Using ZFITTER in CDF/Tevatron A_{fb} template calculations

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Outline

- Introduction
- Standard Model (SM) context adopted for ZFITTER calculations
- CDF Drell-Yan QCD calculations and ZFITTER
- PDF and mixing angle effects on A_{fb} at the Tevatron
- Tevatron Legacy $\sin^2\theta_{eff}^{lept}$ measurement summary
  - ZFITTER based interpretation for M_W
- Summary

Introduction

- CDF 2011
  - $\sin^2\theta_{eff}^{lept} = 0.2329 \pm 0.0008(stat) \pm 0.0010(syst\ !??)$: $\langle A_4 \rangle$ method, 2 fb^{-1} ee
  - How to do better $\sin^2\theta_{eff}^{lept}$ extractions: ZFITTER deliberations begins
    - ROKANC's $ee \to Z \to q\bar{q}$ scattering amplitude looked like the promised land
    - But is it suitable for Drell-Yan $q\bar{q} \to \ell\ell$?

      Yes, according to Tord Riemann

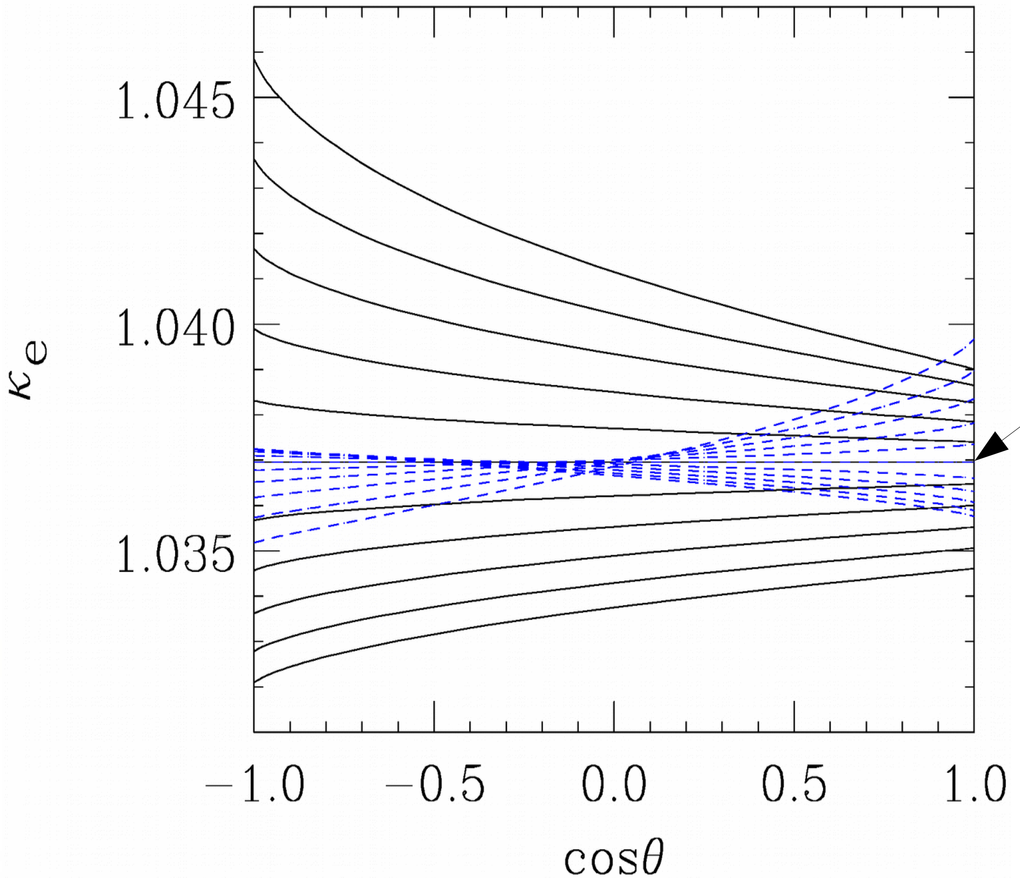
      But CDF may be the first to try ... Oh boy ...

