# Precision Electroweak Measurements at the Tevatron

- The W mass @ Tevatron
- Effective weak mixing angle
- The Top Mass @ Tevatron

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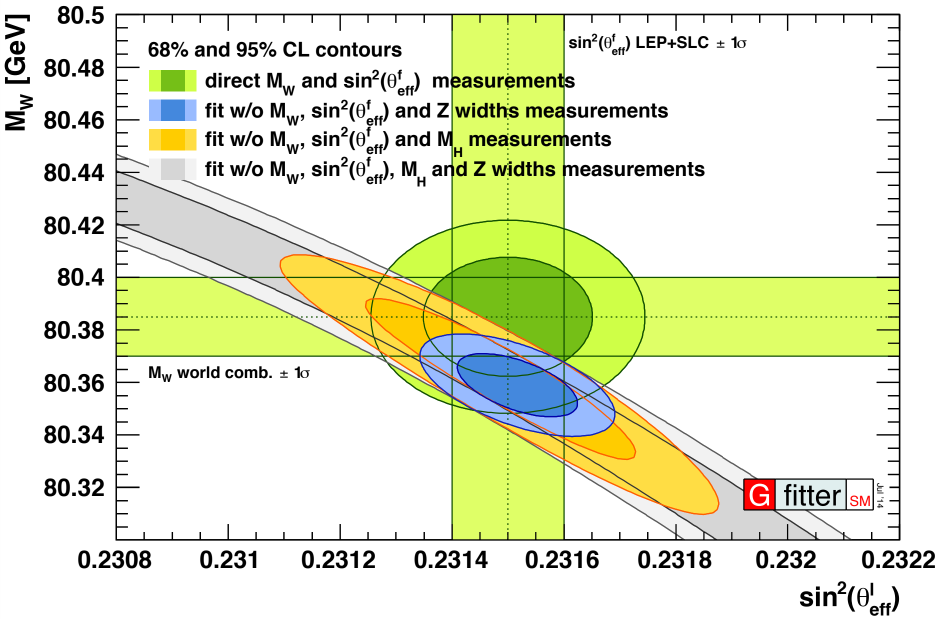
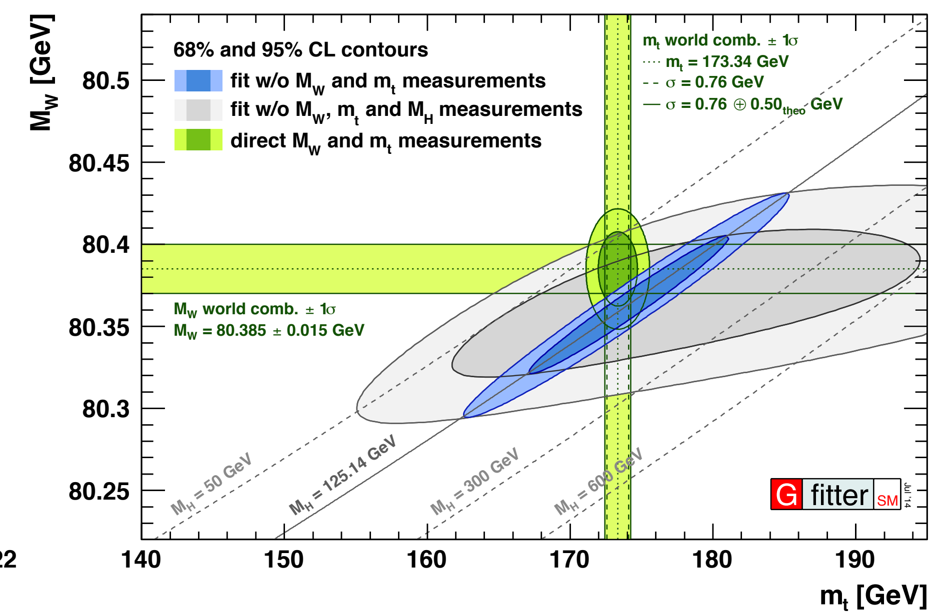
for the D0 Collaboration
DIS 2017 - 6 April 2017

# Motivations

- Consistency tests of electroweak symmetry breaking mechanism




GFitter results 2016

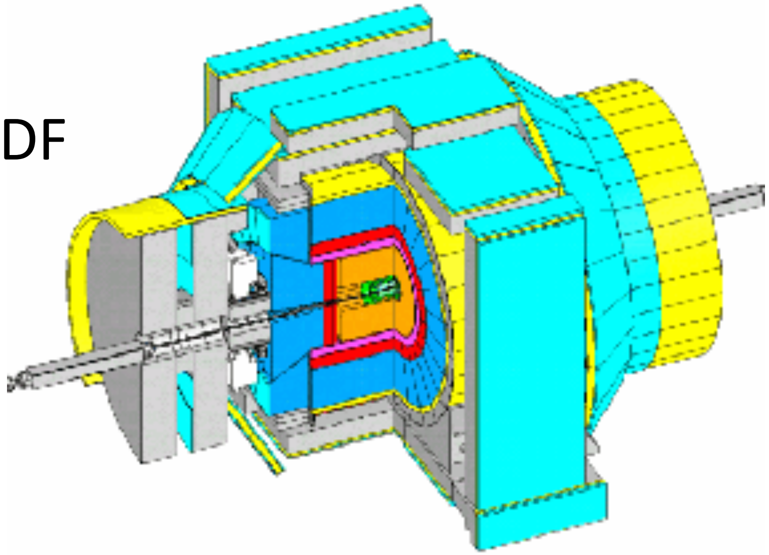
Over-constrained: 3 free parameters in the SM are constrained by 7 experimental measurements.

$$\alpha_{\rm em}, G_F, M_Z, M_W, \sin^2\theta_W, m_{\rm top}, M_H$$

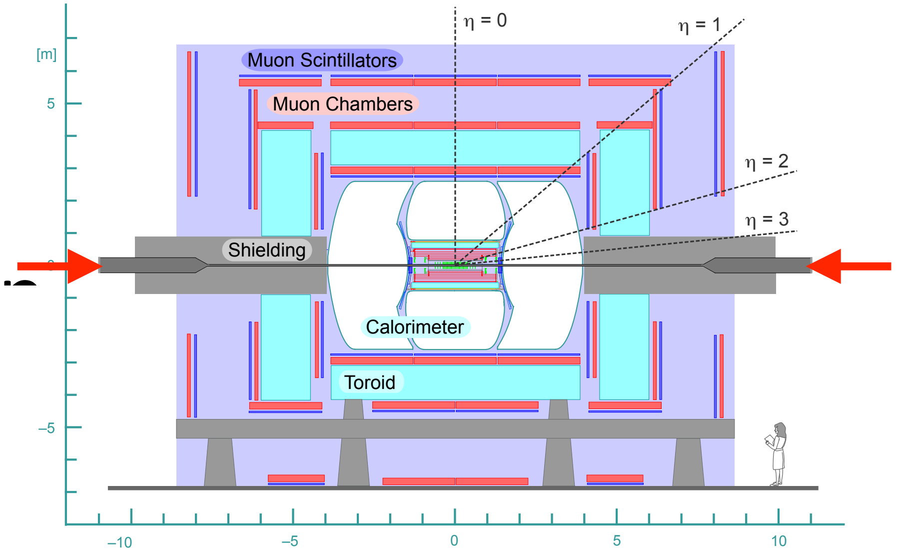
# Tevatron @ Fermilab

- Multi-purpose, high acceptance, well understood detectors.
  $\int \mathscr{L} dt \sim 10\ fb^{-1}$

