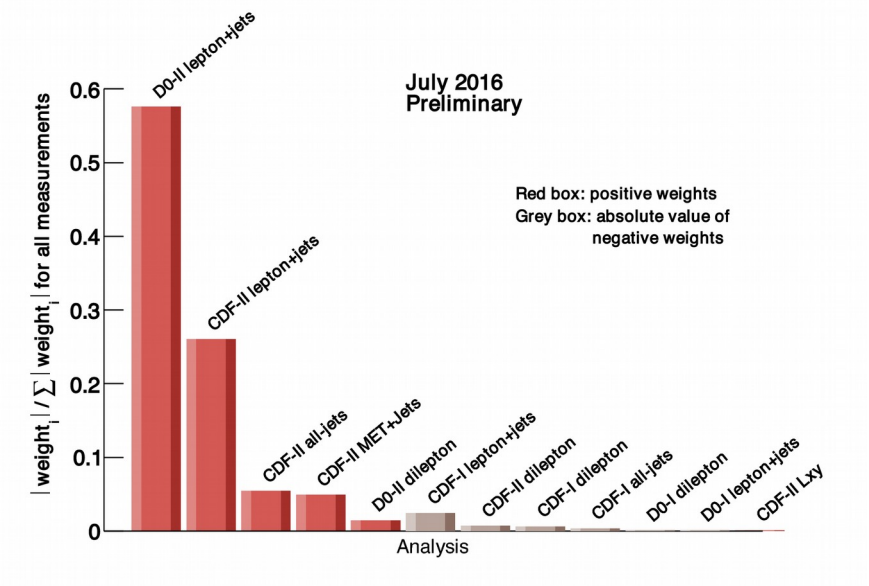
$\mathcal{M}_t = 173.50 \pm 1.56\ GeV \qquad \delta m_t / m_t = 0.90\%$

Top quark mass (II)

Updated Tevatron combination:

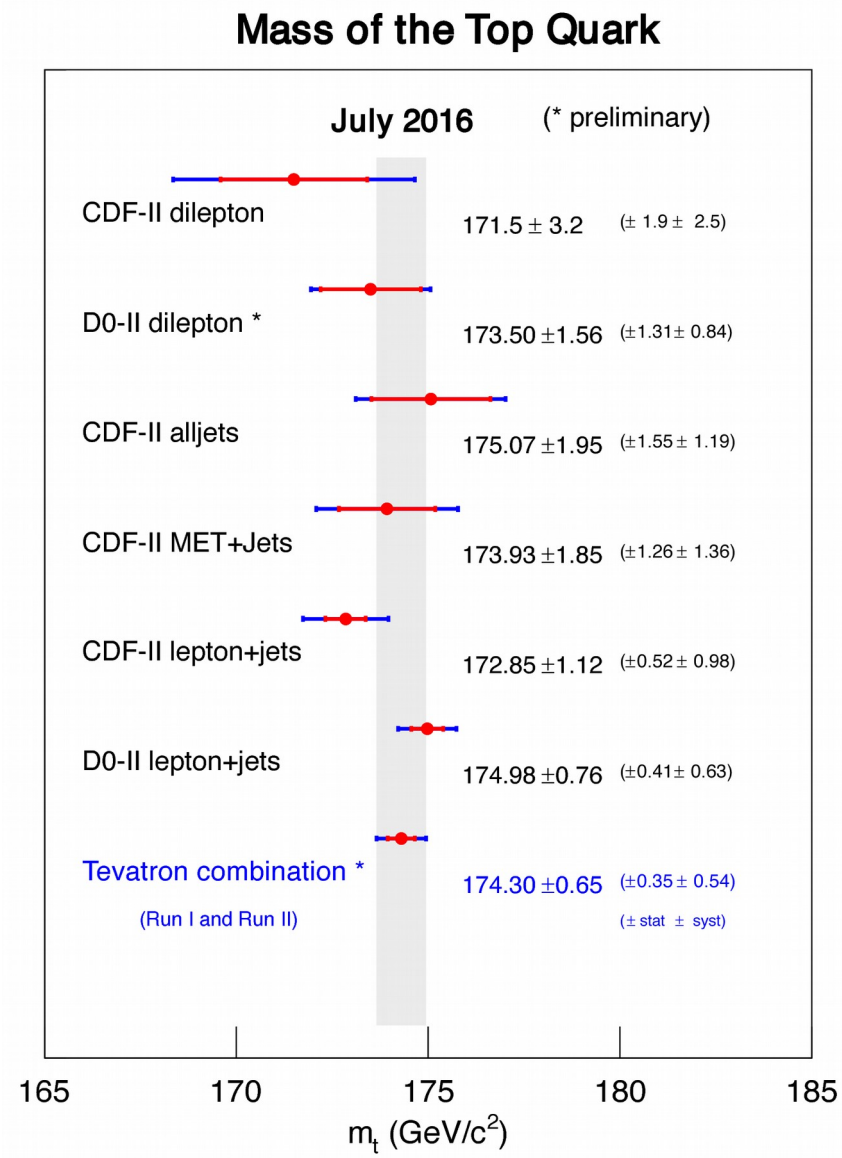
(FERMILAB-CONF-16-298-E)