- ROKANC (ρ-κ-NC) scattering amplitude:
  - $$A_q \propto 4\,\rho_{eq} T_{3,e} T_{3,q}\ \{ \langle e|\gamma_\mu(1+\gamma_5)|e\rangle\langle q|\gamma_\mu(1+\gamma_5)|q\rangle$$
    $$- 4|Q_e|\,\kappa_e \sin^2\theta_W \langle e|\gamma_\mu|e\rangle\langle q|\gamma_\mu(1+\gamma_5)|q\rangle \qquad \leftarrow \sin^2\theta_{eff} = \kappa \sin^2\theta_W$$
    $$- 4|Q_q|\,\kappa_q \sin^2\theta_W \langle e|\gamma_\mu(1+\gamma_5)|e\rangle\langle q|\gamma_\mu|q\rangle$$
    $$+ 16\,|Q_e Q_q|\,\kappa_{eq} \sin^4\theta_W \langle e|\gamma_\mu|e\rangle\langle q|\gamma_\mu|q\rangle\ \}$$
  - ρ_{eq} κ_e κ_q and κ_{eq}: complex-valued form-factor functions
    - External QED and QCD radiation turned off
    - Include W/Z box contribution (only approximate factorization)
    - Massless fermion approximation
    - Functions of s, t, $\sin^2\theta_W$, and weak isospin
    - Gauge invariant "pseudo-observables" (and hence so is $\sin^2\theta_W$)
  - $\sin^2\theta_{eff}$: four effective mixing terms
  - Overall coupling: $\sqrt{2}\, G_F M_Z^2$ (G_F and ρ_{eq} must go together)

SM context for ROKANC

- On-shell renormalization scheme is used
  - Particle masses are on shell: $\sin^2\theta_W = 1 - M_W^{\,2}/M_Z^{\,2}$ to all orders
  - M_Z is well measured: $\sin^2\theta_W$ interpretation equivalent to M_W inference
- ZFITTER input parameters
  - G_F, α_{em} $(e^2/4\pi)$, light particle masses
  - $M_Z = 91.1875 \pm 0.0021$ GeV, $m_t = 173.2 \pm 0.9$ GeV
  - $\Delta\alpha_{em}^{(5)}(M_Z^{\,2})$[DALH5] $= 0.0275 \pm 0.0001$, $\alpha_s(M_Z^{\,2}) = 0.118$
- Fix m_H=125 GeV
  - Otherwise Tevatron A_{fb} fits give strange values for $\sin^2\theta_W/m_H$
  - But now $\sin^2\theta_W$ is not independent
  - To allow $\sin^2\theta_W$ to vary independently, remove G_F constraint
- $\sin^2\theta_W$ as input parameter
  - G_F calculated for the input $\sin^2\theta_W$ (M_W) with DIZET (IMOMS=3)
  - DIZET modified to use recalculated G_F in form factor calculations
  - This yields a family of physics models with SM-like couplings

Example of s and t dependence of Re(κ_e)



θ: ∡ e^- and quark direction
Each curve: different M_{ee} (66-116 GeV)
u-type quark: black curves
d-type quark: blue curves

- κ_e: lepton-Z vertex form factor for $\sin^2\theta_W$
- W/Z box diagrams give small t dependence to form factors
- Form factor (FF) shape at $s=M_Z^2$:
  - All κ,ρ FF independent of $\cos\theta$
  - κ_e(u-type) = κ_e(d-type)

    one leptonic $\sin^2\theta_{eff}$ at Z pole

    $\sin^2\theta_{eff}^{lept} \equiv \kappa_e(M_Z^2)\sin^2\theta_W$

    ⇒ characterizes all FF's
- Implementation approximation
  - Average out t dependence with simple γ^*/Z angular model

- ρ and κ form factor numbers
  - $\sin^2\theta_W$ dependence: very small
  - Quark type dependence: small
  - $s = M_{ll}^2$ dependence: several percent
  - Notation
    - κ_e: 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_e:	(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_e

  - LEP1/SLD SM predictions [Phys. Rep. 427, 257 (2006): Eq. 8.5]
    - $\sin^2\theta_W = 0.22331 \pm 0.00062$
    - $\rho_l = 1.0051 \pm 0.0007$
    - $\kappa_l = 1.0366 \pm 0.0025$