CDF



D0



# The W mass @ Tevatron

- Strategy:
  - Analyse the $p_T^l, \not{E}_T^\nu, m_T^l$ distributions in W→lν (l=e/μ) channels
  - Likelihood fits of $M_W$-parameterized simulation templates
  - Lepton E/p scale and recoil calibration with Z→ll data
- **Results**

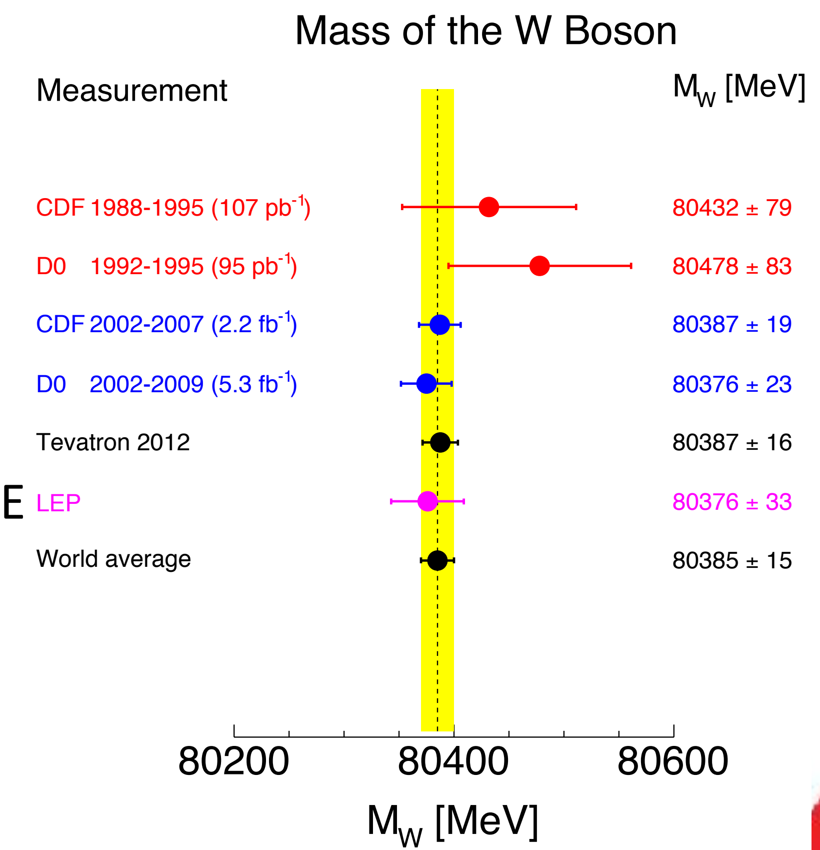
| | $M_W$ (MeV/c$^2$) |
|---|---|
| CDF (2.2 fb$^{-1}$,μ&e) | 80 387 ± 12 ± 15 |
| D0 (5.3 fb$^{-1}$, e) | 80 375 ± 11 ± 20 |

  - Dominant systematic are the lepton E/p scale and PDFs.
  - Tevatron results are combined using BLUE

$$M_W = 80387 \pm 16 \mathrm{MeV/c^2}$$

Consistent with the latest ATLAS result of 80370±19 MeV
arXiv:1701.07240

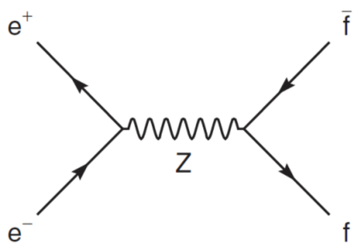
Phys. Rev. D 052018 (2013)




CDF and D0 are working on finalising measurements with the full data set.

# Effective weak mixing angle

- The forward-backward asymmetry $A_{fb}$ arises from the interference of the vector and axial vector couplings.




$$-i\frac{g}{2\cos\theta_W}\bar{f}\gamma^\mu(g_V^f - g_A^f\gamma_5)fZ_\mu$$

$$\begin{cases} g_V^f = I_3^f - 2Q_f\sin^2\theta_W \\ g_A^f = I_3^f \end{cases}$$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

("on-shell")

- Convert $\sin^2\theta_{eff}^{ll}$ to $\sin^2\theta_W$ using conversion factor calculated using ZFitter (depends on well known $M_Z$): Re(κ) ~ 1.037

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{Lept}} = \mathrm{Re}[\kappa_l(M_Z)]\cdot\sin^2\theta_W$$

("effective", Zfitter)

