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Measurements & combination of the weak-mixing angle $\sin^2\theta_W$ at the Tevatron

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On behalf of the CDF & DØ collaborations

Motivation

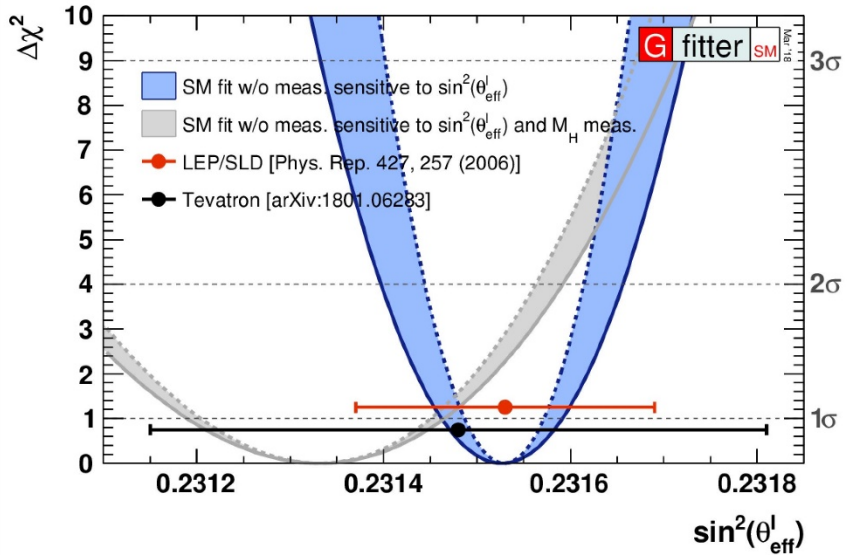
- Fundamental parameters of the Standard Model：

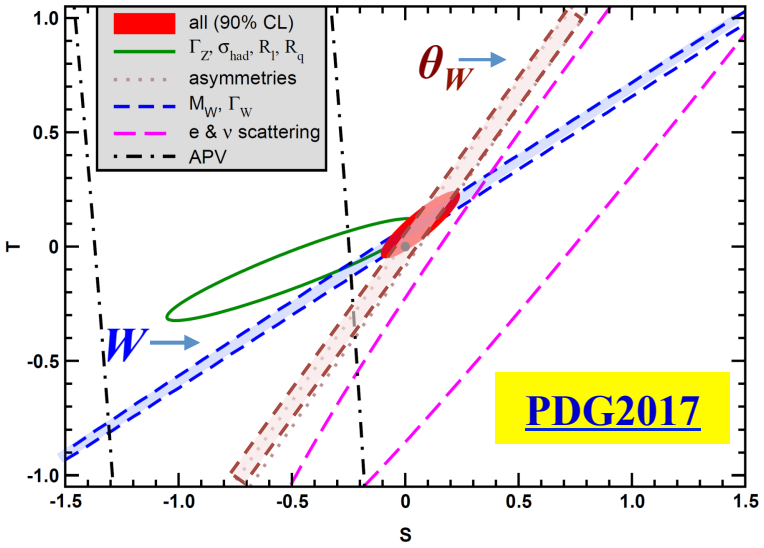
$$\alpha;\quad G_F;\quad M_Z;\quad M_W;\quad \boxed{\sin^2\theta_W = e^2/g^2 = 1 - \frac{M_W^2}{M_Z^2}};\quad m_{top};\quad M_H;$$

(on-shell)

Over-constraint for the electroweak SU(2)⊗U(1) symmetry breaking mechanism

- Input for the SM Global Fits：

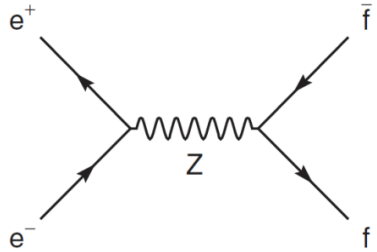




PDG2017: ~1.7σ in the SM EW global fits; sensitive to new physics, e.g. STU parameters

The effective weak-mixing angle

- The weak neutral current g_V-g_A (V-A) couplings:

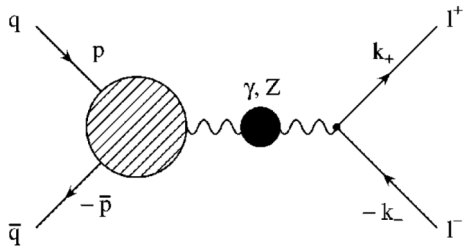


$$-i\frac{g}{2\cos\theta_W}\bar{f}\gamma^\mu(g_V^f - g_A^f\gamma_5)fZ_\mu$$

Born level:

$$\begin{cases} g_V^f = T_3^f - 2Q_f \sin^2\theta_W \\ g_A^f = T_3^f, \end{cases}$$

- Factorization of high order corrections:



$$\begin{cases} g_V^f \rightarrow \sqrt{\rho_{eq}}\,(T_3^f - 2Q_f\kappa_f \sin^2\theta_W) \\ g_A^f \rightarrow \sqrt{\rho_{eq}}\,T_3^f, \end{cases}$$

The 2-loop corrections, included in **ZFITTER** and PDG GAPP, as effective Born approximation.

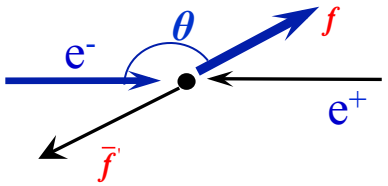
- The effective mixing angle of lepton:

$$\sin^2\theta^l_{\text{eff}} = \text{Re}[\kappa_l(\text{M}_\text{Z})] \cdot \sin^2\theta_\text{W}$$

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

The weak-mixing angle @ LEP/SLD

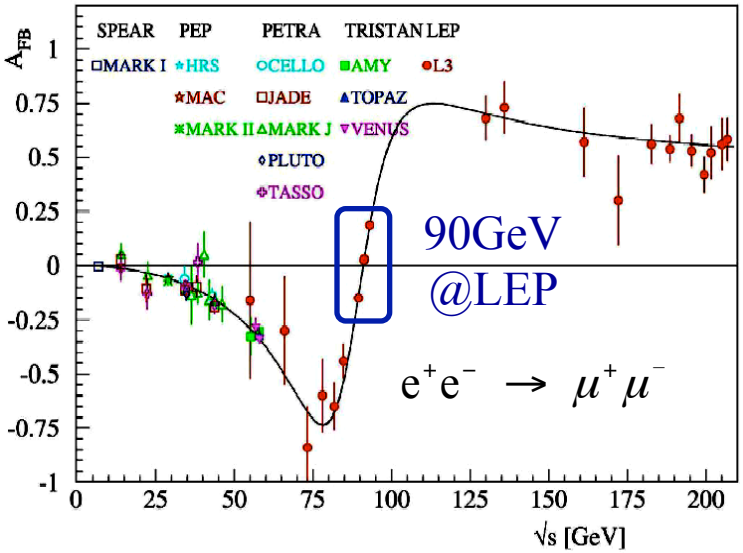
- Parity violation observables at Z-pole :



$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta + A_4\cos\theta \Rightarrow A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}A_4$$

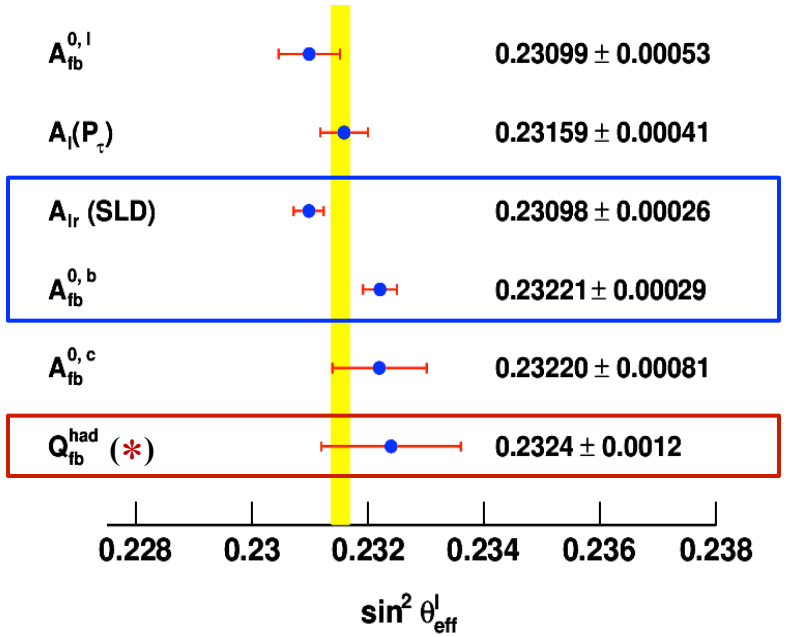
Dominated by the Z-pole V-A self-interference $\propto I_{3l}(1 - 4|Q_l|\sin^2\theta_W) \cdot I_{3f}(1 - 4|Q_f|\sin^2\theta_W)$