Drell-Yan QCD calculations

- Standard fermion (f) couplings with ρ and κ form factors
  - $g_v^f = \sqrt{\rho_f}\, T_3^f (1 - 4|Q_f|\kappa_f \sin^2\theta_W)$
  - $g_A^f = \sqrt{\rho_f}\, T_3^f$
- $\sin^4\theta_W$ term of amplitude needs a small correction
  - g_A/g_V amplitude: $\kappa_e\kappa_q$

    A_q amplitude: κ_{eq}
  - Extra correction for g_A/g_V amplitude: $\kappa_{eq} - \kappa_e\kappa_q$
  - Fairly small: $|\kappa_{eq} - \kappa_e\kappa_q| \sim 0.01$
- Photon propagator QED form factor for fermion-loop corrections utilized
  - $s \rightarrow s[1 - \Delta\alpha_{em}(s)]$ $(\Delta\alpha_{em}(s) \rightarrow 0$ as $s \rightarrow 0)$

W/Z box and FF extraction effects

- Study W/Z box effect on A_4 angular distribution coefficient
  - Drell-Yan angular distribution $\propto 1 + \cos^2\theta + \ldots + A_4\cos\theta + \ldots$

    $(A_{fb} = \tfrac{3}{8} A_4)$
  - Calculations of A_4 over the region $66 < M_{ll} < 116$ GeV: $\langle A_4 \rangle$
    - ZGRad2 calculates box diagrams

      $\langle A_4 \rangle$ with – without box diagrams ≈ -0.0001
    - Powheg-Box/Z with form factor implementation

      $\langle A_4 \rangle$ with – without box diagrams ≈ -0.0001
  - Estimated effect of -0.0001 shift of $\langle A_4 \rangle$ on $\sin^2\theta_W$
    - $\sin^2\theta_W \approx 0.2235 - 0.11 \bullet [\, \langle A_4 \rangle - 0.12 \,]$
    - $\sin^2\theta_W$ shift: ~ 0.00001

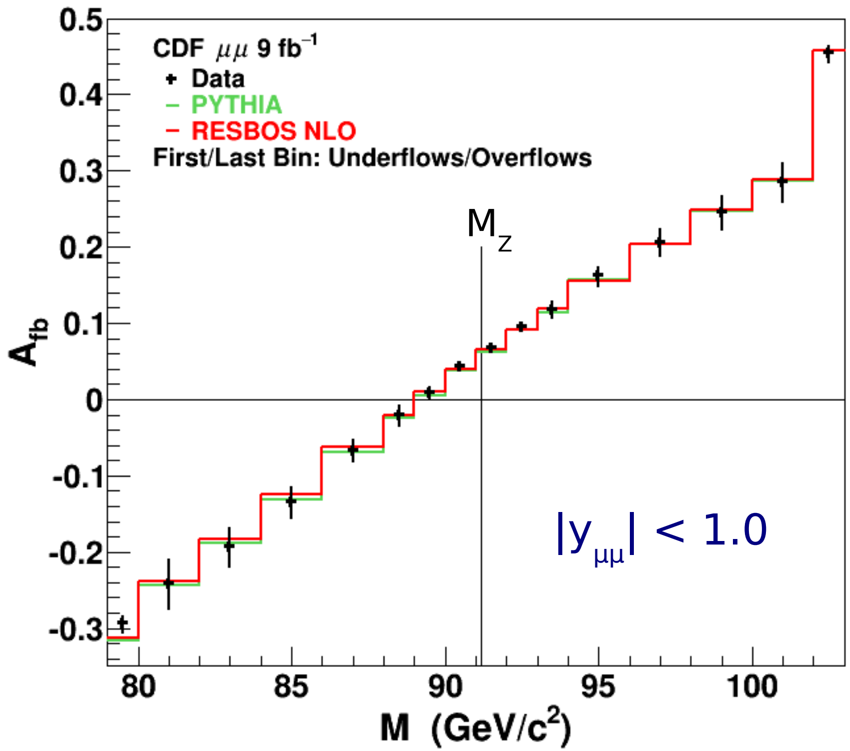
- Relative effect of form factors on extraction of $\sin^2\theta_{eff}^{lept}$
  - Extract $\sin^2\theta_{eff}^{lept}$ using CDF ee and μμ A_{fb} measurements
  - Relative shift: $\sin^2\theta_{eff}^{lept}(\rho,\kappa) - \sin^2\theta_{eff}^{lept}(\rho=\kappa=1) = 0.00022 \pm 0.00004$