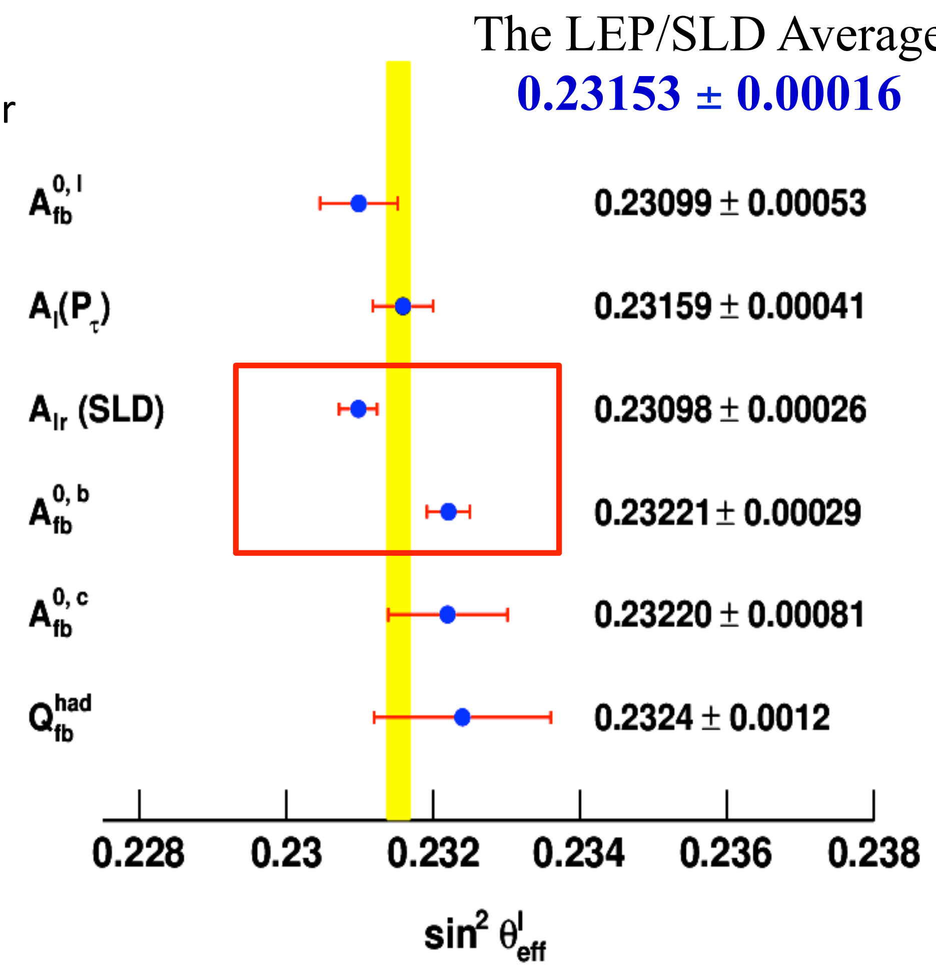
$$\begin{cases} \sin^2\theta_{\mathrm{eff}}^u \approx \sin^2\theta_{\mathrm{eff}}^l - 0.0001, \\ \sin^2\theta_{\mathrm{eff}}^d \approx \sin^2\theta_{\mathrm{eff}}^l - 0.0002. \\ \sin^2\theta_{\mathrm{eff}}^{\mathrm{b}} - \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \approx 0.0014, \end{cases}$$

(modified Resbos)

Can be directly measured via Parity-violating observables at Z-pole

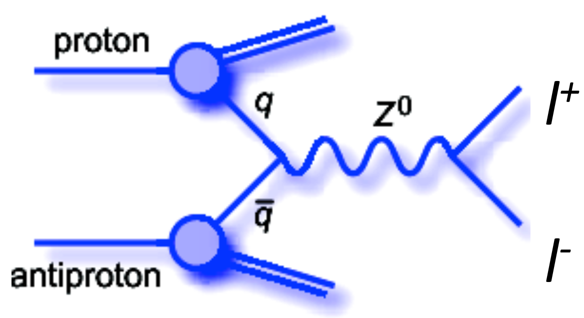
# Effective weak mixing angle

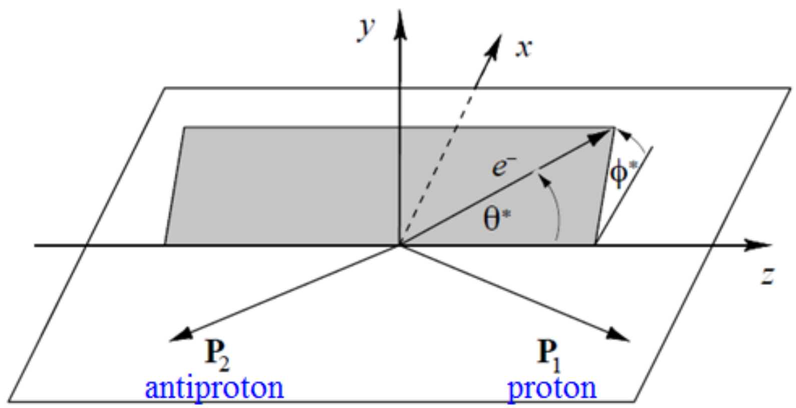
- The best current measurements differ by 3.2σ
  - LEP b-quark $A^{0,b}_{fb}$
  - SLD beam LR-polarization $A_{lr}$

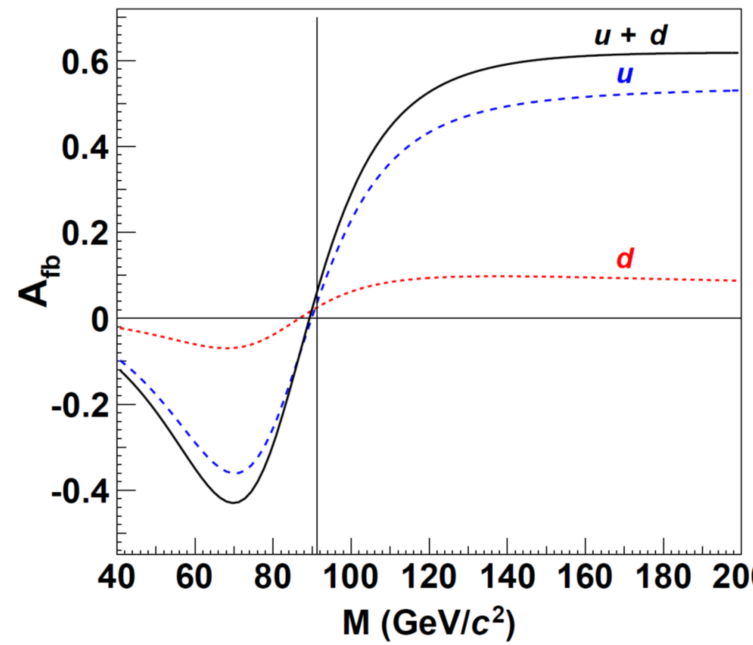


# Weak mixing angle @ the Tevatron

- Measure background-subtracted $A_{fb}$ as function of invariant mass in Collins-Soper frame



