CDF measurement of the effective leptonic electroweak mixing angle parameter

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LHC EWK precision subgroup meeting
25 Apr 2018

Outline

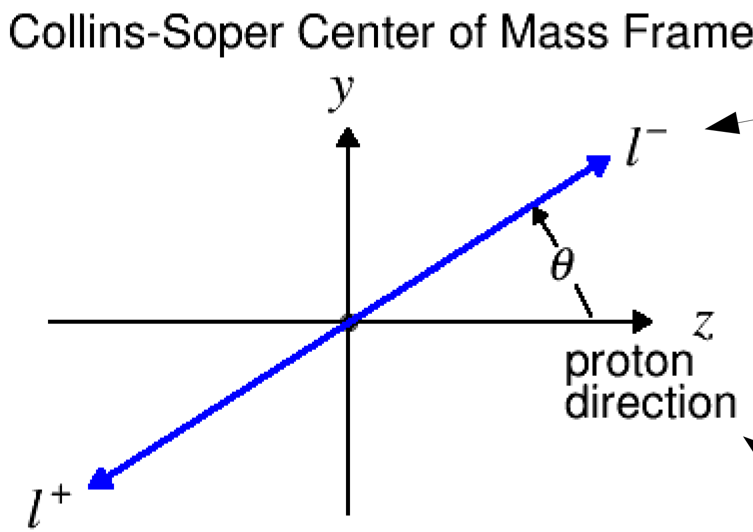
- Introduction
  - Forward-backwards asymmetry of Drell-Yan lepton pairs at the Tevatron
  - Extraction of effective leptonic mixing angle from the asymmetry
- CDF data selection
- A_{fb} measurements
- A_{fb} template calculations
  - ZFITTER electroweak radiative corrections
- $\sin^2\theta_{eff}^{lept}$ measurements from template fits
  - μμ and ee analyses
  - Combination with NNPDF-3.0 ensemble
- Tevatron $\sin^2\theta_{eff}^{lept}$ results
- 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 $\gamma^*/Z \rightarrow l^+l^-$
  - Born level angular distribution: $1 + \cos^2\vartheta + A_4\cos\vartheta$



Negatively charged lepton

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

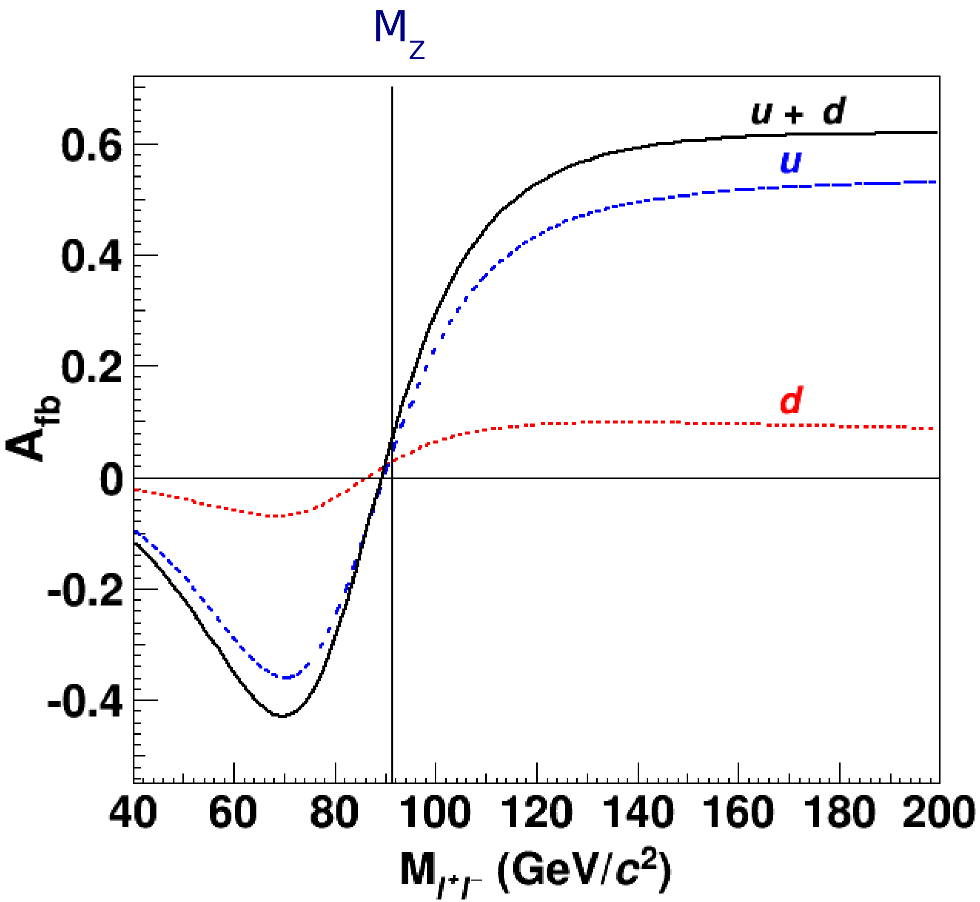
At Tevatron, proton direction good approximation of quark direction

