中国科学技术大学
University of Science and Technology of China

Measurement of the weak-mixing angle in Z→μμ events at DØ and the combined Tevatron $\sin^2\theta_W$ result

Liang HAN

University of Science & Technology of China (USTC)

On behalf of the DØ collaboration

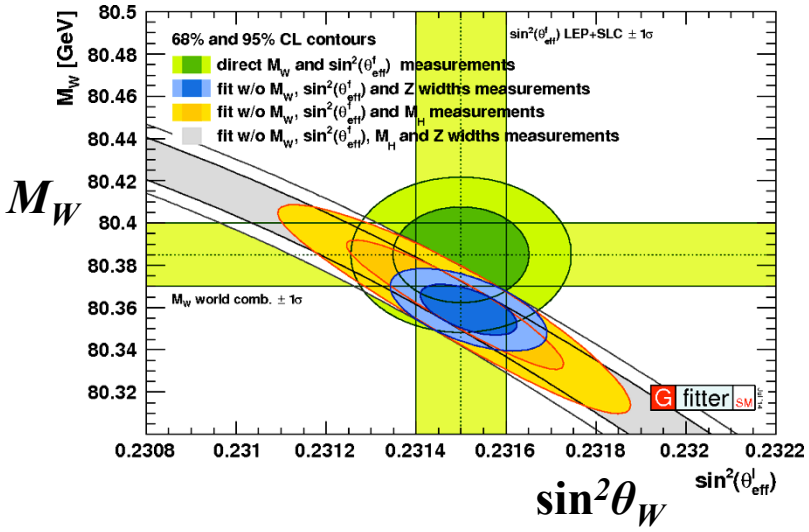
Motivation

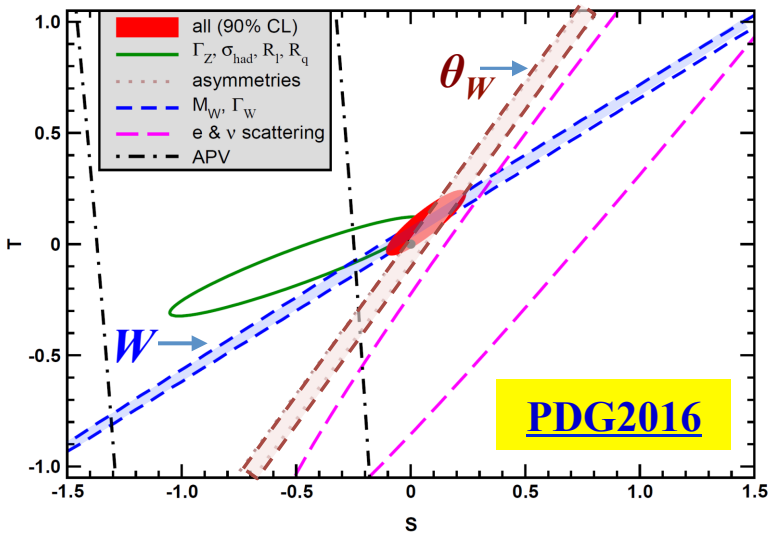
- Fundamental parameters of the Standard Model：

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

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

- Important input for the SM Global Fits：

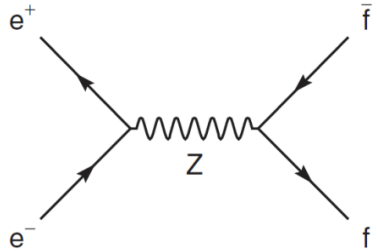




PDG2016: ~1.6σ direct vs. indirect; sensitive to new physics, e.g. STU parameters

The effective weak-mixing angle

- The weak neutral current g_V-g_A couplings:



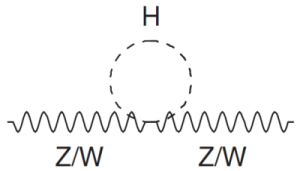
$$-i\frac{g}{2\cos\theta_W}\bar{f}\gamma^{\mu}(g_V^f - g_A^f\gamma_5)fZ_{\mu}$$

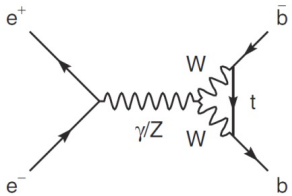
Born level:

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

- Flavor factorization of high order corrections

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





Complete 2-loop corrections included in **ZFITTER** and PDG GAPP etc.

- The effective mixing angle of lepton:

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

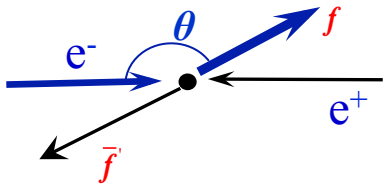
Modified **Resbos**:

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

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

The weak-mixing angle @ LEP/SLD

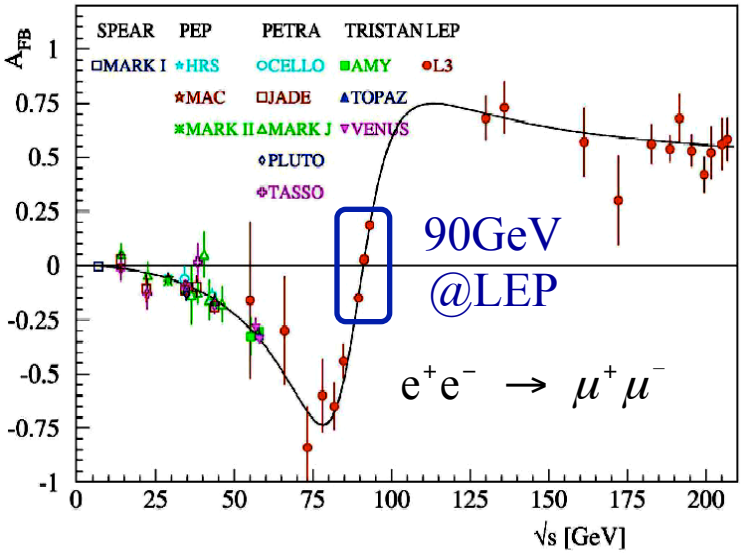
- Parity violation at Z-pole :