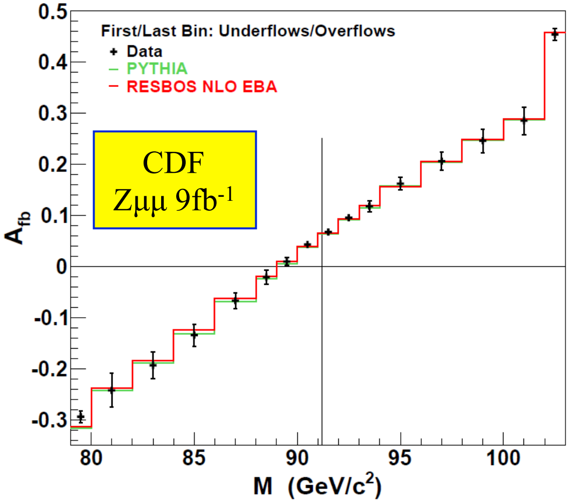

$$\cos\theta^* = \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$

$$A_{fb} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

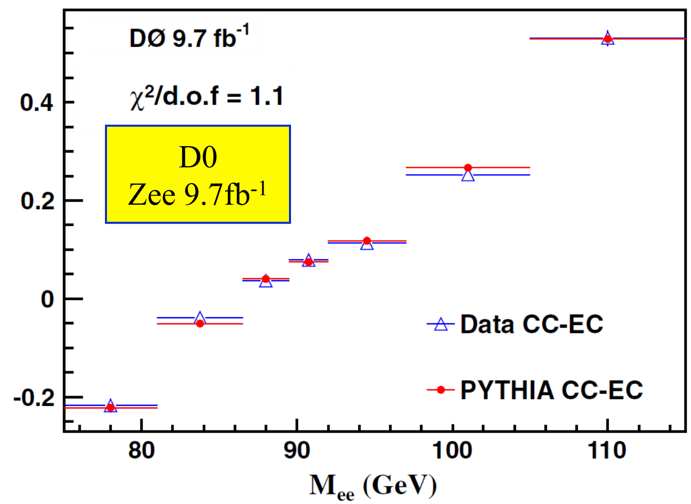
$$p_l^\pm = p_0 \pm p_3$$

# Previous Results

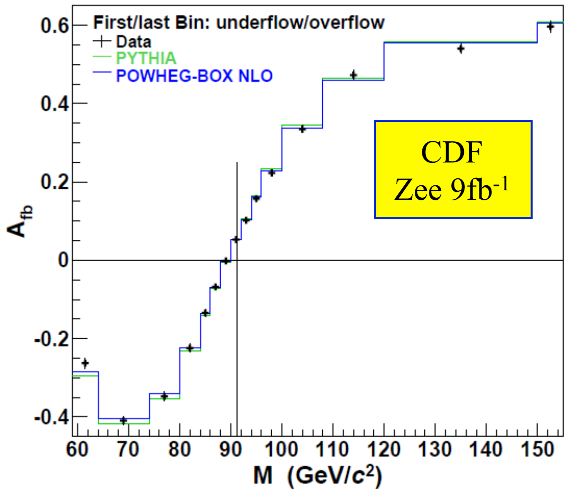
- $\chi^2$ fits between data $A_{FB}$ and MC templates for a series of different Pythia values of $\sin^2\theta_W$




PRD 89(2014)072005




PRL115(2015)041801



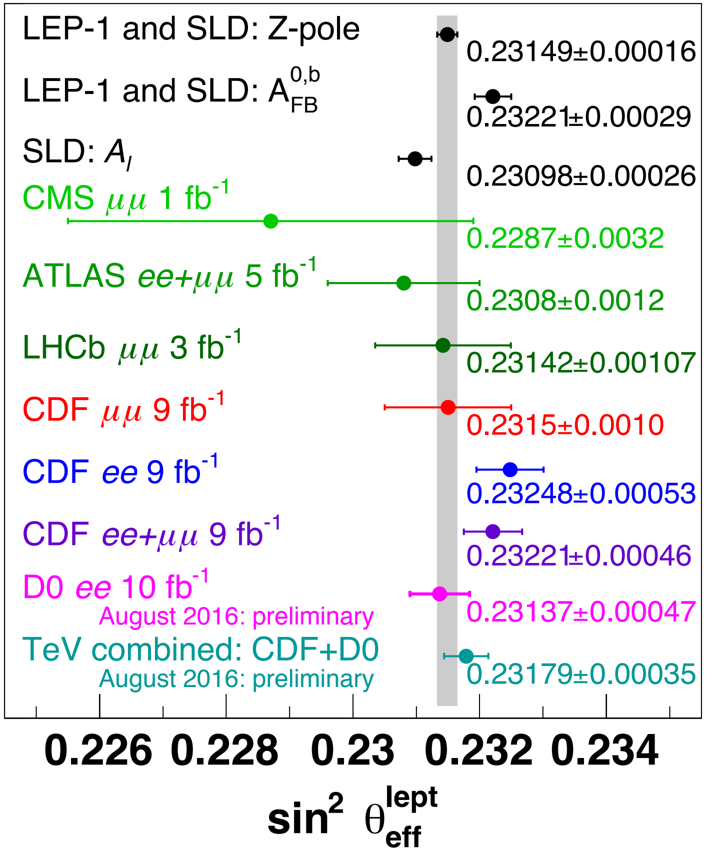

PRD 93(2016)112016

| | $\sin^2\theta_W$ ± stat. ± syst. ± PDF | Total uncertainty |
|---|---|---|
| CDF Zμμ $9fb^{-1}$ | 0.2315 ± 0.0009 ± 0.0002 ± 0.0004 | ±0.0010 |
| DØ Zee $9.7fb^{-1}$ | 0.23147 ± 0.00043 ± 0.00008 ± 0.00017 | ±0.00047 |
| CDF Zee $9fb^{-1}$ | 0.23248 ± 0.00049 ± 0.00004 ± 0.00019 | ±0.00053 |

# Previous Tevatron Combination

- Combination of CDF Zμμ+Zee and D0 Zee results
- Using ZFITTER and NNPDF3.0

$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23179 \pm 0.00030 \pm 0.00017$$