  - Forward/backward cross-section asymmetry

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

Tevatron A_{fb} not binned in y_{ll}

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
  $A_{fb} = (N_f - N_b)/(N_f + N_b)$
- Experimental effects
  removed from asymmetry
- Fit A_{fb} to templates with
  varying values of $\sin^2\theta_{eff}^{lept}$
  to get best-fit value

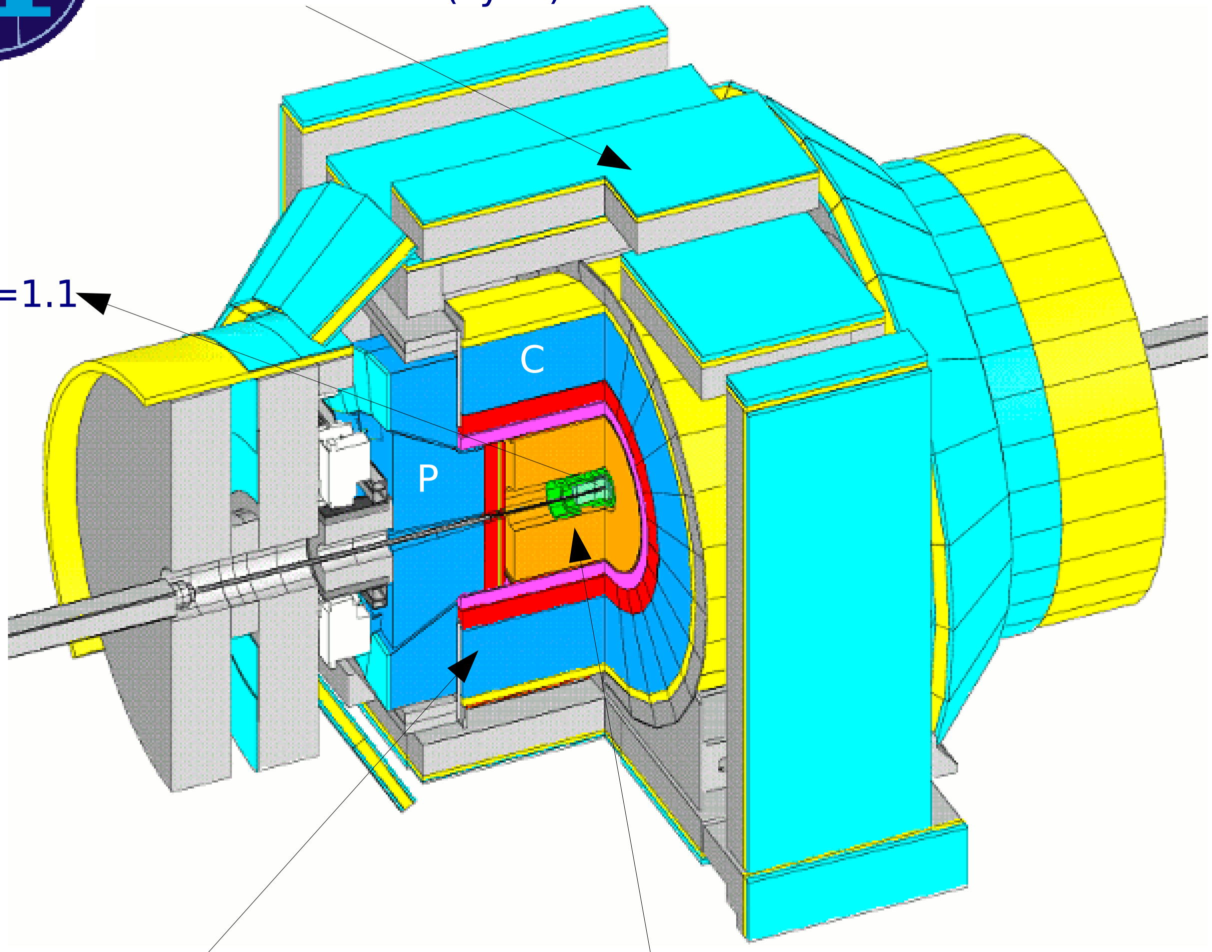
V–A interference terms

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

Data selection

Muon detectors (cyan)

$|\eta|=1.1$



Calorimeters: $|\eta|<3.5$
- EM: red
- Hadronic: blue

Precision tracking: $|\eta|\lesssim 1.1$
- 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

Asymmetry measurement method

- Simulation
  - PYTHIA 6.2(CTEQ5L) with QED FSR ⊕ CDF detector simulation