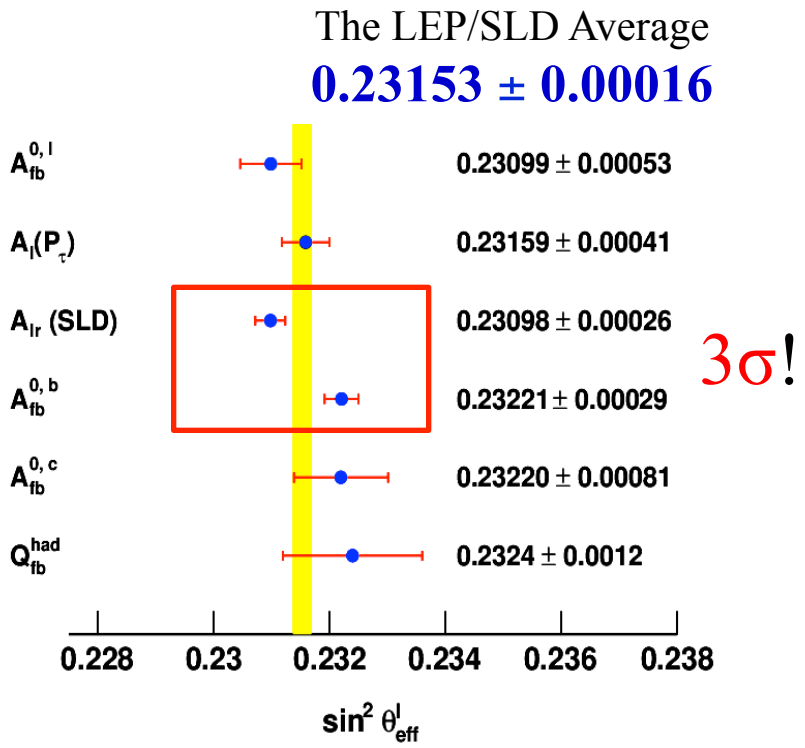


$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta + A_4\cos\theta \Rightarrow A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}A_4$$

Dominated by Z self-interference $Z_{VV} \otimes Z_{AA} \propto I_{3l}(1 - 4|Q_l|\sin^2\theta_W) \cdot I_{3f}(1 - 4|Q_f|\sin^2\theta_W) \cdot I_{3l} \cdot I_{3f}$

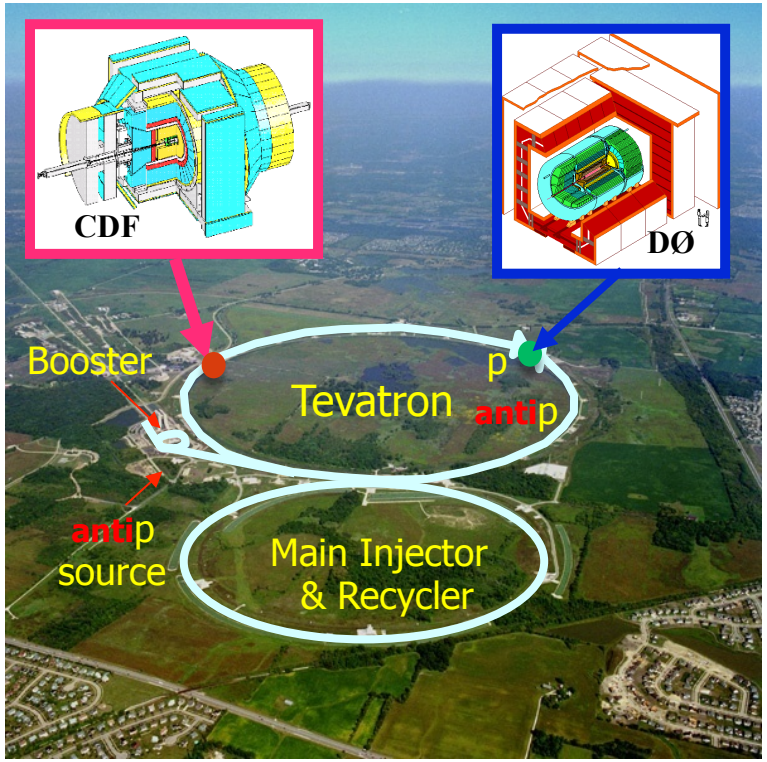
- Combined LEP/SLD results:





The Tevatron Experiments @ Fermilab

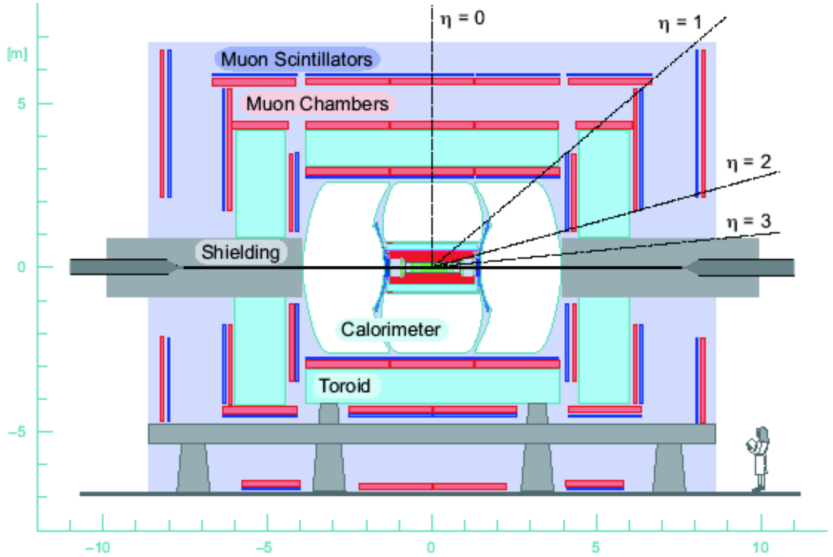
- Collide: proton-antiproton



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

- Experiments: **CDF** and **DØ**

The DØ detector

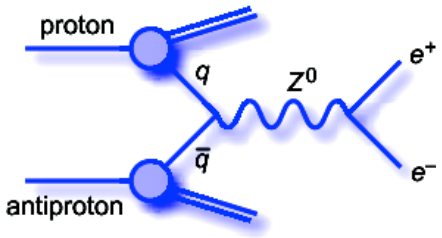


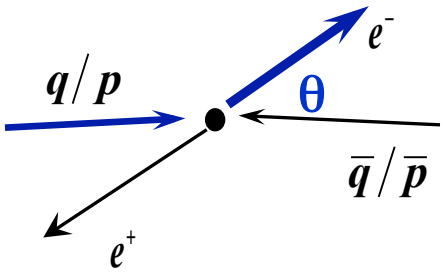
- ✓ **Tracking: silicon strips + scintillator fibers, $|\eta|<3.0$ in 2T solenoid**
- ✓ **LAr Calorimeter: Central (CC) $|\eta|<1.1$, Endcap (EC) $1.5<|\eta|<3.2$**
- ✓ **Muon: $|\eta|<2.0$**

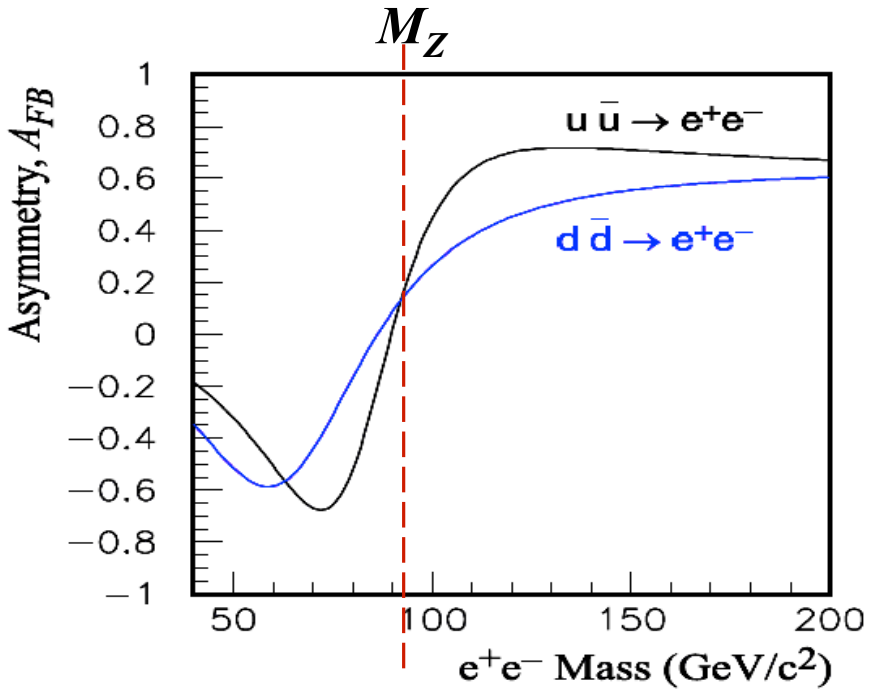
The weak-mixing angle @ Tevatron

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

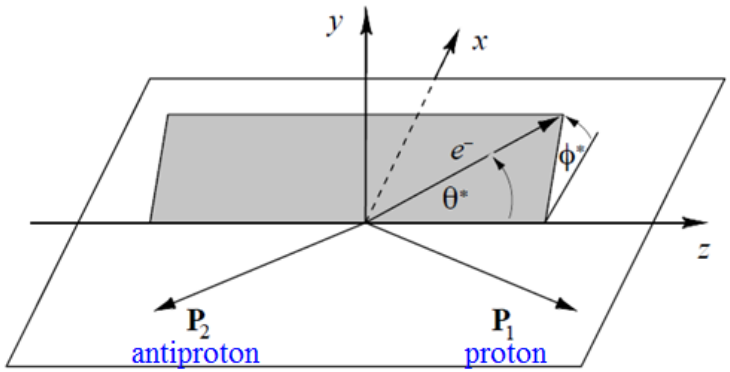
$$p\bar{p} \rightarrow q\bar{q} \rightarrow Z \rightarrow l^- l^+$$







