



Measurements and combination of $\sin^2 \theta_{eff}^l$ at the Tevatron



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*XXXII Rencontres de Physique
de La Vallée d'Aoste
La Thuile, Italy, March 5, 2015*





Outline



◆ Introduction

- ◆ Drell-Yan dilepton production and the weak mixing angle
- ◆ Forward-Backward asymmetry
- ◆ Measurement strategy

◆ CDF Measurements

◆ D0 Measurements

◆ Tevatron Combination of $\sin^2 \theta_{eff}^l$

- ◆ Standardization of results
- ◆ BLUE combination

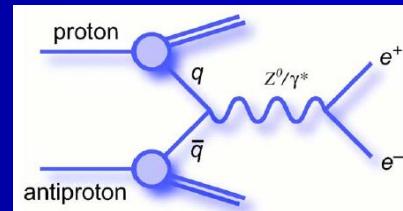
◆ Inferring $\sin^2 \theta_W$ and M_W

◆ Summary



- ◆ Drell-Yan lepton pairs are produced at the Tevatron through

$$p\bar{p} \rightarrow Z/\gamma^* \rightarrow l^+l^-$$



- ◆ The weak mixing angle can be measured from the forward-backward asymmetry of the polar angle distribution of these Drell-Yan pairs

$$\frac{q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-}{g_V^f = Q_f} \quad \begin{matrix} \text{Born level} \\ \text{couplings} \end{matrix}$$

$$g_A^f = 0$$

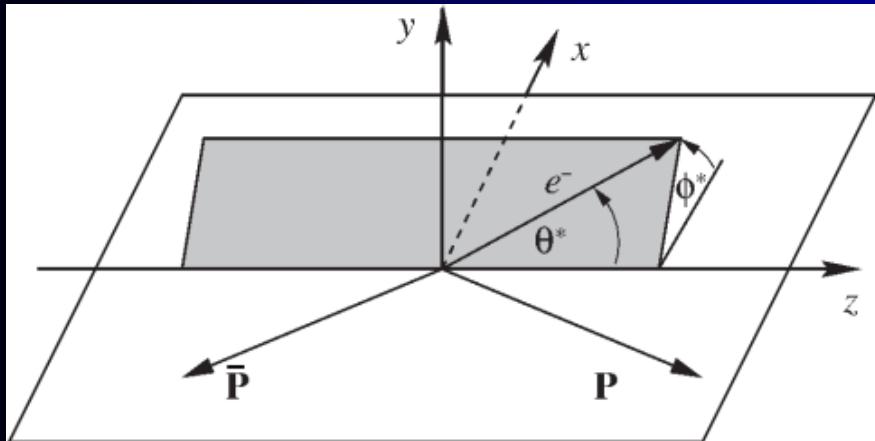
$$\langle \bar{f}|(g_V + g_A \gamma^5) \gamma^\mu |f\rangle$$

$$\frac{q\bar{q} \rightarrow Z \rightarrow l^+l^-}{g_V^f = I_3 - 2Q_f \sin^2 \theta_W} \quad g_A^f = I_3$$

- ◆ Weak couplings altered by radiative corrections

- ◆ Multiplicative factor of a few %
- ◆ Gives effective $\sin^2 \theta_W$ coupling $\rightarrow \sin^2 \theta_{eff}^l$

Forward-Backward Asymmetry



- ◆ Measure $t\bar{t}$ angular distribution in the Collins-Soper rest frame of the boson. Polar angle, θ^* , of the t^- is defined relative to the direction of the incoming quark

◆ Forward: $\cos\theta^* > 0$, Backward: $\cos\theta^* < 0$

◆ $dN/d\Omega \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$

◆ All coefficients[†] but A_4 vanish as $P_T \rightarrow 0$

◆ $A_4 \cos\theta^*$: parity violating, from interference of vector and axial vector currents

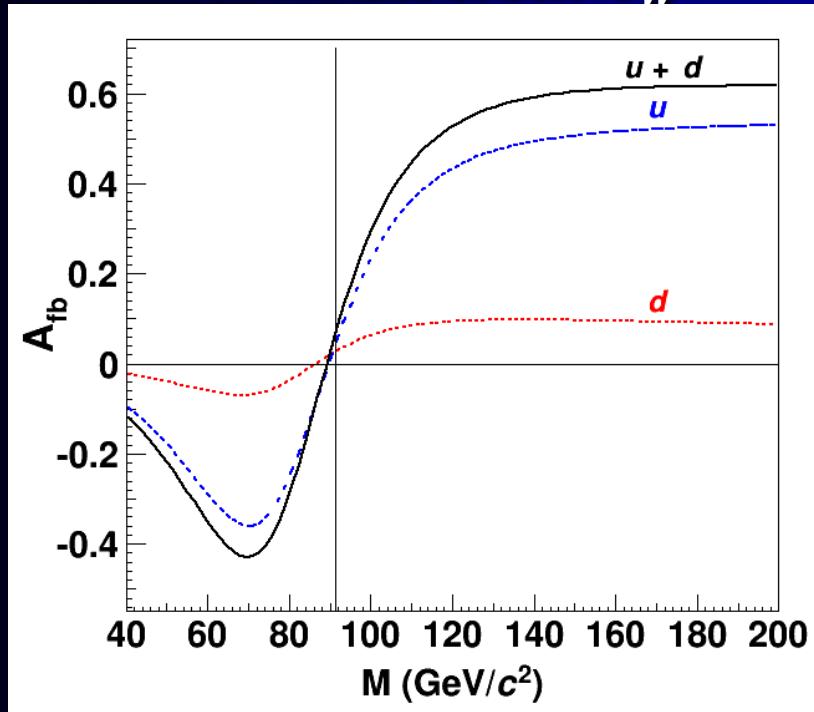
◆ Sensitive to $\sin^2\theta_W$ through Z self-interference in $Z_{VV} \otimes Z_{AA}$:

$$\mathbf{I}_{3l}(1 - 4|Q_l|\sin^2\theta_W)\mathbf{I}_{3q}(1 - 4|Q_q|\sin^2\theta_W)\mathbf{I}_{3q}\mathbf{I}_{3l}$$