- Combined LEP/SLD results:



The LEP/SLD Average

0.23153 ± 0.00016

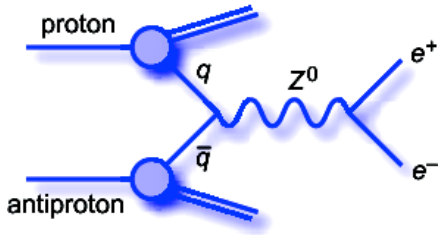


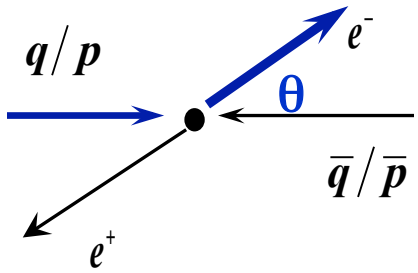
(*) The LEP hadron inclusive $\mathbf{Q_{fb}^{had}}$ measured light quark $q\bar{q}$ asymmetry with large uncertainty!

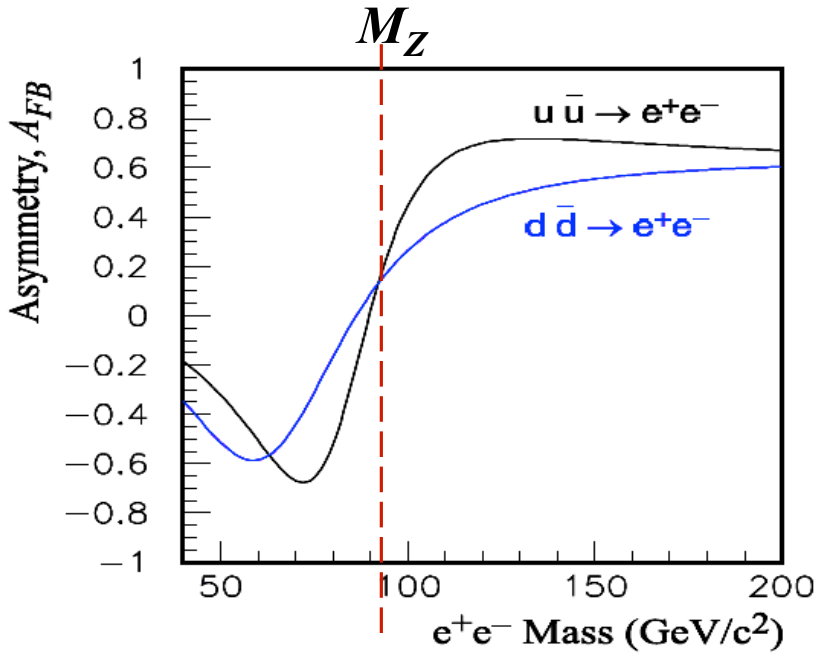
The weak-mixing angle @ Tevatron

- Lepton charge forward-backward asymmetry A_{FB} in Drell-Yan final states

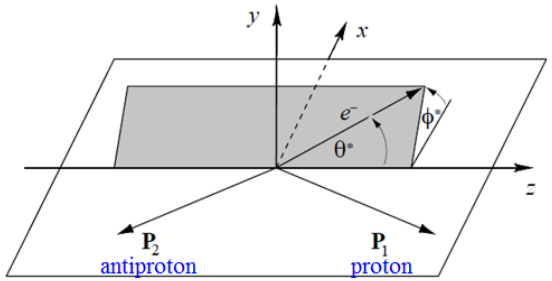
$$p\bar{p} \rightarrow q\bar{q} \rightarrow Z \rightarrow l^- l^+$$