    ↓ ↳ “one-size-fits-all” extraction

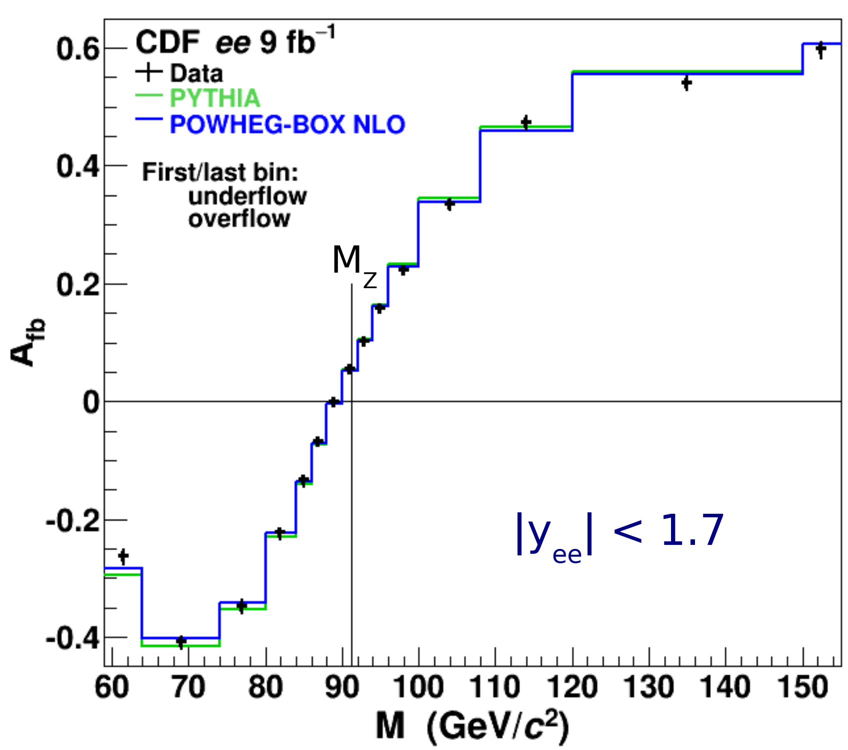
    extract with CDF implementation of form factors
  - 11 MeV in terms of M_W

A_{fb} measurements

PRD 89, 072005 (2014)



PRD 93, 112016 (2016)