  - Higher order QCD effect corrections applied to generated events
- Corrections to data and simulated data
  - E (p) scales calibrated with method developed for CMS: EPJ C73, 2194 (2012)
  - Resolutions of the simulation tuned to data
  - Angular-weighted event sums measurement method: EPJ C 76, 321 (2010)
    - Basic idea

      Measure A_{fb} in localized $|\cos\vartheta|$ bin and combine: $A_{fb}|\cos\vartheta|/(1+\cos^2\vartheta+ ..)$

      εA cancels to first order because of localization
    - Convert back to single bin A_{fb} with event weights that account for

      Numerator and denominator angular factors

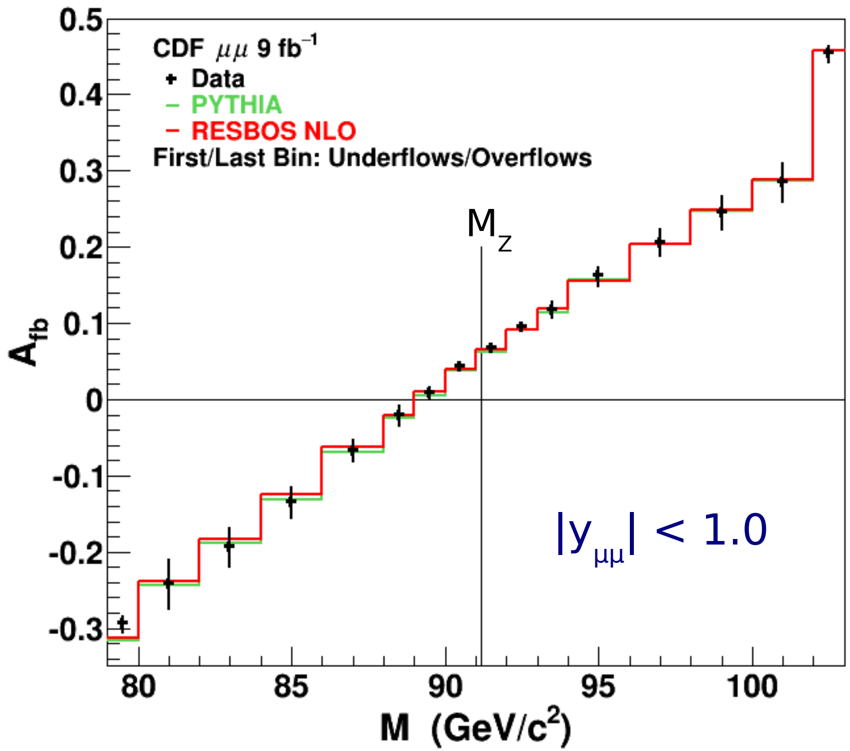
      Statistical factor $|\cos\vartheta|/(1+..)$ for combining across $|\cos\vartheta|$ regions
    - Method needs events to account for small A_{fb} variations with boson y