Collins-Soper frame

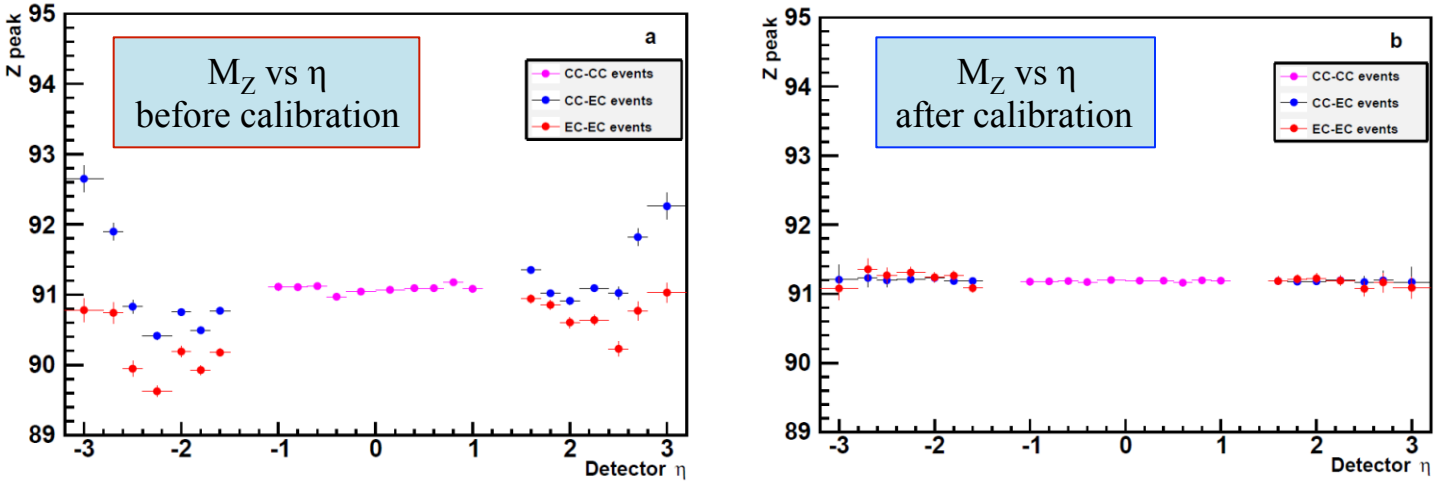


$$\cos\theta^* = \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$

Previous DØ Z→ee results

- Run2a 1fb^{-1}: 0.2326±0.0018(stat.)±0.0006 (syst.), **PRL101(2008)191801**; Feasibility
- Run2b 5fb^{-1}: 0.2309±0.0008(stat.)±0.0006 (syst.), **PRD84(2011)012007**; Calorimeter uniformity
- Run2 full 9.7fb^{-1}:

  Novel electron calibration → systematic uncertainty suppressed + 80% more data



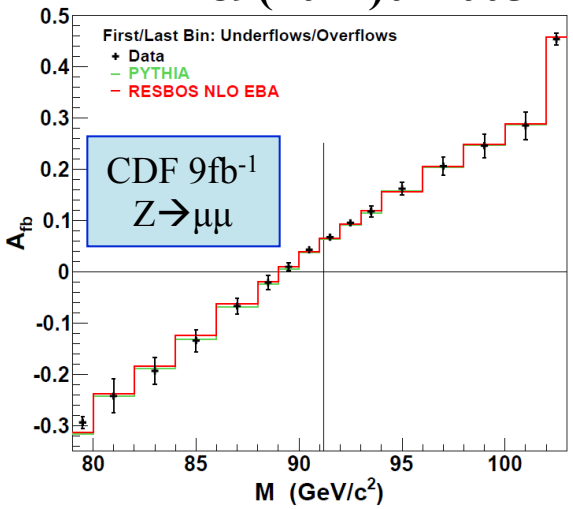
0.23147 ± 0.00043(stat.) ± 0.00008 (syst.) ± 0.00017 (NNPDF)

PRL115 (2015) 041801

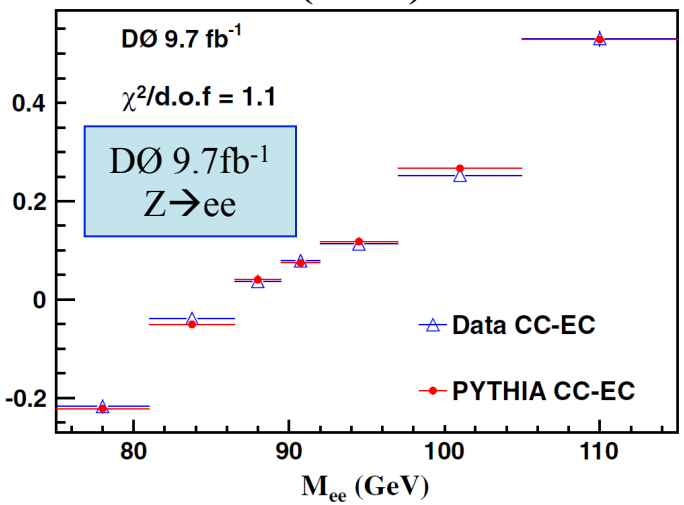
Previous CDF+DØ results

- Tevatron publications:

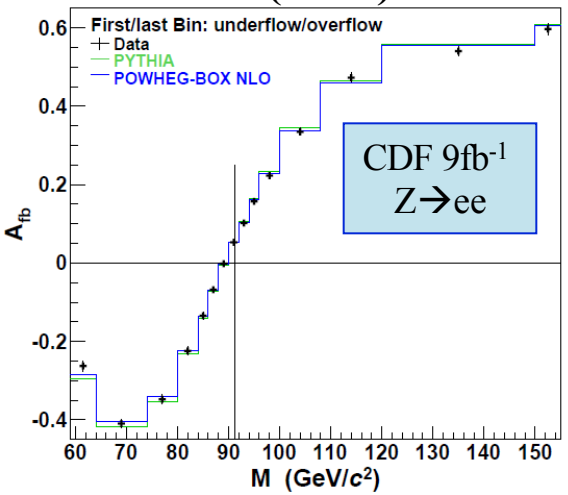
PRD 89(2014)072005



PRL115(2015)041801



PRD 93(2016)112016



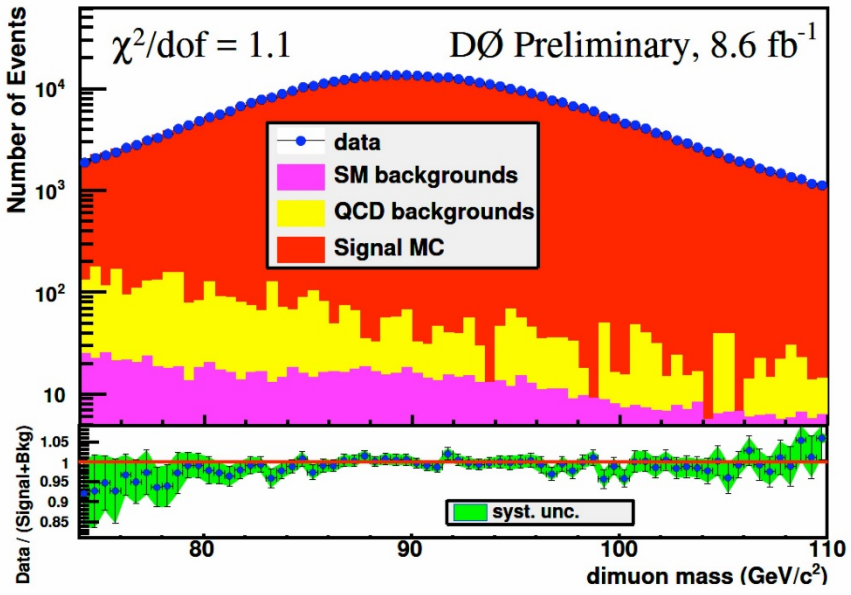
	$\sin^2\theta_W \pm$ stat. $\pm$ syst. $\pm$ PDF	Total uncertainty
CDF Z→μμ 9fb^{-1}	0.2315 ± 0.0009 ± 0.0002 ± 0.0004	±0.0010
DØ Z→ee 9.7fb^{-1}	0.23147 ± 0.00043 ± 0.00008 ± 0.00017	±0.00047
CDF Z→ee 9fb^{-1}	0.23248 ± 0.00049 ± 0.00004 ± 0.00019	±0.00053

