Measurements and combination of $\sin^2\theta^l_{eff}$ at the Tevatron and extraction of the W mass

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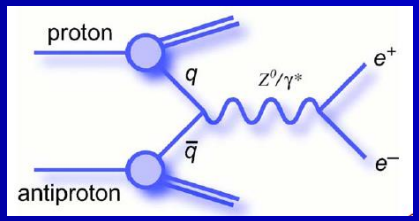
Outline

- **Introduction**
  - Drell-Yan dilepton production and the weak mixing angle
  - Forward-Backward asymmetry
  - Measurement strategy
- **CDF Measurements**
- **D0 Measurements**
- **Tevatron Combination of $sin^2\theta^l_{eff}$**
  - Standardization of results
  - BLUE combination
- **Inferring $sin^2\theta_W$ and M_W**
- **Summary**

Drell-Yan Production

- **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**

$$\frac{q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^-}{g_V^f = Q_f \quad g_A^f = 0}$$

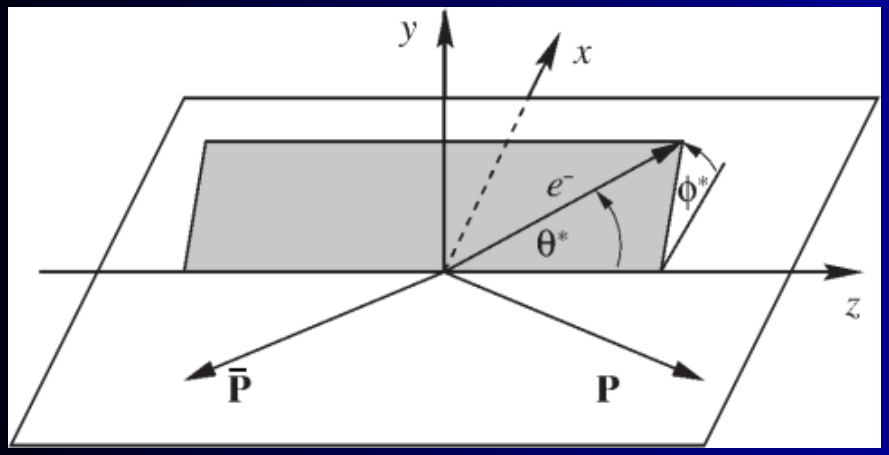
Born level couplings

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

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

- **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 l^-l^+ angular distribution in the Collins-Soper rest frame of the boson. Polar angle, θ^*, of the l^- is defined relative to the direction of the incoming quark
  - Forward: $cos\theta^* > 0$, Backward: $cos\theta^* < 0$

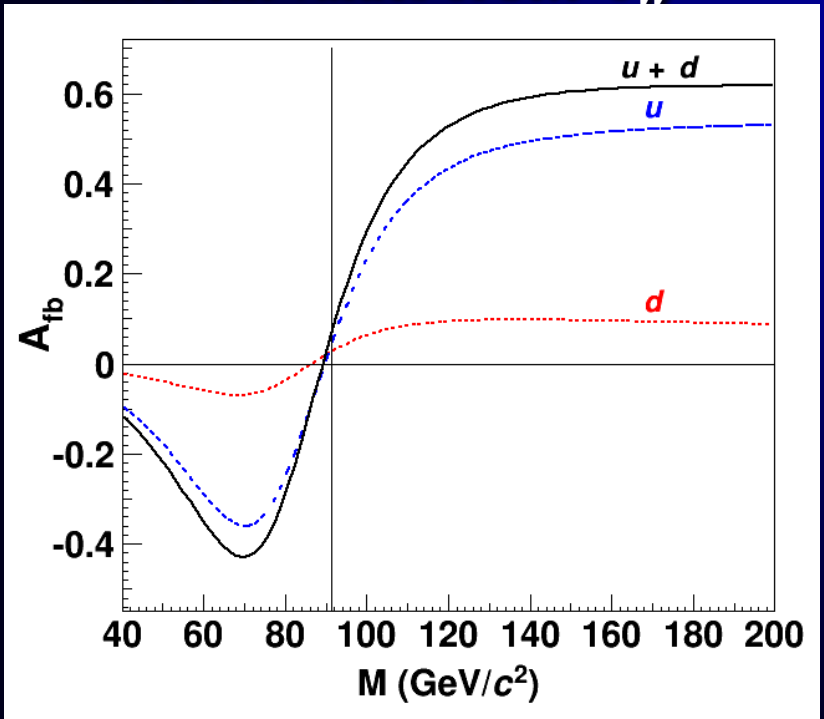
- $dN/d\Omega \propto 1 + cos^2\theta^* + A_4 cos\theta^*$
  - All coefficients† but A_4 vanish as $P_T \to 0$
- $A_4 cos\theta^*$: parity violating, from interference of vector and axial vector currents
  - Sensitive to $sin^2\theta_W$ through Z self-interference in $Z_{VV} \otimes Z_{AA}$: $I_{3l}(1 - 4|Q_l|sin^2\theta_W) I_{3q}(1 - 4|Q_q|sin^2\theta_W) I_{3q} I_{3l}$