      Limit measurement and calculations to regions with sufficient data

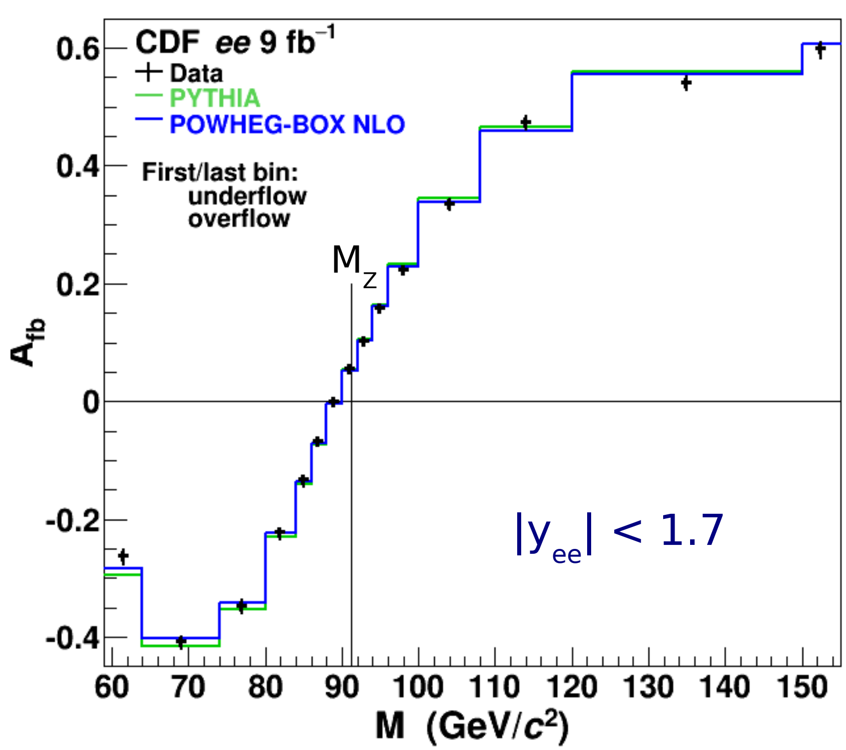
      $|y_{\mu\mu}| < 1$ and $|y_{ee}| < 1.7$
  - Simulation is used for these asymmetry corrections
    - Matrix unfolding of detector smearing effects
    - Residual 2^{nd} order angular-weighting bias corrections (few percent)
- Mass bins
  - Electron and muon channel binning differ
  - Bins of variable widths

A_{fb} measurements

PRD 89, 072005 (2014)



PRD 93, 112016 (2016)