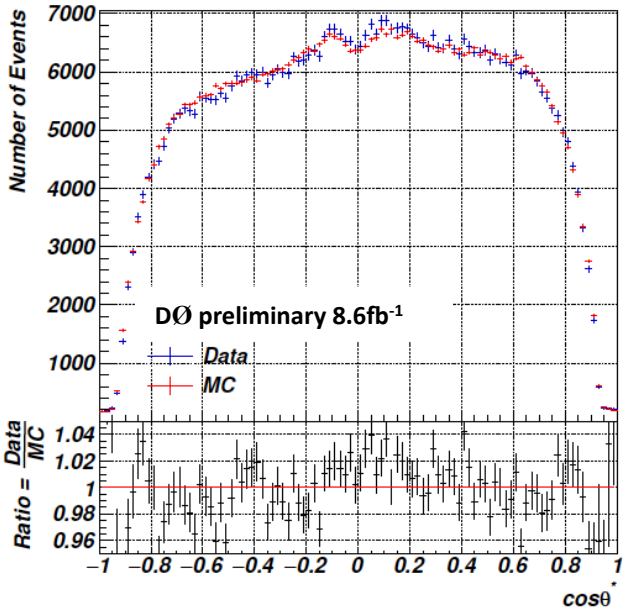
- CDF Z→ee/μμ (2016) = 0.23221 ± 0.00046
- DØ Z→ee (2015) = 0.23147 ± 0.00047

The weak-mixing angle @ DØ Z→μμ preliminary

- The last missing channel @ Tevatron :
  - dimuon data: muon with p_T>15 GeV, |η|<1.8, strict track quality requirements; cosmic veto; 74< $M_{\mu\mu}$<110 GeV; opposite charge → **8.6** fb^{-1}
  - Drell-Yan MC: Pythia LO + NNPDF3.0 + DØ detector-based GEANT simulations

- Data-MC comparisons:
  - 481,239 events selected in data; background subtraction, dijet ~0.68% + SM ~0.20%
  - Good agreements of muon p_T/η, and di-muon p_T/η/M/cosθ* distributions are observed



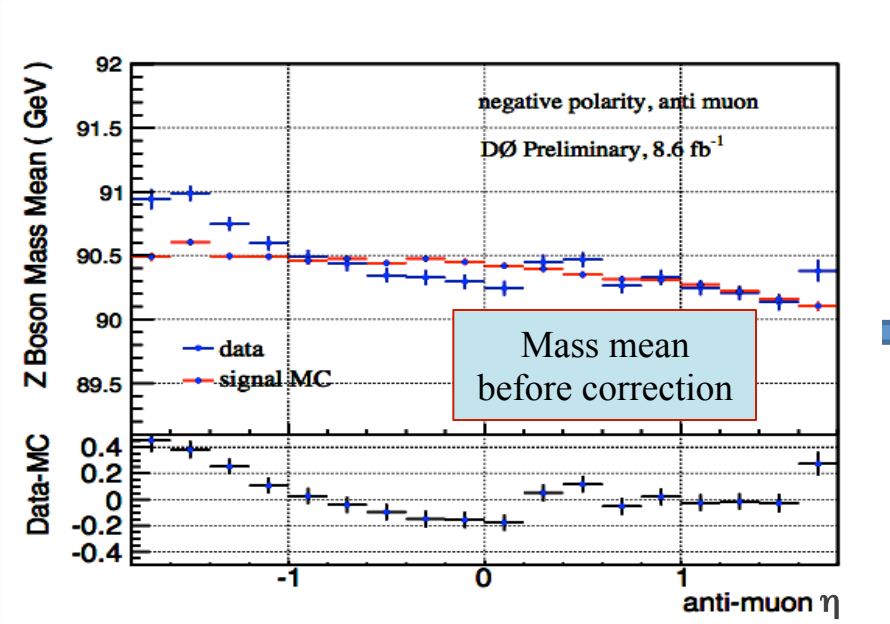


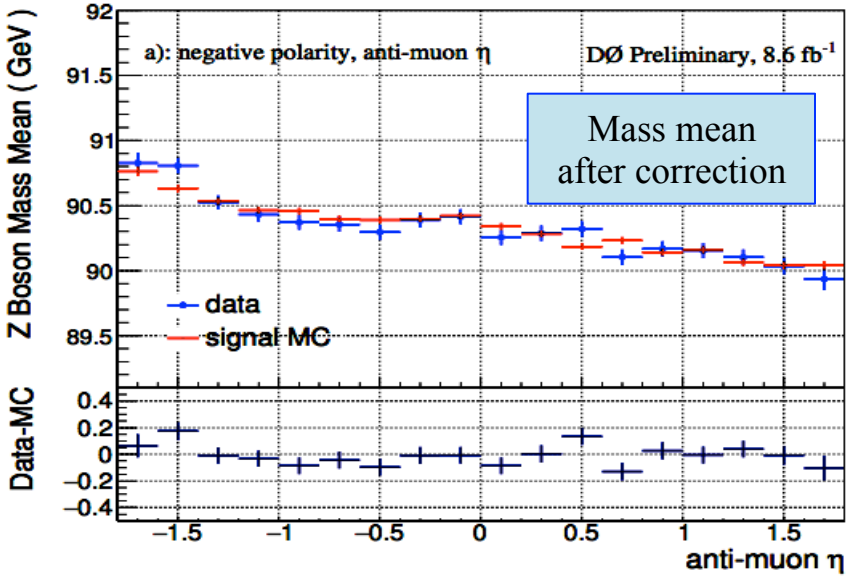
The weak-mixing angle @ DØ Z→μμ preliminary

