Measurements of $\sin^2\theta_W$ and indirect measurments of M_W at the Tevatron

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On behalf of the CDF and D0 Collaborations

Blois2014: 26th Rencontres de Blois.

Wednesday, May 21, 2014 14:00-14:20 Room III

Session: QCD+HF+EW

CDF II   DØ

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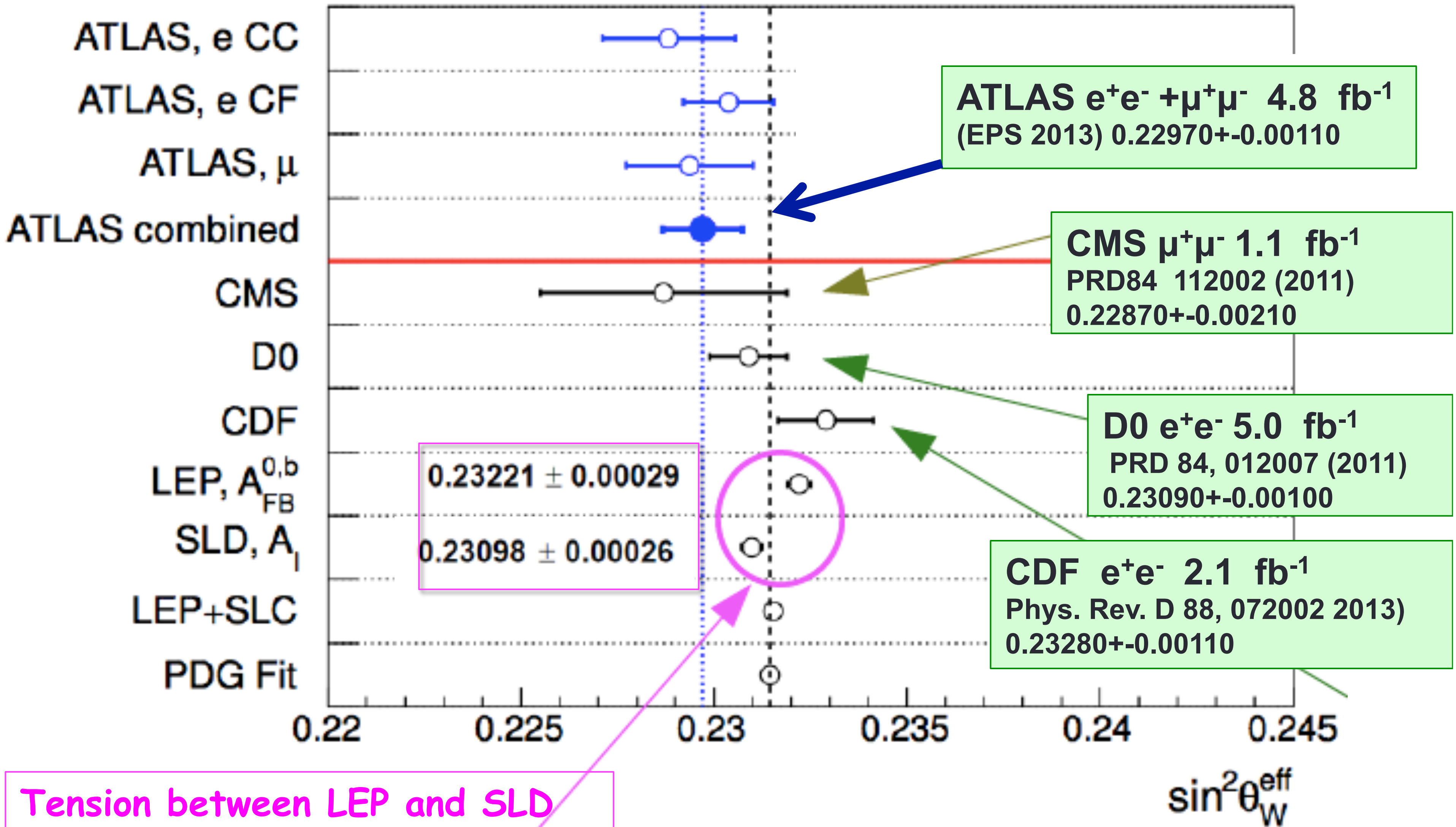
2013: Long standing tension between LEP/SLD measurements of $\sin^2\theta_{eff}$

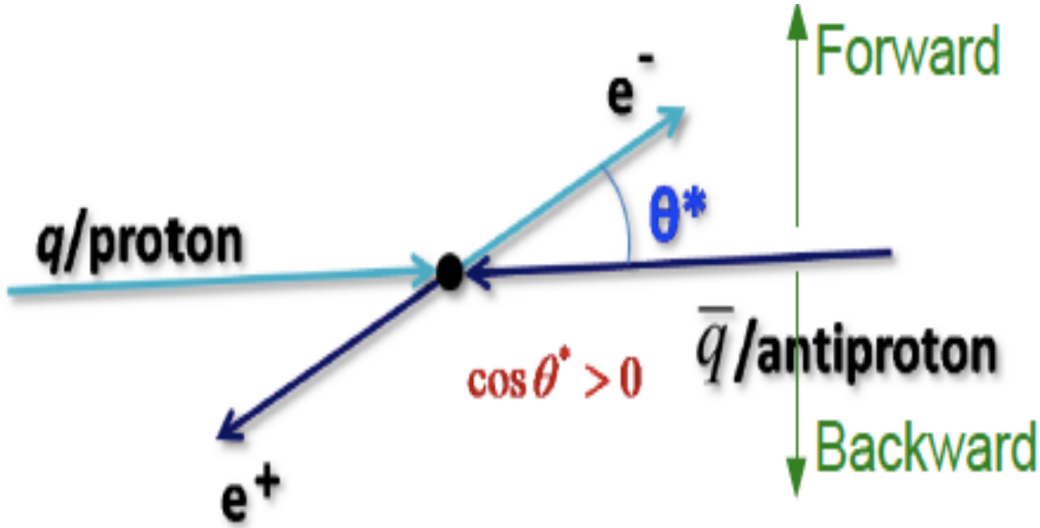


Tension between LEP and SLD

LEP SLD difference is 0.00122 **New precision measurements of $\sin^2\theta_{eff}$ could help resolve this diff.**

In hadron colliders: A_{FB} for e^+e^- or $\mu^+\mu^-$ pairs in the Z boson Region is sensitive to $\sin^2\theta_{eff}^{lept}(M)$ where $M=M_{\mu+\mu-}$

Born level polar angle distribution: $1 + \cos^2\vartheta + A_4\cos\vartheta$



Define Forward-Backward asymmetry:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$A_{FB} = (3/8)\, A_4$

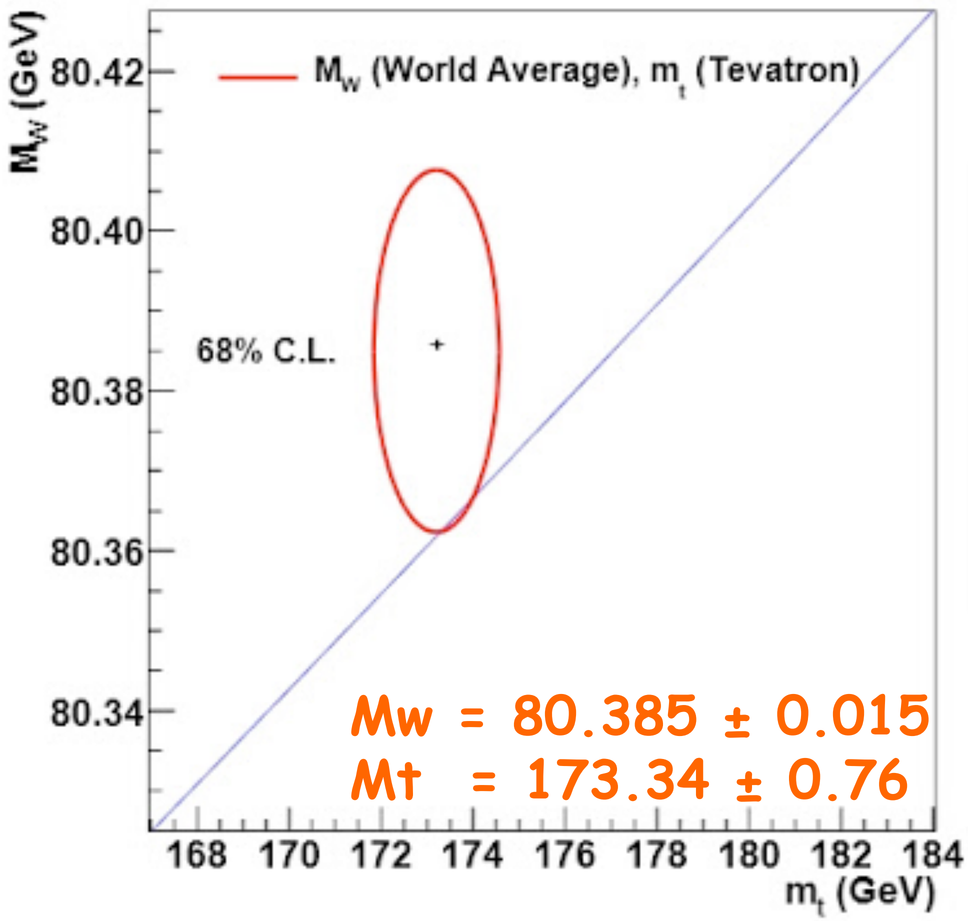
We define for short: $\sin^2\theta_{eff} \equiv \sin^2\theta_{eff}^{lept}(M_Z)$ ***(at the Z pole)***

