Electroweak precise measurements @ the Tevatron

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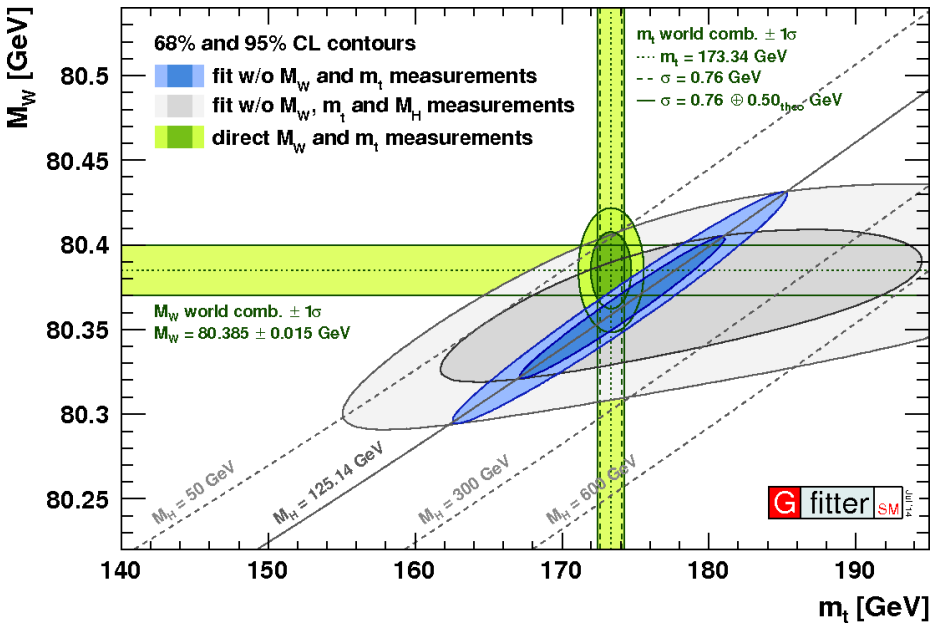
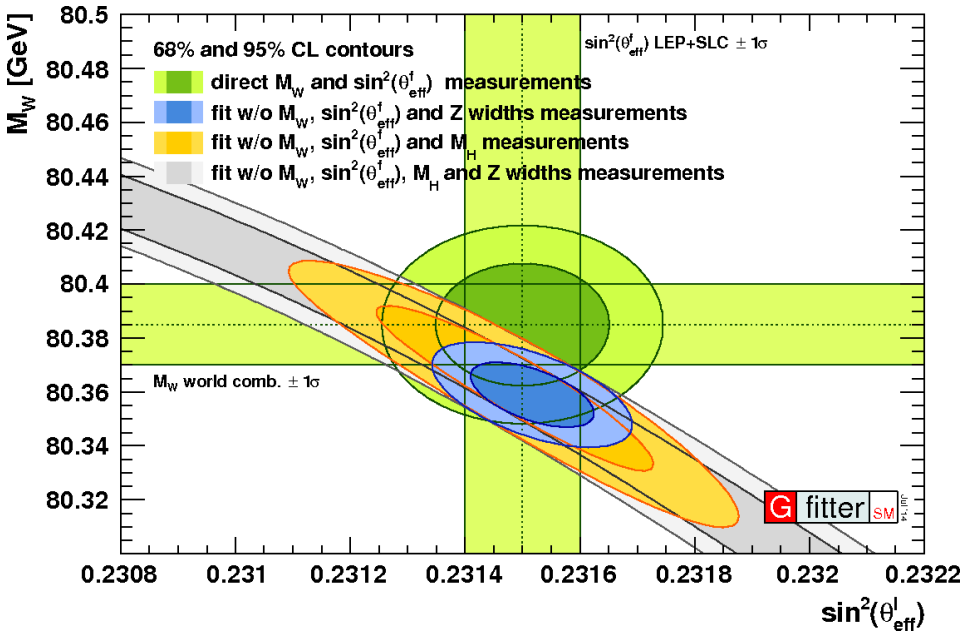
for the D0 and CDF collaborations

Motivations

- Consistency tests of electroweak and symmetry breaking mechanism

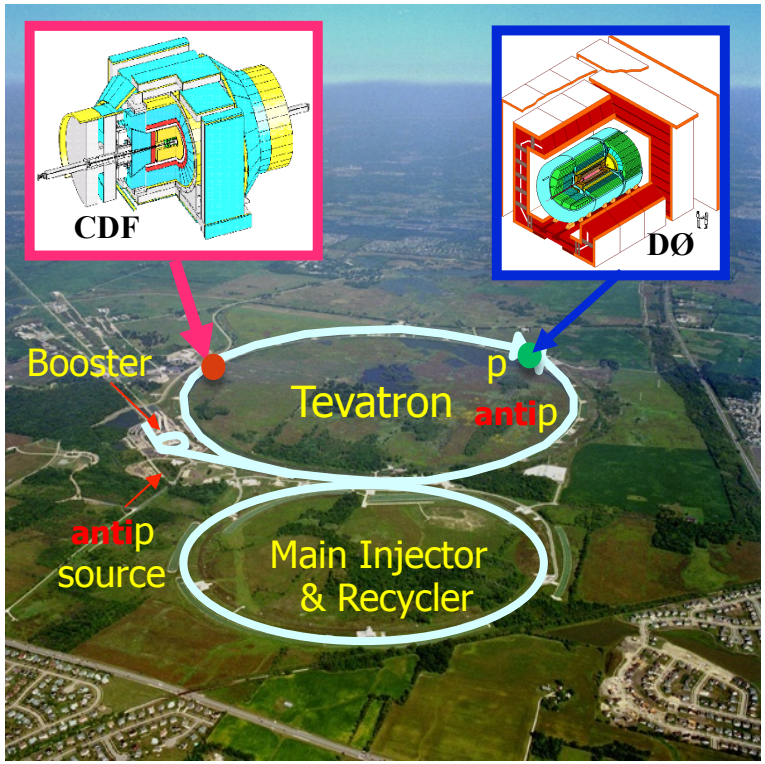




Over-constrained parameters:

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

Tevatron @ Fermilab



- Collider: proton-antiproton

	c.m.s energy (TeV)	integrated L (fb^{-1})
Run I (1992-1996)	1.8	~0.1
Run II (2001-2011)	1.96	~9.7

- Experiments: **CDF** and **D0**
  - General purpose detectors with large coverage and good performance of vertex, tracking, calorimeter and muon spectrometers
  - Physics topics cover B, EW, top, Higgs, QCD and new physics searches as SUSY

The W mass @ Tevatron

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

- Results:

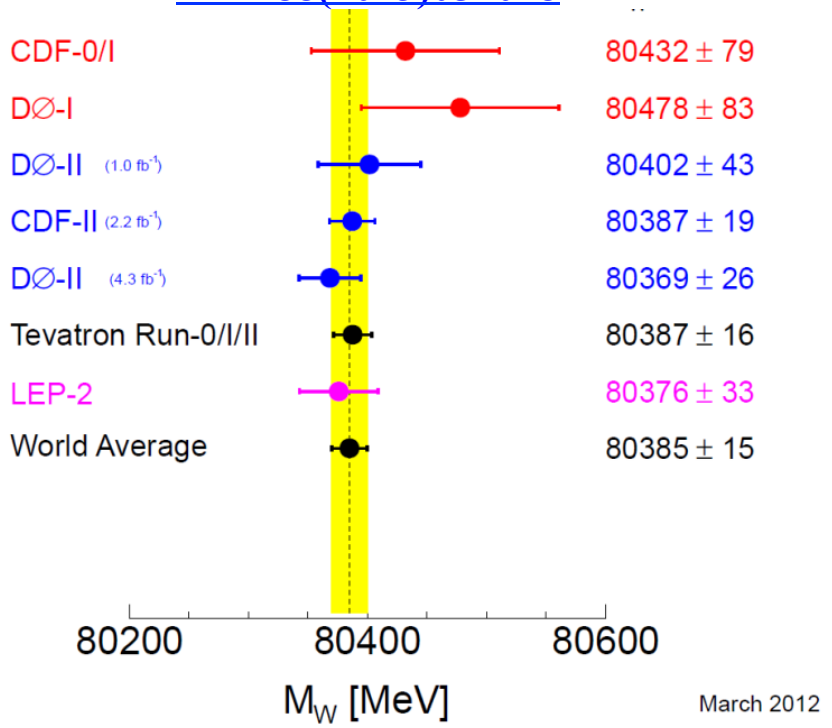
	M_W (MeV)
CDF Run II 2.2fb^{-1} (l=e/μ)	80 387 ± 12 ± 15
D0 Run II 5.3fb^{-1} (l=e)	80 375 ± 11 ± 20

  - Dominant systematic as lepton E/p scale and PDF
  - Tevatron combined with BLUE

$$M_W = 80387 \pm 16 \text{ MeV}$$

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

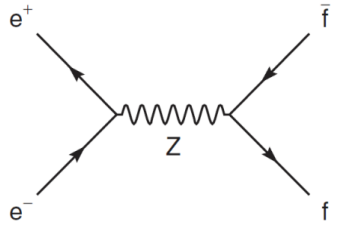
PRD 88(2013)052018



- Status: analysis with full data set of both CDF and D0 are being finalized respectively

The effective weak mixing angle

- Weak neutral current V-A couplings



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

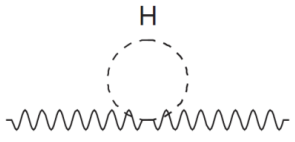
$$\begin{cases} g_V^f = I_3^f - 2Q_f\sin^2\theta_W \\ g_A^f = I_3^f \end{cases}$$

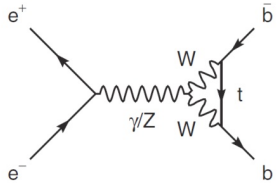
$$\sin^2\theta_W = 1-\frac{M_W^2}{M_Z^2}$$

("on-shell")

- High order corrections factorized as enhanced Born approximation(EBA)

$$\sin^2\theta_{\text{eff}}^f = \text{Re}(\kappa_f)\sin^2\theta_W = \frac{1}{4|Q_f|}\left(1-\frac{\text{Re}[g_V^f]}{\text{Re}[g_A^f]}\right)$$





- The effective mixing angle: converged to leptonic one

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

("effective", Zfitter)

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

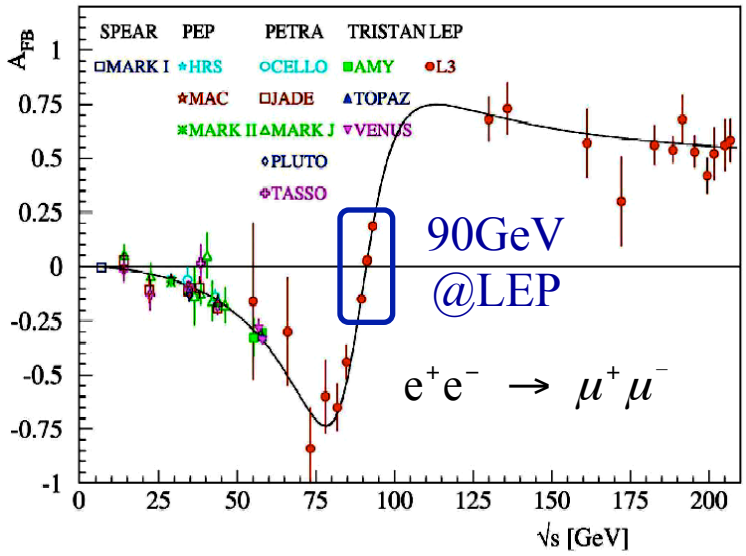
(modified Resbos)

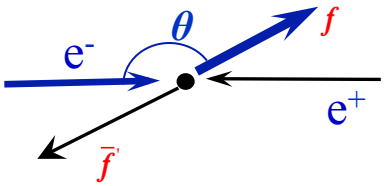
Can be directly measured via Parity-violating observables at Z-pole

The effective weak mixing angle

- The most precise results, LEP b-quark $A^{0,b}_{fb}$ and SLD beam LR-polarization A_{lr}, differ **3.2**σ