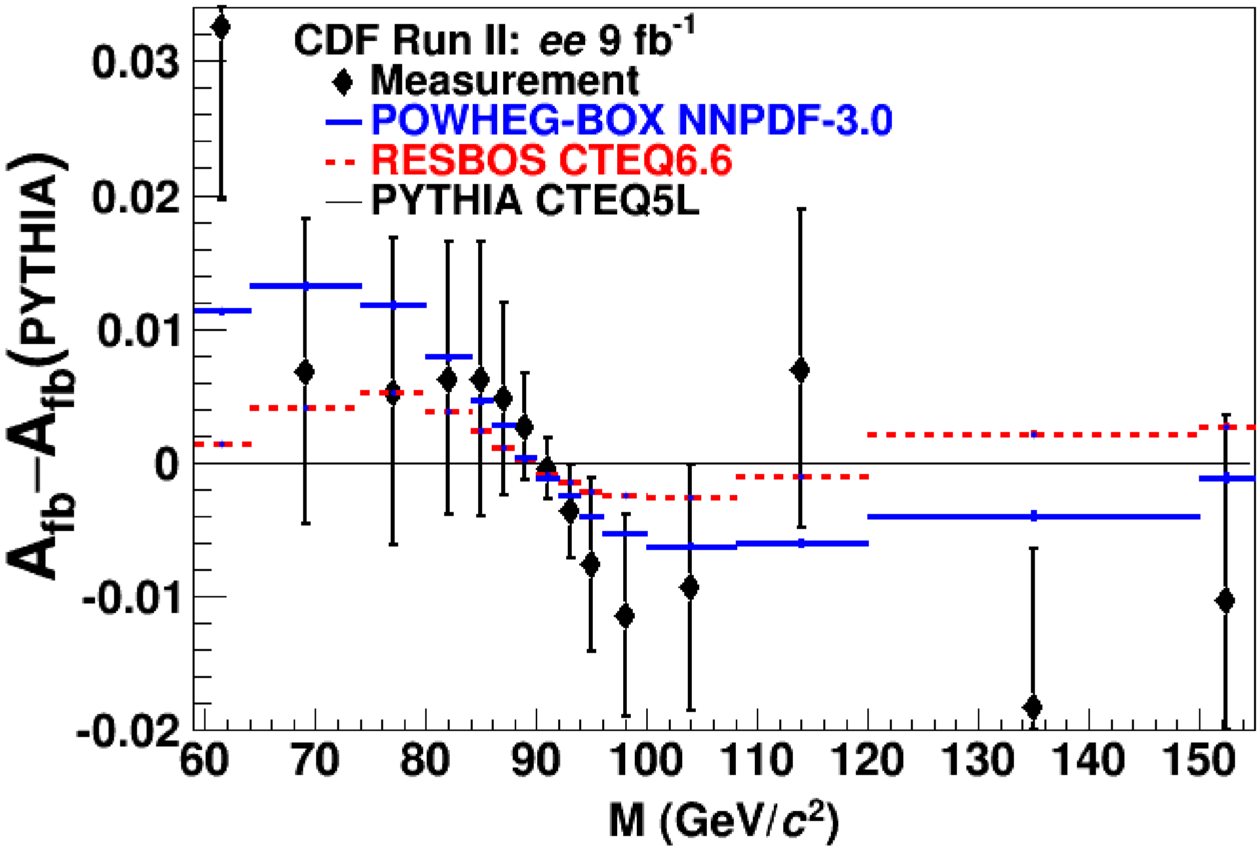


Measurements are fully corrected

RESBOS and POWHEG-BOX templates include EWK radiative corrections
PYTHIA is CDF standard

A_{fb} measurement and PDFs

- A_{fb} shifts relative to PYTHIA with an older PDF
  - Best-fit templates are shown
  - $\sin^2\theta_{eff}^{lept}$: PB = 0.23248; RB = 023249; PY* = 0.23207



Template calculations

- Historical note
  - $\mu\mu$ analysis: RESBOS (CTEQ66) calculated templates
  - ee analysis and ee+$\mu\mu$ combination templates:
    - POWHEG-BOX(NLO)⊕NNPDF-3.0(NNLO) PDFs ⊕ PYTHIA 6.4 parton showers
- ZFITTER 6.43 electroweak radiative corrections
  - Corrections are complex-valued form-factors ρ and κ to fermion-Z couplings

$$g_V^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f(1 - 4|Q_f|\kappa_f \sin^2\theta_W) \qquad [\ \sin^2\theta_{eff} = \kappa_f \sin^2\theta_W\ ]$$

$$g_A^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f$$

ρ_f / κ_f: functions of fermion type, M_{ll}^2, $\sin^2\theta_W$

1-4% corrections to $\rho=\kappa=1$

  - Corrections modify $\sin^2\theta_W$ into *multiple* effective mixing angles $\sin^2\theta_{eff}$
- Template calculations using the model based on ZFITTER
  - Multiple $\sin^2\theta_{eff}$'s incorporated into QCD calculations
    - Goal: Better model of "$\sin^2\theta_{eff}^{lept}$" extraction from A_{fb} over "one-size-fits-all"
  - Photon-propagator form factor from fermion loops is also utilized
  - *Template adjustment "knob" is $\sin^2\theta_W$ but fits extract $\sin^2\theta_{eff}$*

- Guide to ρ and κ form factors of the model
  - $\sin^2\theta_W$ dependence: very small
  - Quark type dependence: small
  - M_{ll}^2 dependence: several percent
    - Away from $M_{ll}=M_Z$, the applied form factor is approximated
  - κ_l: form factor to $\sin^2\theta_W$ at lepton vertex
  - κ_q: form factor to $\sin^2\theta_W$ at quark vertex
  - Example values for $\sin^2\theta_W = 0.22332$ and $M_{ll} = M_Z$

	u-type quark	d-type quark	
ρ :	(1.0054,–0.0042i)	(1.0059,–0.0034i)	
κ_l:	(1.0369, 0.0135i)	(1.0369, 0.0135i)	← equal at M_Z
κ_q:	(1.0364, 0.0128i)	(1.0358, 0.0120i)	← different from κ_l