$\sin^2\theta_{eff}^{lept} \simeq 1.037 \cdot \sin^2\theta_W$ [ZFITTER $\kappa_e(\sin^2\theta_W, M_Z)$ form factor]

$\sin^2\theta_W = 1 - M_W^2 / M_Z^2$

Direct and indirect measurements of M_w in SM

The new key element in the indirect extraction or inference of M_w from A_{FB} in the Standard Model is that the Higgs mass is now known. Therefore we can measure both $\sin^2\theta_{eff}$ AND the on-shell $\sin^2\theta_w = 1 - M_w^2 / M_z^2$ (we use m_H = 125 GeV).



An indirect measurement of M_w is done by measuring the on-shell $\sin^2\theta_w$ and using the SM relation

$$\sin^2\theta_w = 1 - M_w^2 / M_z^2$$

A error of ± 0.00030 in $\sin^2\theta_w$ is equivalent to an indirect measurement of M_w to a precision of ± 15 MeV

W mass provides a stringent test of the SM. Within SM we can measure the W mass both directly and indirectly. They should agree.

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Tevatron measurements of $\sin^2\theta_{eff}$, $\sin^2\theta_W$ and indirect measurments of M_W .

Two New Results in 2014

A: CDF Phys. Rev D. 89, 072005 (2014) Run II 9 fb^{-1} $\mu^+\mu^-$
Reports three measurements with statistical errors of
$\sin^2\theta_{eff}$ (± 0.00090), $\sin^2\theta_W$ (± 0.0008), M_W indirect (±44 MeV)

B: D0 note 6426-conf (2014) Run II 9.7 fb^{-1} e^+e^-. Reports
$\sin^2\theta_{eff}$ (± 0.00042) statistical error (preliminary)

C: CDF: Expected Fall 2014 full Run II data set 9.7 fb^{-1} e^+e^-
will have three measurements with statistical errors of
$\sin^2\theta_{eff}$ (± 0.00044), $\sin^2\theta_W$ (± 0.00040) and Mw (indirect) (±22 MeV)

Which means that a measurement of M_W (indirect) with the combined CDF/D0 9 fb^{-1} run II data would have a statistical error of ±15 MeV, which is equal to the ±15 MeV error in average of all world measurements of M_W (direct)
In addition, it could address the LEP-SLD Difference. LEP SLD difference is 0.00122

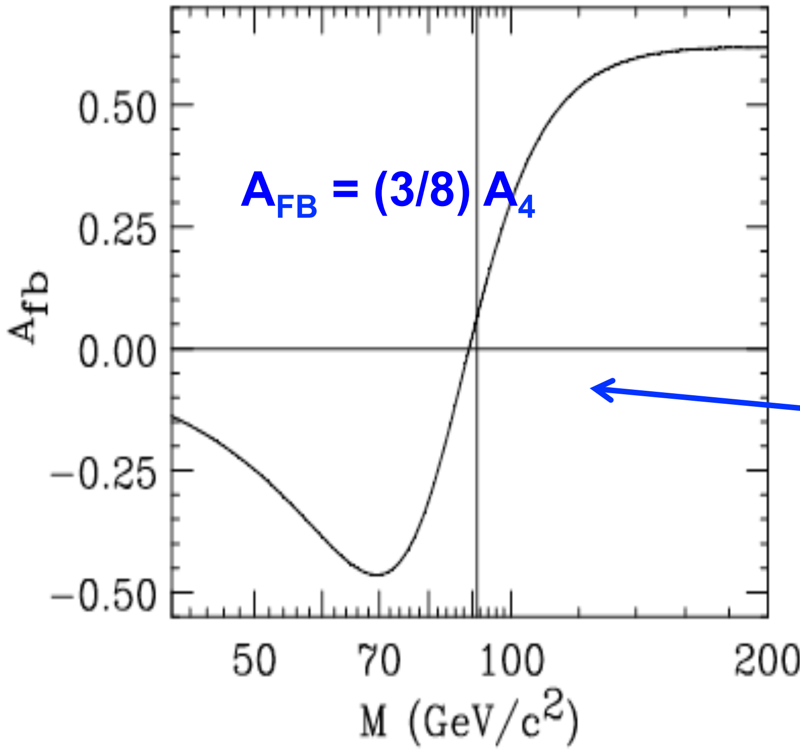

FIG. 2. The typical behavior of A_{fb} as a function of the lepton-pair mass. The vertical line is at $M = M_Z$.

$$
\begin{aligned}
\frac{dN}{d\Omega} \propto\ & (1+\cos^2\vartheta) + \\
& A_0\,\frac{1}{2}\,(1-3\cos^2\vartheta) + \\
& A_1\,\sin 2\vartheta\cos\varphi + \\
& A_2\,\frac{1}{2}\,\sin^2\vartheta\cos 2\varphi + \\
& A_3\,\sin\vartheta\cos\varphi + \\
& A_4\,\cos\vartheta + \\
& A_5\,\sin^2\vartheta\sin 2\varphi + \\
& A_6\,\sin 2\vartheta\sin\varphi + \\
& A_7\,\sin\vartheta\sin\varphi\,.
\end{aligned}
$$

Terms in boxes are zero when integrating over φ, and we get

(1+**cos²θ) +** $A_0(M,P_T)$ (1- 3**cos²θ)/2**
+ A_4 **cosθ**

Note that A_{FB} is not Zero at the Z pole. Most of the sensitivity to $\sin^2\theta_{eff}$ is at the Z pole.

*For dileptons with a P_T, the change in the **cosθ** distribution in the Collins-Soper frame is well understood. CDF has measured it, and data agrees with POWHEG QCD prediction. It is accounted for in the analysis and does not have much impact to the results.*

CDF measurement published in 2014.
Phys. Rev D. 89, 072005 (2014) full Run II data set 9 fb^{-1} $\mu^+\mu^-$

Analysis uses three new innovations which are essential:

1st innovation:
Full ZFITTER EW radiative corrections, Enhanced Born Approximation (EBA), include full complex form factors
(implemented private versions of RESBOS, POWHEG, and LO)
CDF: Phys. Rev. D 88, 072002 (2013) Appendix A'
arXiv:1307.0770v3 [hep-ex]

2nd innovation:
Precise lepton momentum/energy scale corrections using a new method
A. Bodek et al. Euro. Phys. J. C72, 2194 (2012)
arXiv:1208.3710v3 [hep-ex]

3rd innovation: Event weighting method for A_{FB} analyses
(all systematic errors in acceptance and efficiencies cancel)
A. Bodek. Euro. Phys. J. C67, 321 (2010)
arXiv:0911.2850v4 [hep-ex]

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1st innovation:
Full FITTER EW radiative corrections Enhanced Born Approximation (EBA)