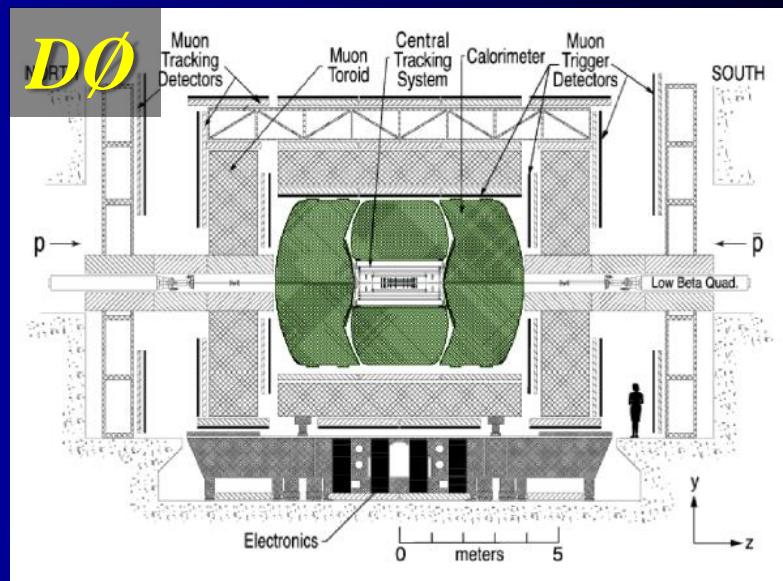
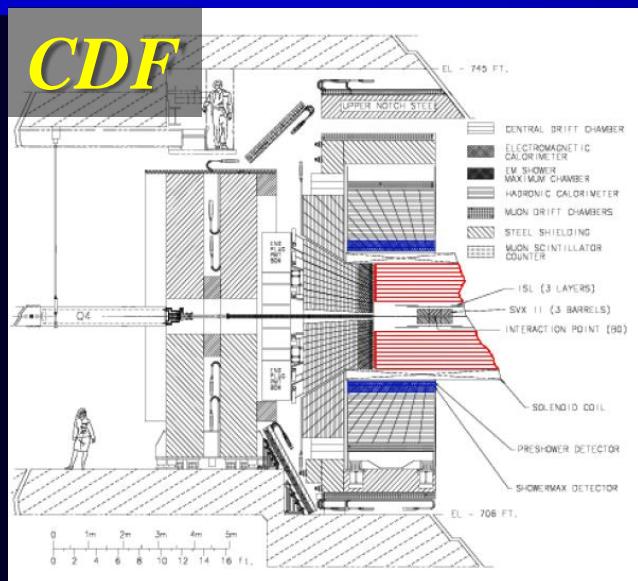
$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{3}{8} A_4$$

[†]@ NLO QCD: $dN/d\Omega = 1 + \cos^2\theta^* + A_0(1 - 3\cos^2\theta^*)/2 + A_1 \sin 2\theta^* \cos \phi + A_2 (\sin^2\theta^* \cos 2\phi)/2 + A_3 \sin \theta^* \cos \phi + A_4 \cos \theta^* + A_5 \sin^2\theta^* \sin 2\phi + A_6 \sin 2\theta^* \sin \phi + A_7 \sin \theta^* \sin \phi$

- ◆ Measure A_{FB} in bins of lepton pair invariant mass
- ◆ Produce Monte Carlo $A_{FB}(M, \sin^2 \theta_W)$ templates
- ◆ Perform full corrections to data and simulation
- ◆ Extract $\sin^2 \theta_W$ by a χ^2 comparison between data and MC generated at different values of $\sin^2 \theta_W$



- ◆ ZZ interference
 - ◆ Sensitive to $\sin^2 \theta_W$
 - ◆ near Z-pole: Best statistics/precision, minimal γZ interference
- ◆ γZ interference
 - ◆ Independent of $\sin^2 \theta_W$
 - ◆ Zero at Z-pole
 - ◆ Dominates away from Z-pole and sensitive to PDFs
- ◆ Measure at the Z pole!



◆ Dimuons: 9.4 fb^{-1}

- ◆ $p_T > 20 \text{ GeV}/c$
- ◆ $|\eta| \lesssim 1.1$ (277K events)

◆ Dielectrons: 9.4 fb^{-1}

- ◆ Central (C): $0.05 < |\eta| < 1.05$
- ◆ End plug (P): $1.2 < |\eta| < 2.8$
- ◆ CC: $E_T > 25/15 \text{ GeV}$ (227K events)
- ◆ CP: $E_T > 20 \text{ GeV}$ (258K events)
- ◆ PP: $E_T > 25 \text{ GeV}$ (80K evts cal only)