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

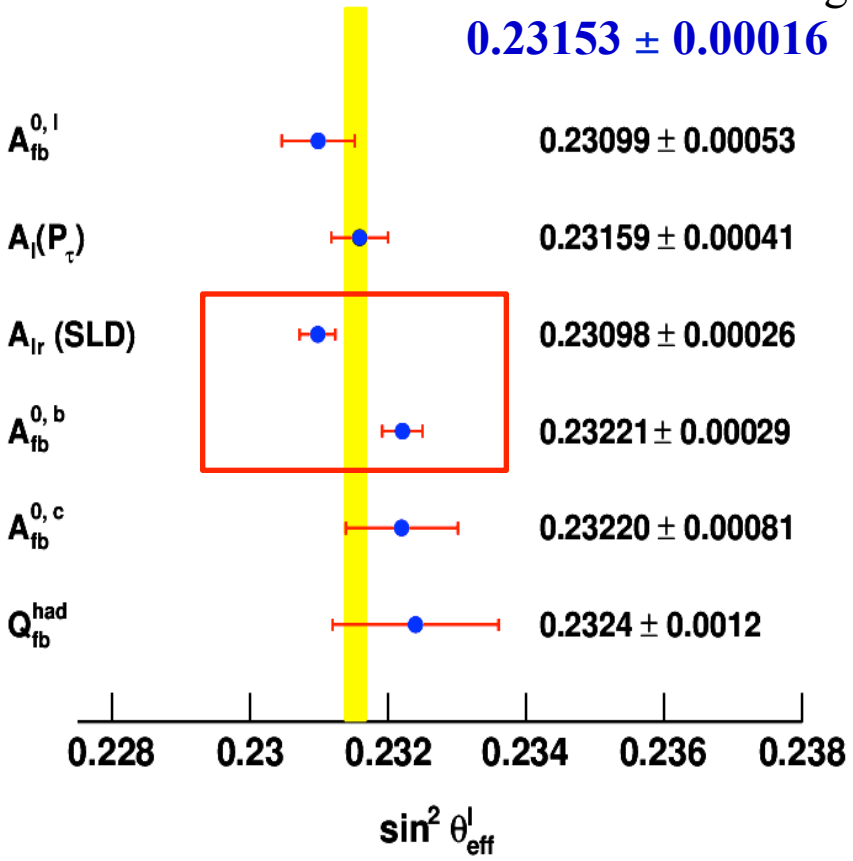




$$\sigma_{F/B} = \int_{0/-1}^{+1/0} \frac{d\sigma}{dcos\theta} dcos\theta$$

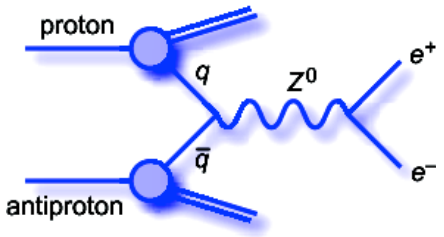
The LEP/SLD Average

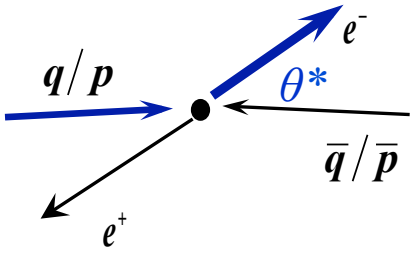
0.23153 ± 0.00016



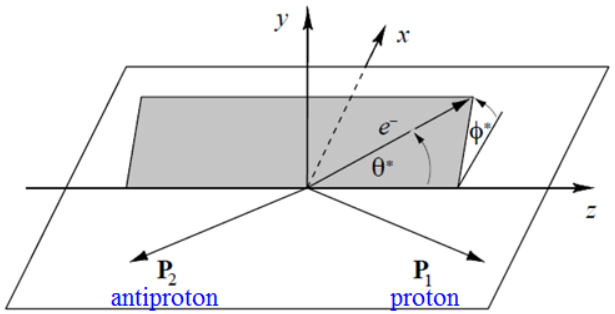
The weak mixing angle @ Tevatron

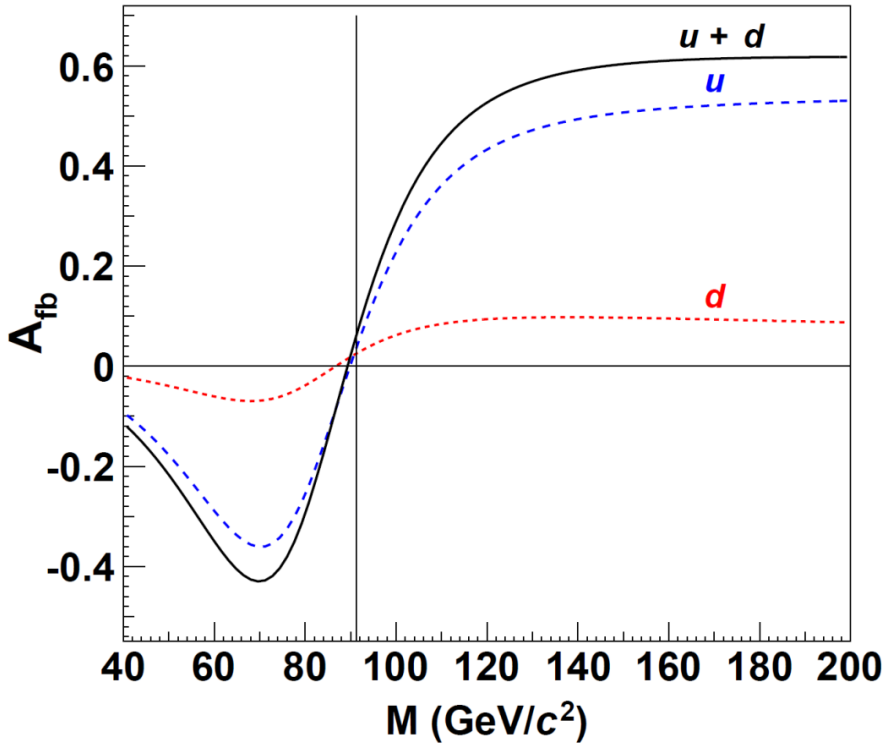
- Measure background-subtracted A_{FB} as function of invariant mass in Collins-Soper frame





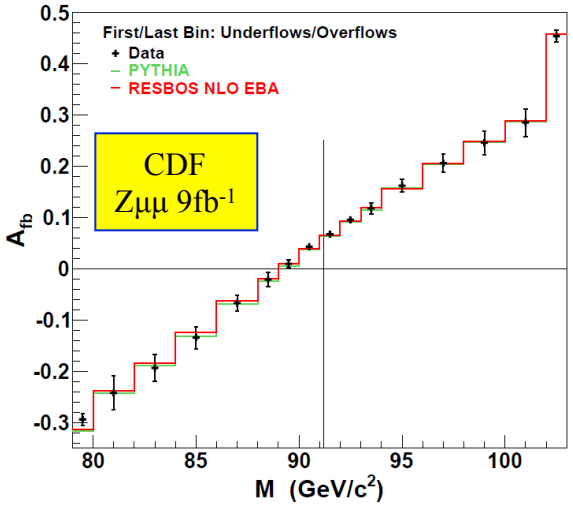
$$\cos\theta^* = \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$



