Measurements and combination of the effective leptonic weak mixing angle from Drell-Yan events at the Tevatron

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Outline

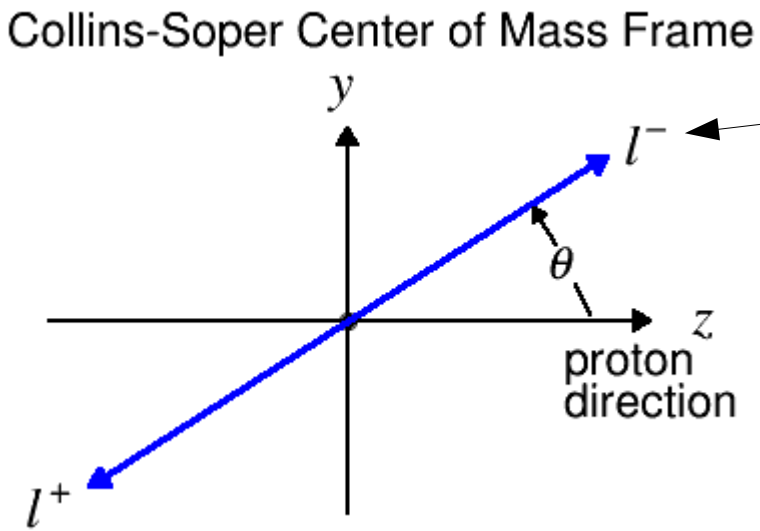
- Introduction
  - Forward-backwards asymmetry of Drell-Yan lepton pairs at the Tevatron
  - Extraction of effective leptonic mixing angle from the asymmetry
- D0 measurement
- CDF measurements
- CDF and D0 combination
  - Standardization of results for the combination
  - BLUE method combination
- Inference of $\sin^2\theta_W$
- Summary

Tevatron $p\bar{p}$ Collider

Run II: $\sqrt{s}$ = 1.96 TeV
2001-2011: 12 fb^{-1} Delivered

Forward-backwards asymmetry: A_{fb}

- Drell-Yan process at the Tevatron: $p\bar{p} \rightarrow \gamma^*/Z + X$, with $\gamma^*/Z \rightarrow l^+l^-$
  - l^+l^- polar-angle (ϑ) distribution in center-of-mass frame is asymmetric
    - Parity violation of Z decays
  - Born level angular distribution: $1 + \cos^2\vartheta + A_4\cos\vartheta$



Negatively charged lepton

- Forward (f): $\cos\vartheta \geq 0$
- Backward (b): $\cos\vartheta < 0$

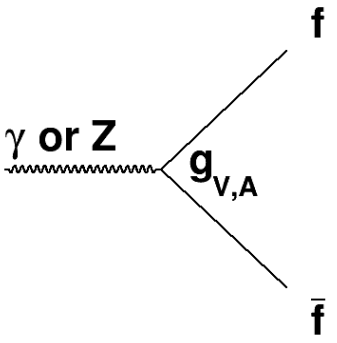
  - Forward/backward cross-section asymmetry

    $A_{fb} = (\sigma_f - \sigma_b)/(\sigma_f + \sigma_b) = \frac{3}{8} A_4$

    Is a probe to the electroweak mixing angle $\sin^2\theta_W$

- Born level $q\bar{q} \to \gamma^*/Z \to l^+l^-$ asymmetry

  – SM vector (V) and axial (A) current couplings of fermions
    - Z : $g_V = T_3(1-4|Q|\sin^2\theta_W)$ $g_A = T_3$; $\sin^2\theta_W = 1-(M_W/M_Z)^2$
    - γ: $g_V = Q$ $g_A = 0$