$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.23179 \pm 0.00035$$

- Translate into $M_W$ Tevatron from $\sin^2\theta_W$

$$M_W = 80351 \pm 18\,{\rm MeV/c^2}$$

- Compare with Tevatron and LEP direct measurements

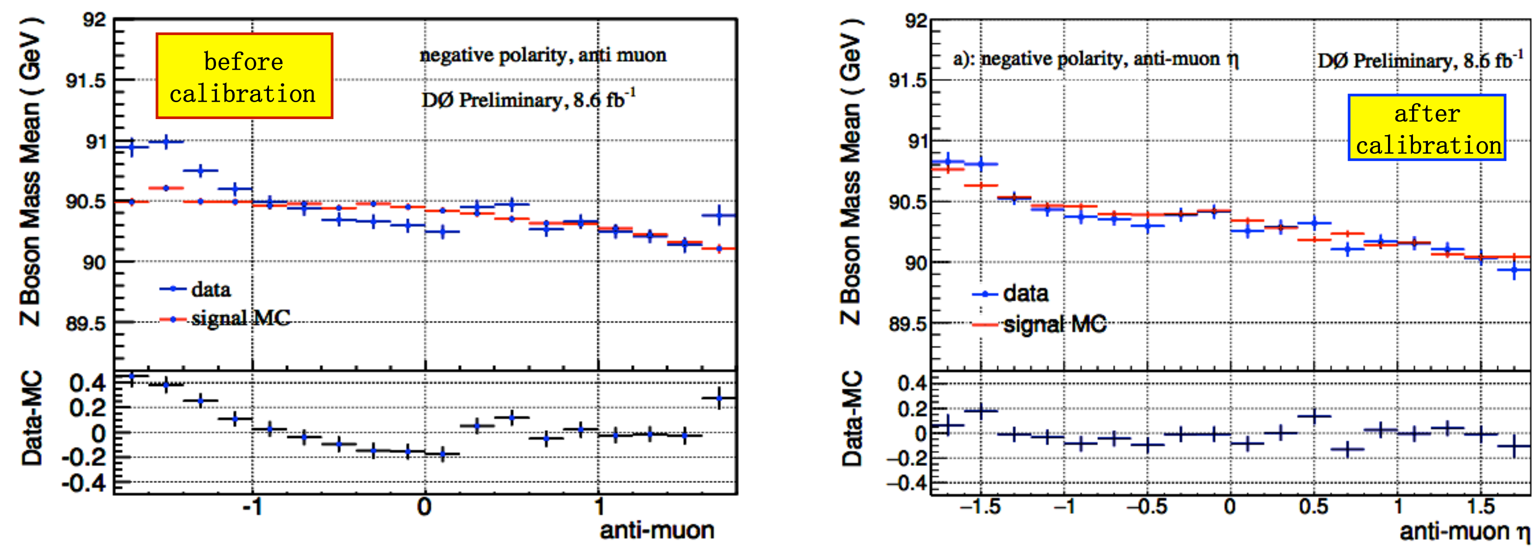
$$M_W = 80385 \pm 15\,{\rm MeV/c^2}$$

FERMILAB-CONF-16-295-E

# New: D0 Zμμ

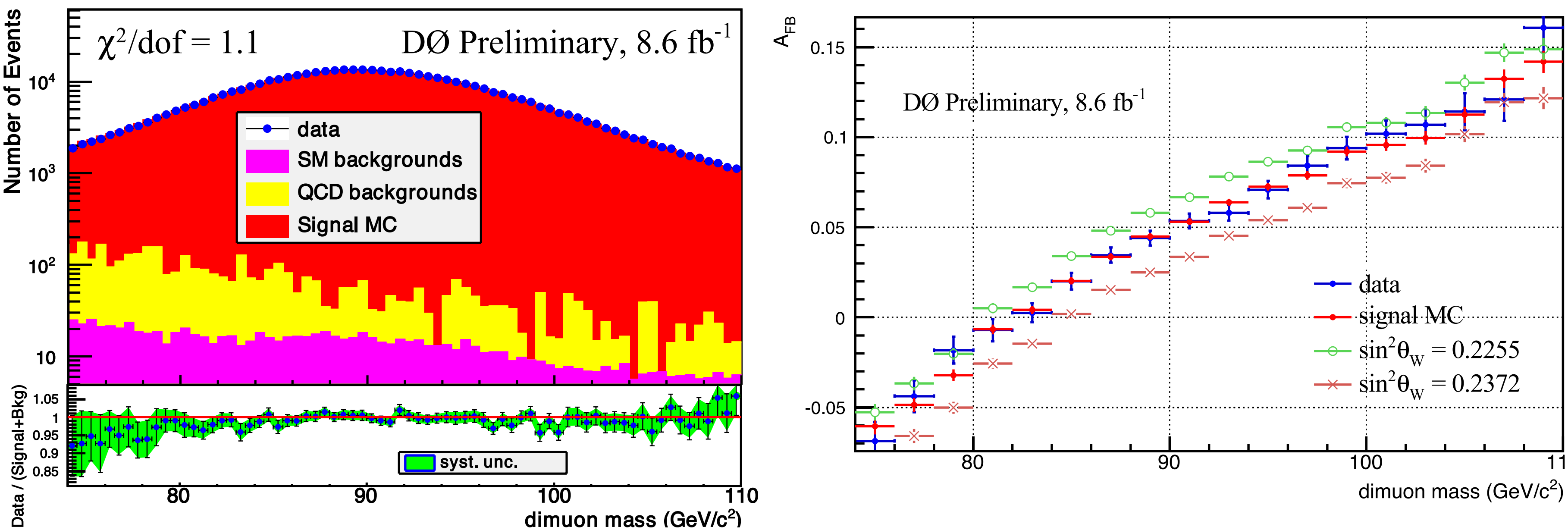
- Last channel @ Tevatron :
  - 8.6 $fb^{-1}$ Zμμ events, $p_T$>15GeV/c, |η|<1.8; opposite charge, 74 < $M_{\mu\mu}$ < 110 GeV/$c^2$
  - Modified Resbos + NNPDF3.0
  - The D0 Zμμ result is less precise than Zee due to the more central muon acceptance and the less precise muon momentum measurement.
- We reweight the MC to data separately as a function of eta for each muon charge and solenoid polarity so as to correct for residual mis-alignments

$$P(\eta, q, S) = \alpha(\eta, q, S) \times P_{\mathrm{obs}}(\eta, q, S)$$



# MC—Data Comparison

- Check agreement in multiple kinematic distributions
  - Muon $p_T/\eta$, and di-muon $p_T/\eta/M/\cos\theta^*$ distribution
  - Good agreement




- We fit the data to templates for varying values of the Born level $\sin^2\theta_W^B$ in Pythia in a mass region of $74<M_{\mu\mu}<110$ GeV

$$\sin^2\theta_W^B = 0.22994 \pm 0.00059\,(\text{stat}) \pm 0.00011\,(\text{syst}) \pm 0.00027\,(\text{pdf})$$
$$= 0.22994 \pm 0.00066$$

# Systematics

- Dominated by uncertainty due to the PDF and modelling the background.

| | |
|---|---|
| $\sin^2\theta_W^B$ | 0.22994 |
| Statistical uncertainty | 0.00059 |
| Systematic uncertainties | |
| Momentum calibration | 0.00002 |
| Momentum resolution | 0.00004 |
| Background | 0.00010 |
| Efficiencies | 0.00001 |
| Total systematic | 0.00011 |
| PDF | 0.00027 |
| Total | 0.00066 |

# Result

$$\sin^2\theta_W^B = 0.22994 \pm 0.00059\,(\text{stat}) \pm 0.00011\,(\text{syst}) \pm 0.00027\,(\text{pdf})$$
$$= 0.22994 \pm 0.00066$$

D0 Note 6497-CONF

- Convert $\sin^2\theta_W{}^B$ to $\sin^2\theta_{eff}{}^{ll}$ using comparison of LO Pythia and NLO Resbos:
  $\sin^2\theta_{eff}{}^{ll} = \sin^2\theta_W{}^B + 0.00008$