- Muon momentum calibration:
  - Correct momentum for residual q-η-solenoid dependence after standard DØ muon calibration

$$P_{\text{corr}} = \alpha(\eta, q, S) \cdot P_{\text{obs}}$$

  - Tune the dimuon mass means of data/MC to the generator level with the same kinematic cuts



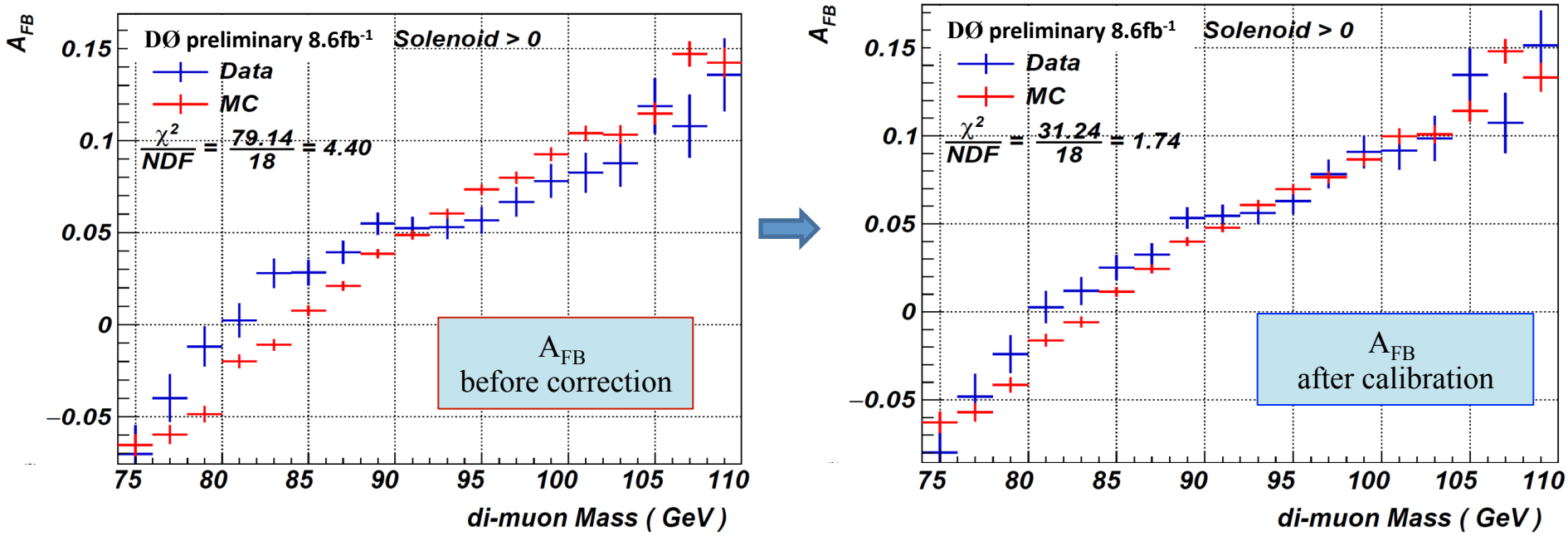


$\delta M_{\text{MC-data}} \sim$ **1** GeV

$\delta M_{\text{MC-data}} <$ **100** MeV

The weak-mixing angle @ DØ Z→μμ preliminary

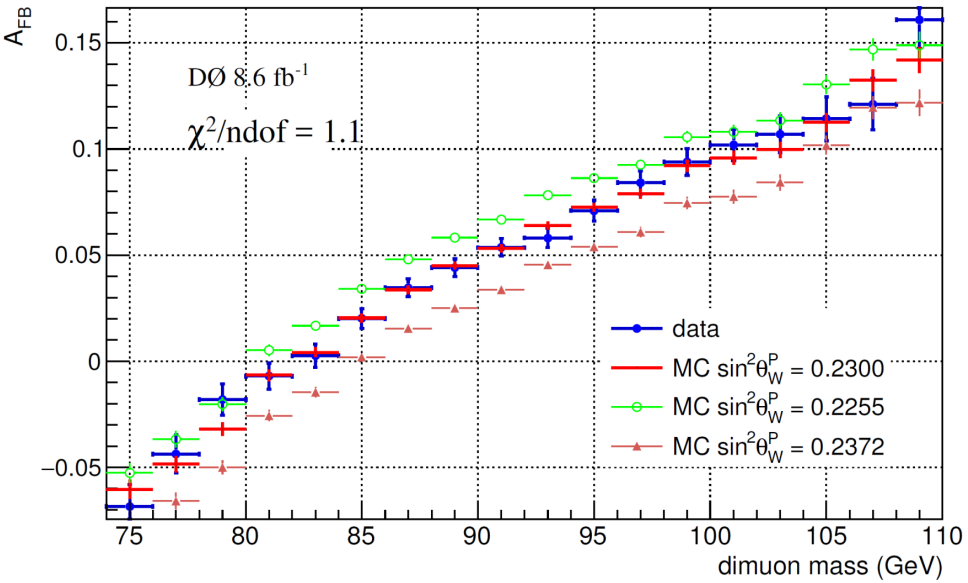
- Muon momentum calibration:
  - The apparent difference in A_{FB} mass distributions between data and MC has been mitigated



The systematic uncertainty due to muon momentum scale is suppressed, i.e. ~ 0.00002 on the weak mixing angle extraction