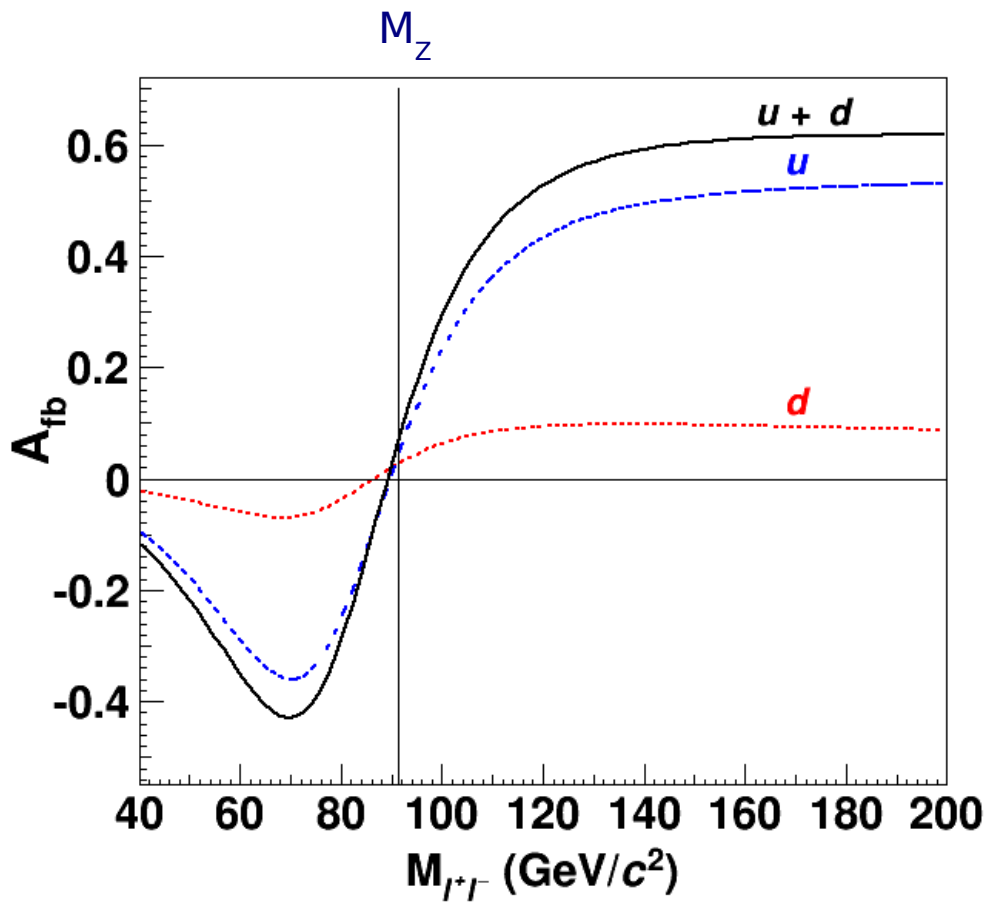


  – $(\sigma_f - \sigma_b)$ asymmetry arises from two V-A interference terms
    - $\gamma_{V\,V} \otimes Z_{A\,A}$: $Q^{(l)}Q^{(q)}$ $T_3^{(q)}T_3^{(l)}$ ← independent of $\sin^2\theta_W$
    - $Z_{V\,V} \otimes Z_{A\,A}$: $T_3^{(l)}(1-4|Q^{(l)}|\sin^2\theta_W)$ $T_3^{(q)}(1-4|Q^{(q)}|\sin^2\theta_W)$ $T_3^{(q)}T_3^{(l)}$
      [↳ 0.1] [↳ 0.4, 0.7]

  – Electroweak radiative corrections

    - Turns $\sin^2\theta_W$ into fermion-type dependent effective mixing angles $\sin^2\theta_{eff}$
      - leptonic
      - u-type quark
      - d-type quark
    - A_{fb} most sensitive to effective leptonic mixing angle @ M_Z : $\sin^2\theta_{eff}^{lept}$