Implemented by the Rochester CDF group (**Willis Sakumoto**, A. Bodek, J.-Y. Han), see Phys. Rev. D88, 072002 (2013) Appendix A arXiv:1307.0770v3 [hep-ex]

$g_V^f \gamma_\mu + g_A^f \gamma_\mu \gamma_5$. The Born-level couplings are

$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$
$$g_A^f = T_3^f,$$

If PYTHIA is used then the EBA EW correction to $\sin^2\theta_{eff}$= 0.00040 +-0.00012
Vs. stat error 0.00080 ($\mu^+\mu^-$) 9 fb^{-1}
Vs. stat error 0.00040 (e^+e^-) 9 fb^{-1}

They are modified by ZFITTER 6.43 form factors (which are complex)

$$g_V^f \rightarrow \sqrt{\rho_{eq}}(T_3^f - 2Q_f\kappa_f \sin^2\theta_W), \text{ and}$$
$$g_A^f \rightarrow \sqrt{\rho_{eq}} T_3^f,$$

$$\mathrm{SM}(\sin^2\theta_W) \overset{\mathrm{EWK}}{\longmapsto} \sin^2\theta_{\mathrm{eff}}(s) \overset{\mathrm{QCD}}{\longleftrightarrow} A_4(s),$$

$$A_{FB} = (3/8)\, A_4$$

- T_3 and $\sin^2\theta_W$ → effective T_3 and $\sin^2\theta_W$: 1-4% multiplicative form factors
- On-mass shell scheme: $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ to all orders

$$\sin^2\theta_{eff}^{lept} \simeq 1.037 \cdot \sin^2\theta_W \quad [\text{ ZFITTER } \kappa_e(\sin^2\theta_W, M_Z) \text{ form factor }]$$

2nd innovation: Precise momentum/energy scale corrections
A. Bodek et al. Euro. Phys. J. C72, 2194 (2012) Xiv:1208.3710v3 [hep-ex]

This new technique is used in CDF (for muons and electrons). It is currently used in CMS to get a precise measurement of the Higgs mass.

The Problem

Muons: There are η, Φ and charge dependent errors in the measured momentum because of residual misalignments in the detector.

Electrons: There are η, Φ dependent energy miscalibrations.

These errors exist **in both data and in the hit level Monte Carlo**

The Solution :

Step 1 : Remove the correlations between the scale for the two leptons by getting an initial calibration using Z events and requiring that the **mean <1/P_T>** of each lepton in bins of η, Φ and charge be correct.

Step2: The Z mass is is used as a calibration. The method requires that the **Z mass as a function of η,Φ, or charge** of each lepton be correct.

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After corrections, the Z mass as a function of η, Φ for both the data and hit level MC agree with the **generator level Monte Carlo**. All charge bias is removed T

	Stat. Error in $\sin^2\theta_{eff}$	Error in $\sin^2\theta_{eff}$ from momentum/energy scale:	
CDF (2014)	+-0.00090	+-0.00005	(using EPJC-2012 method)
Dzero (2014)	+-0.00040	+-0.00008	(using a method which is the same as EPJC-2012)
ATLAS (2013)	+-0.00040	+-0.00050	
CMS (2011)	+-0.00200	+-0.00130	(prior to using EJC-2012)

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3^{rd} innovation: Event weighting method for A_{FB} analyses

A. Bodek, Euro. Phys. J. C67, 321 (2010). arXiv:0911.2850v4 [hep-ex]

$$dN/d\cos\theta = 1+\cos^2\theta + A_0(M,P_T)(1-3\cos^2\theta)/2 + A_4(M)\cos\theta$$

Two kinds of event weighting can be used, (1) **angular weighting** and (2) **dilution weighting**, or both. In the CDF analysis, angular event weighting is used.

Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of cos θ, and averaging the results. It is all done at once using event weights. Events at large cosθ provide better determination of A4, so they are weighted more than events at small cosθ. (events cosθ=0 have zero weight).

In this technique, all cosθ acceptance and efficiencies cancel to first order and the statistical errors are 20% smaller. Therefore acceptance/efficiency corrections are NOT needed to measure $A_{fb} = (3/8)A_4$

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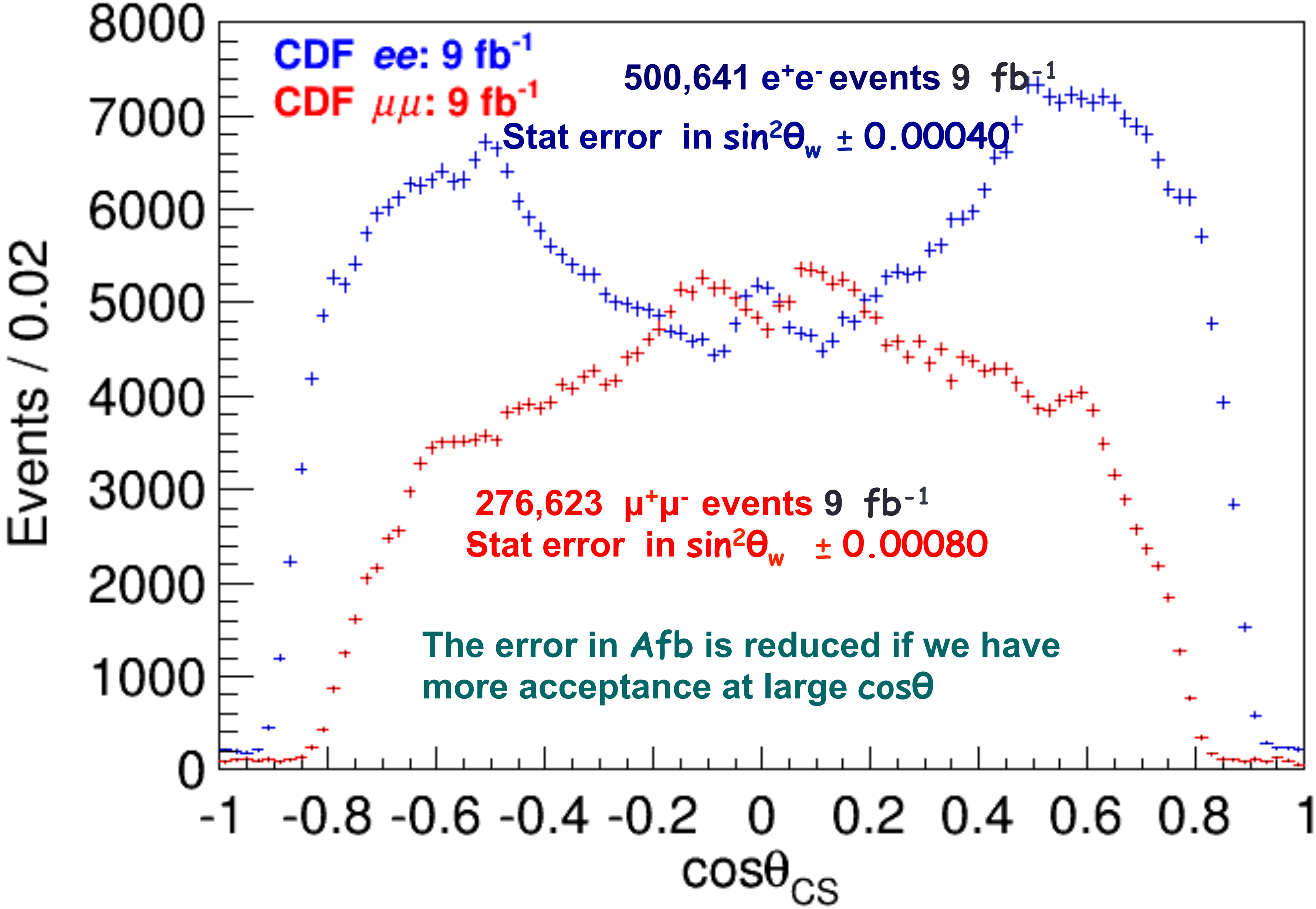
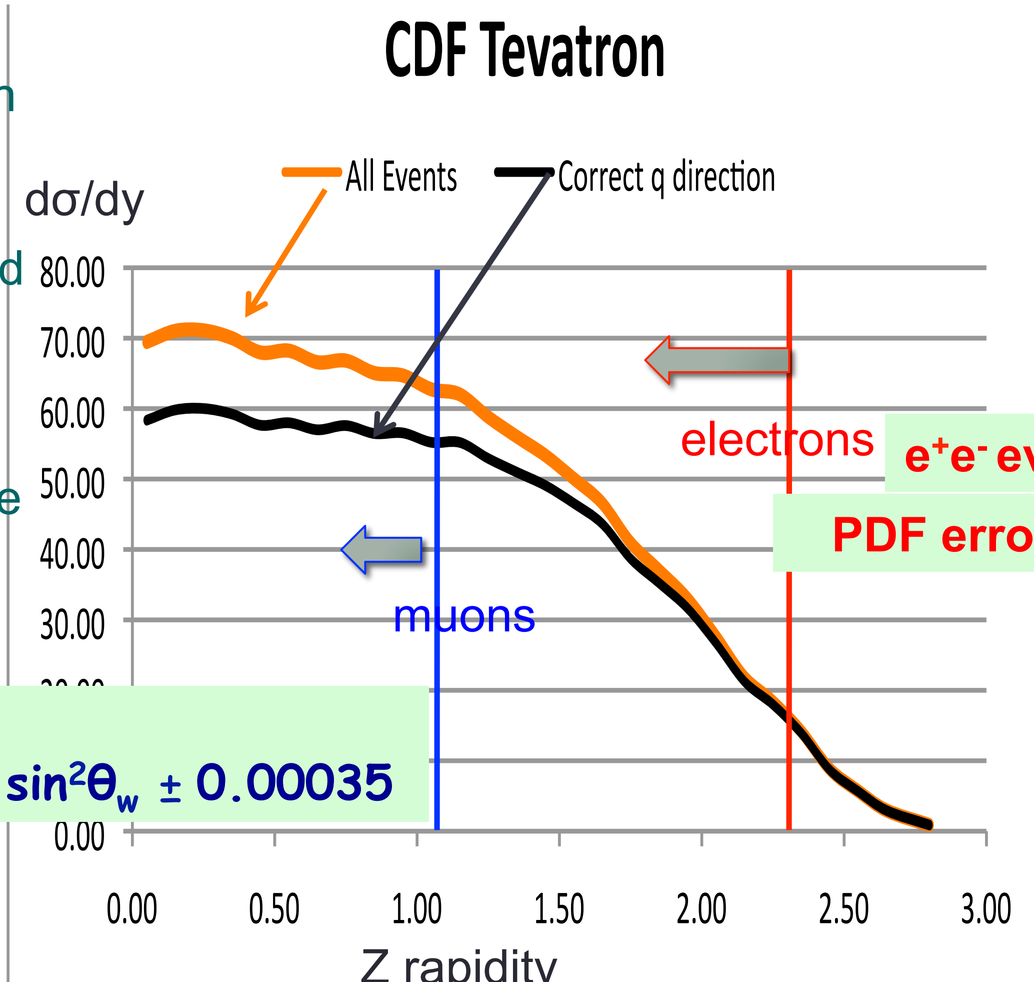
Afb extracted with Angular event weighting is not sensitive to acceptance in cosθ