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

†@ NLO QCD: $dN/d\Omega = 1 + cos^2\theta^* + A_0(1 - 3cos^2\theta^*)/2 + A_1 sin2\theta^* cos\phi + A_2(sin^2\theta^* cos2\phi)/2 + A_3 sin\theta^* cos\phi + A_4 cos\theta^* + A_5 sin^2\theta^* sin2\phi + A_6 sin2\theta^* sin\phi + A_7 sin\theta^* sin\phi$

Measurement Strategy

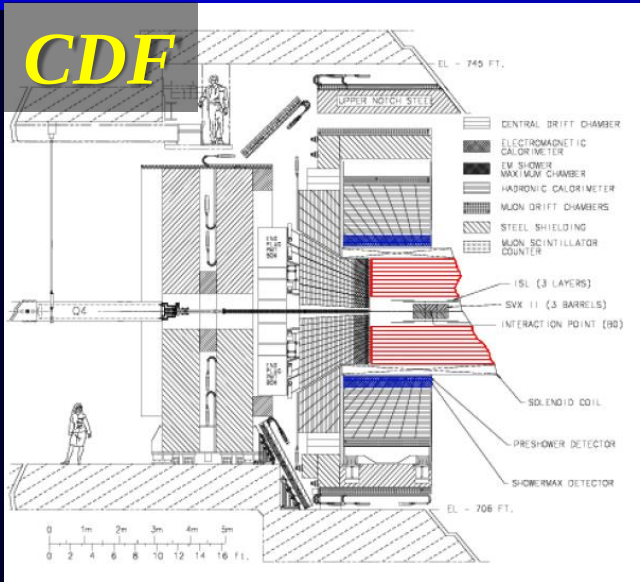
- Measure A_{FB} in bins of lepton pair invariant mass
- Produce Monte Carlo $A_{FB}(M, sin^2\theta_W)$ templates
- Perform full corrections to data and simulation
- Extract $sin^2\theta_W$ by a χ^2 comparison between data and MC generated at different values of $sin^2\theta_W$



- 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!