- All $\sin^2\theta_{eff}$'s are related to each other: what $\sin^2\theta_{eff}$ should be reported?
  - $\sin^2\theta_{eff}^{lept} \equiv \mathrm{Re}[\kappa_l(M_Z^2,\sin^2\theta_W)]\sin^2\theta_W$
    - A_{fb} is most sensitive to variations of lepton vertex $\kappa_l\sin^2\theta_W$
    - Extracted $\sin^2\theta_{eff}$'s reflect values where all the data is: Z-pole region
  - Analog to LEP1/SLD's Z-pole $\sin^2\theta_{eff}^l$

$\sin^2\theta_{eff}^{lept}$ extracted from template fits

- $\sin^2\theta_{eff}^{lept}$ results
  - μμ analysis: 0.2315 ±0.0009 (stat) ±0.0009 (syst) RESBOS/CTEQ66
  - μμ analysis: 0.23141±0.00086 (stat) POWHEG/NNPDF3
  - ee analysis: 0.23248±0.00049 (stat) ±0.00019 (syst) POWHEG/NNPDF3

  - ee + μμ : 0.23221±0.00043 (stat) ±0.00018 (syst) POWHEG/NNPDF3
    - A_{fb} measurement-template χ^2's for ee and μμ are combined
    - Results from the joint ee-μμ χ^2 are used
- Systematic uncertainty categories

	μμ	ee	ee + μμ	
E (p) scale	0.00005	0.00003	0.00002	uncorr
Backgrounds	0.00010	0.00002	0.00003	uncorr
QCD scale	0.00012	0.00002	0.00007	joint fit
PDF	0.00037	0.00019	0.00016	joint fit

  - QCD scale: NLO – Tree template fit result difference
    - μμ + ee: combined fit results used
  - PDF uncertainty
    - μμ historical: CTEQ error PDFs
    - μμ + ee: combined fit result used