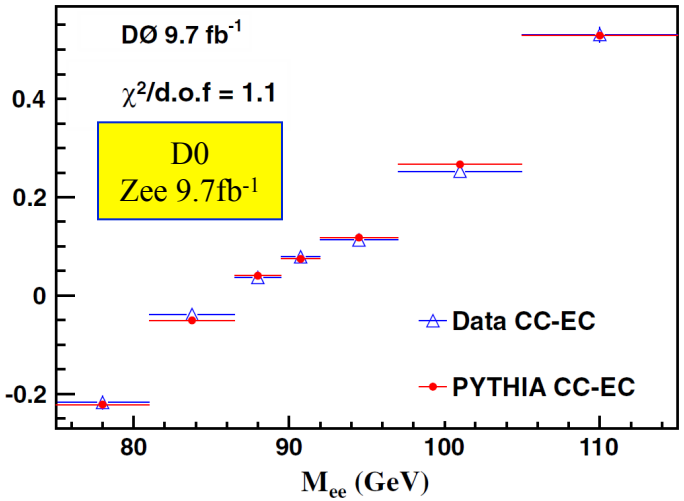


- Minimal-χ^2 fits between data A_{FB} versus $\sin^2\theta_W$-parameterized MC simulations

The weak mixing angle @ CDF + D0



PRD 89(2014)072005



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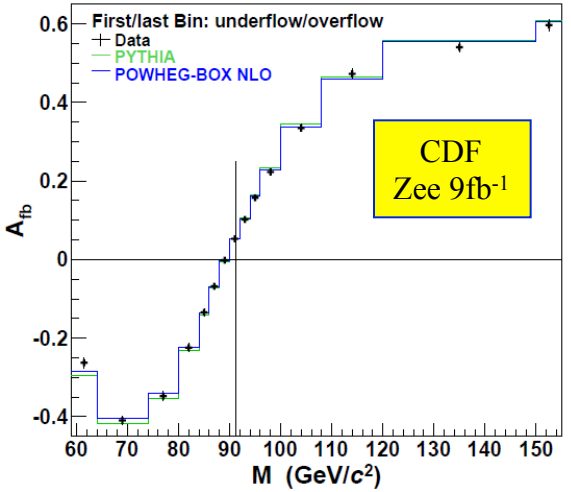


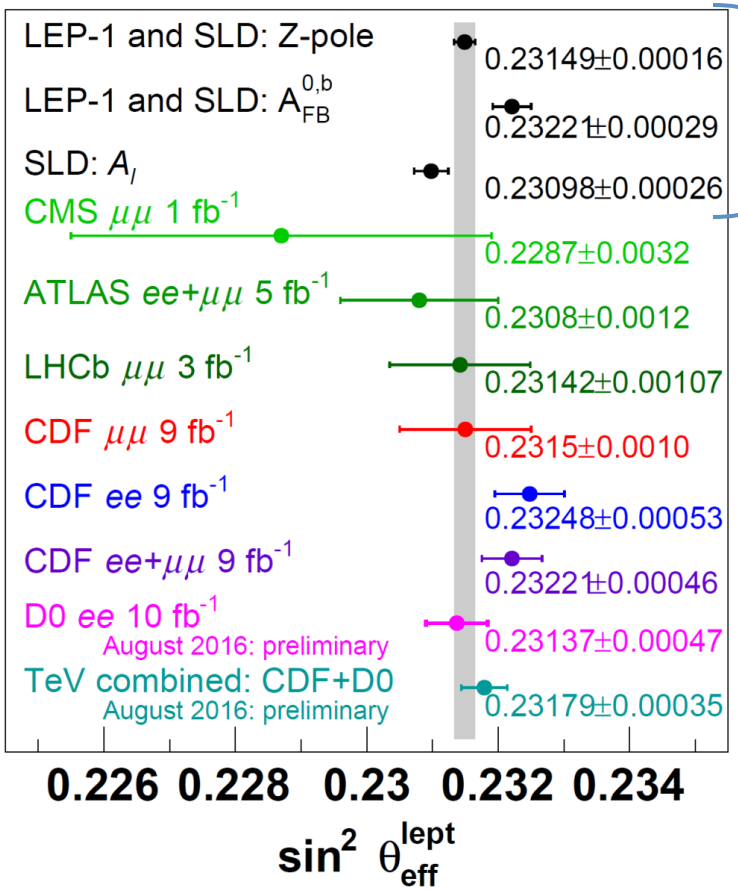
PRD 93(2016)112016

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

The weak mixing angle @ Tevatron

- Preliminary combination of CDF Zμμ+Zee and D0 Zee results
- Transferred to ZFitter and NNPDF3.0 conventions

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23179 \pm 0.00030 \pm 0.00017$$



$\Leftrightarrow$ **0.23179 ±0.00035**

extra ~21% sensitivity to the LEP/SLD Average

- M_W determination:

80.385 ± 0.015 (LEP+Tevatron Direct)

80.351 ± 0.018 (Tevatron Indirect)

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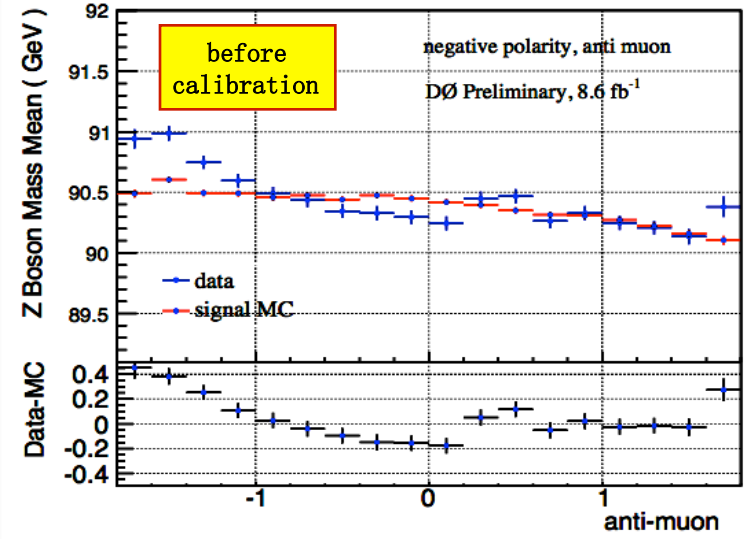
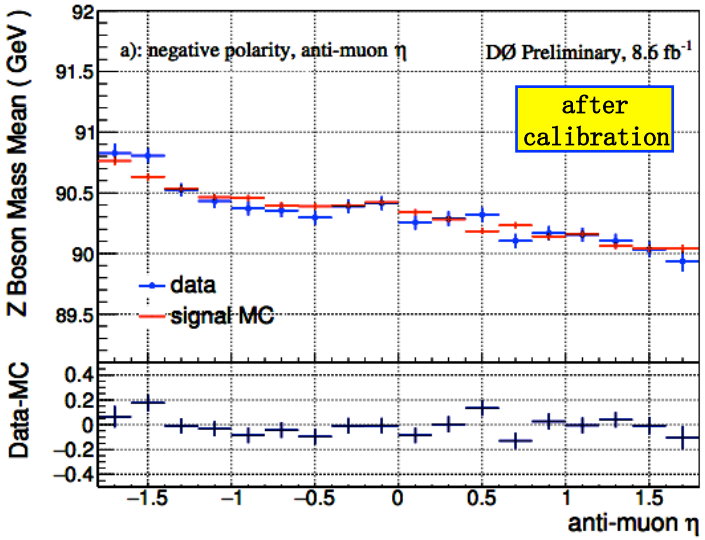
The weak mixing angle @ D0 Zμμ preliminary