Collins-Soper frame

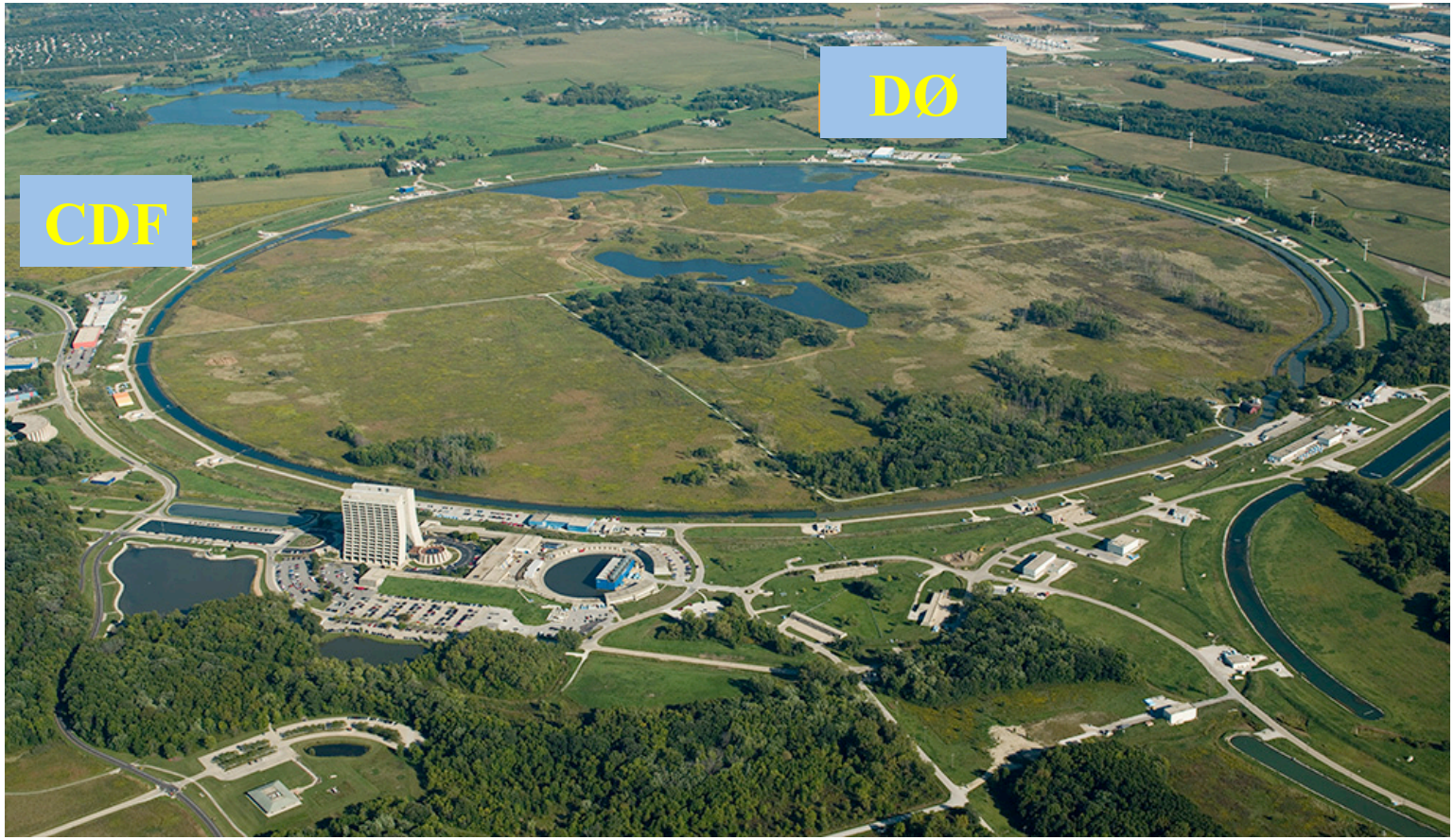


$$\cos\theta^* = \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$

- Expected $\delta\sin^2\theta_W \sim 0.0005$ @ D0 10fb^{-1}, predicted in 2000 [arXiv:hep-ex/0011009]