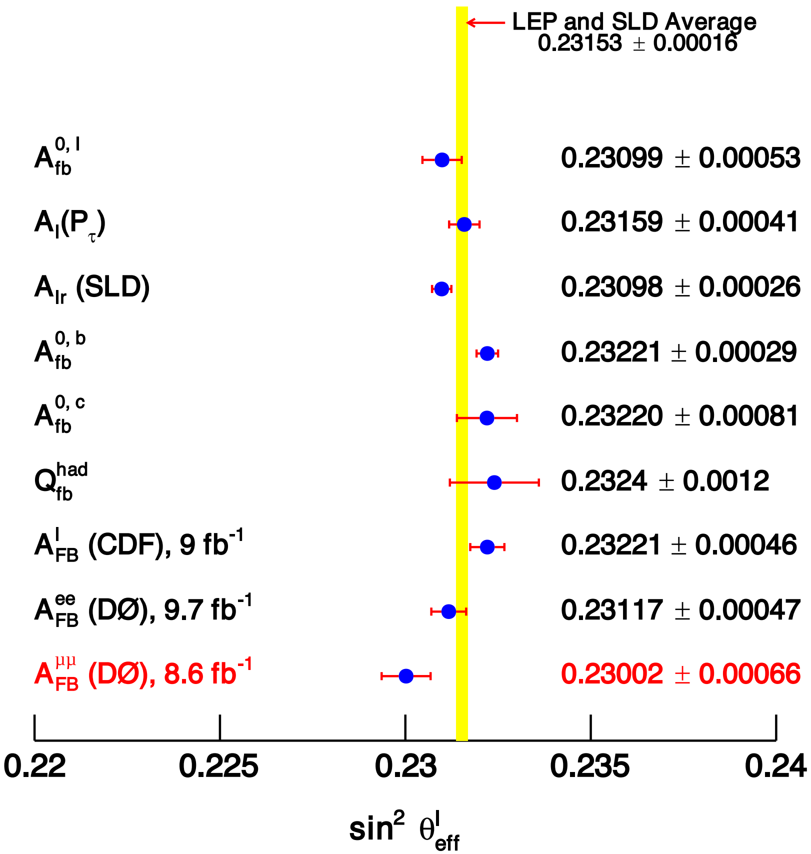
$$\sin^2\theta^l_{\text{eff}} = 0.23002 \pm 0.00066$$

- This is converted to the on-shell normalisation for $\sin^2\theta_W$ using ZFitter

$$\sin^2\theta_W(\text{on-shell}) = 0.22181 \pm 0.0064$$

corresponding to

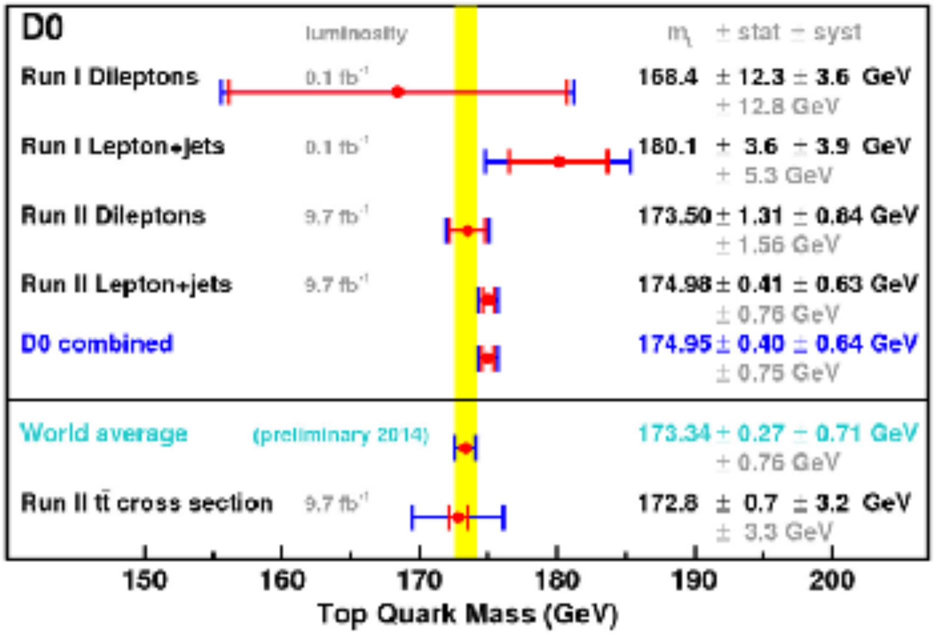
$$M_W = 80441 \pm 33\,\text{MeV/c}^2$$




- D0's Zμμ and Zee results agree to 1.4σ (when referred to the same PDF set).

# Direct Top Mass from D0

- Full D0 combination of Run1 0.1 $fb^{-1}$ and Run2 9.7 $fb^{-1}$ results
- Systematic uncertainties and correlations among channels have been taken into account



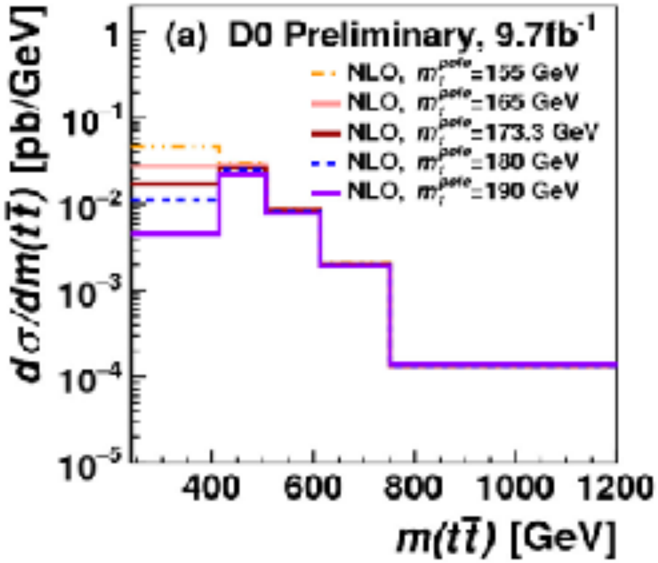

| | D0 combined values (GeV) |
|---|---|
| top quark mass | 174.95 |
| In situ light-jet calibration | 0.41 |
| Response to $b$, $q$, and $g$ jets | 0.16 |
| Model for $b$ jets | 0.09 |
| Light-jet response | 0.21 |
| Out-of-cone correction | $< 0.01$ |
| Offset | $< 0.01$ |
| Jet modeling | 0.07 |
| Multiple interaction model | 0.06 |
| $b$ tag modeling | 0.10 |
| Lepton modeling | 0.01 |
| Signal modeling | 0.35 |
| Background from theory | 0.06 |
| Background based on data | 0.09 |
| Calibration method | 0.07 |
| Systematic uncertainty | 0.64 |
| Statistical uncertainty | 0.40 |
| Total uncertainty | 0.75 |