- NNPDF-3.0 PDF ensemble profile

  - The ee and μμ A_{fb} measurements are independently profiled

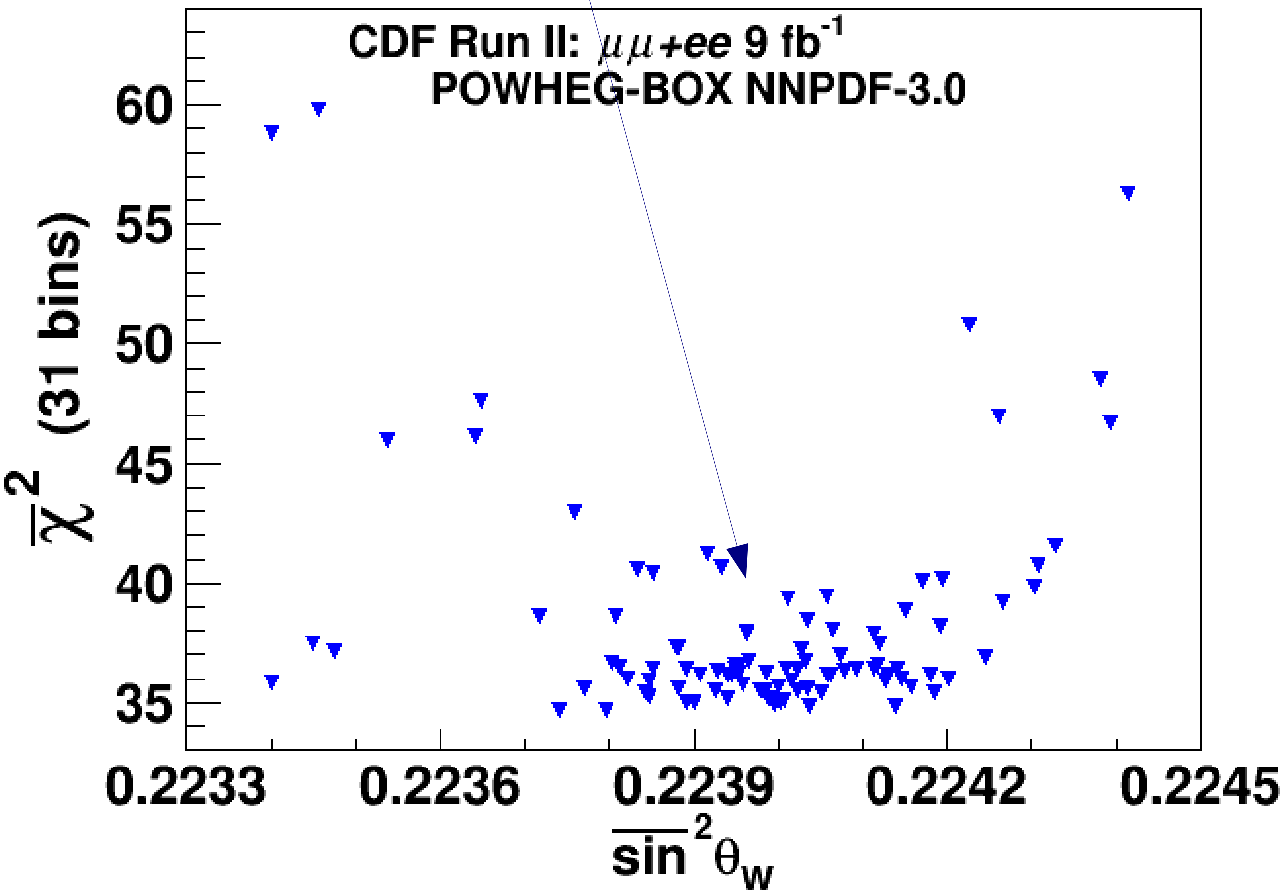
  - Standard template fit technique applied to each ensemble PDF
    - A set of $\sin^2\theta_W$ points is defined
    - Separate ee and μμ templates for each $\sin^2\theta_W$ point
    - χ^2 's are evaluated using measurement error matrices
    - χ^2 's of the $\sin^2\theta_W$ points are fit to a χ^2 parabola to give
      $\chi^2_{\text{best-fit}}$, $\sin^2\theta_W$ parameter, and $\sin^2\theta_W$ statistical uncertainty
    - ee+μμ results: combine ee and μμ χ^2 into a joint χ^2 for
      Joint $\chi^2_{\text{best-fit}}$, $\sin^2\theta_W$ parameter, and $\sin^2\theta_W$ statistical uncertainty
      ee and μμ data and PDF related correlations are accounted for

  - Giele-Keller ensemble average/rms method
    - Ensemble PDF weight ∝ $\exp(-\chi^2_{\text{best-fit}}/2)$
    - Value of a calculated quantity: weighted ensemble average
    - PDF uncertainty of the quantity: rms about average

- Fit profile over the 100 ensemble PDFs for ee + μμ combination
  - Measurement consistent with ensemble
  - Ensemble average $\sin^2\theta_{eff}^{lept}$:

0.23221 ± 0.00043 (stat) ± 0.00016 (PDF)