The Tevatron Experiments @ Fermilab

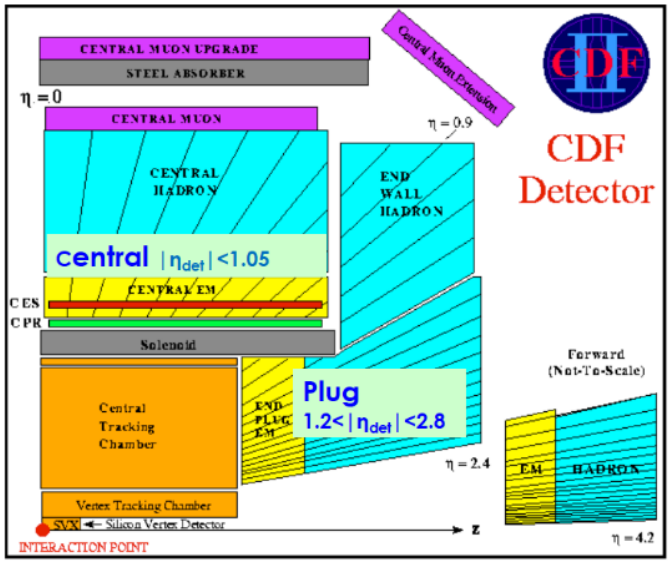
- Collidor: proton-antiproton

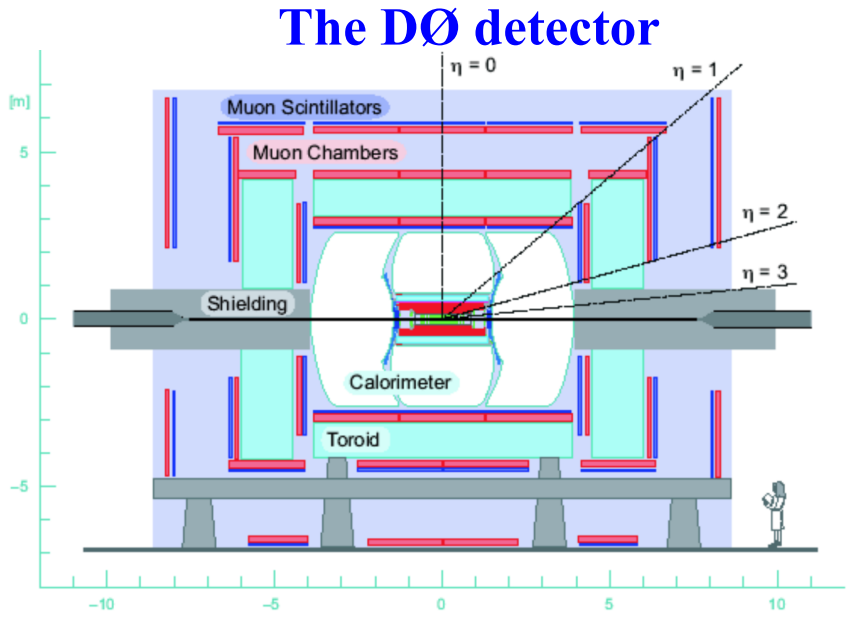


	√s (TeV)	L (fb^{-1})
Run II (2001-2011)	**1.96**	**~ 9-10**

The Tevatron Experiments @ Fermilab

- Experiments: **CDF** and **DØ**
  - General purpose detectors for broad spectrum of physics researches





- CDF had a better tracker;
- DØ had better coverage for e and μ

The weak-mixing angle @ CDF & DØ

- Common strategy:
  - Selection: strict di-lepton events in Z-pole mass region
  - Extraction: observed $A_{FB}(M_{ll})$ vs MC templates with different $\sin^2\theta_W$ inputs
  - Uncertainty: statistical + PDF + systematic dominated by lepton calibrations

- Summary of final measurements:

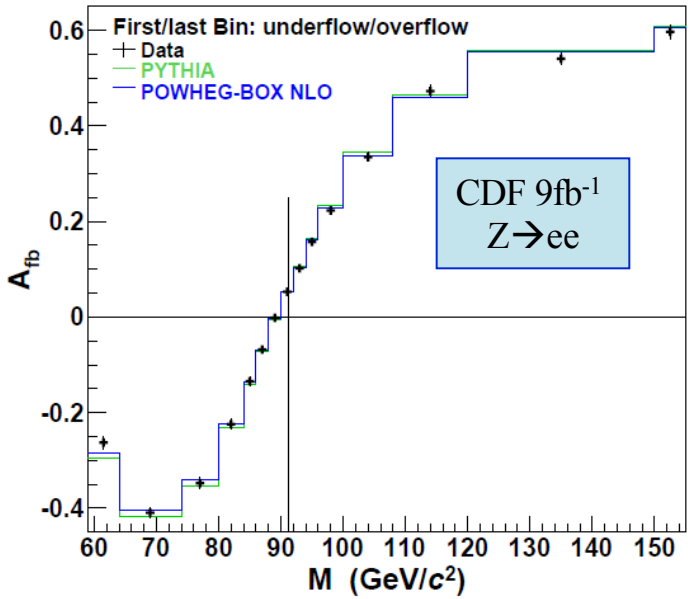
	$\sin^2\theta_W \pm$ stat. $\pm$ syst. $\pm$ PDF	Total uncertainty
CDF Z→ee 9fb^{-1}	0.23248 ± 0.00049 ± 0.00004 ± 0.00019	±0.00053
DØ Z→ee 9.7fb^{-1}	0.23147 ± 0.00043 ± 0.00008 ± 0.00017	±0.00047
CDF Z→μμ 9fb^{-1}	0.2315 ± 0.0009 ± 0.0002 ± 0.0004	±0.0010
DØ Z→μμ 8.6fb^{-1}	0. 23016 ± 0.00059 ± 0.00005 ± 0.00024	±0.00064