Extracting $\sin^2\theta_{eff}^{lept}$



$A_{fb}^{(u)}$: u-quark contribution

$A_{fb}^{(d)}$: d-quark contribution

$$A_{fb}^{(u)} + A_{fb}^{(d)} = A_{fb}^{(u+d)}$$

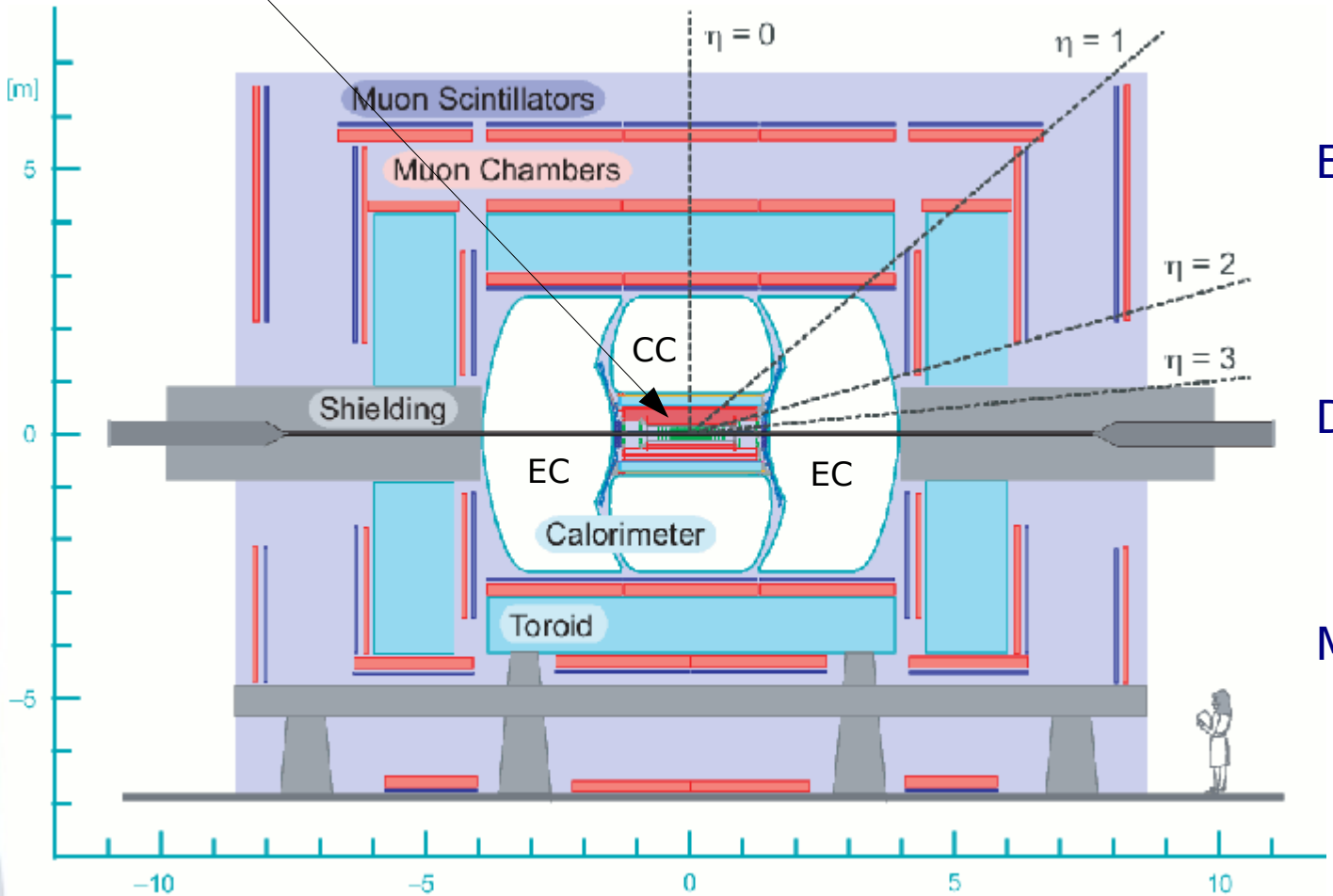
- Measure asymmetry in mass bins
  $A_{fb} = (N_f - N_b)/(N_f + N_b)$
- Fit A_{fb} to templates with
  varying values of $\sin^2\theta_{eff}^{lept}$
  to get best-fit value
- Experimental effects applied to
  templates or corrected in A_{fb}

Expectation:

- Z-Z interference term:
  sensitive to $\sin^2\theta_{eff}^{lept}$
  best precision near M_Z
  - most events at the pole
  - minimal γ-Z interference
- γ-Z interference term:
  zero at Z pole [$\sim 1-(M_Z/M)^2$]
  dominates away from pole
  sensitive to PDFs

D0 A_{fb} dataset selection

Precision tracking
- Solenoid field 1.9 T
- Fiber tracker $|\eta| < 2$
- Silicon tracker $|\eta| < 3$



Electrons: CC + EC

$P_T > 25$ GeV/c

CC: $|\eta| < 1.1$

EC: $1.5 < |\eta| < 3.2$

Dielectrons

CC-CC: 248K events

CC-EC: 241K events

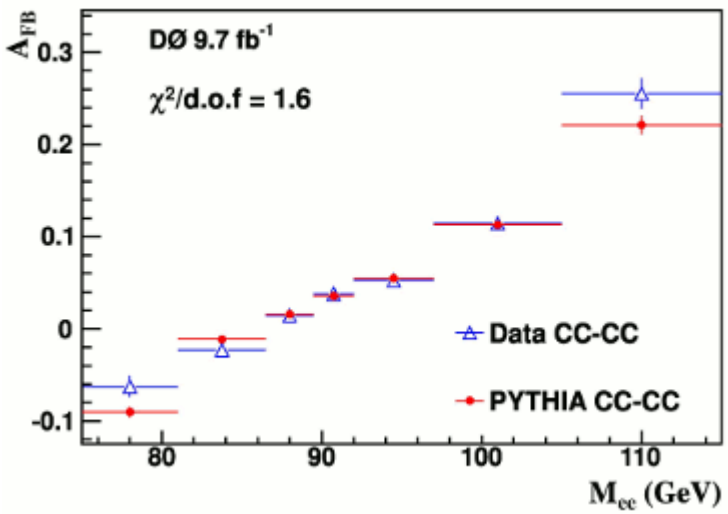
EC-EC: 71K events

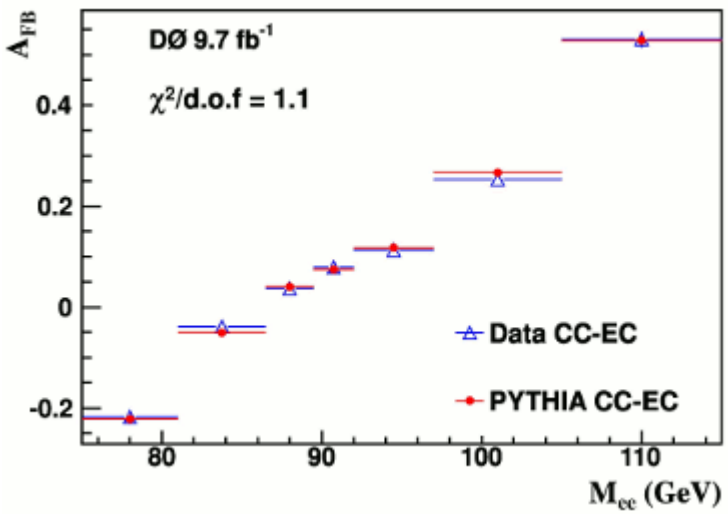
Muon analysis:

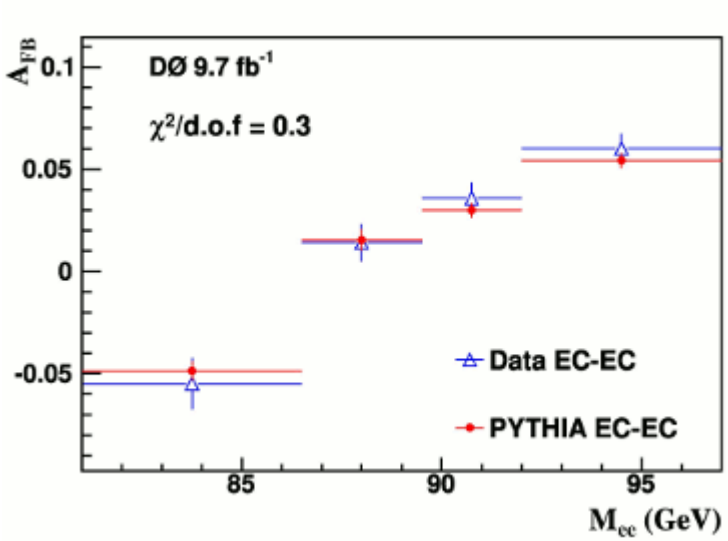
in progress

A_{fb} measurements

PRL 115, 041801 (2015), PRD 84, 012007 (2011)







Inputs:

- A_{fb} measurement
- templates (PYTHIA)
  include detector simulation,
  varying values of $\sin^2\theta_{eff}^{lept}$

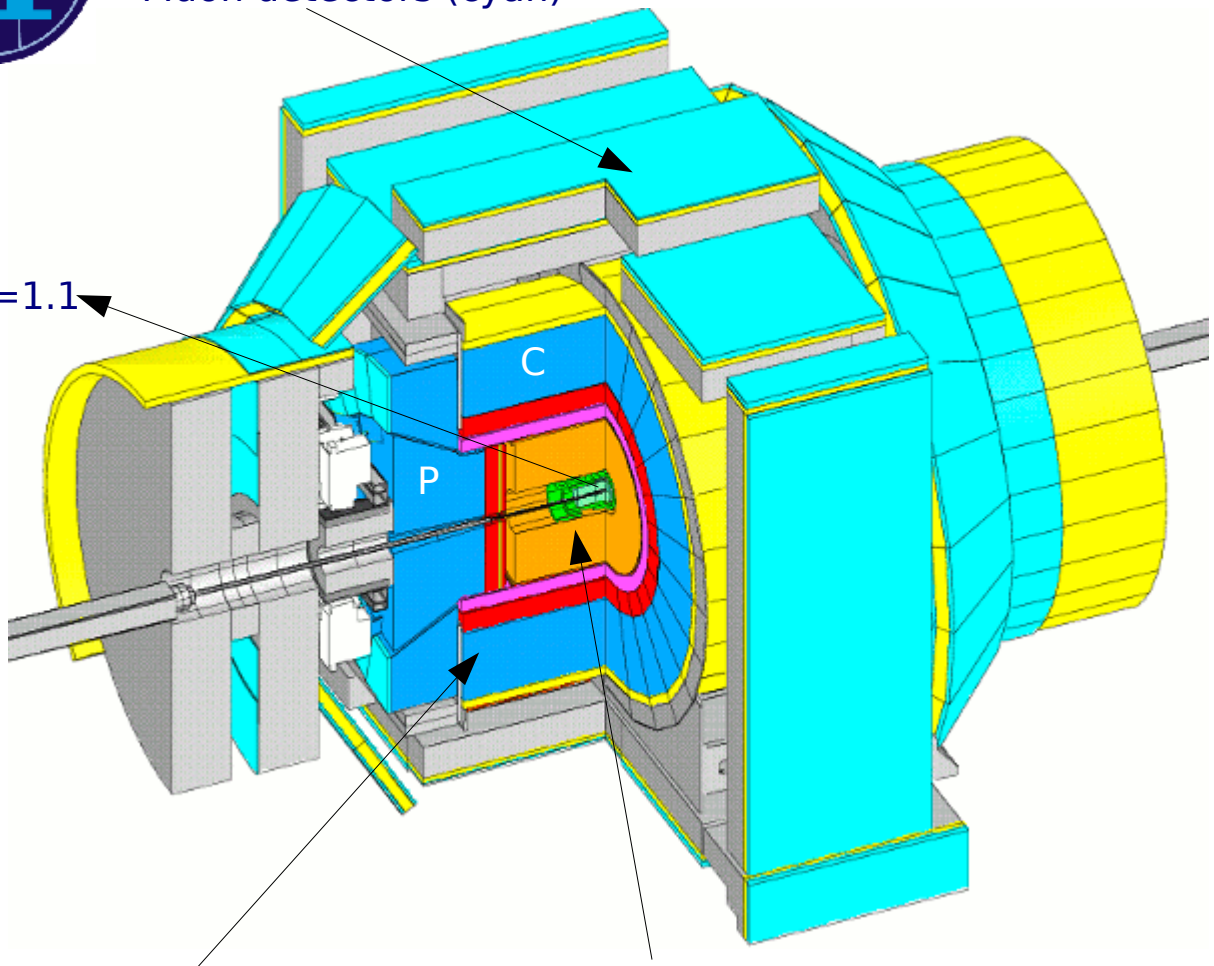
Fit A_{fb} to templates for best-fit $\sin^2\theta_{eff}^{lept}$