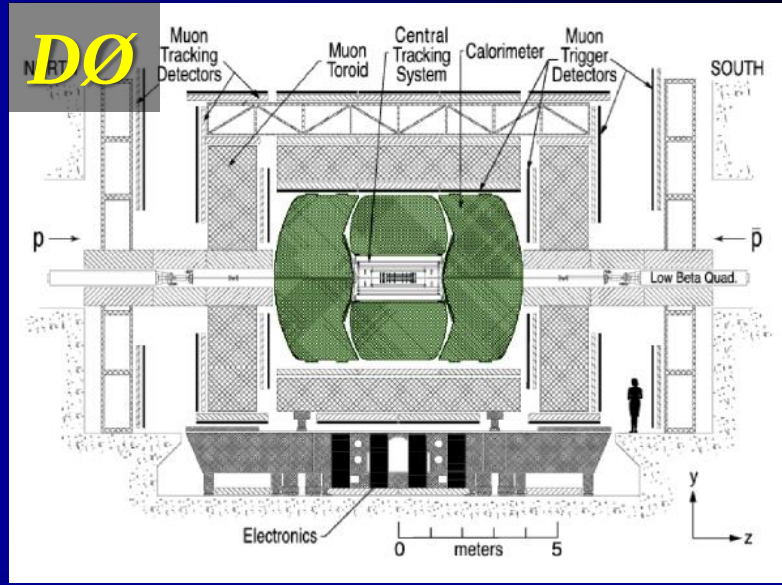
The Detectors and Data

CDF



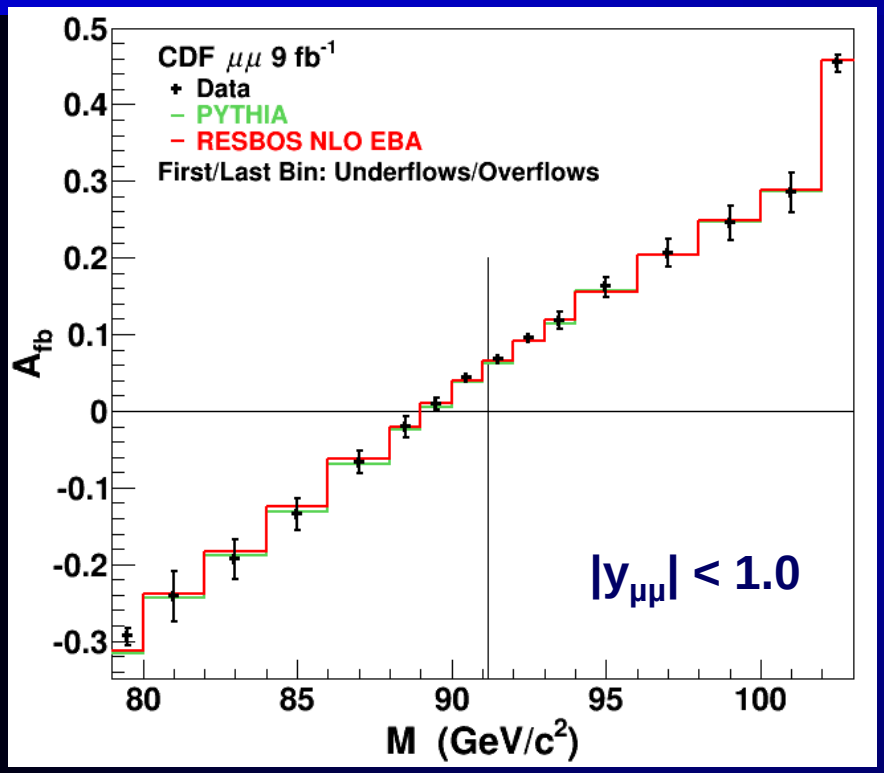
- **Dimuons: 9.4 fb^{-1}**
  - $p_T > 20$ GeV/c
  - $|\eta| \lesssim 1.1$ (277K events)
- **Dielectrons: 9.4 fb^{-1}**
  - Central (C): $0.05<|\eta|<1.05$
  - End plug (P): $1.2<|\eta|<2.8$
  - CC: $E_T > 25/15$ GeV (227K events)
  - CP: $E_T > 20$ GeV (258K events)
  - PP: $E_T > 25$ GeV (80K evts cal only)

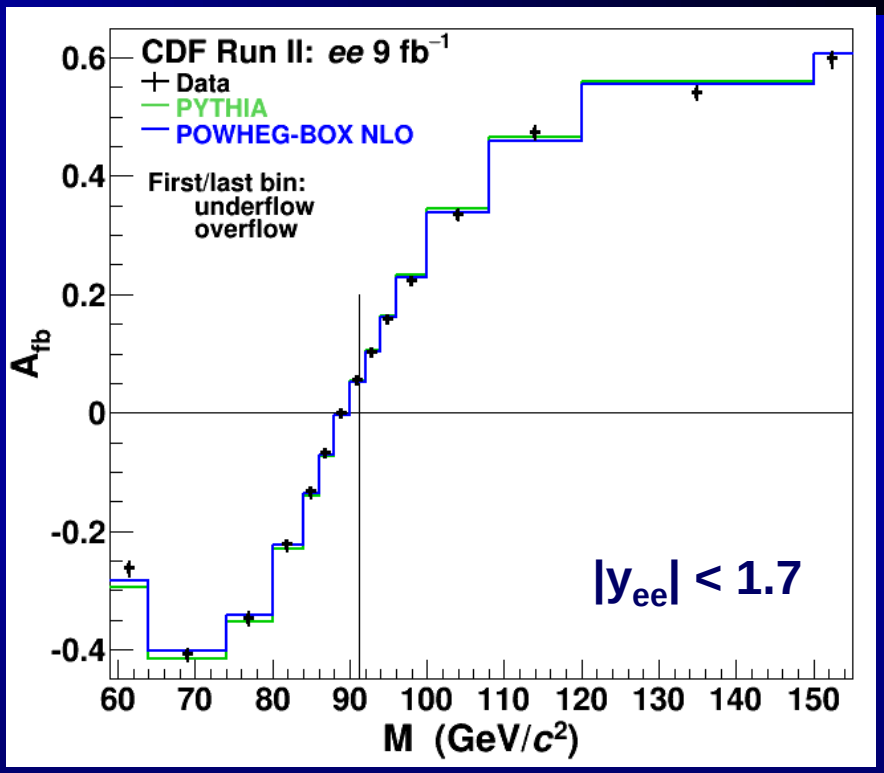
DØ



- **Dimuons: 8.6 fb^{-1}**
  - $p_T > 15$ 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: $p_T > 25$ GeV/c (248K events)
  - CC-EC: $p_T > 25$ GeV/c (241K events)
  - EC-EC: $p_T > 25$ GeV/c (71K events)