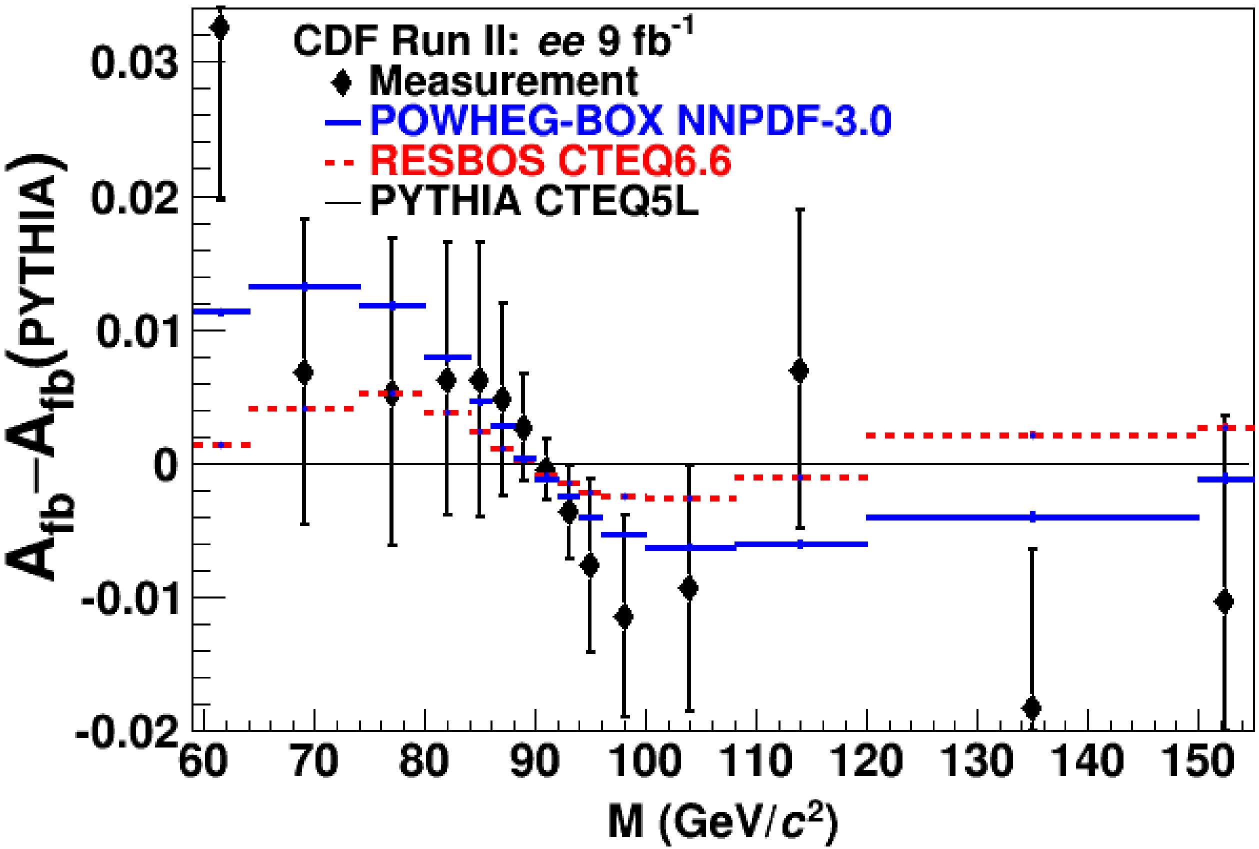


Measurements are fully corrected

RESBOS and POWHEG-BOX calculations include form factors
PYTHIA is CDF standard

PDF variations relative to CTEQ5L