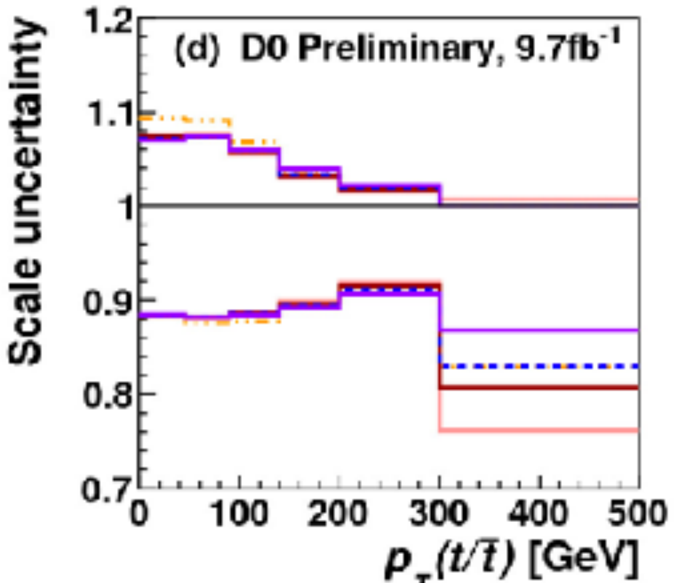
$$m_t = 174.9 \pm 0.75\,\mathrm{GeV/c^2}$$

arXiv:1703.06994 [hep-ex] Submitted to PRD

# Top pole mass from differential cross sections

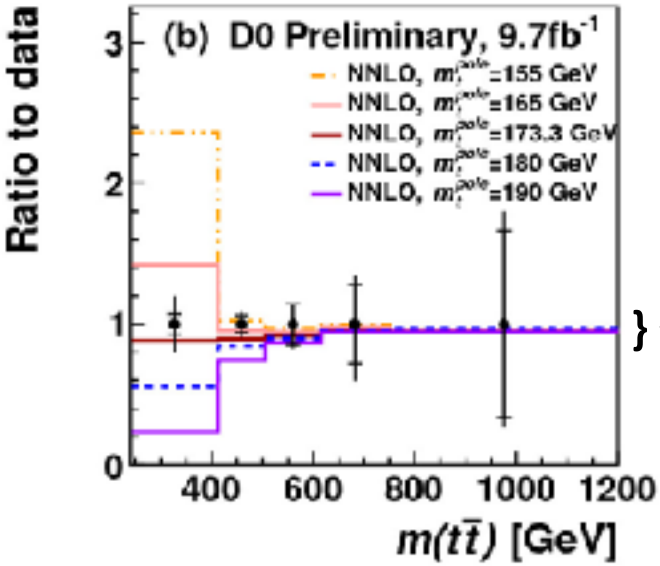
- Top quark momentum, $t\bar{t}$ invariant mass distributions, etc. are sensitive to the top quark mass
  - Expect improvement vs extraction from total cross-section
    eg. Phys. Rev. D 94, 092004 (2016)
  - Use the D0 lepton+jets measurement:
    Phys. Rev. D 90, 092006 (2014)
  - Compare differential distributions to NNLO QCD calculation of TOP++ using the pole mass:
    Czakon, Fiedler, Heymes and Mitov, JHEP 1605, 034 (2016)



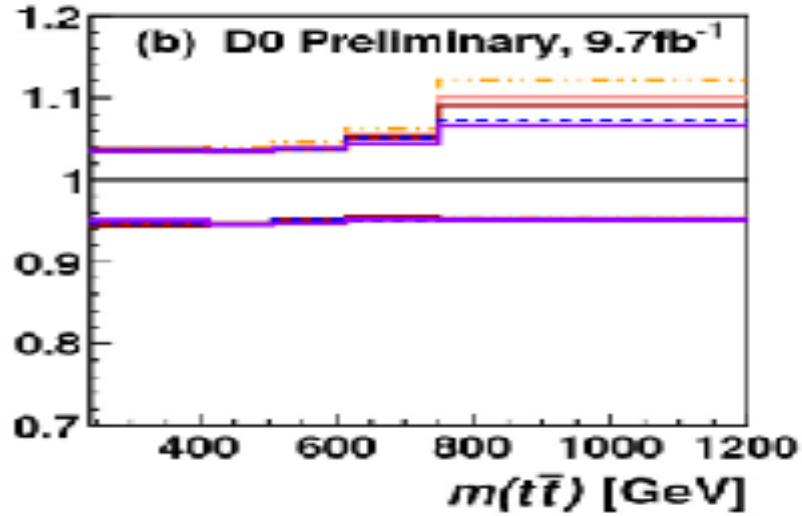



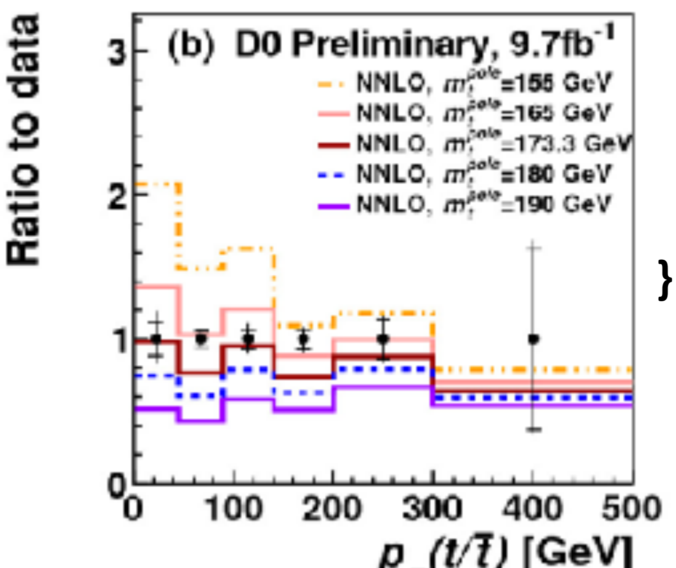

See D Heymes talk on Tuesday

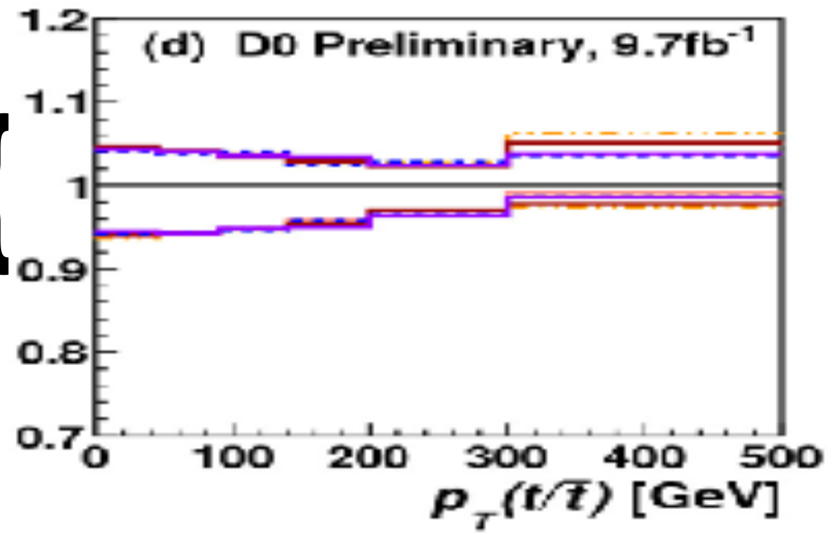
# Top pole mass from differential cross sections