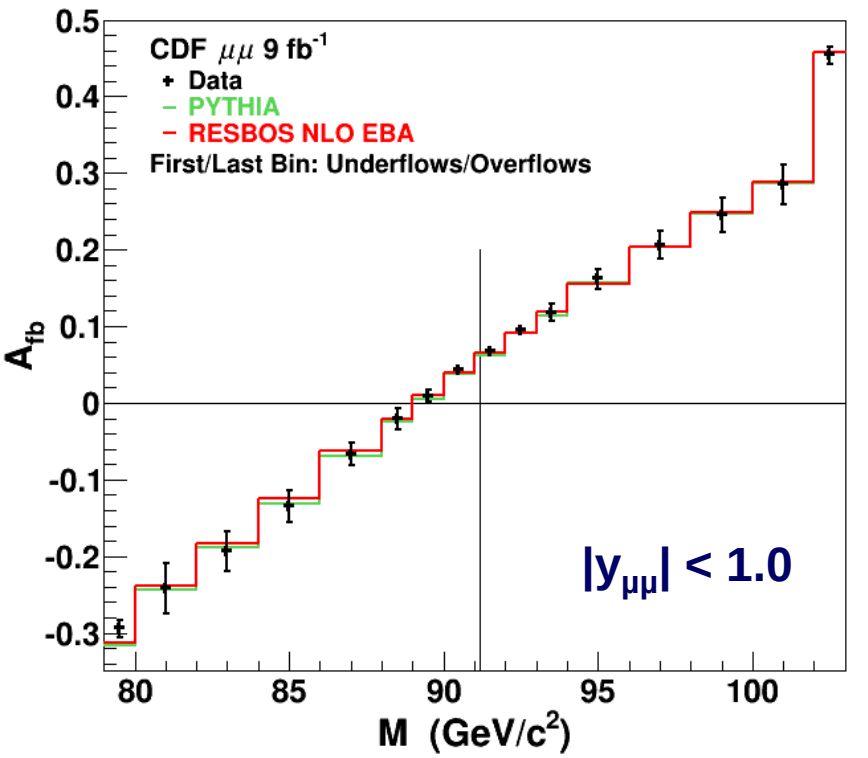
CDF Measurements

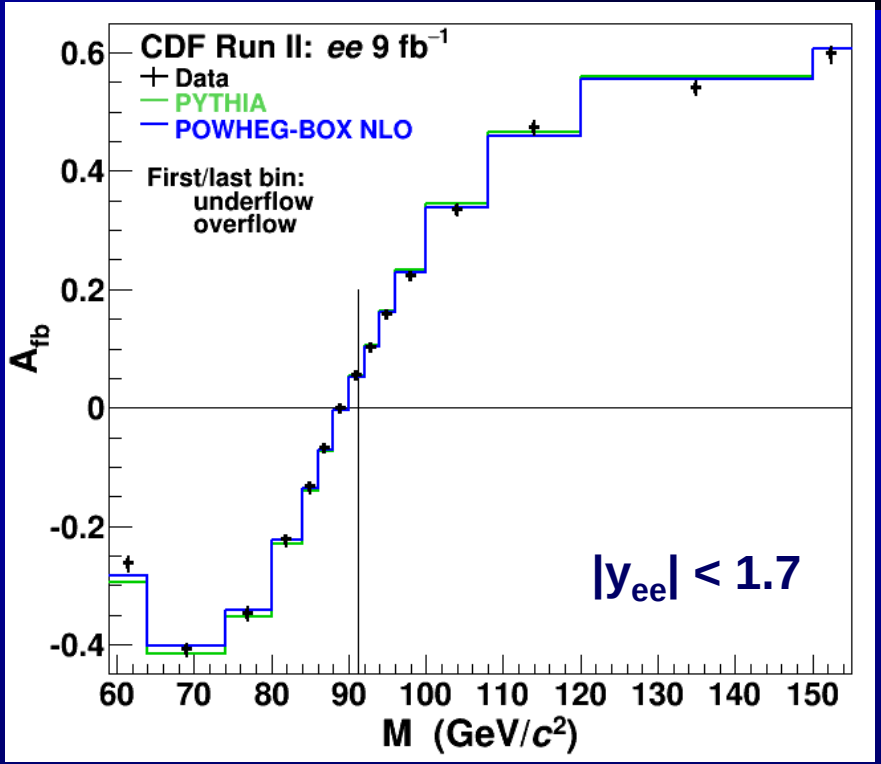




- **Asymmetry measurements corrected for direct fits to calculations**
  - angular-weighted event sums method [EPJ C 76, 321 (2010)]
  - matrix unfolding of detector and QED FSR smearing; residual bias correction of few %
- **Simulation: PYTHIA 6.2(CTEQ5L) ⊕ PHOTOS 2.0 ⊕ CDF detector simulation**
  -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