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

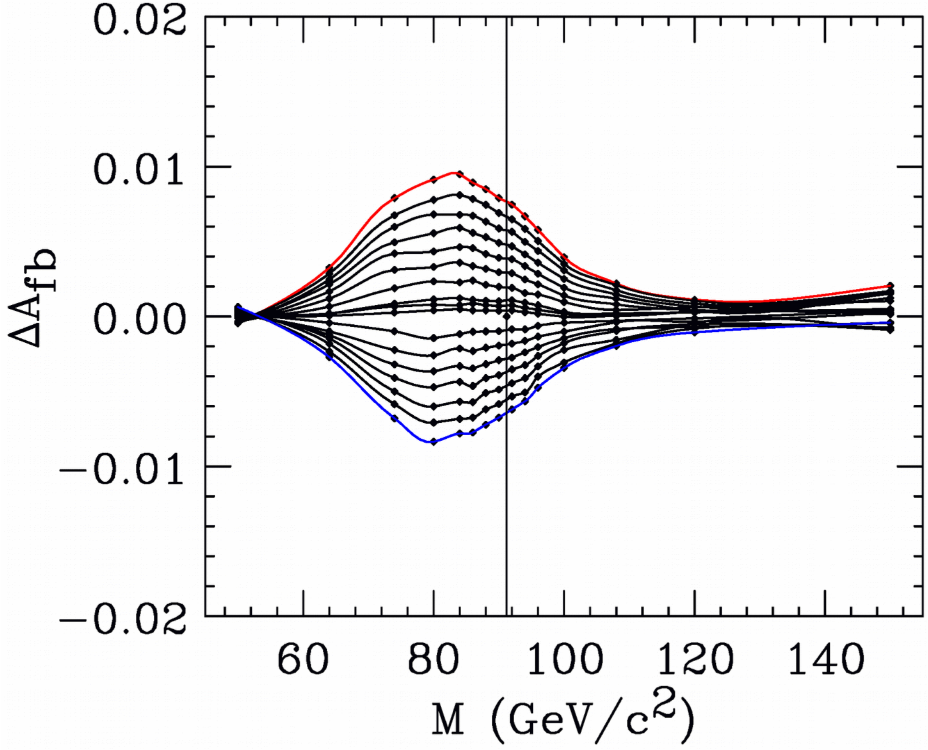


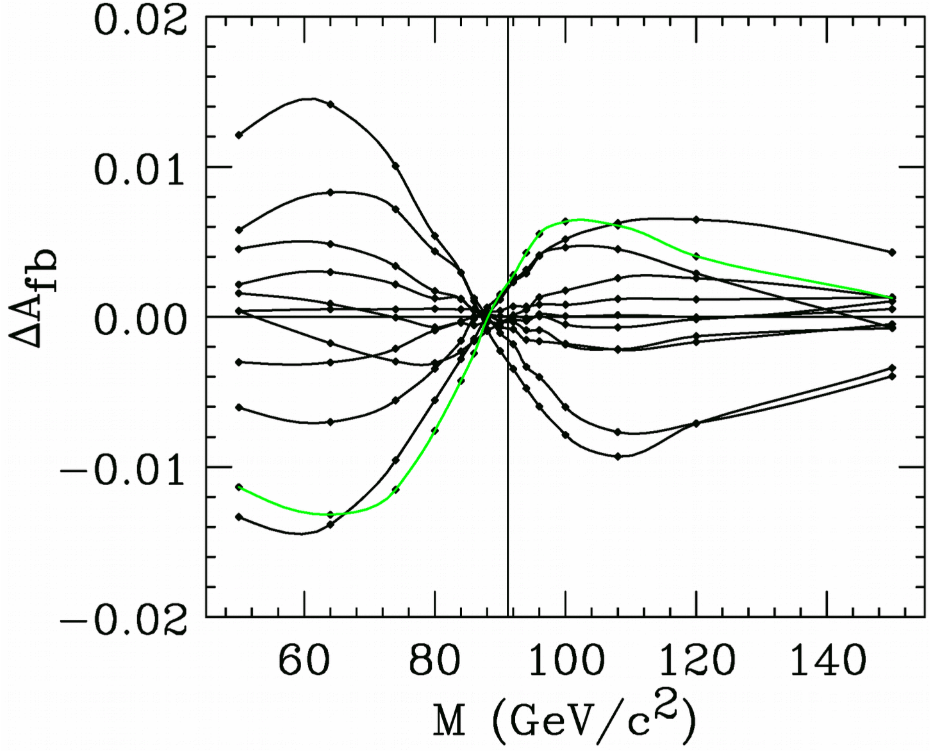
$\sin^2\theta_W$ and PDF dependence study