- Last channel @ Tevatron :
  - 8.6 fb^{-1} Zμμ events, p_T>15GeV, |η|<1.8; opposite charge, 74<$M_{\mu\mu}$<110GeV
  - Modified Resbos + NNPDF3.0
  - Compared to Zee result, lower sensitivity and charge *q*-dependence in μ p_T reconsrtuction

- Muon momentum calibration:
  - Corrections for q-η-solenoid dependence raised by residual mis-alignment
  - Determined by observing dimuon mass mean

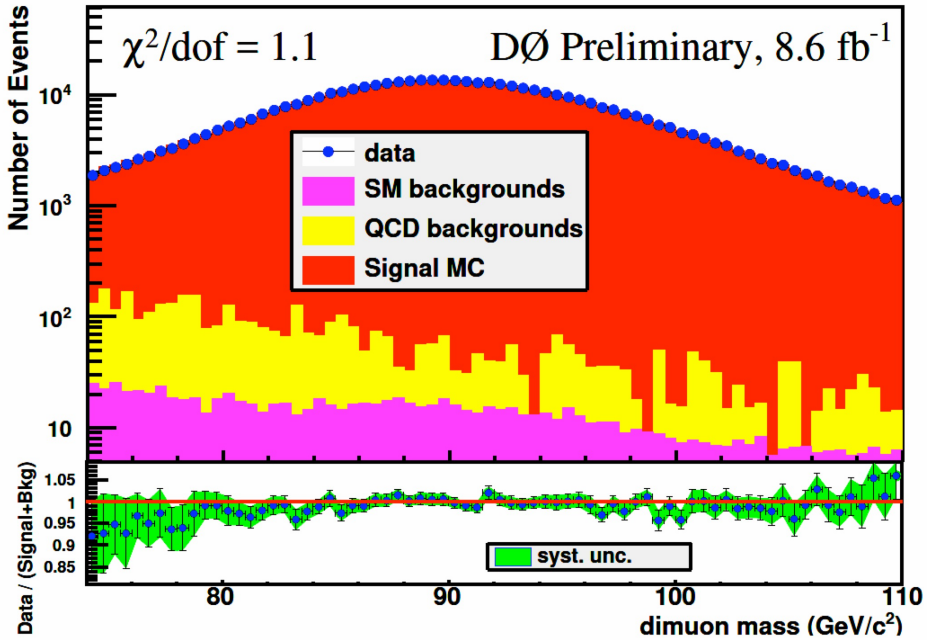
$$P(\eta, q, S) = \alpha(\eta, q, S) \times P_{\text{obs}}(\eta, q, S)$$

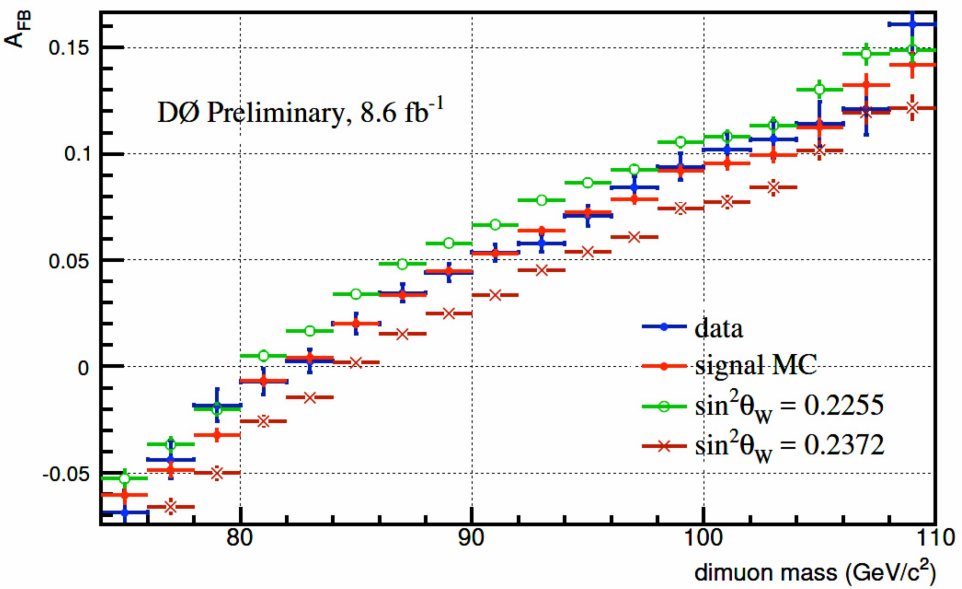




The weak mixing angle @ D0 Zμμ preliminary

- Data-MC comparisons:
  - 481,239 events selected in data; dijet background ~0.68%, SM background ~0.20%
  - Good agreements of muon p_T/η, and di-muon $p_T/\eta/M/\cos\theta^*$ distributions are observed





- The effective $\sin^2\theta_W$ is extracted from A_{FB} distributions in a mass region of $74<M_{\mu\mu}<110$GeV