CDF Measurements





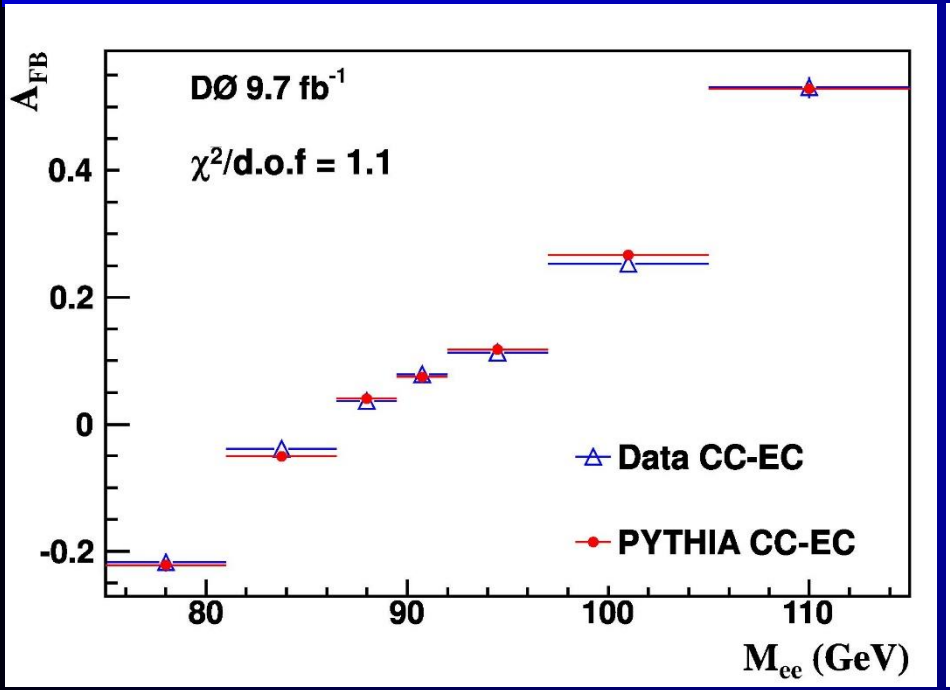
$sin^2\theta^l_{eff}$ = 0.2315 ± 0.0009 (stat)
± 0.0002 (syst)
± 0.0004 (PDF)

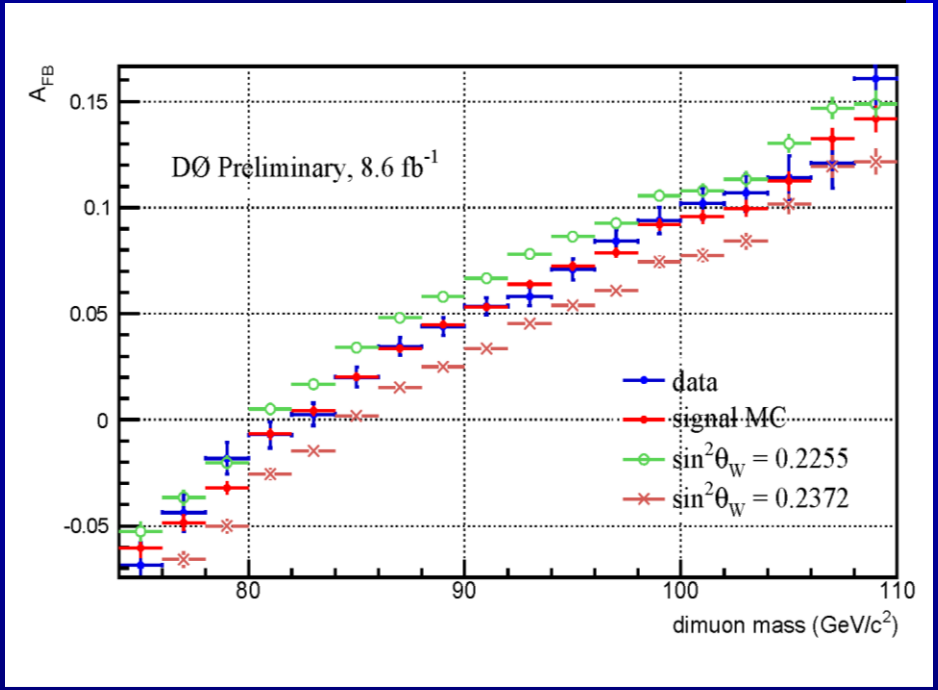
PRD 89, 072005 (2014)

$sin^2\theta^l_{eff}$ = 0.23248 ± 0.00049 (stat)
± 0.00004 (syst)
± 0.00019 (PDF)