Summary of $\sin^2\theta_{eff}^{lept}$ extraction

- Analysis
  - Asymmetries separately fit to templates then best-fit values combined
  - Template calculation
    - PYTHIA 6.23 with NNPDF v2.3(NLO) PDFs
    - Higher order QCD effect corrections applied to generated events
    - Detector simulation included
  - Adjustment for electroweak radiative corrections
    - Fit value biased: $\sin^2\theta_{eff}^{lept}$ and quark $\sin^2\theta_{eff}$'s differ in value
    - Bias correction +0.00008 estimated by ZGrad+ResBos applied to result
- Final result
  - $\sin^2\theta_{eff}^{lept} = 0.23147 \pm 0.00047$ (total)

statistics:	0.00043
PDF:	0.00017
other systematics:	0.00008

CDF A_{fb} dataset selection



Calorimeters: |n|<3.5
EM: red
Hadronic: blue

Precision tracking: |η|≲1.1
Solenoid field 1.4 T
Drift chamber (r=1.3 m)
Silicon vertex detector

Dimuons:

$P_T^{(\mu)} > 20$ GeV/c

$|\eta^{(\mu)}| \lesssim 1.1$ (277K events)
well measured tracks

Electrons

Central (C): $0.05<|\eta|<1.05$
well measured tracks

End plug (P): $1.2<|\eta|<2.8$
significantly reduced tracking volume

Dielectrons

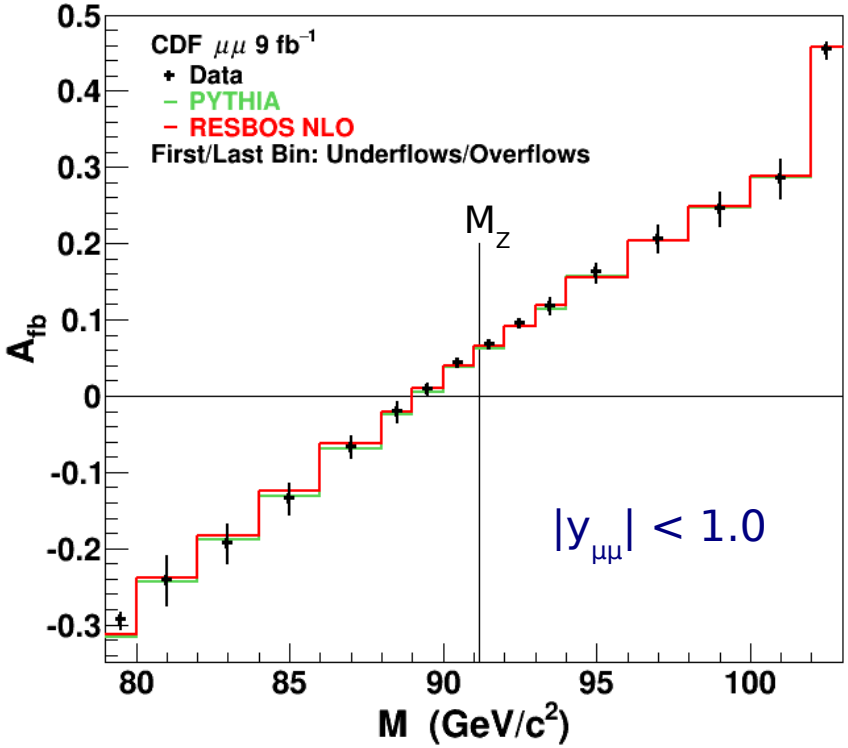
CC: $E_T^{(e)} > 25/15$ GeV
227K events

CP: $E_T^{(e)} > 20$ GeV
258K events

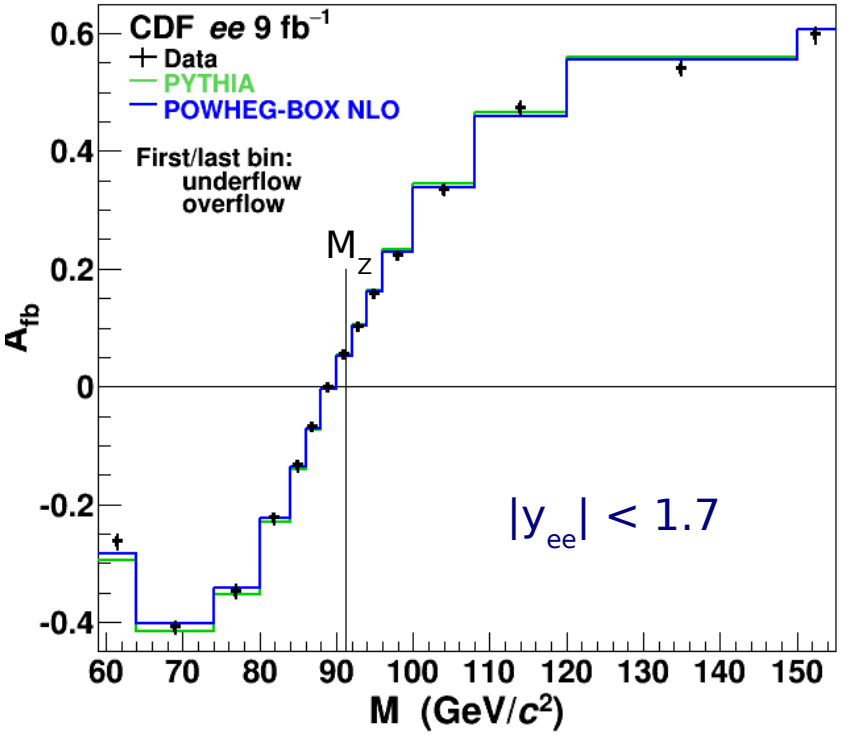
PP: $E_T^{(e)} > 25$ GeV
80K events, calibration only

A_{fb} measurements

PRD 89, 072005 (2014)



PRD 93, 112016 (2016)



Measurements corrected, templates are pure calculations and for the specified kinematic range

RESBOS and POWHEG-BOX best-fit templates include EWK radiative corrections

Summary of $\sin^2\theta_{eff}^{lept}$ extraction

- Analysis
  - Asymmetry measurements corrected for direct fits to calculations
    - Measurement: angular-weighted event sums method [EPJ C 76, 321 (2010)]
    - Simulation: matrix unfolding of detector and QED FSR smearing; residual bias correction of a few percent
  - Simulation