The weak-mixing angle @ CDF

- CDF 2.1fb^{-1} Zee A_4 : 0.2328±0.0010, **PRD88(2013)072002**

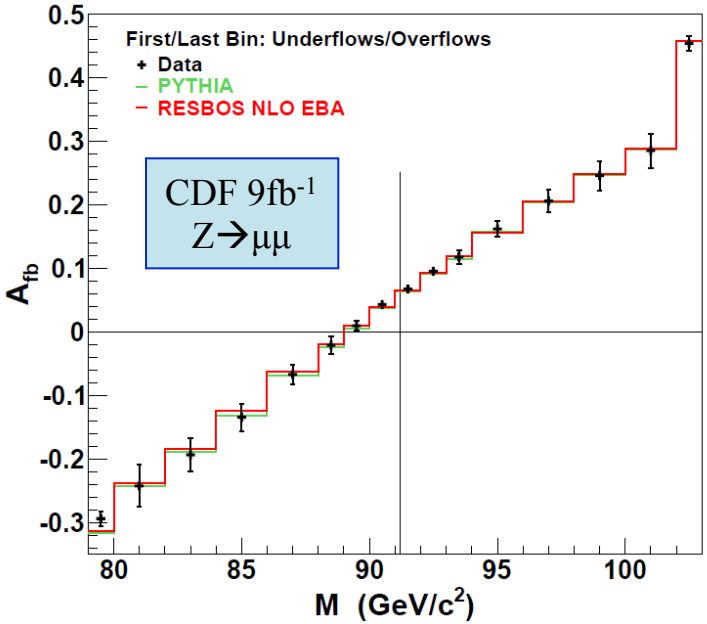
- CDF full data Zee + Zμμ A_{FB} : ZFITTER + lepton E/p calibration + event weighting