PRD 93, 112016 (2016)

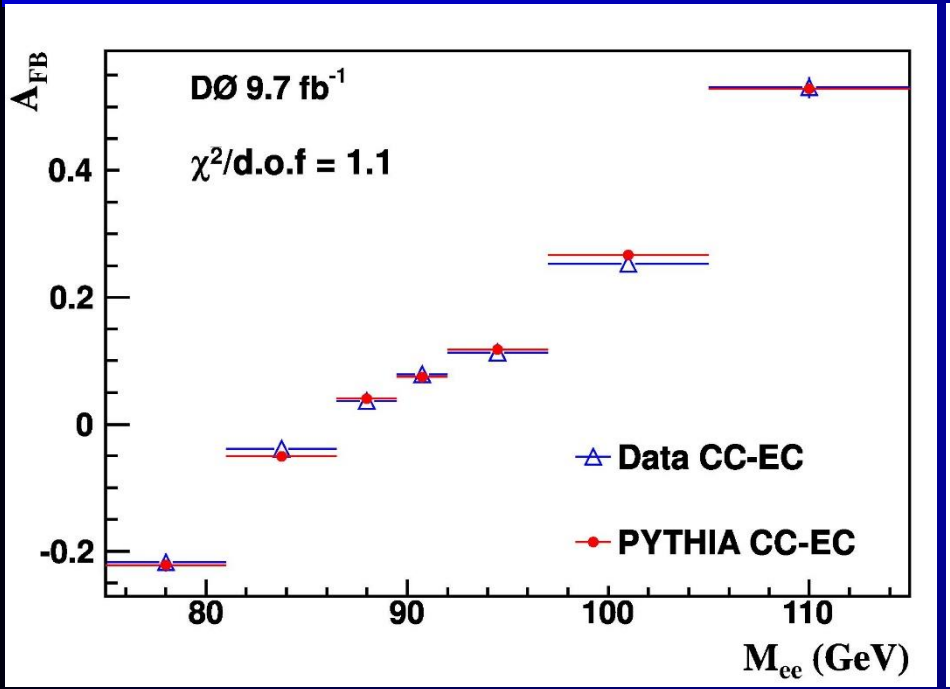
D0 Measurements

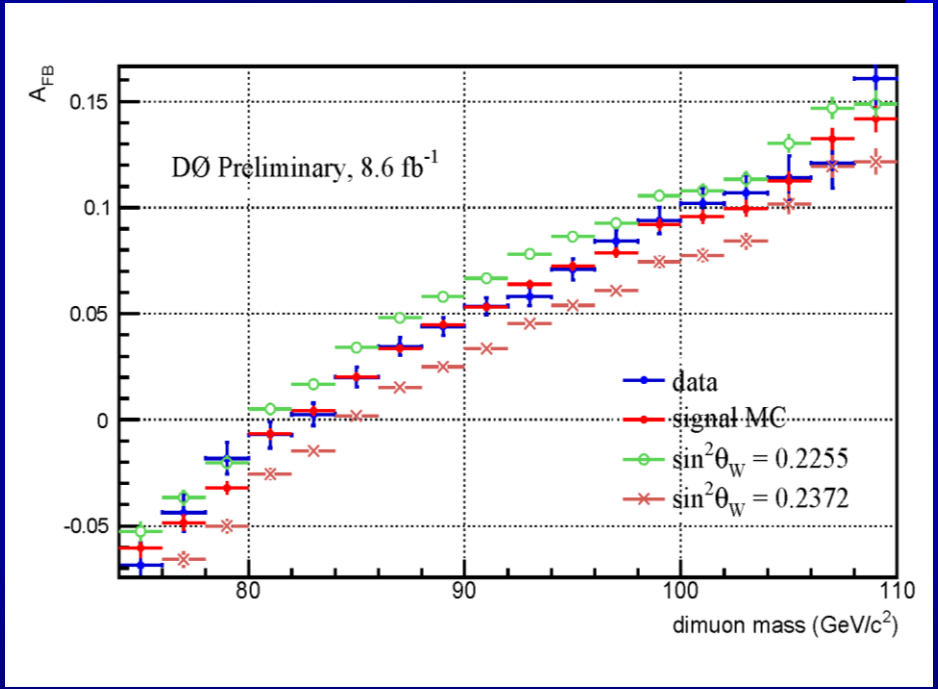




- **Asymmetries for electrons separately fit to CC-CC, CC-EC, EC-EC templates then best-fit values combined**
- **Simulation: PYTHIA 6.323(CTEQ6L1), ALPGEN**
  - Higher order QCD effect corrections applied to generated events
- **Templates: PYTHIA 6.323 with NNPDF 2.3(ee) 3.0(μμ) NLO PDFs**
  - Higher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