The weak-mixing angle @ DØ Z→μμ preliminary

- Extraction of $\sin^2\theta_W$:
  - Compare bkg-subtracted raw A_{FB} to parameterized simulation templates in 74 <$M_{\mu\mu}$<110 GeV
  - Minimal-χ^2 to get the best fit of the LO Pythia predictions



$$\sin^2\theta_W^B = 0.22994 \pm 0.00059(\text{stat.}) \pm 0.00005\ (\text{syst.}) \pm 0.00024\ (\text{PDF})$$

- Interpret the Pythia LO result to the effective $\sin^2\theta_W$ with high order corrections of ZFITTER convention, a shift is applied of + 0.00022 ± 0.00004

The weak-mixing angle @ DØ Z→μμ preliminary

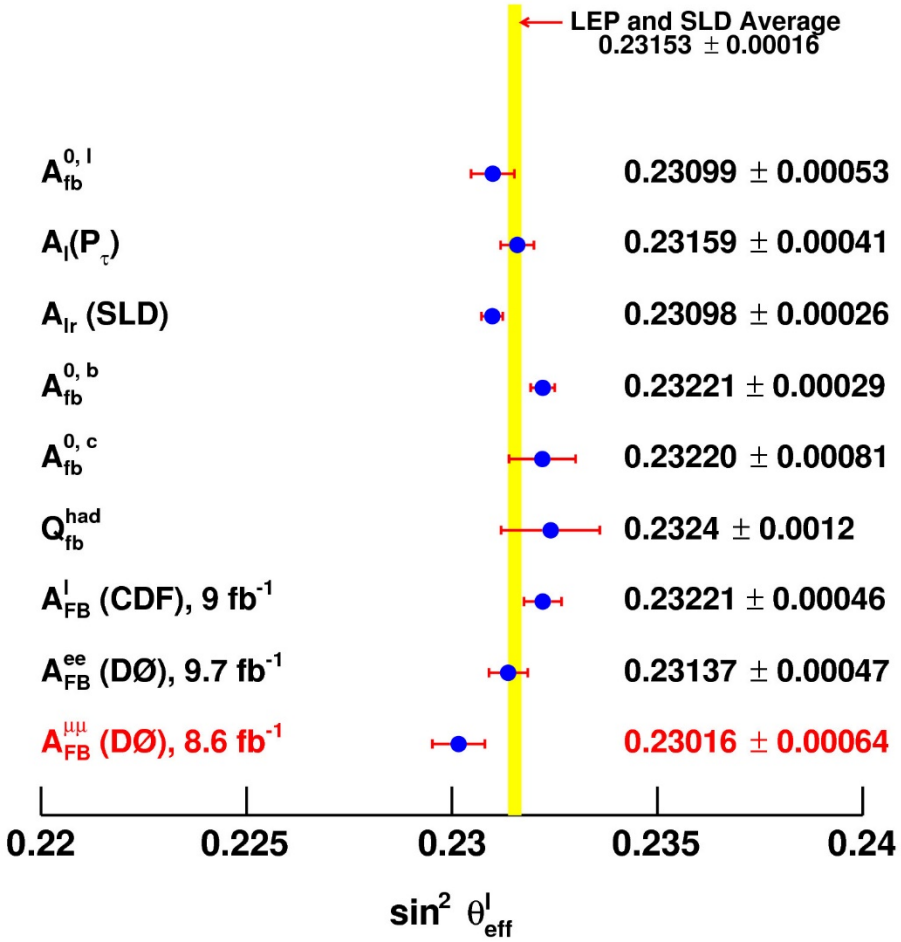
- Result of DØ 8.6 fb^{-1} Z→μμ measurement:

$$\sin^2\theta^B_W = 0.22994 \pm 0.00059(\text{stat.}) \pm 0.00005(\text{syst.}) \pm 0.00024(\text{PDF})$$
$$= 0.22994 \pm 0.00064$$

$\sin^2\theta^B_W$	0.22994
Statistical uncertainty	0.00059
Systematic uncertainties	
Momentum calibration	0.00002
Momentum resolution	0.00004
Background	0.00003
Efficiencies	0.00001
Total systematic	0.00005
PDF	0.00024
Total	0.00064

$$\sin^2\theta^\ell_{\text{eff}} = 0.23016 \pm 0.00064$$

Public: D0 Note 6500-CONF



The weak-mixing angle @ DØ preliminary

- The combination[*] of DØ 9.7 fb^{-1} Z→ee and 8.6 fb^{-1} Z→μμ measurements:
  - Modify DØ Z→ee result to incorporate the full high order correction (Resbos → ZFITTER) and the usage of NNPDF3.0 (from NNPDF2.3)
  - Statistical and systematic uncertainties, except those from theoretical high order corrections, are treated as uncorrelated
  - A combined PDF uncertainty is estimated to incorporate the full correlation of the acceptance between the DØ Z→ee and Z→μμ channels