PRD 93(2016)112016



0.23248 ± 0.00053

PRD89(2014)072005

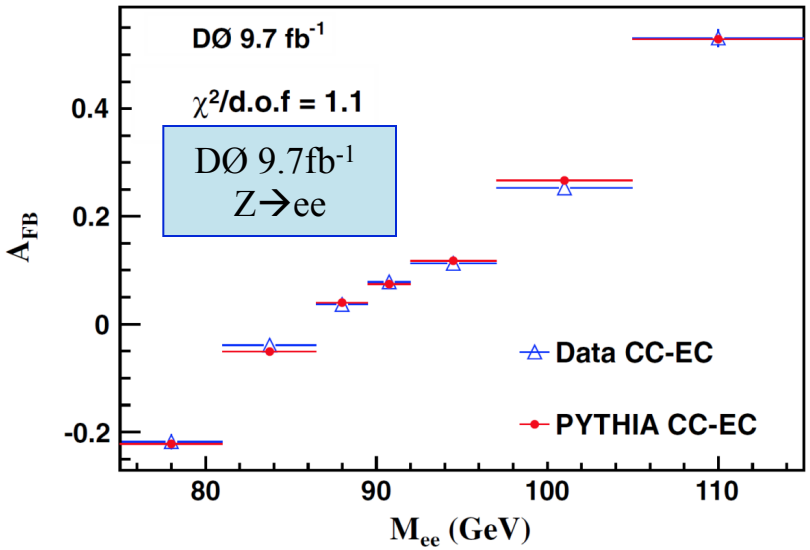


0.2315 ± 0.0010

The weak-mixing angle @ DØ

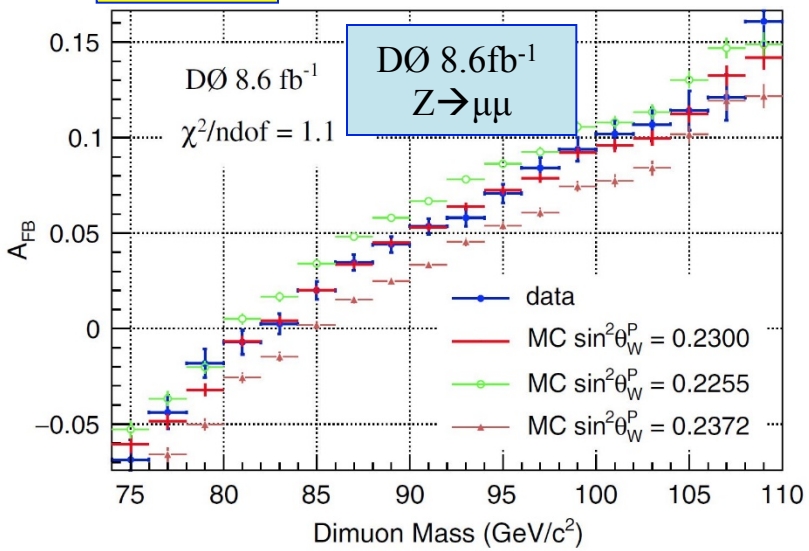
- DØ 1fb^{-1} Zee A_{FB} : 0.2326±0.0019, **PRL101(2008)191801**; feasibility
- DØ 5fb^{-1} Zee A_{FB} : 0.2309±0.0010, **PRD84(2011)012007**; calorimeter uniformity
- DØ full data Zee + Zμμ A_{FB} : improved lepton calibration method