D0 Measurements





$sin^2\theta^l_{eff}$ = 0.23147 ± 0.00043 (stat) ± 0.00008 (syst) ± 0.00017 (PDF)

PRL 115, 041801 (2015)

$sin^2\theta^l_{eff}$ = 0.23016 ± 0.00059 (stat) ± 0.00006 (syst) ± 0.00024 (PDF)

D0NOTE 6500 (2017)

Weak Radiative Corrections

- **PYTHIA template: single mixing angle and running α_{em}**
- **D0 ZGRAD+RESBOS corrected results: improved**
  - ZGRAD+RESBOS adjustment: improves accounting for differences of fermion-dependent (u,d,l) effective mixing angles @ M_Z
- **CDF ZFITTER based results: improved even more**
  - Complex-valued form-factors ρ and κ for Born Z-couplings
  - $g_V^f = \sqrt{\rho_f} I_{3f}\left(1 - 4|Q_f|\kappa_f \sin^2\theta_W\right) \qquad g_A^f = \sqrt{\rho_f} I_{3f}$
  - 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})

Standardizing Results for Combination

- **Need common 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 standardization corrections**
  - Δ(PDF), ee only: NNPDF v2.3 → v3.0 offset = –0.00024±0.00004
    - Found by comparing v3.0 pseudodata with v2.3 templates
  - Δ(RadCor): + 0.00008 [ZGRAD+RESBOS (*u*,*d* effect)] +0.00014
    [ZGRAD+RESBOS → ZFITTER offset] = +0.00022±0.00004
  - ee: ZGRAD+RESBOS already applied to published result, additional –0.00010±0.00004 correction required: $sin^2\theta^l_{eff}$ = 0.23137 ± 0.00047
  - μμ: full RadCor already applied to preliminary result

CDF and D0 Combinations

CDF Combination

Systematic Uncertainties

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

$sin^2\theta^l_{eff}$ = 0.23221 ± 0.00043 (stat)
± 0.00007 (syst)
± 0.00016 (PDF)

D0 Combination

Systematic Uncertainties

Source	$\sin^2\theta^{\text{lept}}_{\text{eff}}$
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

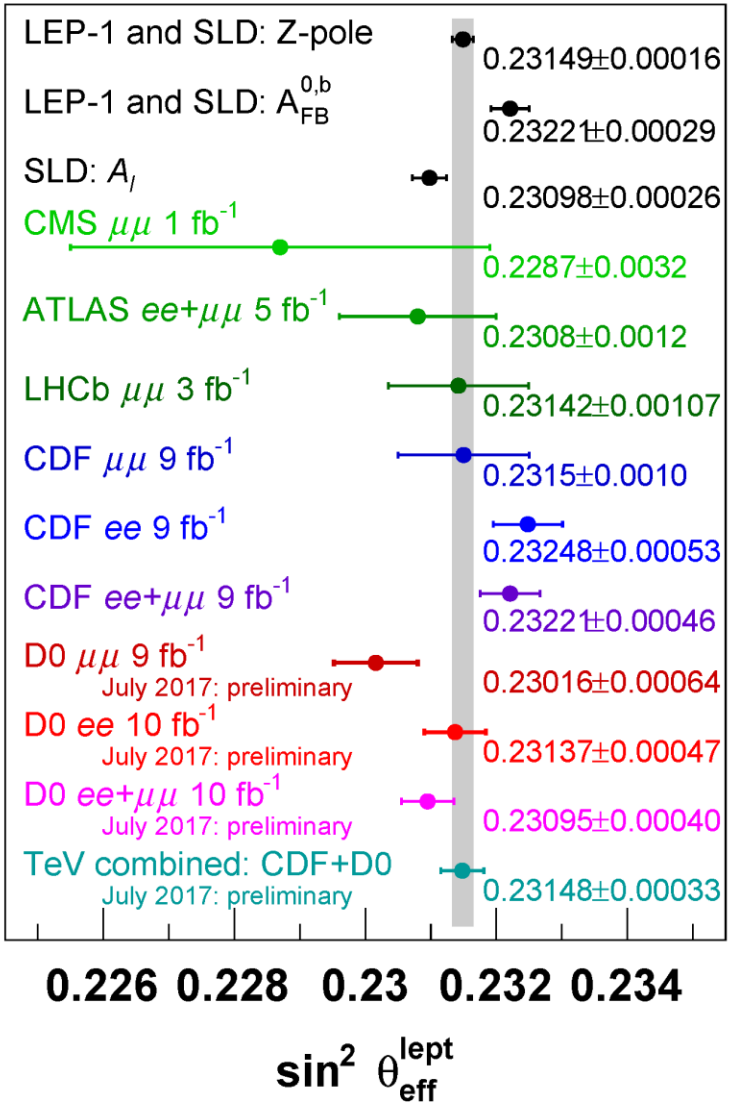
$sin^2\theta^l_{eff}$ = 0.23095 ± 0.00035 (stat)
± 0.00007 (syst)
± 0.00019 (PDF)