Example of a 2nd order correction

The measured Afb depend on the coverage in rapidity, Sometimes the quark direction is not in the direction of the proton. This small dilution effect depends on the antiquark distributions i.e. on PDFs. (we used CT10), ands the **rapidity range of the data.**

If an additional dilution correction is included in the event weights than the extracted Afb is also **independent of the acceptance in rapidity**. (more important for the LHC)



e^+e^- events
PDF error in $\sin^2\theta_w$ ± 0.00029

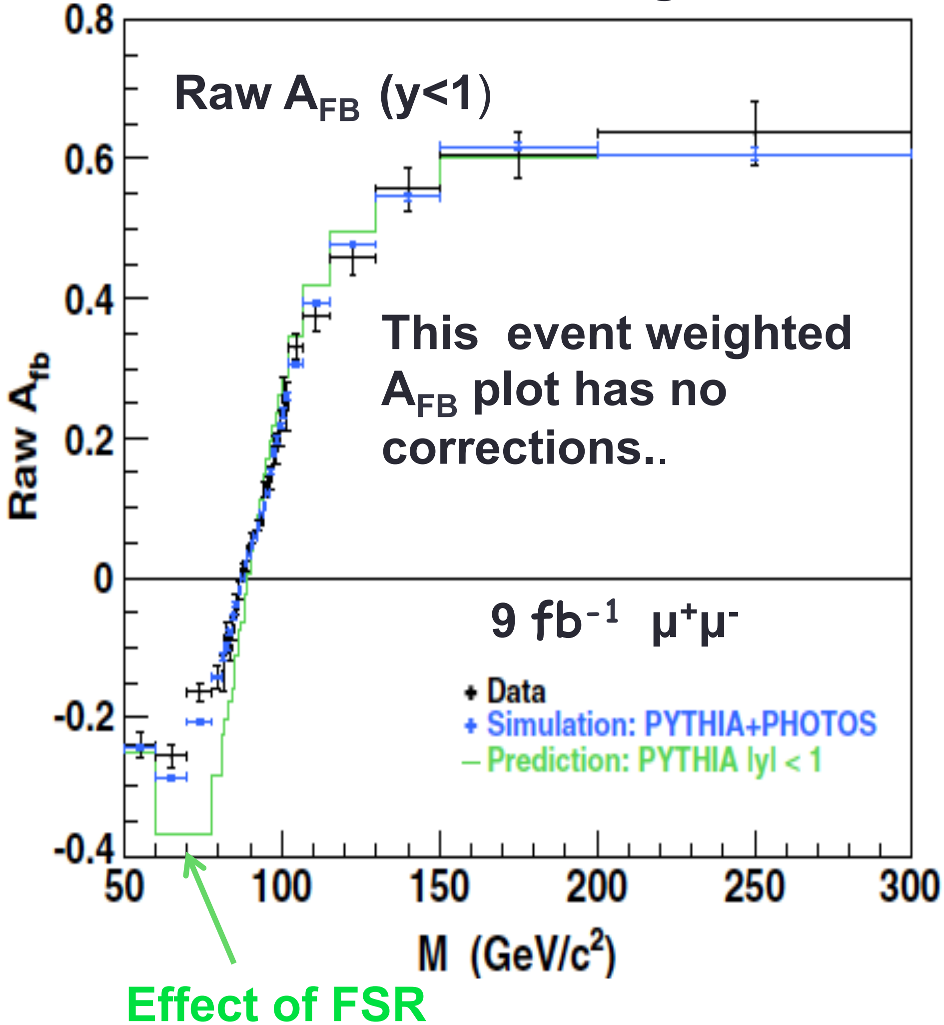
$\mu^+\mu^-$ events
PPD error in $\sin^2\theta_w$ ± 0.00035