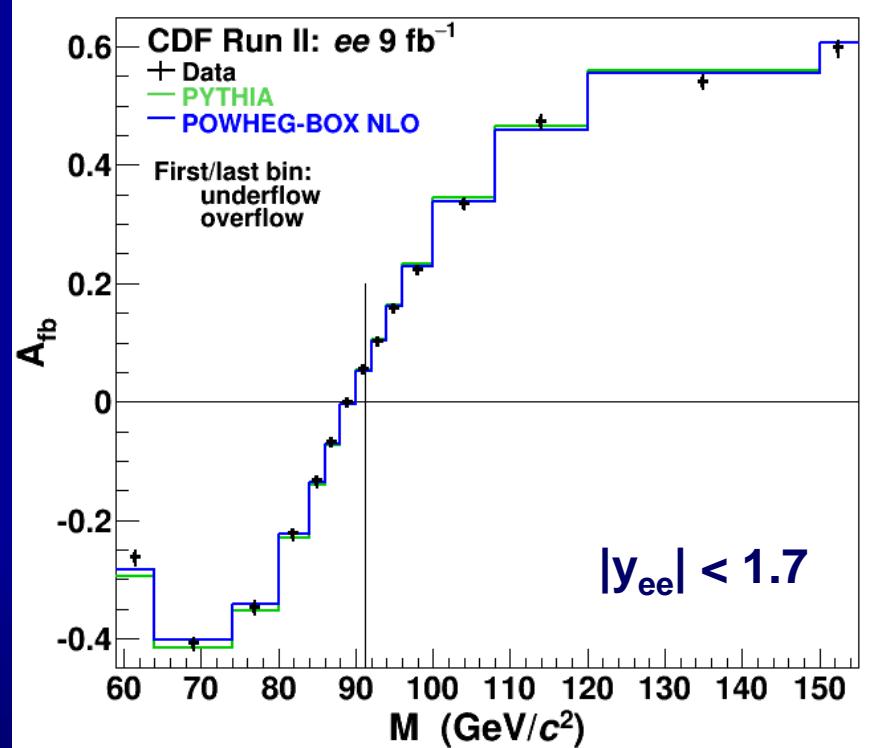
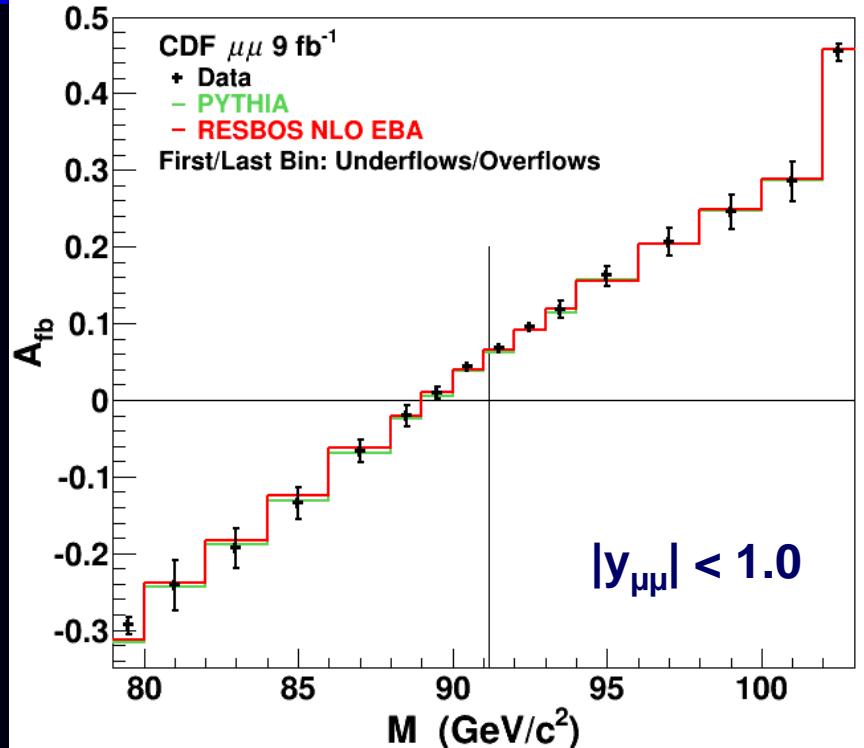
◆ Dimuons: 8.6 fb^{-1}

- ◆ $p_T > 15 \text{ GeV}/c$
- ◆ $|\eta|_1 \lesssim 1.6, |\eta|_2 \lesssim 1.8$ (481K events)