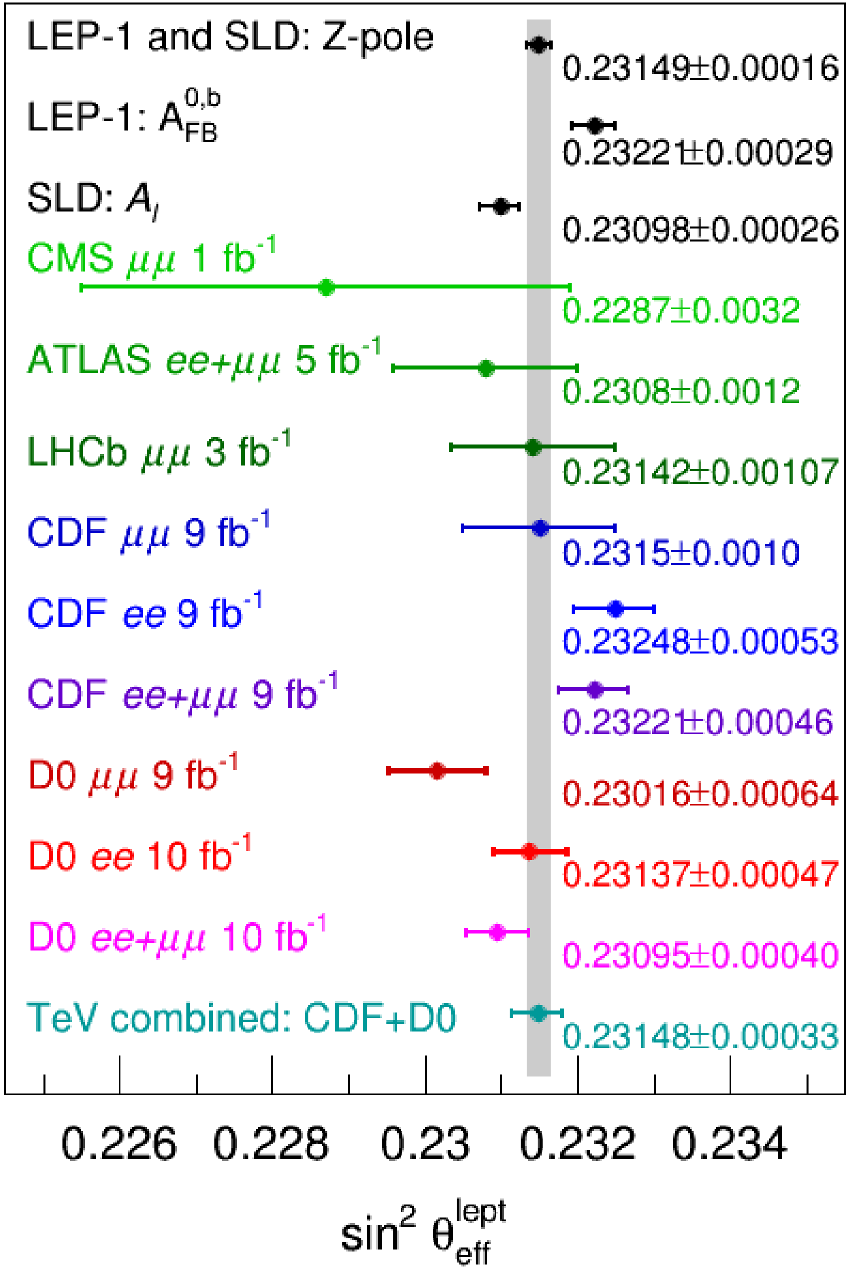
$\Delta A_{fb} = A_{fb}(\text{Test}) - A_{fb}(\text{Reference})$

Ref: POWHEG-BOX/Z + NNPDF3 261000
$\sin^2\theta_W = 0.2244$
Test $\sin^2\theta_W$: 0.2220 to 0.2262

Ref: POWHEG-BOX/Z + NNPDF3 261000
$\sin^2\theta_W = 0.2244$
Test: various NNPDFs with $\sin^2\theta_W = 0.2244$;
PYTHIA+CTEQ5L







Phys. Rep. 427, 257 (2006)
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Phys. Rev. D89, 072005 (2014)

Phys. Rev. D93, 112016 (2016)

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arXiv:1801.06283 [hep-ex]