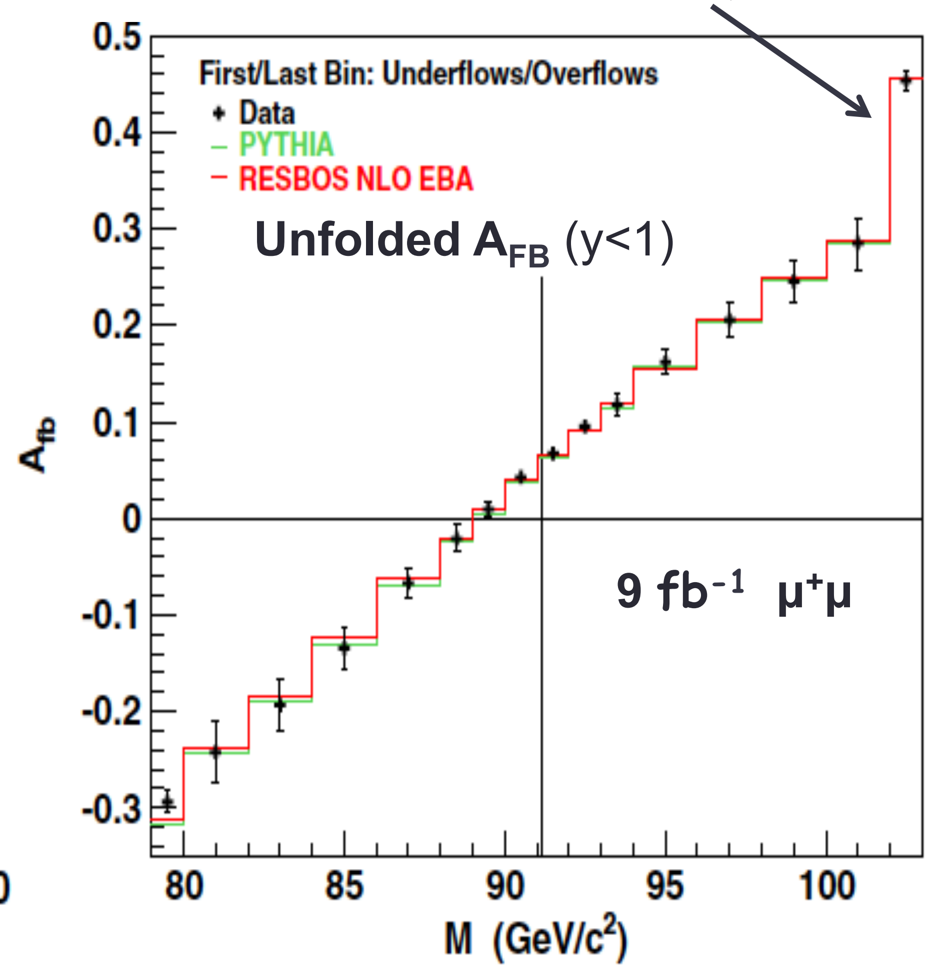
PDF error can be further reduced with better PDFs as LHC data is included in newer PDF sets.

Results

QED FSR and detector resolution smear events between mass bins. We correct for this smearing using matrix unfolding.

(Here, the edge bins are underflow and overflow bins)





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INPUT M_W to RESBO- EBA or POWHEG-EBA

MH = 125 GeV

$\sin^2\theta_w = 1 - M_w^2 / M_z^2$

EW Rad Corrections yield

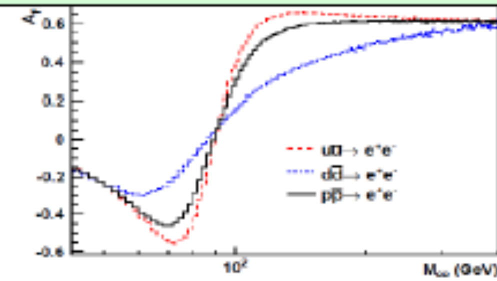
$\sin^2\theta_{eff}^{leponic}(s)$

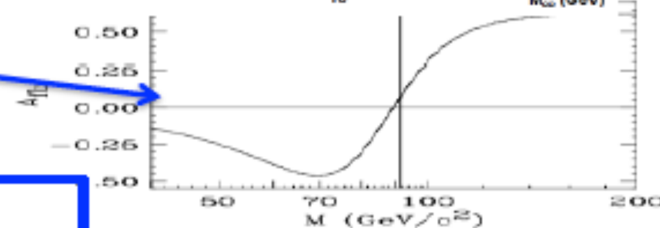
$\sin^2\theta_{eff}^{u\text{-}type}(s)$, $\sin^2\theta_{eff}^{d\text{-}type}(s)$

PDFs + QCD predict $A_4(s)$

Predicted $A_{FB}(s) = (3/8)\, A_4(s)$

CDF SM analysis with Full ZFITTER EBA rad corrections analogous to LEP analysis

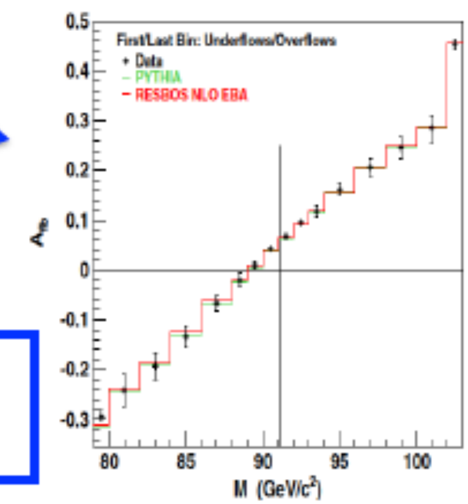




Compare Predicted $A_{FB}(s)$ to $A_{FB}(s)$ experiment (unfolded for resolution and FSR) to extract the $\sin^2\theta_w$ that describes the data best

$\sin^2\theta_w = 1 - M_w^2 / M_z^2$

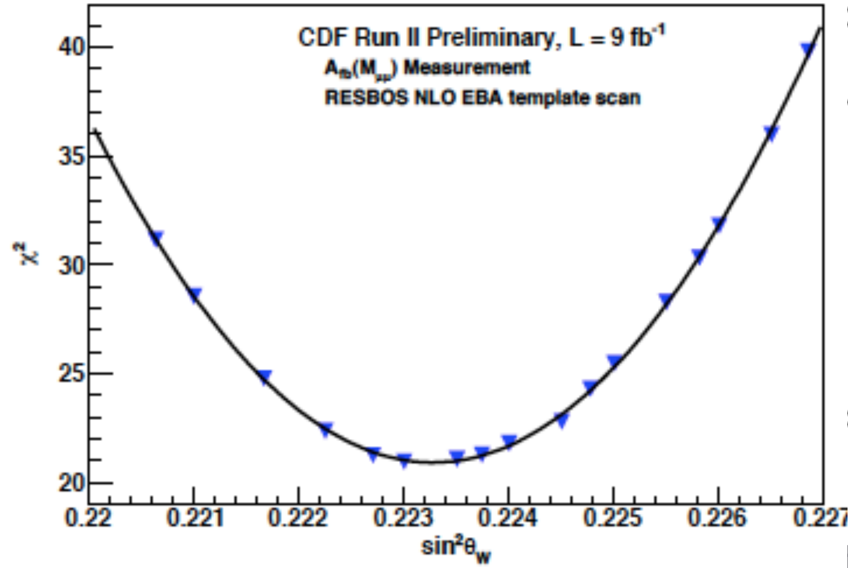
is used to get a measured M_w indirect



In addition

$\sin^2\theta_{eff}^{lept}(Mz) \equiv \mathrm{Re}\,\kappa(Mz, \sin^2\theta_W)\, \sin^2\theta_W = 1.037\, \sin^2\theta_W$

Is used to compare to $\sin^2\theta_{eff}^{lept}(Mz)$ at LEP



Source	$\sin^2\theta_{\rm eff}^{\rm lept}$	$\sin^2\theta_W$
Momentum scale	± 0.00005	± 0.00005
Backgrounds	± 0.00010	± 0.00010
QCD scales	± 0.00003	± 0.00003
CT10 PDFs	± 0.00037	± 0.00036
EBA	± 0.00012	± 0.00012

stat syst PDFs

ResBos $\sin^2\theta_{\rm eff}^{\rm lept}$ = **0.23150+-0.00090+-0.00011 +-0.00035 (CT10 PDFs)**

$\sin^2\theta_W$ = **0.22330+-0.00080+-0.00011+-0.00035 CT10(PDFs)**

M_W = **80.365+-0.043 +- 0.005 +- 0.018 (CT10 PDFs)**

stat syst PDFs

Template (measurement)		$\sin^2\theta_{\rm eff}^{\rm lept}$	$\sin^2\theta_W$	$\bar{\chi}^2$
RESBOS NLO	**Full ZFITTER EBA**	0.2315 ± 0.0009	0.2233 ± 0.0008	21.1
POWHEG-BOX NLO	**Full ZFITTER EBA**	0.2314 ± 0.0009	0.2231 ± 0.0008	21.4
Tree LO	**Full ZFITTER EBA**	0.2316 ± 0.0008	0.2234 ± 0.0008	24.2
PYTHIA	No EW radiative cor. CT5L	0.2311 ± 0.0008	⋯	20.8