    - PYTHIA 6.2(CTEQ5L) ⊕ PHOTOS 2.0(QED FSR) ⊕ CDF detector simulation
    - Higher order QCD effect corrections applied to generated events
  - Templates
    - POWHEG-BOX(NLO) ⊕ NNPDF v3.0(NNLO) PDFs ⊕ PYTHIA 6.4 parton showers
    - ZFITTER 6.43 electroweak radiative corrections incorporated
      - fermion-type dependent effective mixing angles $\sin^2\theta_{eff}$
- $\sin^2\theta_{eff}^{lept}$ values from template fits
  - μμ analysis: 0.23141±0.00086 (stat) ← refit - same template framework as ee
  - ee analysis: 0.23248±0.00049 (stat) fit χ^2's simply combined into a joint χ^2
  - Best-fit value of joint χ^2: 0.23221±0.00046 (total)

statistics:	0.00043
PDF:	0.00016
other systematics:	0.00006

Radiative correction treatments

- D0 mixing angle results: improved
  - PYTHIA template: single mixing angle and running α_{em}
  - ZGrad+ResBos adjustment: improves accounting for differences of fermion-dependent effective mixing angles @ M_Z

- CDF ZFITTER based results: improved even more
  - Complex-valued form-factors ρ and κ for Born Z-couplings

$$g_v^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f(1 - 4|Q_f|\kappa_f \sin^2\theta_W)$$
$$g_A^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f$$

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})

Result standardization for the combination

- Common PDF and electroweak correction baselines for consistency
  - NNPDF v3.0
    - 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
- Standardization paths for CDF and D0
  - CDF: Already at baseline
  - D0 : Standardization corrections to $\sin^2\theta_{eff}^{lept}$ value
- D0 standardization corrections
  - Δ(PDF): NNPDF v2.3 → v3.0 offset = −0.00024±0.00004
    - Difference of v3.0 pseudodata $\sin^2\theta_{eff}^{lept}$ and v2.3 template fit value

      A_{fb} pseudodata: v3.0 default PDF with reference value of $\sin^2\theta_{eff}^{lept}$