◆ Dielectrons: 9.7 fb^{-1}

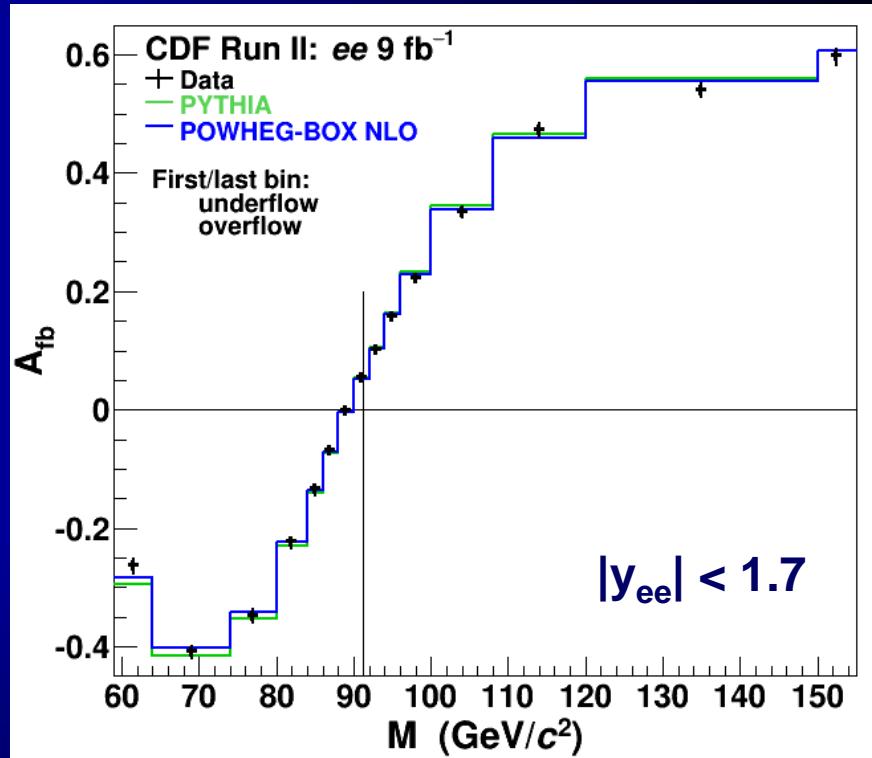
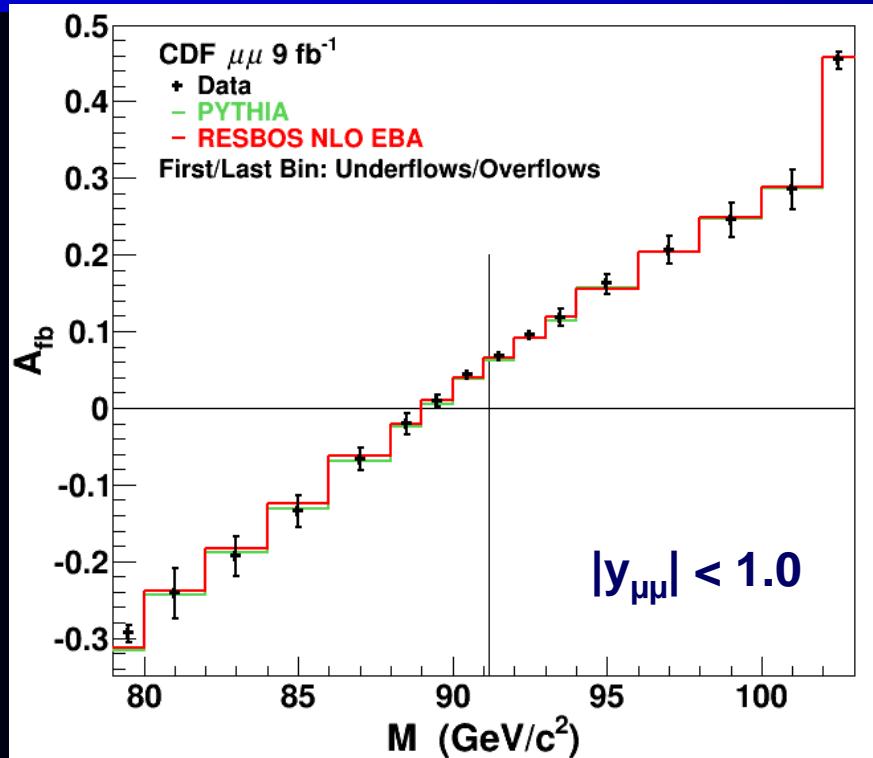
- ◆ Central (CC): $|\eta| < 1.1$
- ◆ End (EC): $1.5 < |\eta| < 3.2$
- ◆ CC-CC: $p_T > 25 \text{ GeV}/c$ (248K events)
- ◆ CC-EC: $p_T > 25 \text{ GeV}/c$ (241K events)
- ◆ EC-EC: $p_T > 25 \text{ GeV}/c$ (71K events)

CDF Measurements



- ◆ Asymmetry measurements corrected for direct fits to calculations
 - ◆ angular-weighted event sums method [EPJ C 76, 321 (2010)]
 - ◆ matrix unfolding of detector and QED FSR smearing; residual bias correction of few %
- ◆ Simulation: PYTHIA 6.2(CTEQ5L) \oplus PHOTOS 2.0 \oplus CDF detector simulation
 - ◆ Higher order QCD effect corrections applied to generated events
- ◆ Templates: POWHEG-BOX(NLO) \oplus NNPDF 3.0(NNLO) PDFs \oplus PYTHIA 6.4

CDF Measurements



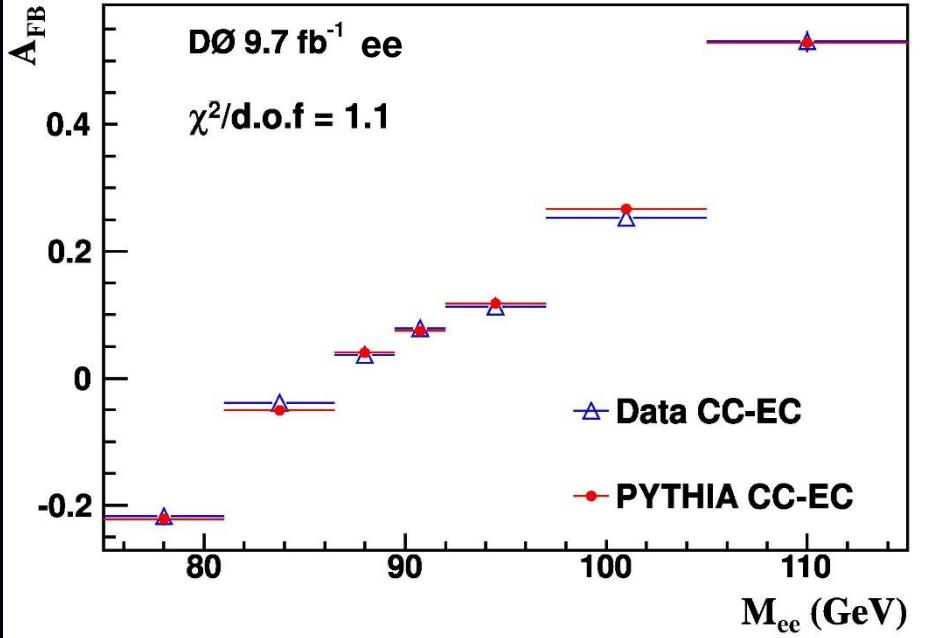
$$\sin^2 \theta_{eff}^l = 0.2315 \pm 0.0009 \text{ (stat)} \\ \pm 0.0002 \text{ (syst)} \\ \pm 0.0004 \text{ (PDF)}$$

[PRD 89, 072005 \(2014\)](#)

$$\sin^2 \theta_{eff}^l = 0.23248 \pm 0.00049 \text{ (stat)} \\ \pm 0.00004 \text{ (syst)} \\ \pm 0.00019 \text{ (PDF)}$$

[PRD 93, 112016 \(2016\)](#)

D0 Measurements



$$\sin^2 \theta_{eff}^l = 0.23147 \pm 0.00043 \text{ (stat)} \\ \pm 0.00008 \text{ (syst)} \\ \pm 0.00017 \text{ (PDF)}$$