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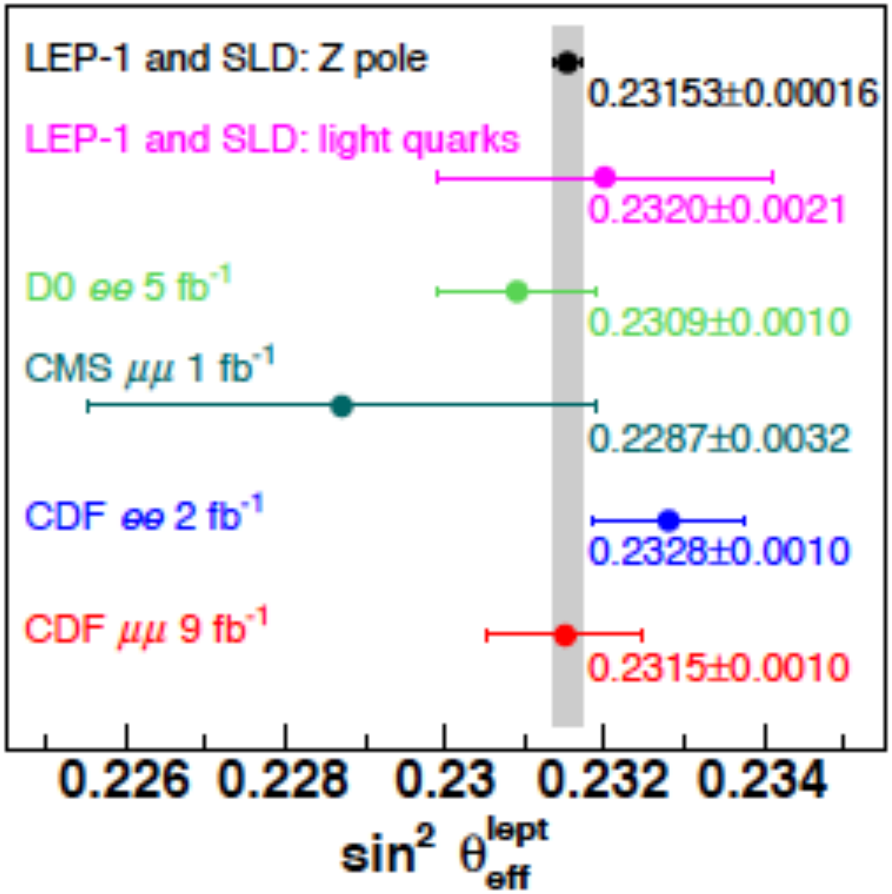
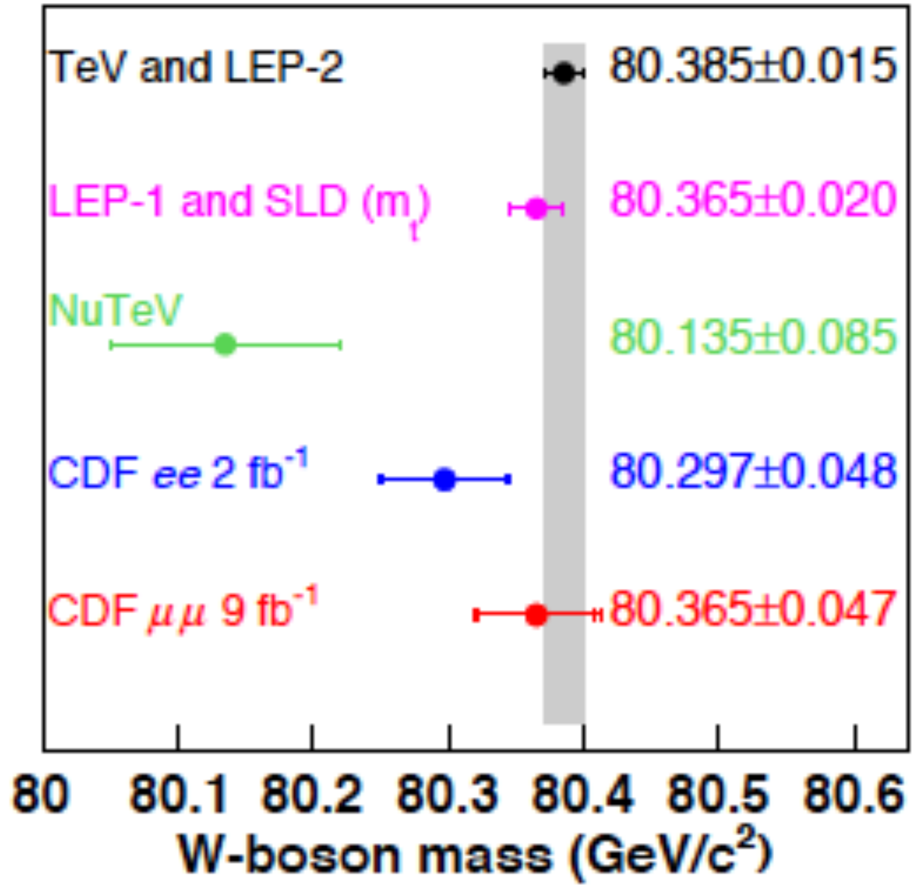
Comparison to other measurements





* A factor of 2 reduction in errors is expected in Fall 2014 when the analysis of the CDF e+e- (9 fb^{-1}) data is completed.

Part II D0 Results: D0 (preliminary e+e- 9.7 fb^{-1})

Reference: **D0 note 6426-conf (2014) and**

talk by Breese Quinn (D0), EW Moriond March 19, 2014

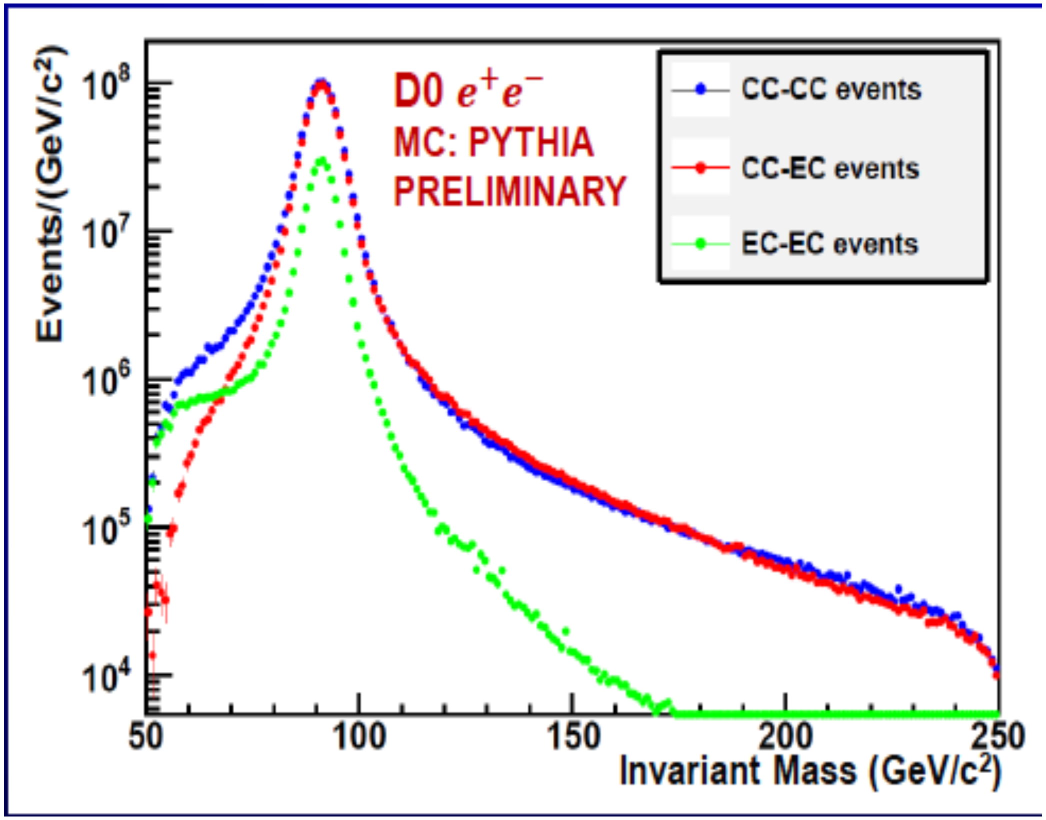
Event selection: Two PT>25 GeV electrons, Central (CC) and endcap (EC)

Use 75< M_{e+e-} < 115 GeV

Total 560,367 events.