PRL115(2015)041801



0.23147 ± 0.00047

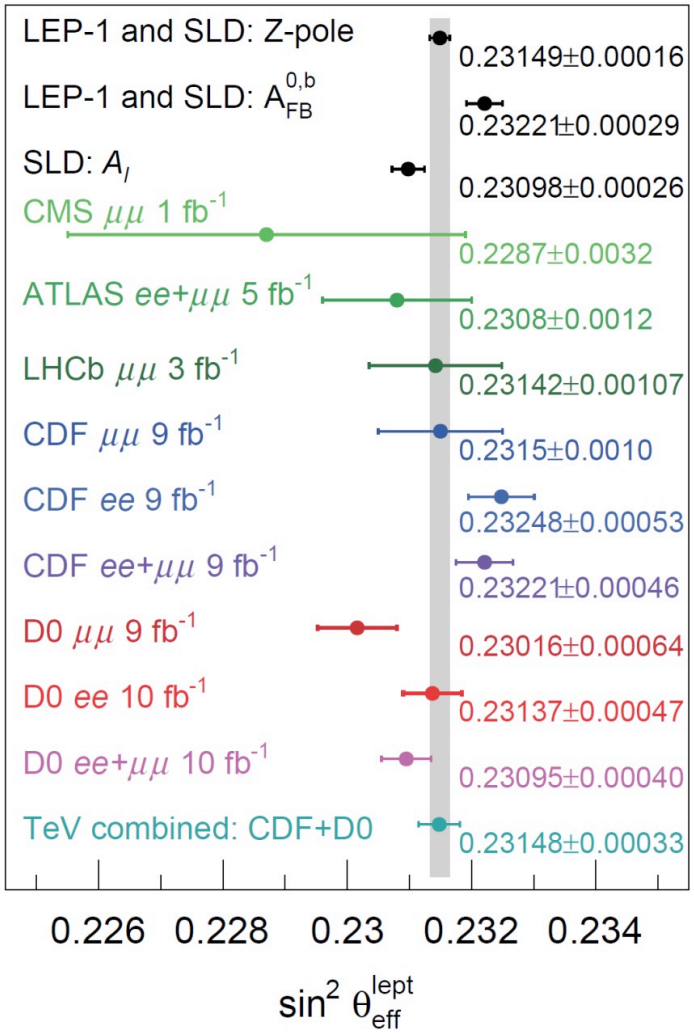
New! **PRL120(2018)241802**



0.23016 ± 0.00064

The weak-mixing angle @ Tevatron

- Combination : High order corrections as ZFITTER + NNPDF3.0



CDF: $0.23221 \pm 0.00043 \pm 0.00007 \pm 0.00016$
$= 0.23221 \pm 0.00046$

DØ: $0.23095 \pm 0.00035 \pm 0.00007 \pm 0.00019$
$= 0.23095 \pm 0.00040$

- PDF uncertainty 100% correlated

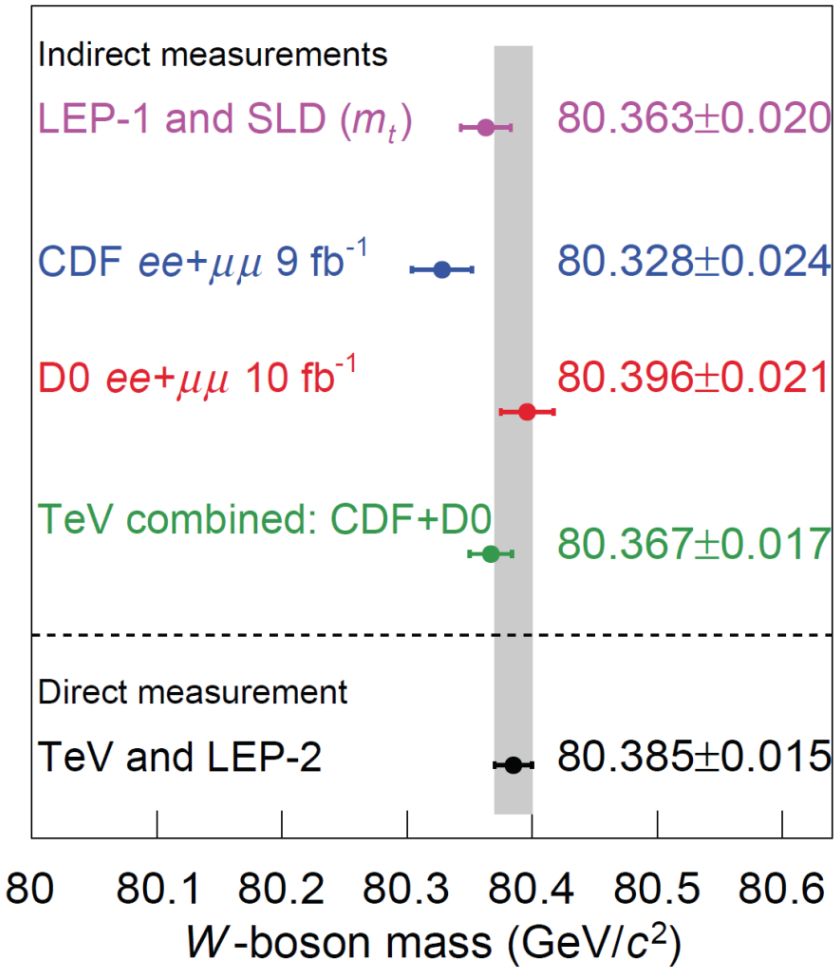
$$\sin^2\theta^l_{eff}[\text{Tev}] = 0.23148 \pm 0.00027(\text{stat}) \pm 0.00005(\text{syst}) \pm 0.00018(\text{PDF}) = \mathbf{0.23148 \pm 0.00033}$$

- Weight CDF/DØ: 0.4/0.6

New! Tevatron legacy published in **Phys. Rev. D 97, 112007**

Indirect W mass @ Tevatron

- Using ZFITTER SM conversion of the effective and on-shell definitions as



$$\sin^2\theta^{l}_{\text{eff}} = \mathrm{Re}[\kappa_l(\mathrm{M_Z})] \cdot \sin^2\theta_{\mathrm{W}}$$

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

- M_W determination in the SM context:

80.367 ± 0.017 (Tevatron Indirect)

80.385 ± 0.015 (Tevatron+LEP Direct)

Summary

- The combined Tevatron $\sin^2\theta^l_{eff}$ achieves the most precise light-quark related measurement at hadron colliders, uncertainty of which is still dominated by statistics

CDF	0.23221 ± 0.00046	PRD 93,112016
DØ	0.23095 ± 0.00040	**PRL 120, 241802**
Tevatron	0.23148 ± 0.00033	**PRD 97, 112007**

New!

- The Tevatron legacy of 0.23148 ± 0.00033 is consistent with the LEP /SLD average of 0.23149 ± 0.00016, providing extra ~24% sensitivity

- Tevatron indirect M_W result assuming the SM, 80.367 ± 0.017 GeV, is consistent with the Tevatron/LEP direct measurement of 80.385 ± 0.015 GeV