→ using BLUE method



$$\mathcal{M}_t = 174.30 \pm 0.65\ GeV$$

$$\delta m_t / m_t = 0.37\%$$



World combination: arXiv:1403.4427

$$\mathcal{M}_t = 173.34 \pm 0.76\ GeV \qquad \delta m_t / m_t = 0.44\%$$

Top quark pole mass (I)

→ Results presented so far measures **mass** ($\mathbf{m_t^{MC}}$) used as input in MC generator ≠ $\mathbf{m_t^{pole}}$ (but must be close ~1 GeV)

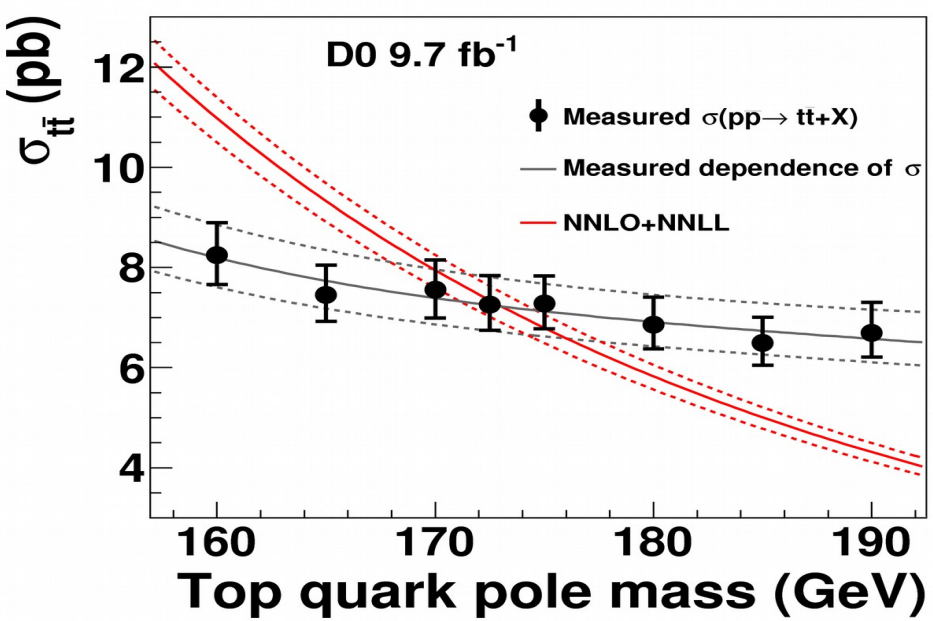
→ can not be used directly for precise NLO / NNLO theoretical predictions

→ $\mathbf{m_t^{pole}}$ can be extracted from inclusive cross-section meas.

→ measure cross section in different mass points

→ parametrize distribution with quartic fit

→ use normalized joint likelihood function



$$172.8 \pm 1.1(theo)^{+3.3}_{-3.1}(exp)\ GeV$$

$$\delta m_t / m_t = 1.9\%$$

PRD 94, 092004 (2016)

Top quark pole mass (II)

D0 measurement

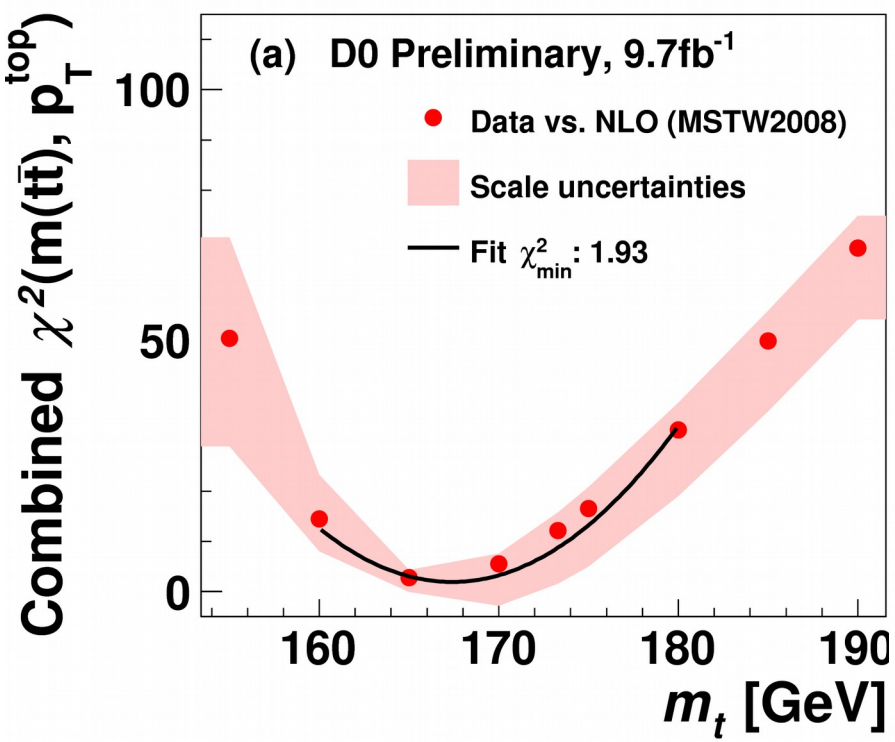
→ $\mathbf{m_t^{pole}}$ is extracted from differential cross-section measurement