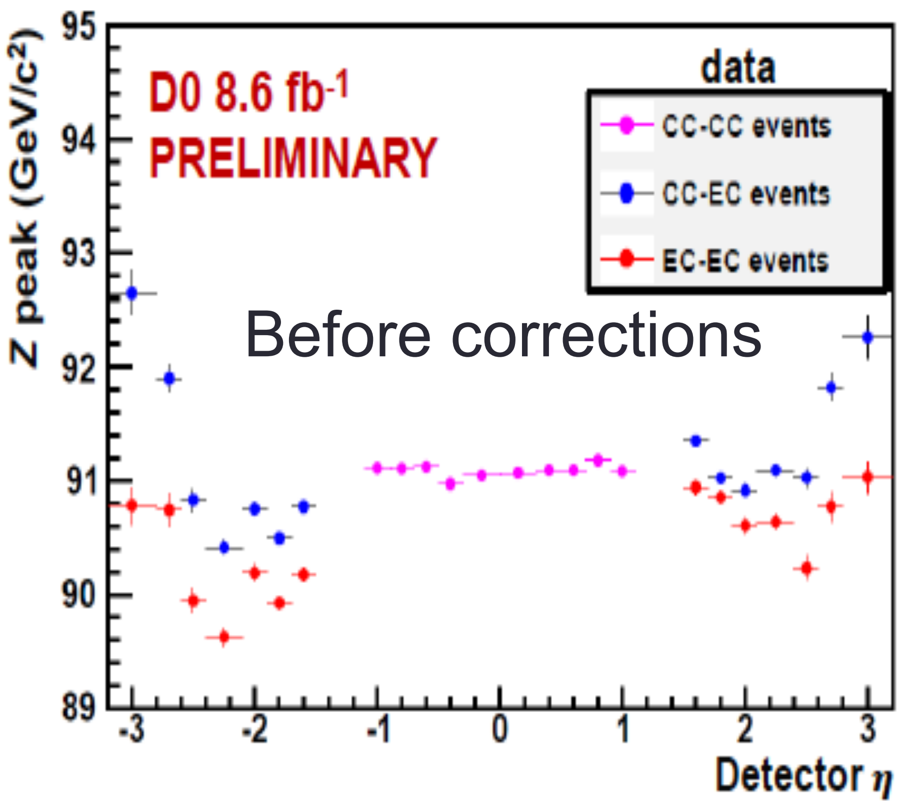
Low QCD background, EW background (t-tbar, tau-tau, diboson) negligible,

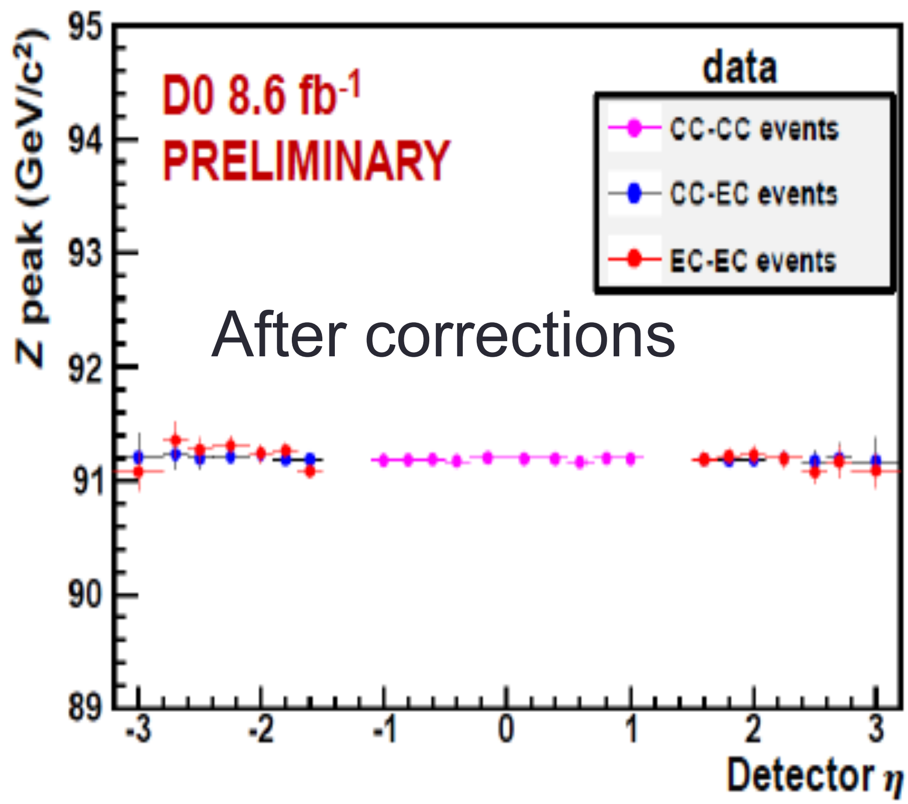
MC: PYTHIA with CTEQ6L1



Energy calibration: D0 recently implemented the momentum/ energy scale corrections similar to those used in CDF and CMS [A. Bodek Euro. Phys. J. C72, 2194 (2012)]

i.e. Require that the Z mass be correct as a function of η

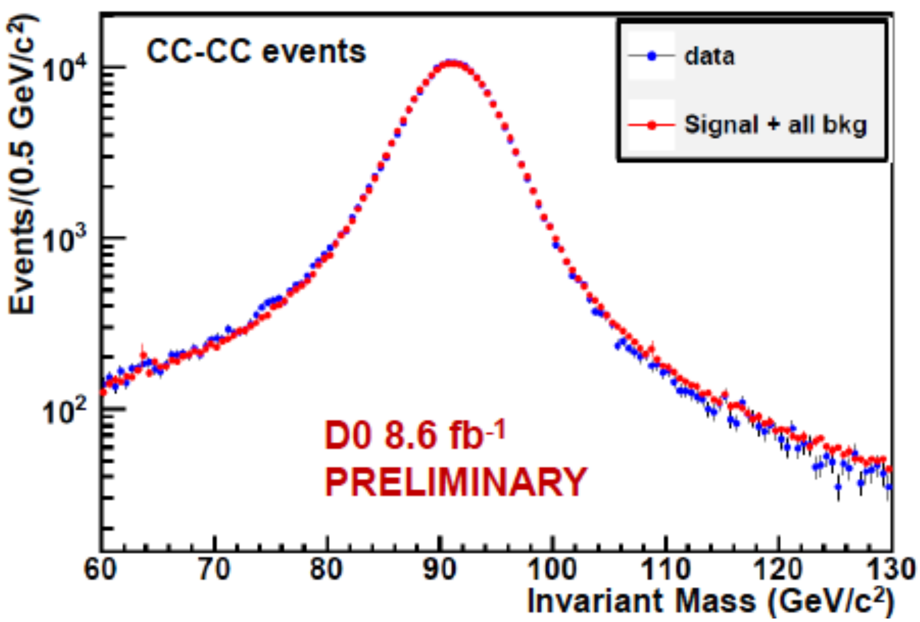


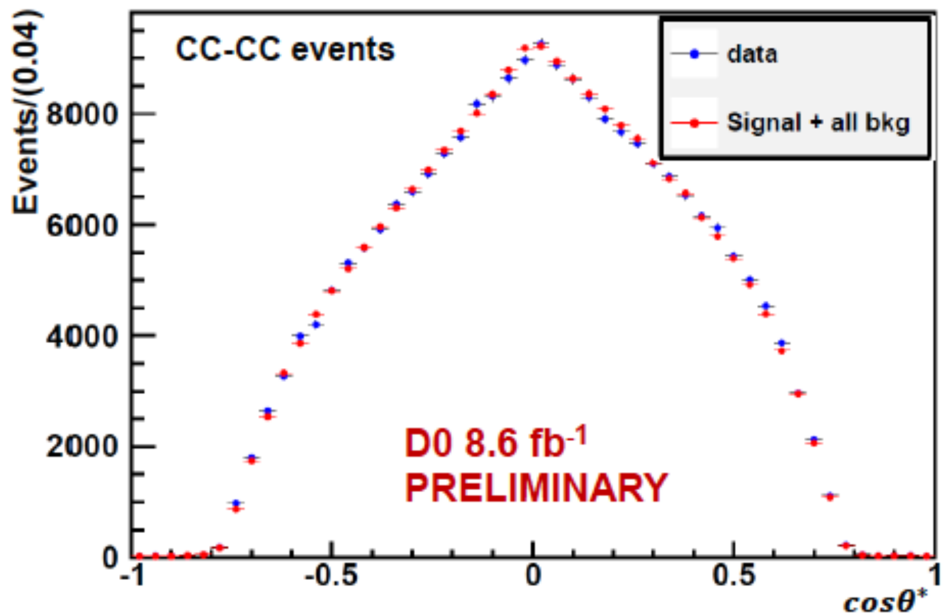


For the D0 analysis, it is imperative that the various physics distributions, experimental acceptance and efficiencies, and resolution (in cos θ, rapidity, PT and mass) are modeled perfectly.