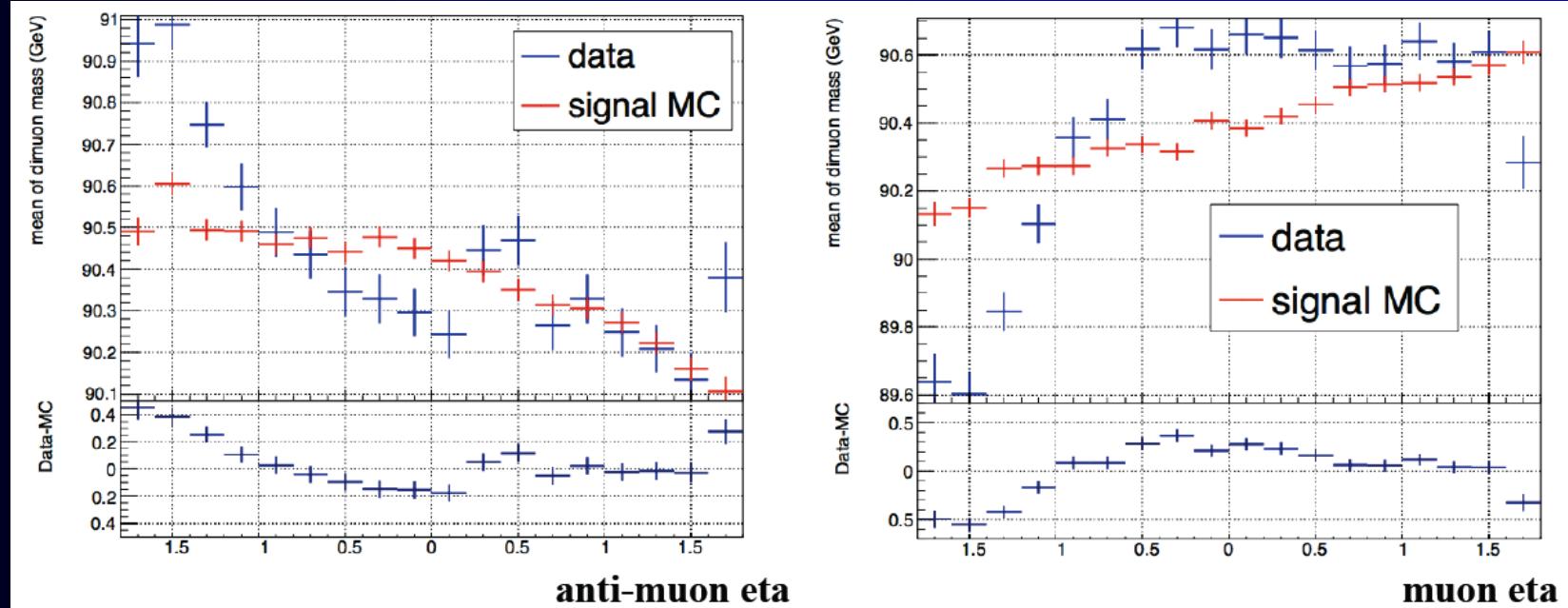
[PRL 115, 041801 \(2015\)](#)

- ◆ Asymmetries for electrons separately fit to CC-CC, CC-EC, EC-EC templates then best-fit values combined
- ◆ Simulation: PYTHIA 6.323(CTEQ6L1), ALPGEN
 - ◆ Higher order QCD effect corrections applied to generated events
- ◆ Templates: PYTHIA 6.323 with NNPDF 2.3(ee) 3.0($\mu\mu$) NLO PDFs
 - ◆ Higher order QCD effect corrections applied to generated events
 - ◆ Detector simulation included

D0 $\mu\mu$ Measurement

Main challenge: Charge Dependence

- A_{FB} vs. $M_{\mu\mu}$ is extremely sensitive to charge-dependence in muon momentum



Solution: Charge-Eta-Solenoid Polarity dependent calibration

- Data/MC separately calibrated to generator level: $P_{corr} = \alpha(q, \eta, S) \cdot P_{obs}$
- Calibration parameter determined by requiring consistent M_Z mean in each charge-eta-solenoid category