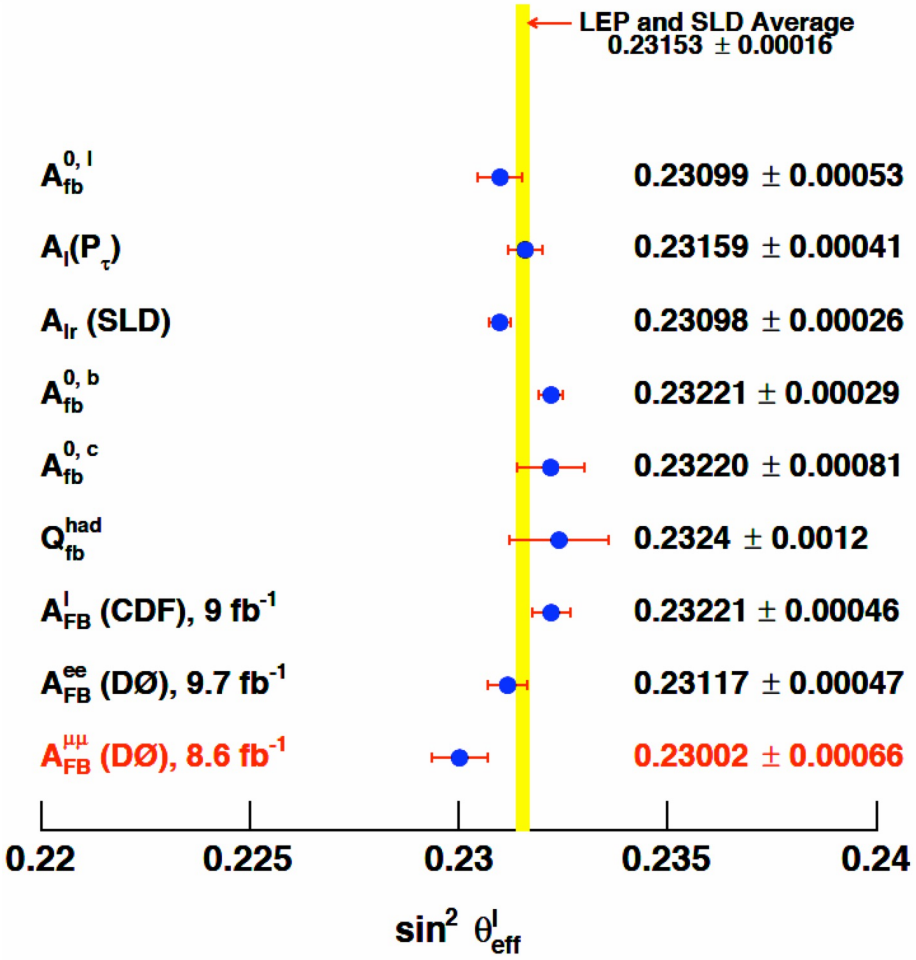
The weak mixing angle @ D0 Zμμ preliminary

- Result: $\sin^2\theta_W^B = 0.22994 \pm 0.00059(\text{stat.}) \pm 0.00011(\text{syst.}) \pm 0.00027(\text{PDF})$
  $= 0.22994 \pm 0.00066$

$\sin^2\theta_W^B$	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

$$\sin^2\theta_{\text{eff}}^{\ell} = 0.23002 \pm 0.00066$$
$$M_W = 80441 \pm 33 \text{ MeV}/c^2$$

New! **D0 Note 6497-CONF**



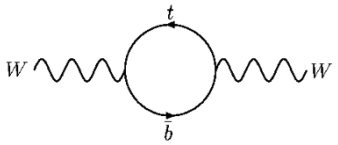
* The D0 Z→ee/μμ channels differ ~1.4 σ

The top mass @ Tevatron

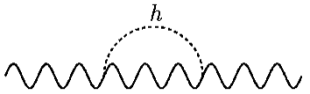
- m_t: the heaviest for Yukawa couplings, and affect W mass at NLO

$$m_W = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W} \frac{1}{(1+\Delta r)}$$

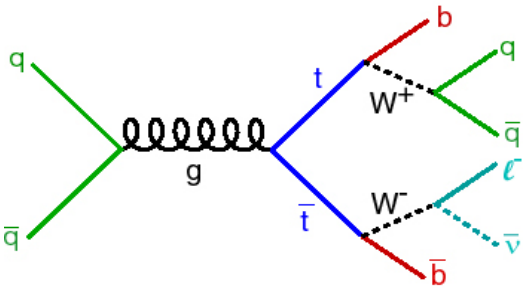
$$\Delta r_{top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2 \tan^2\theta_W} \propto m_t^2$$



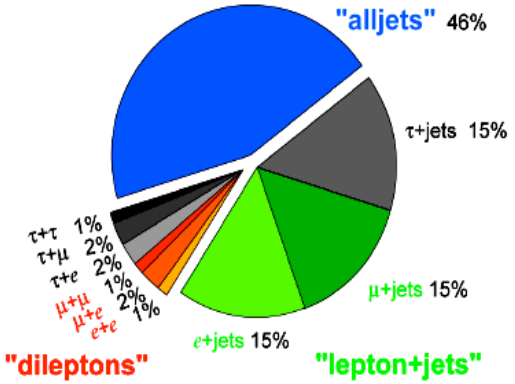
$$\Delta r_{Higgs} \approx \frac{11 G_F M_Z^2 \cos^2\theta_W}{24\sqrt{2}\pi^2} \ln\frac{m_h^2}{M_Z^2} \propto \ln(m_h)$$



- Measure from top pair production with Br(t→Wb) ~ 100%



σ_{NLO} ~ 6.7 pb



- "lepton+jets" channels : 1*l*(*l*=e/μ), 4 well isolated jets, b-tagging, MET; Br~30%
- "dileptons" channels: 2*l*(*l*=e/μ), 2 isolated jets, b-tagging, MET; Br~4.5%
- "alljets" channels: 6 isolated jets, b-tagging; Br~46%

The top mass: lepton+jets @ D0

- Event Probability Density :

$$P_{\text{evt}} = A(\vec{x})\left[f P_{\text{sig}}(\vec{x}; m_t, k_{\text{JES}}) + (1-f) P_{\text{bkg}}(\vec{x}; k_{\text{JES}})\right]$$

$A(\vec{x})$: l+4j's vector; P_{sig}: signal probability; f: signal fraction; P_{bkg}: background probability; k_{JES}: overall JES *in situ* calibration W→qq'

- Matrix element (ME) of signal probability:

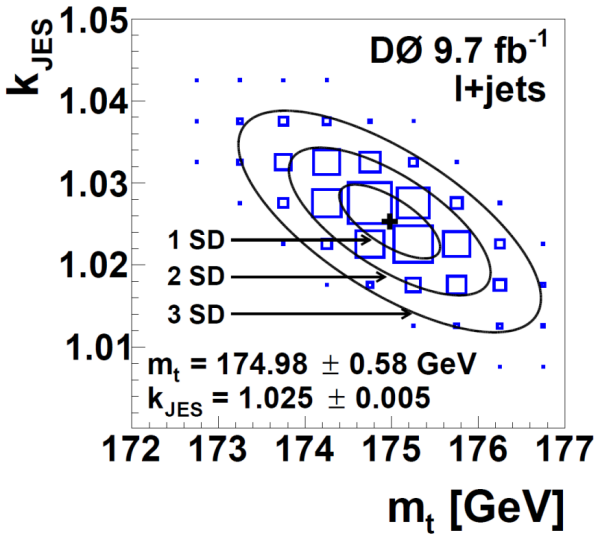
$$P_{\text{sig}}(\vec{x}; m_t, k_{\text{JES}}) = \frac{1}{\sigma_{p\bar{p}\to t\bar{t},\text{obs}}(m_t, k_{\text{JES}})} \sum_{\substack{\text{quark} \\ \text{flavors}}} \int_{\vec{q}_1,\vec{q}_2} \mathrm{d}\vec{q}_1 \mathrm{d}\vec{q}_2 f(\vec{q}_1) f(\vec{q}_2) \frac{(2\pi)^4 \left|\mathscr{M}_{q\bar{q}\to t\bar{t}}\right|^2}{2 g_{\mu\nu} q_1^{\mu} q_2^{\nu}} \mathrm{d}\Phi_6 \; W(\vec{x}, \vec{y}; k_{\text{JES}})$$

- Likelihood fits:

Contribution	e+jets			μ+jets		
$t\bar{t}$	918.1	±	3.6	824.9	±	3.5
Other backgrounds	97.8	±	0.5	79.2	±	0.9
W + hf	126.0	±	2.1	162.2	±	2.8
W + lf	77.9	±	2.1	101.0	±	2.9
Multijet	144.4	±	24.2	48.2	±	16.1
Expected	1364.1	±	24.7	1215.5	±	17.0
Observed	**1502**			**1286**		

174.98 ± 0.58 (stat.) ± 0.49 (syst.) GeV

* Dominant syst. as S/B modeling and JES residual



PRD 91(2015)112003

The top mass: dilepton @ D0

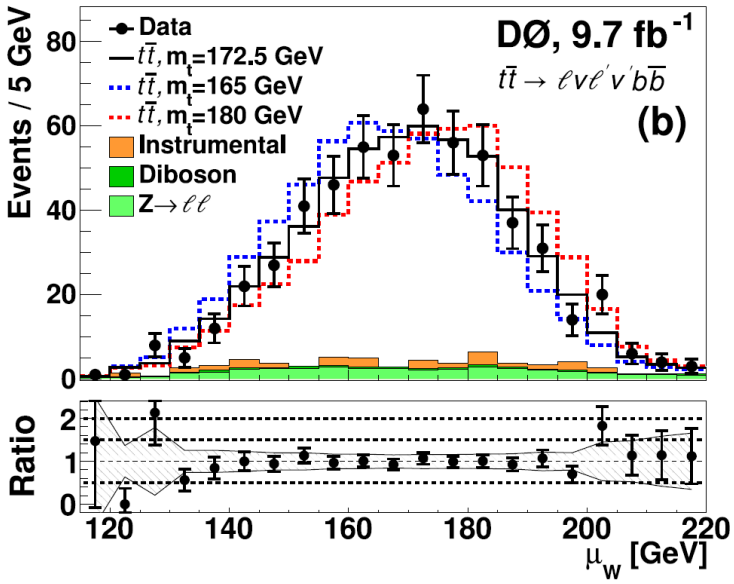
- Under-constrained for m_t :

$$3\times(e^-\bar{\nu}_e b+\mu^+\nu_\mu \bar{b})-3\times(e\mu jj)-\not{E}_T(x,y)-m_W(e^-\bar{\nu}_e)-m_W(\mu^+\nu_\mu)-(m_t=m_{\bar{t}})$$
$$=3\times6-3\times4-2-1-1-1=18-17=1$$

- Neutrino weighting (NW) method:

$$\omega=\frac{1}{N}\sum_{i=1}^{N}\prod_{j=x,y}\exp\left(-\frac{(\not{E}_{T_{j,i}}^{\text{calc}}-\not{E}_{T_j}^{\text{obs}})^2}{2\sigma^2_{\not{E}^u_{T\,j}}}\right)$$

- ✓ Event $\omega(m_t)$ distribution calculated with m_t points
- ✓ The first 2 moments $[\mu_\omega,\sigma_\omega]$ as estimators for LH fit



- Results:

m_t (NW) = 173.32 ± 1.36 ± 0.85 GeV
PLB 752(2016)18

m_t (ME) = 173.93 ± 1.61 ± 0.88 GeV
PRD 94(2016)032004

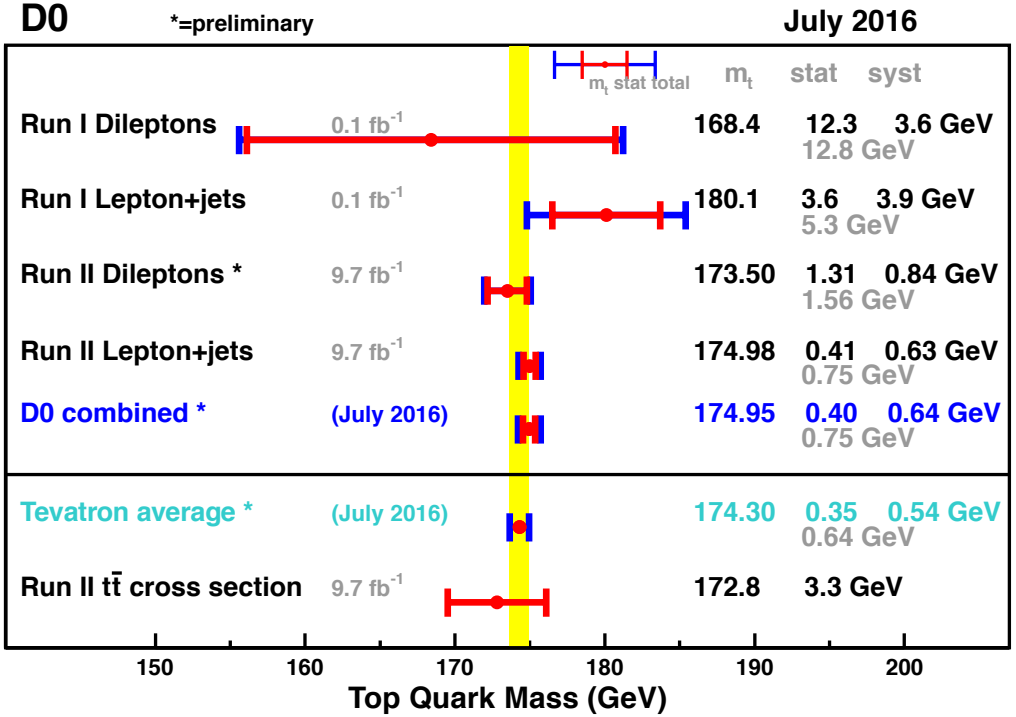
173.50 ± 1.31 ± 0.84 GeV

D0 Note 6484-CONF

* Dominant syst. as JES and signal modeling;
Stat. correlation between NW and ME by BLUE