→ using measured $m_{t\bar{t}}$, and $p_T(t)$ dependences unfolded to parton level

→ employed theoretical cross section for 3 PDF sets at NLO and NNLO as a function of m_t^{pole}

→ minimum of χ^2 comparison obtained for 3 different PDF sets

→ m_t^{pole} corresponds to average of the 3 values



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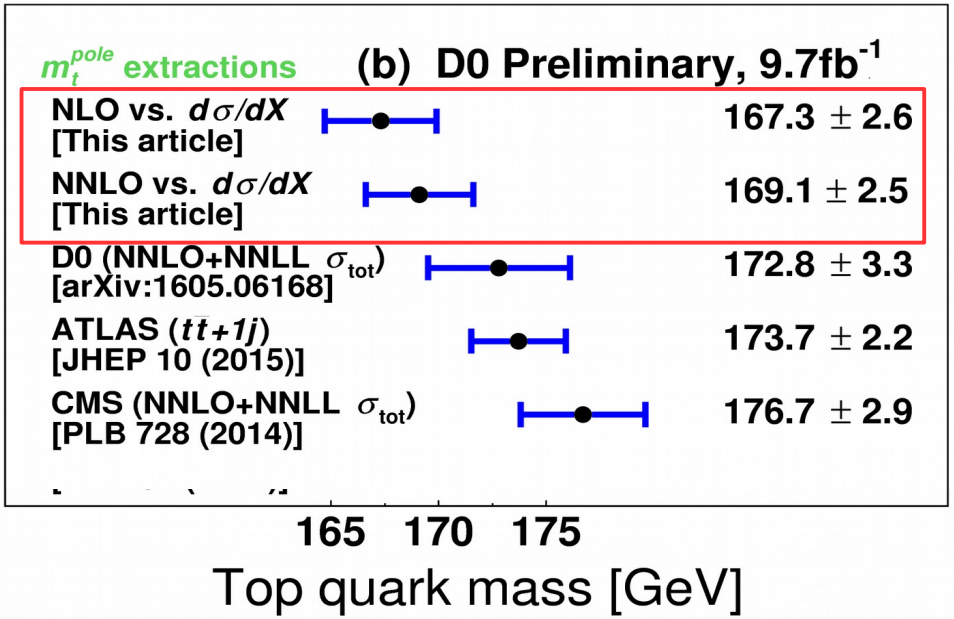

Conclusions

→ top quark cross section is in very good agreement with NNLO predictions

→ the final measurements of the top-quark production asymmetry and more refined predictions are in better agreement (~1.5σ)

→ top quark polarization consistent with expectations

→ top mass measurements are still competitive to the LHC results

→ still some ongoing measurements – stay tuned!

Back up

Top quark mass - systematics

Source	Uncertainty (GeV)
Signal and background modeling:	
Higher order corrections	$+0.16$
ISR/FSR	± 0.16
Hadronization and UE	$+0.31$
Color Reconnection	$+0.15$
b-jet modelling	$+0.21$
PDF uncertainty	± 0.20
Heavy flavor	∓ 0.06
$p_T(t\bar{t})$	$+0.03$
Multiple $p\bar{p}$ interactions	-0.10
Detector modeling:	
Residual jet energy scale	-0.20
Uncertainty on k_{JES} factor	∓ 0.46
Flavor-dependent jet response	∓ 0.30
Jet energy resolution	∓ 0.15
Electron momentum scale	∓ 0.10
Electron resolution	∓ 0.16
Muon resolution	∓ 0.10
b-tagging efficiency	∓ 0.28
Trigger	± 0.06
Jet ID	$+0.08$
Method:	
MC calibration	± 0.03
Instrumental background	± 0.07
MC background	± 0.06
Total systematic uncertainty	± 0.88
Total statistical uncertainty	± 1.61
Total uncertainty	± 1.84

Top quark polarization - systematics

Source	Beam	Helicity	Transverse
Jet reconstruction	±0.010	±0.008	±0.008
Jet energy measurement	±0.010	±0.023	±0.006
b tagging	±0.009	±0.014	±0.005
Background modeling	±0.007	±0.021	±0.004
Signal modeling	±0.016	±0.020	±0.008
PDFs	±0.013	±0.011	±0.003
Methodology	±0.013	±0.007	±0.009
Total systematic uncertainty	±0.030	±0.042	±0.017
Statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.061	±0.035

Top quark pole mass

Order & PDF	$m(t\bar{t})$	$m_t^{\rm pole}$ [GeV] $p_T^{\rm top}$	$m(t\bar{t}) \oplus p_T^{\rm top}$
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