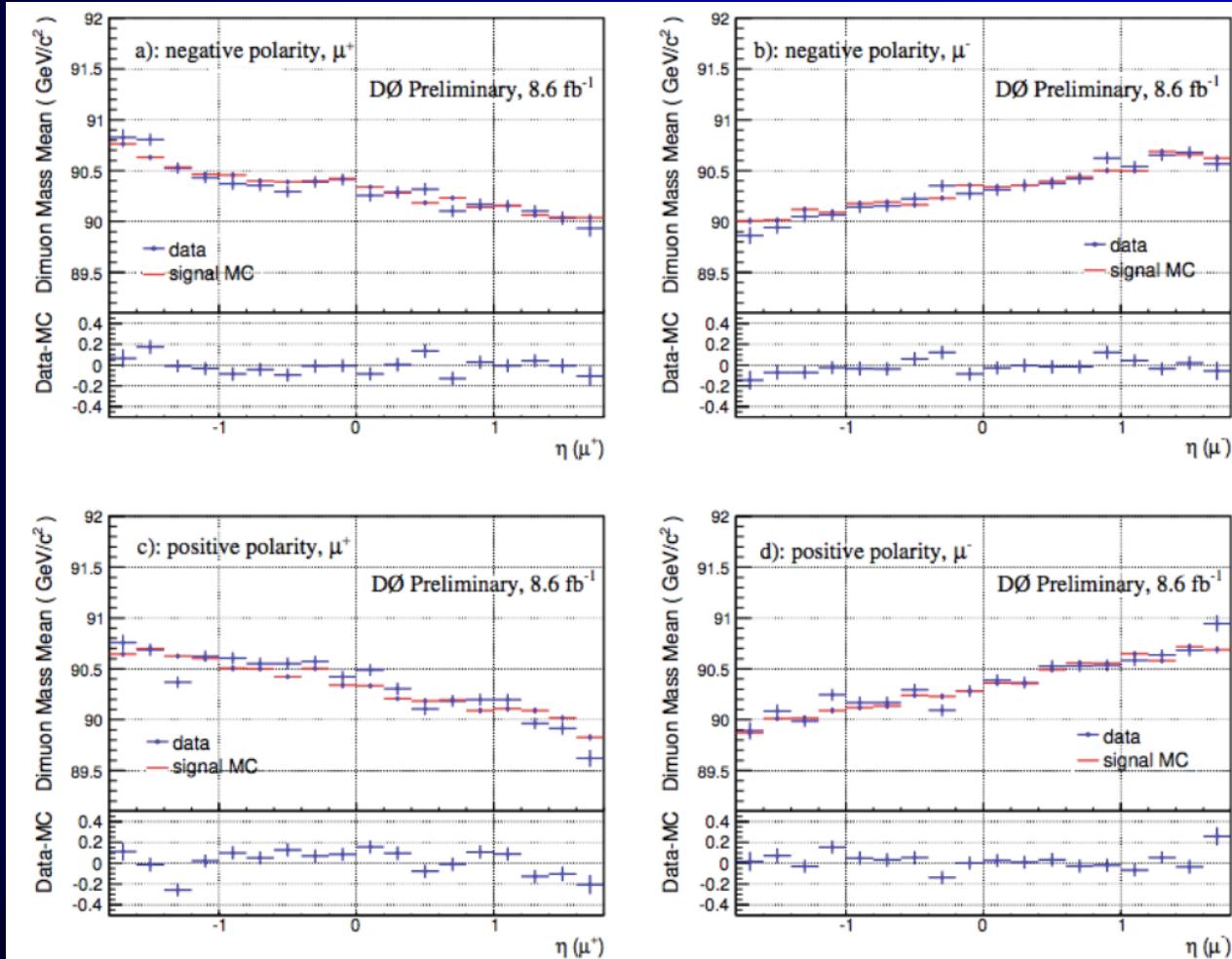


D \emptyset $\mu\mu$ Measurement



After Charge-Eta-Solenoid calibration

- ◆ Data/MC consistent within statistical uncertainty; residual difference taken as systematic





Weak Radiative Corrections

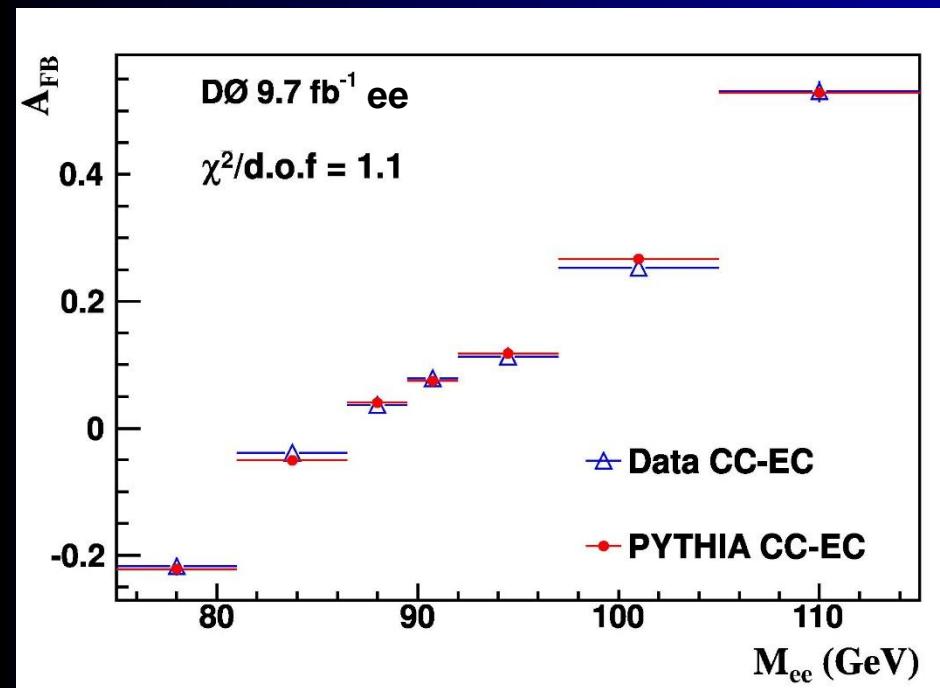


- ◆ PYTHIA template: single mixing angle and running α_{em}
- ◆ D0 ZGRAD+RESBOS corrected results
 - ◆ ZGRAD+RESBOS adjustment: improves accounting for differences of fermion-dependent (u,d,l) effective mixing angles @ M_Z
- ◆ CDF ZFITTER-based results: Enhanced Born Approximation (EBA)
 - ◆ Complex-valued form-factors ρ and κ for Born Z -couplings
 - ◆ $g_V^f = \sqrt{\rho_f} I_{3f}(1 - 4|Q_f|\kappa_f \sin^2 \theta_W)$ $g_A^f = \sqrt{\rho_f} I_{3f}$
 - ◆ ρ_f/κ_f : functions of fermion type, M_{ll}^2 , $\sin^2 \theta_W$; 1-4% corrections
 - ◆ Photon-propagator form factor (real part aka running α_{em})