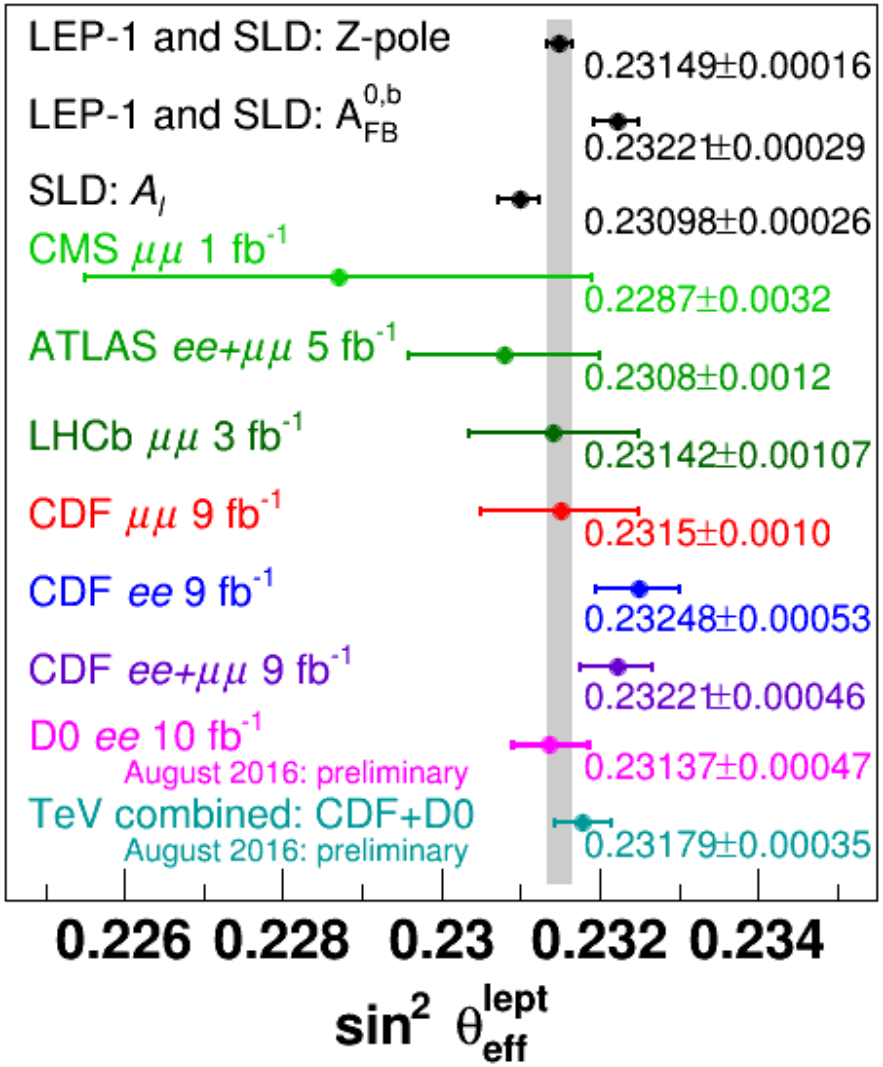
      Templates : v2.3 default PDF with varying values of $\sin^2\theta_{eff}^{lept}$
  - Δ(RadCor): ZGrad+ResBos → ZFITTER offset = +0.00014±0.00004
    - Difference of $\sin^2\theta_{eff}^{lept}$ results *with* and *without* ZFITTER corrections

      ↳ analog of PYTHIA templates

BLUE combination of $\sin^2\theta_{eff}^{lept}$ results

- Input observable values
  - Standardized D0 value : 0.23137±0.00043 (stat) ± 0.00019 (syst)
  - CDF ee⊕μμ value : 0.23221±0.00043 (stat) ± 0.00018 (syst)
- Input uncertainty categories
  - Statistics: CDF: 0.00043, D0: 0.00043
  - PDF: CDF: 0.00016, D0: 0.00017 (100% correlated)
  - Other systematics: CDF: 0.00007, D0: 0.00008 (uncorrelated)
  - Standardization: D0 0.00005 (only applies to D0)
- Results of BLUE method
  - $\sin^2\theta_{eff}^{lept} = 0.23179 \pm 0.00030$ (stat) ± 0.00017 (syst)
  - χ^2 of combination: 1.8 (18% probability)
  - Uncertainties

Statistics:	0.00030
PDF:	0.00017
Other systematics:	0.00005
Standardization:	0.00003



Phys. Rep. 427, 257 (2006)
Phys. Rep. 532, 119 (2013)

Phys. Rev. D84, 11202 (2011)

J. High Energy Phys. 09 (2015) 049

J. High Energy Phys. 11 (2015) 190

Phys. Rev. D89, 072005 (2014)