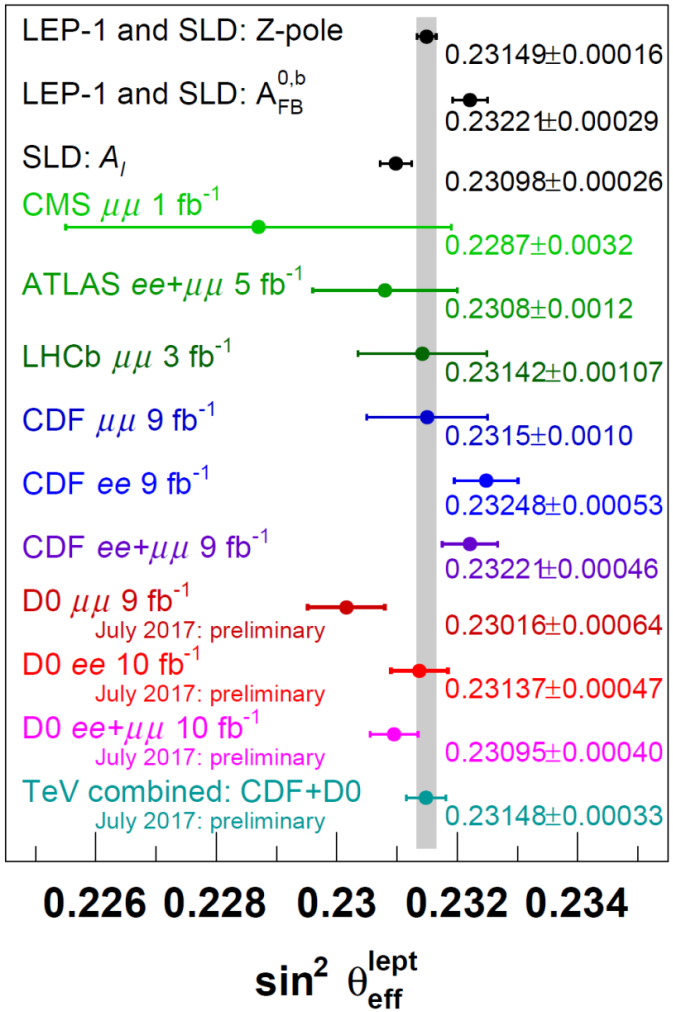
	electron channel	muon channel	combined
$\sin^2\theta^{\ell}_{\rm eff}$	0.23137	0.23016	0.23095
Statistical	0.00043	0.00059	0.00035
Systematic	0.00009	0.00006	0.00007
PDF	0.00017	0.00024	0.00019
Total	0.00047	0.00064	0.00040

$$\sin^2\theta^{l}_{eff}[\text{DØ}] = 0.23095 \pm 0.00040$$

[*] Follow the same strategy of Tevatron CDF+ DØ combination

The weak-mixing angle @ Tevatron preliminary

- The combination of CDF and DØ results of Z→ee/μμ channels with full dataset:



- 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

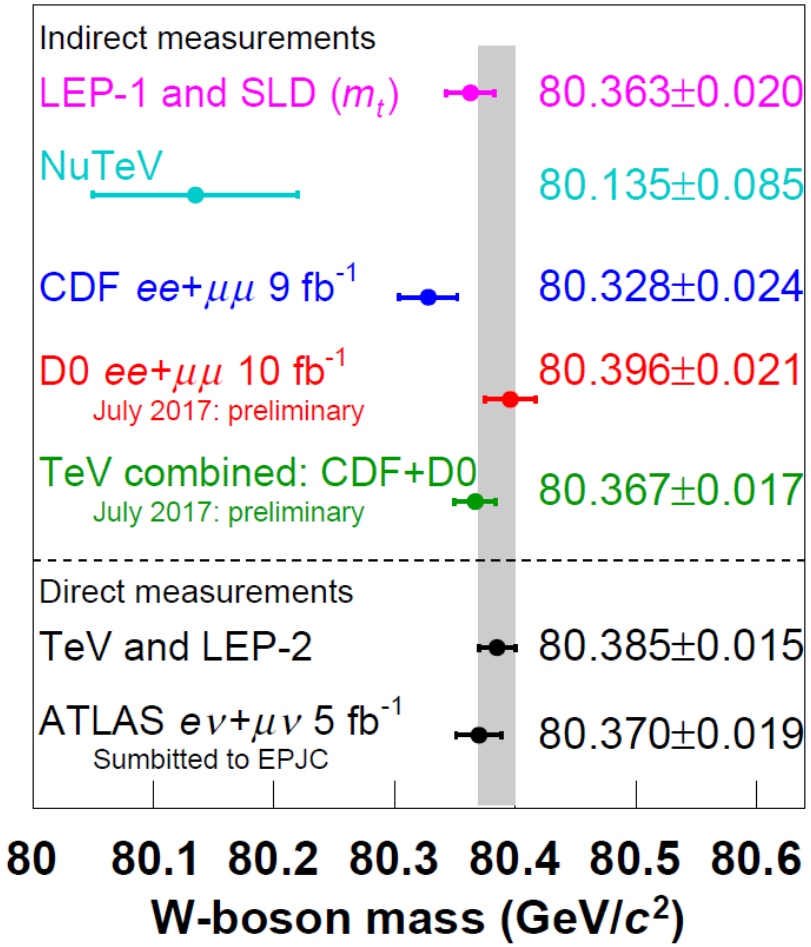
$$\sin^2\theta^l_{eff}[\text{Tev}] = 0.23148 \pm 0.00027(\text{stat}) \pm 0.00005(\text{syst}) \pm 0.00018(\text{PDF}) = \mathbf{0.23148 \pm 0.00033}$$

- Weight CDF/DØ: 0.4/0.6

- Tevatron legacy result : FERMILAB-CONF-17-201-E

Indirect W mass @ Tevatron preliminary

- Using ZFITTER SM conversion and on-shell renormalization scheme



- M_W determination:

80.385 ± 0.015 (LEP+Tev Direct)

80.370 ± 0.019 (ATLAS Direct)

80.367 ± 0.017 (Tev Indirect)

Summary (I)

- The effective $\sin^2\theta_W$ has been measured from the forward-backward asymmetry A_{FB} distribution, by using the full DØ Run2 8.6 fb^{-1} $Z \rightarrow \mu\mu$ data, with strict data quality requirements and new muon momentum charge-dependence corrections.

- The latest DØ $Z \rightarrow \mu\mu$ measurement, **0.23016 ± 0.00064**, is consistent to the DØ $Z \rightarrow ee$ result of **0.23147 ± 0.00047**, with the ZFITTER and NNPDF3.0 intrepretation

Summary (II)

- The full DØ Run2 $\sin^2\theta^l_{eff}$ result, gives the most precise measurement of a single experiment at hadron collider:

DØ Run2	**0.23095 ± 0.00040**	D0 Note 6500-CONF
CDF Run2	0.23221 ± 0.00046	PRD 93,112016
CMS 8TeV	0.23101 ± 0.00052	EPS2017, Venice

- 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 W mass result, **80.367 ± 0.017** GeV, consistent with the LEP/Tevatron direct measurement of 80.385 ± 0.015 GeV