Utilizing PDF χ^2 handle improves uncertainty: 21→16

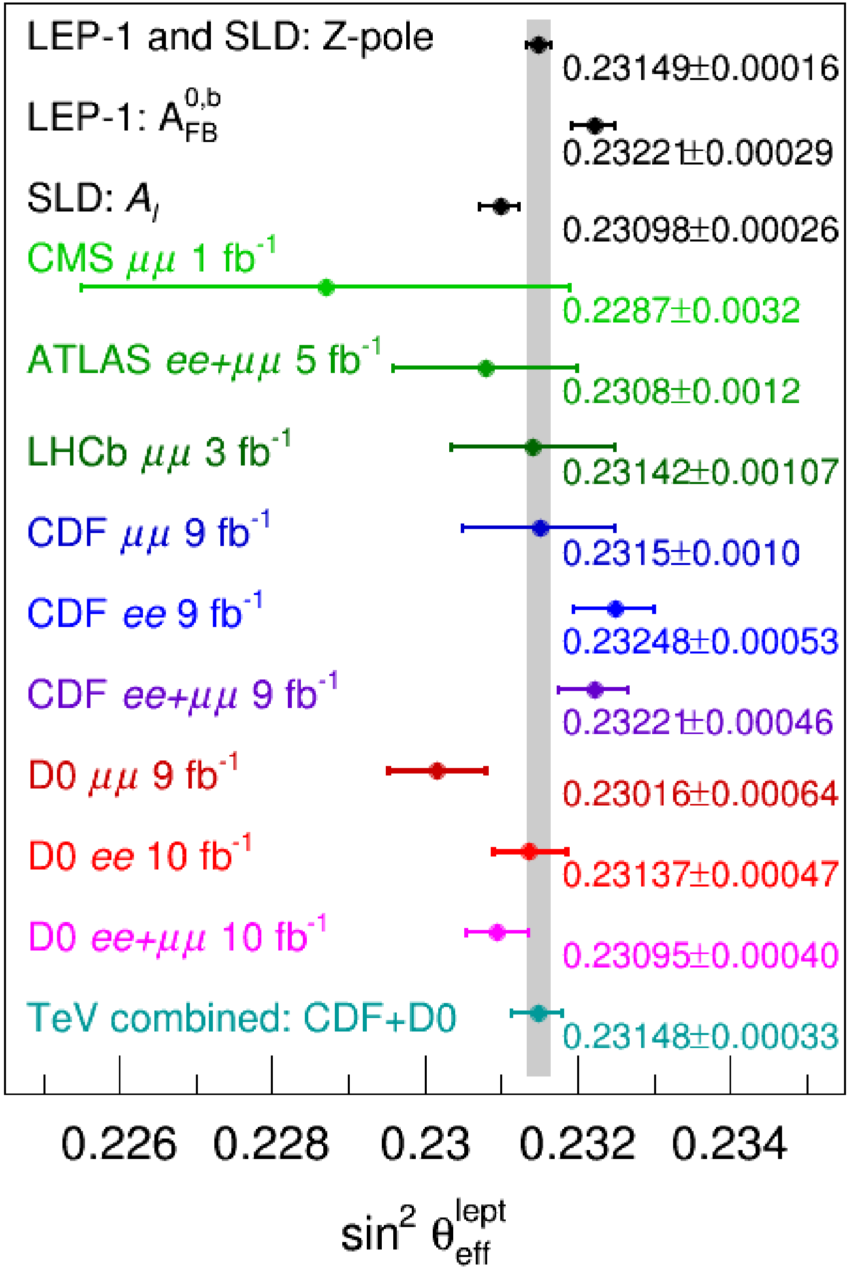


Effect of $\sin^2\theta_{eff}$ model on extracted $\sin^2\theta_{eff}^{lept}$

- $\sin^2\theta_{eff}$ model
  - Complex valued $\sin^2\theta_{eff}$
  - Multiple $\sin^2\theta_{eff}$'s depending on lepton and quark type
  - $\sin^2\theta_{eff}^{lept} \equiv \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$ where $\sin^2\theta_W$ is a tuning knob
- "One-size-fits-all" model
  - Single, constant, real-valued $\sin^2\theta_{eff}$: "$\sin^2\theta_{eff}^{lept}$"
- Effect calculation
  - Extract $\sin^2\theta_{eff}^{lept}$ from CDF ee and μμ A_{fb} measurements
  - Relative shift: $\sin^2\theta_{eff}^{lept}(\rho,\kappa) - \sin^2\theta_{eff}^{lept}(\rho=\kappa=1) = 0.00022 \pm 0.00004$

    ↓ $\sin^2\theta_{eff}$ model (with ρ,κ form factors)

    ↳ "one-size-fits-all" model



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Accepted by PRD:
arXiv:1801.06283 [hep-ex]

Summary

- CDF ee and μμ channel asymmetry measurements
  - utilizes techniques developed for CMS
    - calibration method for E (p) scales of both the data and simulation
    - angular event-weighting method for measuring A_{fb}
  - fully corrected to account for experimental effects
    - measurement error matrices for comparisons with templates
- Template calculations
  - CDF's attempt at using ZFITTER race car technology
    - to improve model for extracting $\sin^2\theta_{eff}$'s from A_{fb}
  - Powheg-Box/Z is friendly to the model
    - Complex amplitudes used in partonic calculations
  - NNPDF3.0 ensemble PDF
    - simplified combination of ee and μμ A_{fb} measurements with PDF correlations