The top mass @ 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



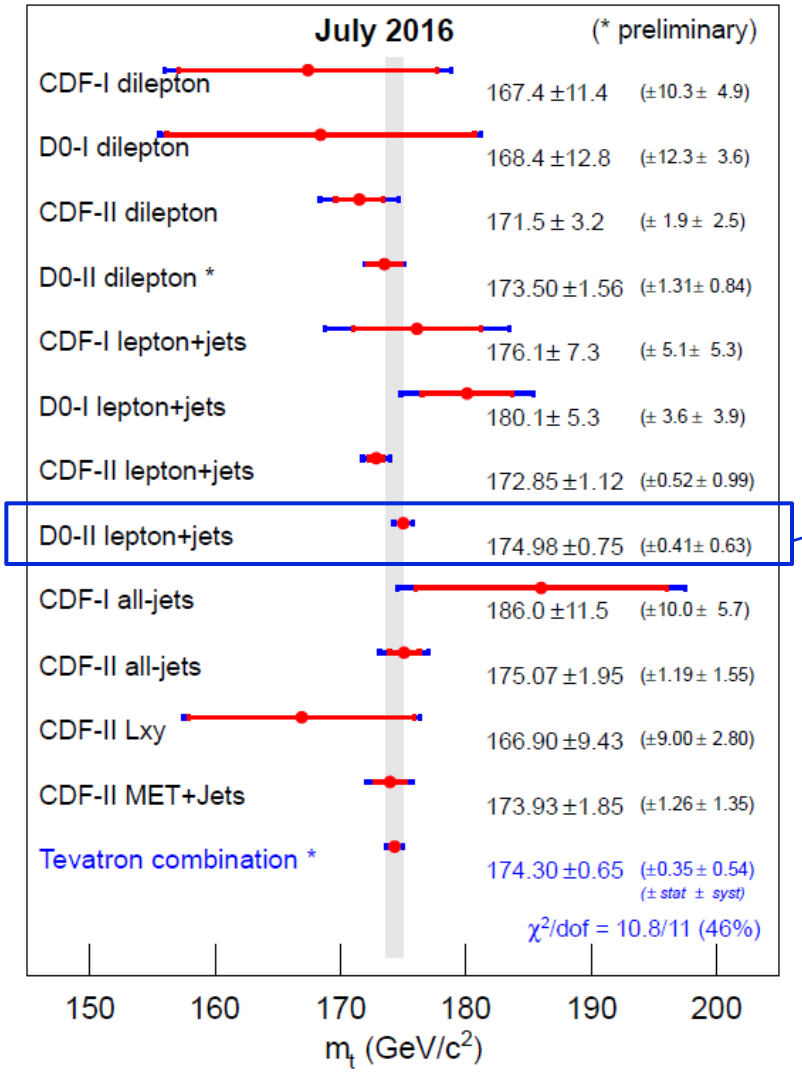
	D0 combined values (GeV)
m_t	174.95
In situ light-jet calibration	0.41
Response to b, q, and g jets	0.16
Model for b jets	0.09
Light-jet response	0.21
Out-of-cone correction	< 0.01
Offset	< 0.01
Jet modeling	0.07
Multiple interaction model	0.06
b tag modeling	0.10
Lepton modeling	0.01
Signal modeling	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

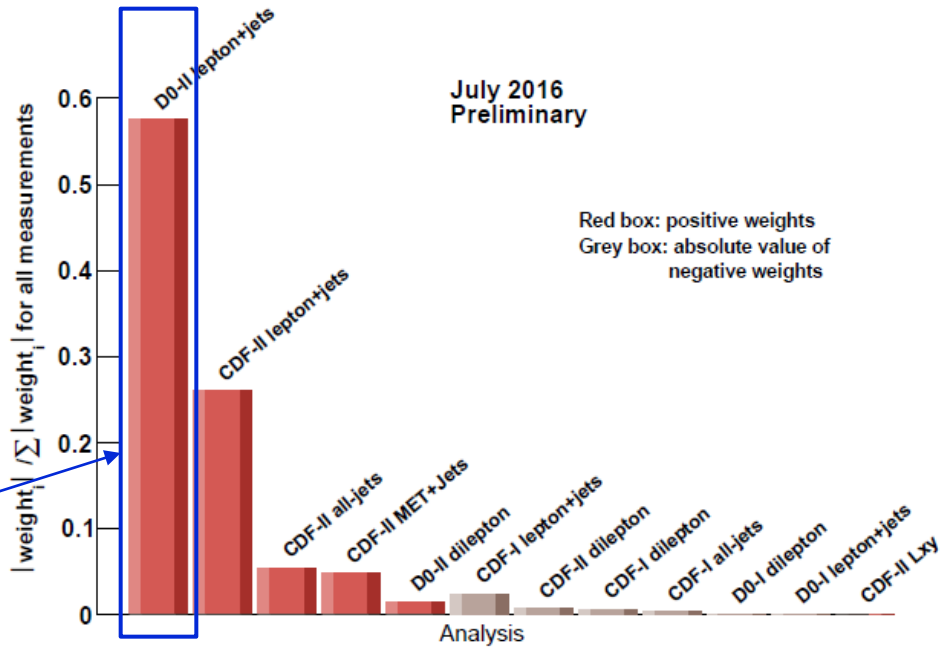
174.95 ± 0.75 GeV

D0 Note 6485-CONF

The top mass @ Tevatron

- Combination of 12 CDF and D0 results, with the same uncertainty and correlation definition





174.30 ± 0.65 GeV

arXiv:1608.01881

Summary

- W mass:
  - The current Tevatron combination, **80387 ± 16** MeV, the most precise direct measurement
  - Analysis of full CDF and D0 data are in progress

- Weak mixing angle:
  - Preliminary Tevatron combination of **0.23179 ± 0.00035** with CDF Z(ee/μμ) and D0 Z(ee), and Tevatron indirect W mass result of **80351 ± 18** MeV
  - The preliminary result of **0.23002 ± 0.00066** for D0 Z(μμ) measurement
  - The final Tevatron combination will be done, and expected to significantly contribute to the sensitivity of direct Z-pole measurements as the LEP/SLD/Tevatron Average

- Top mass:
  - The full Tevatron combination, **173.30±0.65** GeV
  - The latest D0 combination update, **174.95±0.75** GeV, submitted to PRD