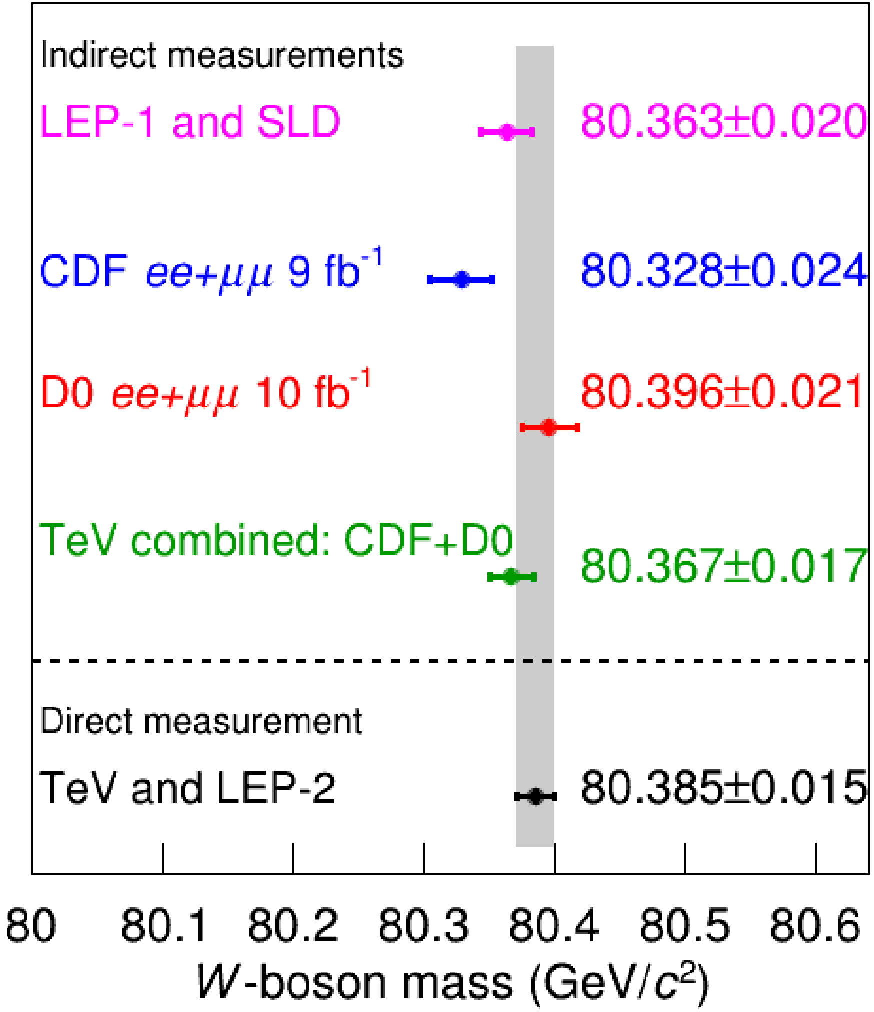
$\sin^2\theta_W$ / M_W interpretations

- ZFITTER with SM context of slide 4 provides the interpretation
  - $\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_e(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$

    ↳ ≈1.037

  - Input uncertainty considered
    - Form factors most sensitive to top-quark mass 173.2±0.9 GeV/c^2
    - m_t uncertainty to $\sin^2\theta_W$: 0.00008
- Tevatron Legacy 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:	0.22269±0.00034±0.00021	80.396±0.017±0.011 GeV/c^2
– Combination:	0.22324±0.00026±0.00019	80.367±0.014±0.010 GeV/c^2
	(stat) (syst)	(stat) (syst)



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Phys. Rep. 532, 119 (2013)

Phys. Rev. D89, 072005 (2014)

Phys. Rev. D93, 112016 (2016)

Phys. Rev. D88, 05218 (2013)

Summary

- CDF timeline
  - 2011: $\sin^2\theta_{eff}^{lept} = 0.2329 \pm 0.0008 \pm 0.0010$; $\langle A_4 \rangle$, 2 fb^{-1} ee
  - 2012: Add ZFITTER technology to CDF QCD Drell-Yan calculations
    - Goal: Improve $\sin^2\theta_{eff}$ extraction model relative to one-size-fits-all
    - POWHEG-BOX/Z, RESBOS and QCD tree level calculations
  - 2013: $\sin^2\theta_{eff}^{lept} = 0.2328 \pm 0.0009 \pm 0.0003$; $\langle A_4 \rangle$, 2 fb^{-1} ee
  - 2014: $\sin^2\theta_{eff}^{lept} = 0.2315 \pm 0.0009 \pm 0.0004$; $\mu\mu$, 9 fb^{-1}
  - 2016: $\sin^2\theta_{eff}^{lept} = 0.23221 \pm 0.00043 \pm 0.00018$; $\mu\mu$+ee, 9 fb^{-1}
- Tevatron Legacy combination: 2018
  - $\sin^2\theta_{eff}^{lept} = 0.23148 \pm 0.00027(stat) \pm 0.00019(syst)$
  - M_W interpretation: $80.367 \pm 0.014(stat) \pm 0.010(syst)$
  - Calls for improving the extraction model and understanding
- ZFITTER: may be nice if development continued … (?)
  - 6.43 precision region: $50 < s < 150$ GeV … Problem?