Tevatron Combination

- **Tevatron Combination**
  - BLUE Method
    - PDF uncertainty 100% correlated
    - Other uncertainties uncorrelated

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

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



Inference of $sin^2\theta_W$

- **On-shell renormalization scheme (ZFITTER)**
  - $sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$
  - $M_Z = 91.875 \pm 0.0021$ 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: $M_t = 173.2 \pm 0.9$ GeV/c^2, $M_H = 125$ 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 ± 0.00041 (stat) ± 0.00019 (syst)

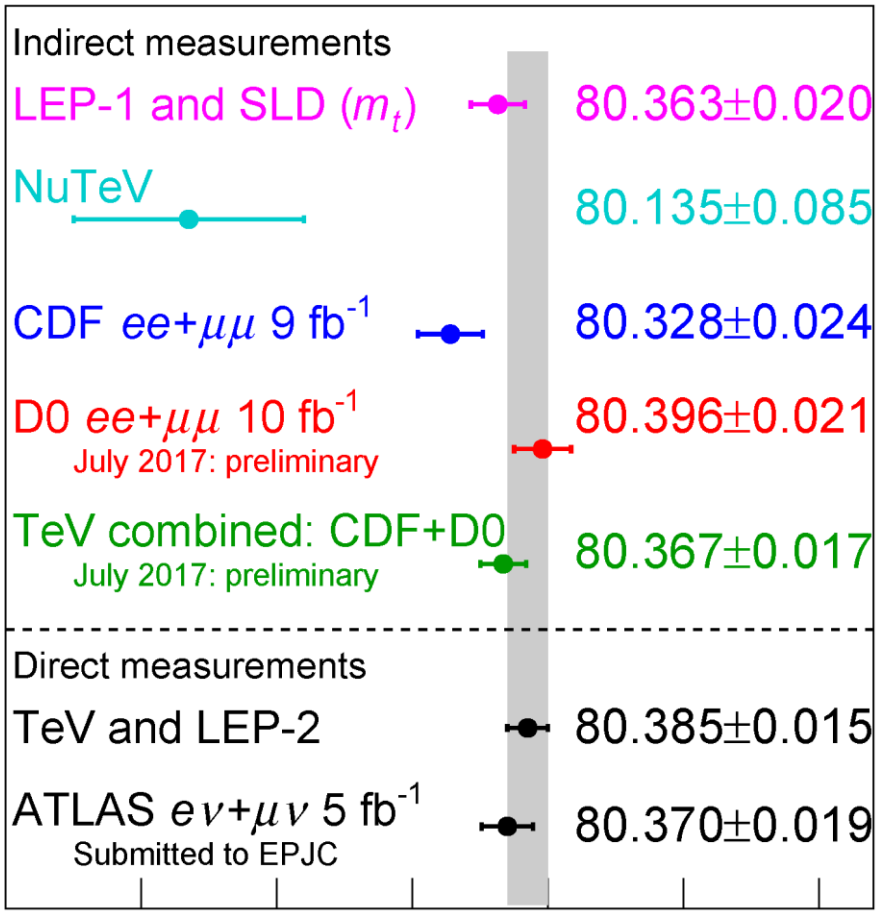
- **D0**

  $sin^2\theta_W$ = 0.22269 ± 0.00034 (stat) ± 0.00021 (syst)

- **Tevatron Combination**

  $sin^2\theta_W$ = 0.22324 ± 0.00026 (stat) ± 0.00019 (syst)

Inference of W Boson Mass



- **CDF**

  M_W = 80.328 ± 0.021 (stat) ± 0.010 (syst) GeV/c^2

- **D0**

  M_W = 80.396 ± 0.017 (stat) ± 0.011 (syst) GeV/c^2

- **Tevatron Combination**

  M_W = 80.367 ± 0.014 (stat) ± 0.010 (syst) GeV/c^2

Summary

- CDF and D0 have measured $sin^2\theta^l_{eff}$ 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: D0NOTE 6500 (2017)
- Produced combination result
  - $sin^2\theta^l_{eff}$ = 0.23148 ± 0.00033
- Using ZFITTER SM calculations, inferred W mass
  - M_W = 80.367 ± 0.017 GeV/c^2
- Tevatron legacy result
  - TeV combination note: FERMILAB-CONF-17-201-E
  - https://tevewwg.fnal.gov/wz/sw2eff17/

Backup Slides

The Tevatron

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