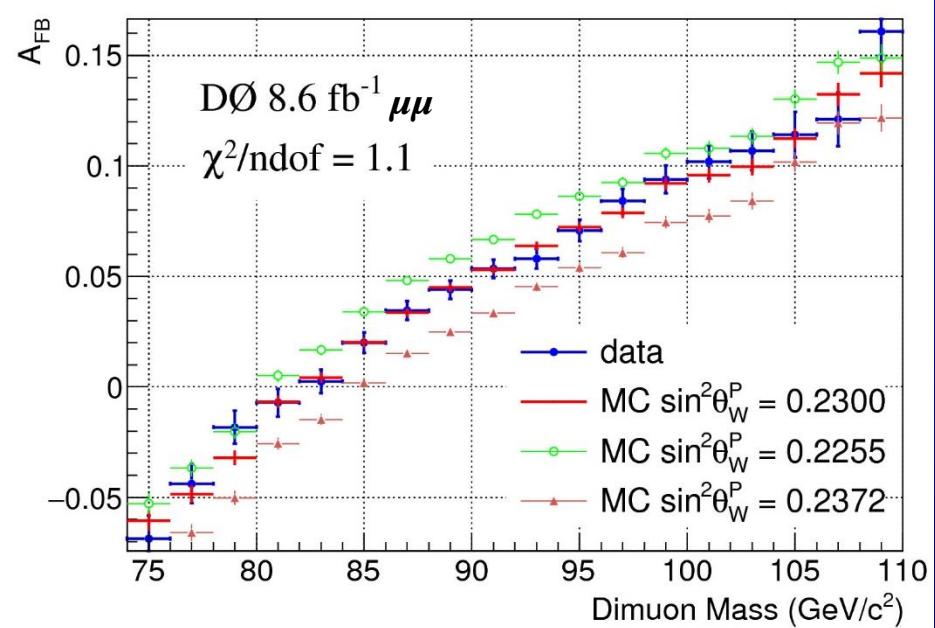
- ◆ Need common framework for PDF and electroweak correction baselines for consistency
 - ◆ NNPDF 3.0: Includes LHC data, improved implementation for PDFs and ensembles
 - ◆ ZFITTER SM electroweak radiative corrections: Used by LEP-1 and SLD for standard-model analysis at Z pole
- ◆ CDF: Results already at baseline
- ◆ D0 common framework corrections
 - ◆ $\Delta(\text{PDF})$, ee only: NNPDF v2.3 → v3.0 offset = -0.00024 ± 0.00004
 - ◆ Found by comparing v3.0 pseudodata with v2.3 templates
 - ◆ $\Delta(\text{ZITTER}) = \sin^2 \theta_{eff}^l(\text{EBA}) - \sin^2 \theta_{eff}^l(\text{nonEBA}) = +0.00022 \pm 0.00004$
 - ◆ i.e. PYTHIA-based → ZITTER-based template correction
 - ◆ ee: ZGRAD+RESBOS correction of $+0.00008$ already applied to published result, additional $+0.00014$ correction required
 - ◆ $\mu\mu$: full $\Delta(\text{ZITTER})$ applied to published result

◀ Fully corrected to common framework



$$\sin^2 \theta_{eff}^l = 0.23137 \pm 0.00043 \text{ (stat)} \\ \pm 0.00009 \text{ (syst)} \\ \pm 0.00017 \text{ (PDF)}$$

[arXiv:1801.06283](https://arxiv.org/abs/1801.06283)
Submitted to PRD 1/19/18



$$\sin^2 \theta_{eff}^l = 0.23016 \pm 0.00059 \text{ (stat)} \\ \pm 0.00006 \text{ (syst)} \\ \pm 0.00024 \text{ (PDF)}$$

[arXiv:1710.03951](https://arxiv.org/abs/1710.03951)
Submitted to PRL 10/11/17



CDF and D0 Combinations



◆ CDF Combination Systematic Uncertainties

Source	$\sin^2 \theta_{\text{eff}}^{\text{lept}}$
Energy scale and resolution	± 0.00002
Backgrounds	± 0.00003
QCD scale	± 0.00006
NNPDF-3.0 PDF	± 0.00016

$$\begin{aligned} \sin^2 \theta_{\text{eff}}^l &= 0.23221 \pm 0.00043 \text{ (stat)} \\ &\quad \pm 0.00007 \text{ (syst)} \\ &\quad \pm 0.00016 \text{ (PDF)} \end{aligned}$$

◆ D0 Combination Systematic Uncertainties

Source	$\sin^2 \theta_{\text{eff}}^{\text{lept}}$
Energy/Momentum calibration	± 0.00001
Energy/Momentum smearing	± 0.00002
Background	± 0.00001
Charge misidentification	± 0.00002
Lepton identification	± 0.00005
Fiducial asymmetry	± 0.00001
Correction (PDF and ZFITTER)	± 0.00005
NNPDF 2.3/NNPDF 3.0 PDF	± 0.00019

$$\begin{aligned} \sin^2 \theta_{\text{eff}}^l &= 0.23095 \pm 0.00035 \text{ (stat)} \\ &\quad \pm 0.00007 \text{ (syst)} \\ &\quad \pm 0.00019 \text{ (PDF)} \end{aligned}$$