NNLO QCD scale uncertainties < 5% for $p_T^{top}$
c.f. 10% maximum for m(tt)



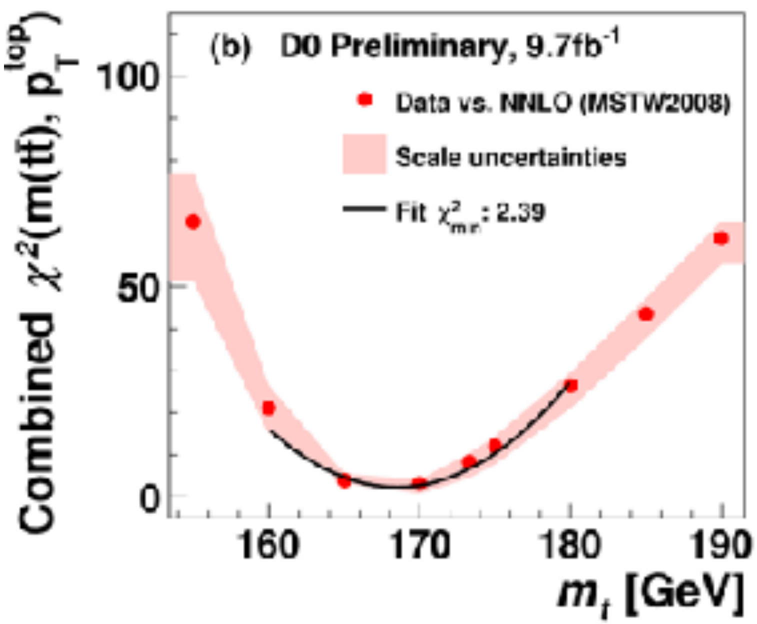



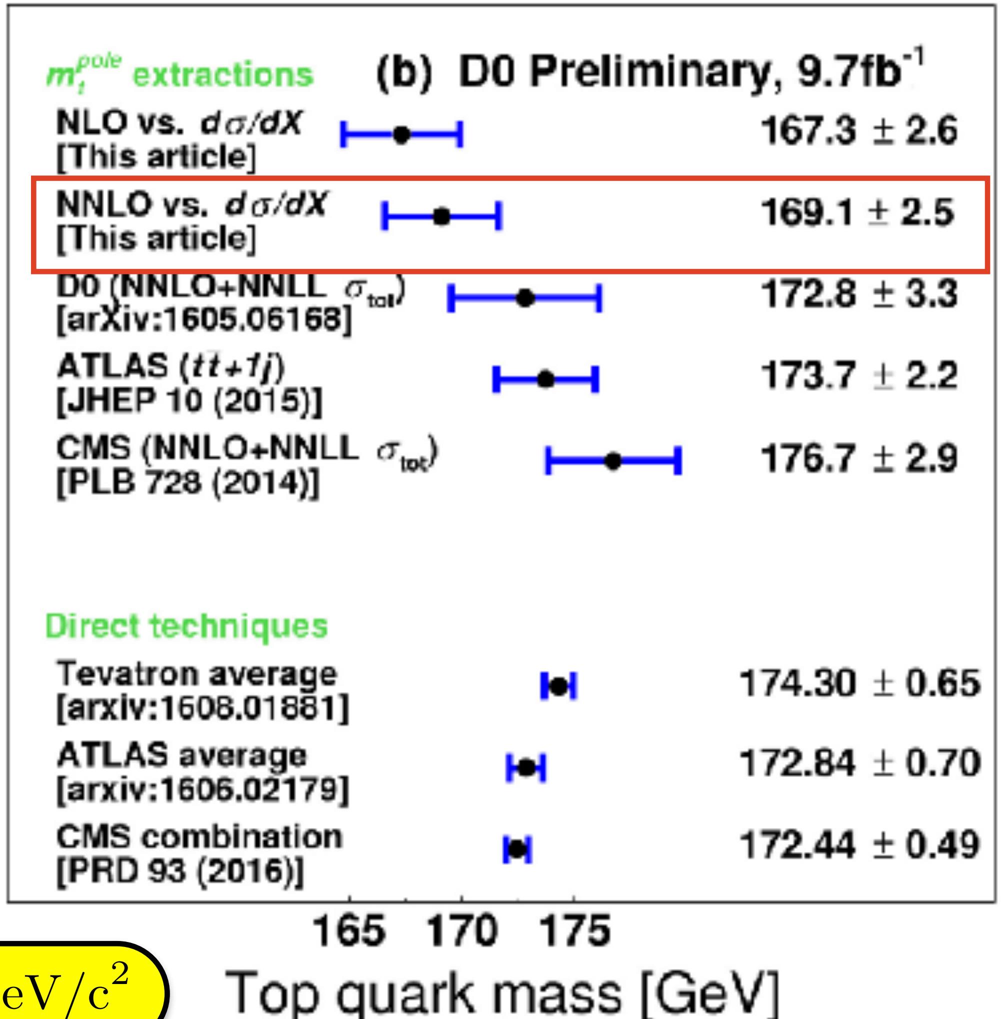



# Top pole mass from differential cross sections

D0CONF 6473

- Use $\chi^2$ fit to measure the mass
- Include full 2-D correlation matrix in m(tt), $p_T^{top}$




$$m_t = 169.1 \pm 1.4\,(\mathrm{theo}) \pm 2.2\,(\mathrm{exp})\ \mathrm{GeV/c^2}$$

Precision: 1.5% ~ 25% improvement over using inclusive XS

# Summary

- W Mass
  - Current Tevatron combination is 80387 ± 16 MeV
  - Analysis of full data sample is ongoing.
- Weak Mixing Angle
  - Preliminary Tevatron combination of 0.23179 ± 0.00035 using CDF Z(ee/μμ) and D0 Z(ee)
  - **NEW** preliminary result of 0.23002±0.00066 with D0 Z(μμ) measurement
  - Once the D0 Z(μμ) result is finalised the full Tevatron combination will be completed.
  - Will make a significant contribution to improving the world average.
- Top Mass
  - New D0 combination of all direct measurements from Run I and Run II.
  - New D0 preliminary measurement of top quark pole mass using $d\sigma/dp_T$ and $d\sigma/M_{tt}$.