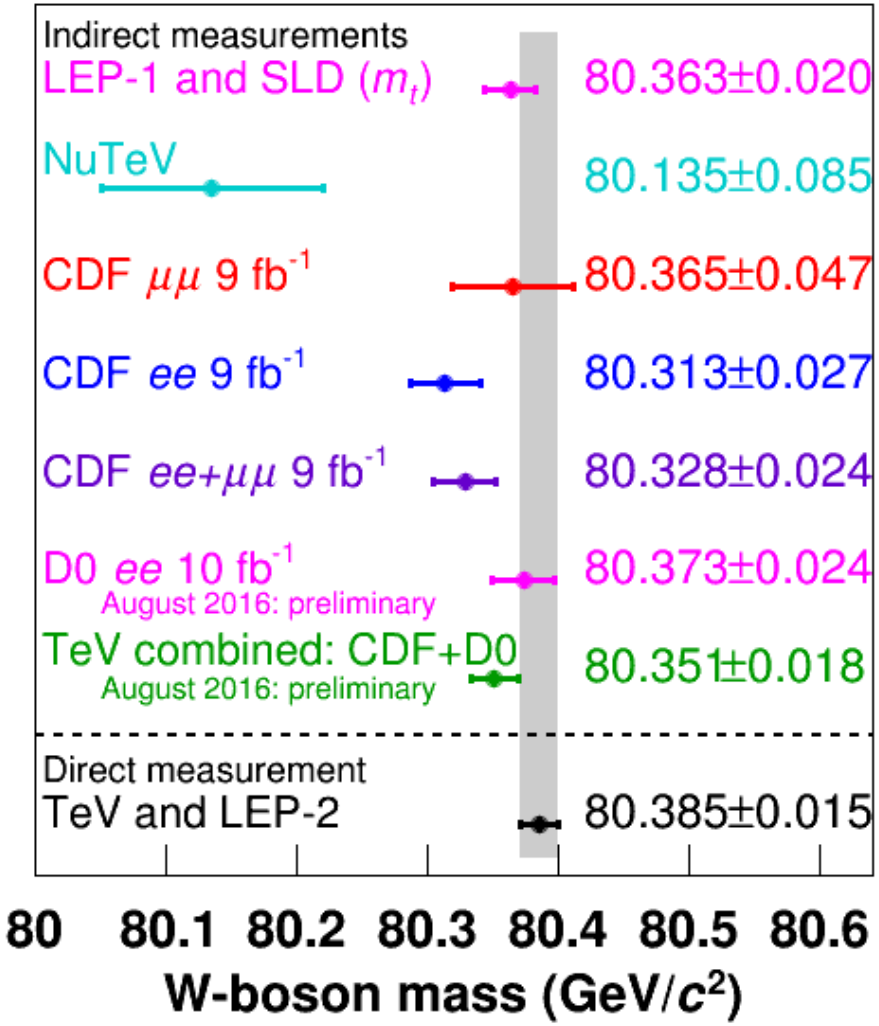
Phys. Rev. D93, 112016 (2016)

ICHEP preliminary: this talk

Inference of W-boson mass

- $\sin^2\theta_W$ and M_W equivalent in SM on-shell renormalization scheme (ZFITTER)
  - $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ all orders definition
  - M_Z well measured by LEP-1 and SLD: 91.1875±0.0021 GeV/c^2
- Standard model help from ZFITTER is needed
  - $\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2,\sin^2\theta_W)]\sin^2\theta_W$
    ↳ ≈1.037
  - Form factors depend on standard-model input parameters
    - Most sentitive to top-quark mass 173.2±0.9 GeV/c^2
    - Form factor uncertainty to $\sin^2\theta_W$: 0.00008
    - Higgs mass value: 125 GeV/c^2
- Inferences

	$\sin^2\theta_W$	M_W
– CDF only:	0.22400±0.00041±0.00019	80.328±0.021±0.010 GeV/c^2
– D0 only:	0.22313±0.00041±0.00020	80.373±0.021±0.010 GeV/c^2
– Combination:	0.22356±0.00029±0.00019	80.351±0.015±0.010 GeV/c^2
	(stat) (syst)	(stat) (syst)



Phys. Rep. 427, 257 (2006)
Phys. Rep. 532, 119 (2013)*

Phys. Rev. Lett. 88, 091802 (2002)

Phys. Rev. D89, 072005 (2014)*

Phys. Rev. D93, 112016 (2016)*

* m_t = 173.2±0.9 GeV/c^2

ICHEP preliminary: this talk*

Phys. Rev. D88, 05218 (2013)

Summary

- CDF and D0 have
  - extracted $\sin^2\theta_{eff}^{lept}$ from Drell-Yan lepton-pair asymmetries
    - CDF: electron and muon pairs
    - D0 : electron pairs
  - combined the resulting values of $\sin^2\theta_{eff}^{lept}$
- Using ZFITTER SM calculations, inferred $\sin^2\theta_W$ or equivalently M_W
- D0 muon-pair asymmetry analysis is in progress — stay tuned!

The End

http://tevewwg.fnal.gov/wz/