Tevatron Combination



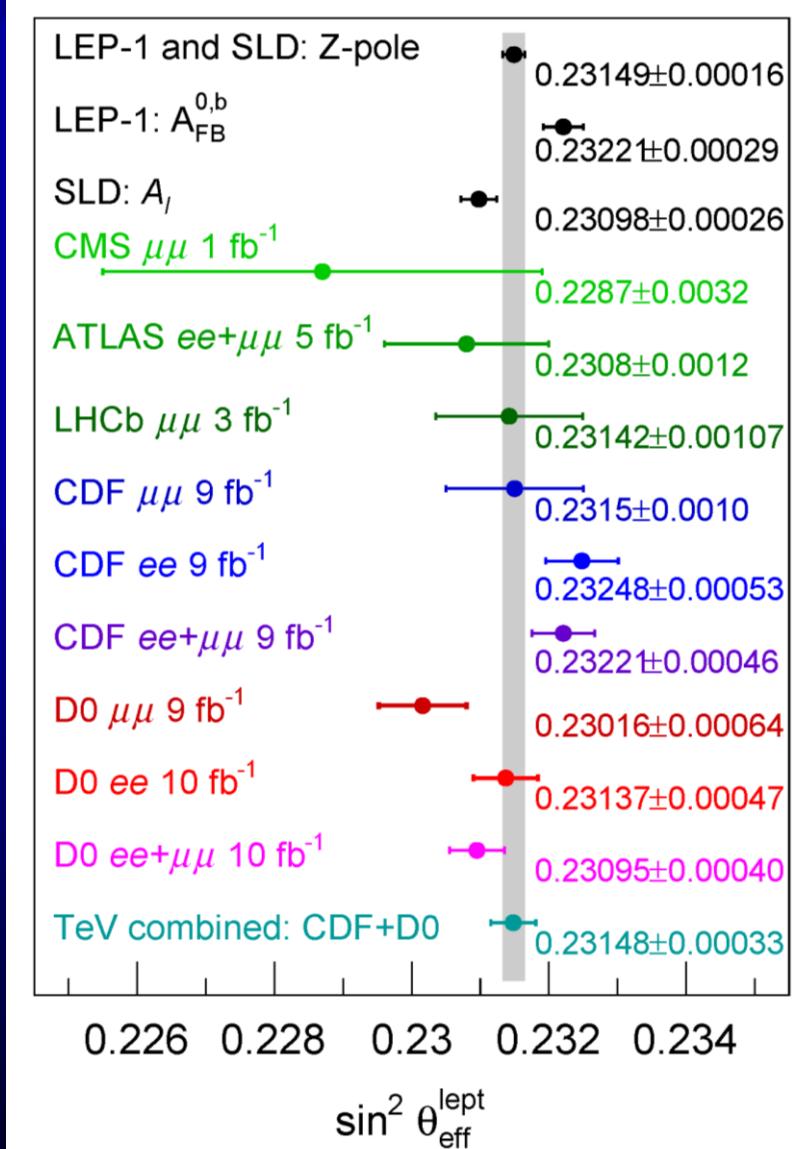
◆ Tevatron Combination

◆ BLUE Method

- ◆ PDF uncertainty 100% correlated
- ◆ Other uncertainties uncorrelated

$$\sin^2 \theta_{eff}^l = 0.23148 \pm 0.00027 \text{ (stat)} \\ \pm 0.00005 \text{ (syst)} \\ \pm 0.00018 \text{ (PDF)}$$

- ◆ Weight CDF/D0: 0.42/0.58
- ◆ Combination χ^2 probability 2.6%





Inference of $\sin^2 \theta_W$



◆ On-shell renormalization scheme (ZFITTER)

- ◆ $\sin^2 \theta_W \equiv 1 - M_W^2/M_Z^2$
- ◆ $M_Z = 91.875 \pm 0.0021 \text{ GeV}/c^2$

◆ ZFITTER SM conversion

- ◆ $\sin^2 \theta_{eff}^l = Re[\kappa_l(M_Z^2, \sin^2 \theta_W)] \sin^2 \theta_W$
- ◆ Input: $M_t = 173.2 \pm 0.9 \text{ GeV}/c^2$,
 $M_H = 125 \text{ GeV}/c^2$
- ◆ Form factor ~ 1.0371
- ◆ 0.00008 uncertainty on $\sin^2 \theta_W$ from form factor

◆ CDF

$$\sin^2 \theta_W = 0.22400 \pm 0.00041 \text{ (stat)} \\ \pm 0.00019 \text{ (syst)}$$

◆ D0

$$\sin^2 \theta_W = 0.22269 \pm 0.00034 \text{ (stat)} \\ \pm 0.00021 \text{ (syst)}$$

◆ Tevatron Combination

$$\boxed{\sin^2 \theta_W = 0.22324 \pm 0.00026 \text{ (stat)} \\ \pm 0.00019 \text{ (syst)}}$$





Inference of W Boson Mass



Indirect measurements

LEP-1 and SLD 80.363 ± 0.020

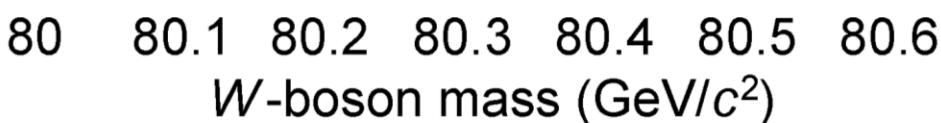
CDF ee+ $\mu\mu$ 9 fb $^{-1}$ 80.328 ± 0.024

D0 ee+ $\mu\mu$ 10 fb $^{-1}$ 80.396 ± 0.021

TeV combined: CDF+D0 80.367 ± 0.017

Direct measurement

TeV and LEP-2 80.385 ± 0.015



CDF

$$M_W = 80.328 \pm 0.021 \text{ (stat)} \\ \pm 0.010 \text{ (syst)} \text{ GeV/c}^2$$

D0

$$M_W = 80.396 \pm 0.017 \text{ (stat)} \\ \pm 0.011 \text{ (syst)} \text{ GeV/c}^2$$

Tevatron Combination

$$M_W = 80.367 \pm 0.014 \text{ (stat)} \\ \pm 0.010 \text{ (syst)} \text{ GeV/c}^2$$





Summary



- ◆ CDF and D0 have measured $\sin^2 \theta_{eff}^l$ from Drell-Yan lepton-pair asymmetries
 - ◆ CDF electrons: [PRD 93, 112016 \(2016\)](#)
 - ◆ CDF muons: [PRD 89, 072005 \(2014\)](#)
 - ◆ D0 electrons: [PRL 115, 041801 \(2015\)](#)
 - ◆ D0 muons: [arXiv:1710.03951 \(October 11, 2017\)](#) NEW!
- ◆ Produced combination result
 - ◆ $\sin^2 \theta_{eff}^l = 0.23148 \pm 0.00033$
- ◆ Using ZFITTER SM calculations, inferred W mass
 - ◆ $M_W = 80.367 \pm 0.017 \text{ GeV/c}^2$
- ◆ Tevatron legacy result
 - ◆ TeV combination: [arXiv:1801.06283 \(January 19, 2018\)](#) NEW!
 - ◆ <https://tevewwg.fnal.gov/wz/tevSw2eff/>





Backup Slides



◆ Great thanks to Accelerator Division for all the luminosity!!