Efficiencies measured using tag and probe as a function of η and φ.

2D (PT and η) reweighting of PYTHIA to correct for higher order QCD corrections, NNLO boson mass reweighting.

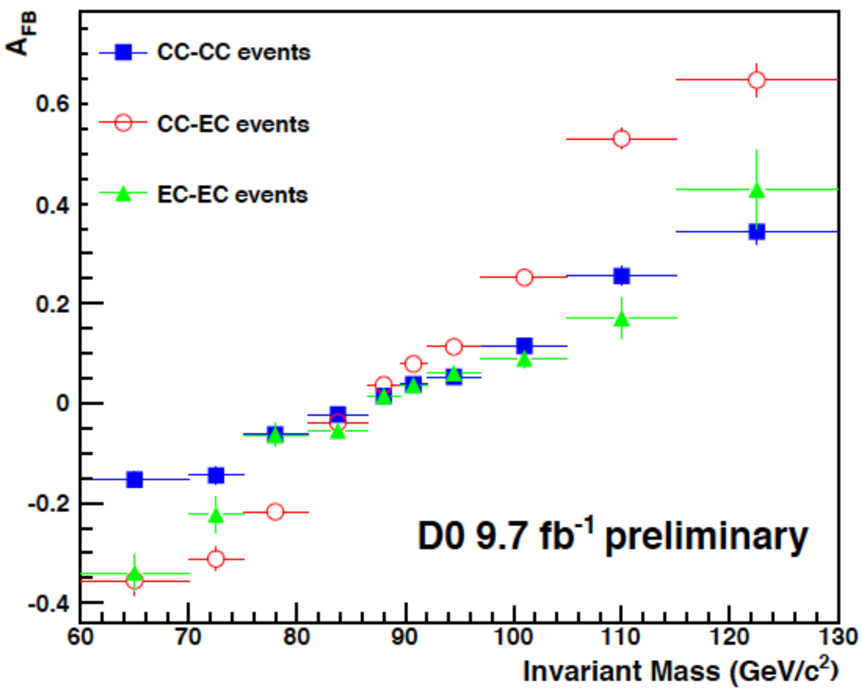


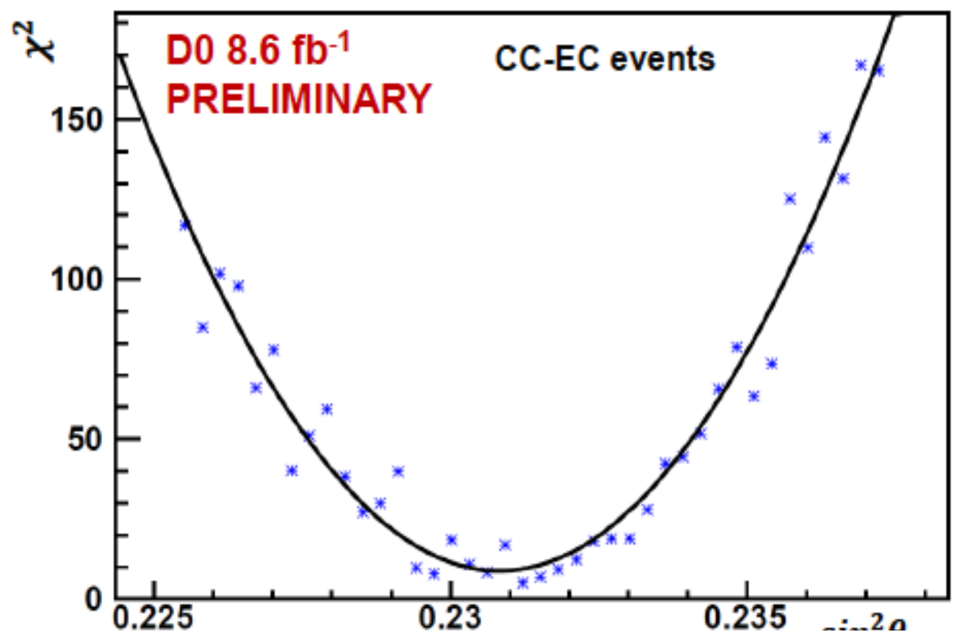


Raw A_{FB} measurement is compared to reweighted MC A_{FB} templates corresponding to different $\sin^2\theta_{eff}$ values

Different $\sin^2\theta_{eff}$ predictions obtained by reweighting generator level 2D (M, $\sin^2\theta_{eff}$) distribution of the default MC ($\sin^2\theta_{eff}$ = 0.232)

Done separately for CC-CC, CC-EC, and EC-EC events, and for different instantaneous luminosity periods





	CC-CC	CC-EC	EC-EC	Combined
$\sin^2\theta_W$	**0.23086**	**0.23108**	**0.22910**	**0.23098**
statistical unc.	0.00116	0.00047	0.00276	0.00042
systematic unc.	0.000086	0.000090	0.00019	0.00008
Energy scale	0.000002	0.000009	0.000059	0.000008
Energy smear	0.000010	0.000022	0.000126	0.000018
Background	0.000018	0.000010	0.000025	0.000008
Charge misID	0.000020	0.000036	0.000121	0.000030
Electron ID	0.000081	0.000078	0.000053	0.000066
total unc.	0.00116	0.00048	0.00277	0.00043
PDF unc.				0.00029

D0
preliminary e+e- 9.7 fb^{-1}

$\sin^2\theta_{eff}$ = 0.23098 ± 0.00042 (stat) ± 0.00014 (sys) ± 0.00029 (PDF)

Dzero adds a partial EW radiative correction of +0.00008

D0 (preliminary e+e- 9.7 fb^{-1})

$\sin^2\theta_{eff}$ = 0.23106 ± 0.00053

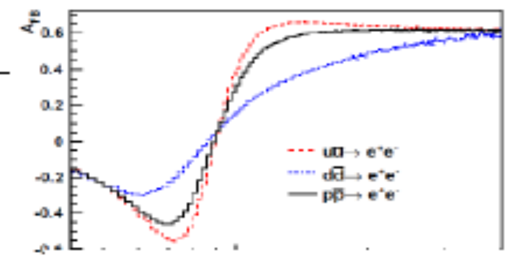
D0 analysis

INPUT to RESBOS $\sin^2\theta_{eff}^{\,leponic}$
which is assumed to be independent of mass

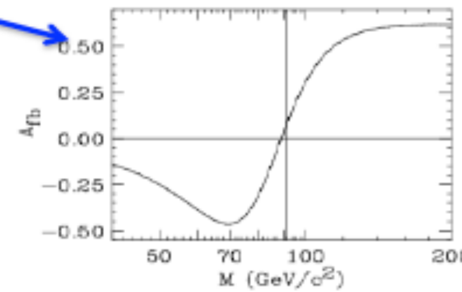
$\sin^2\theta_{eff}^{\,leponic}$(average)
$\sin^2\theta_{eff}^{\,u\text{-}type}(av) = \sin^2\theta_{eff}^{\,u\text{-}type}(av) - 0.0001$
$\sin^2\theta_{eff}^{\,d\text{-}type}(av) = \sin^2\theta_{eff}^{\,d\text{-}type}(av) - 0.0002$

PDFs + QCD predict $A_4(s)$

mimics partial rad correction

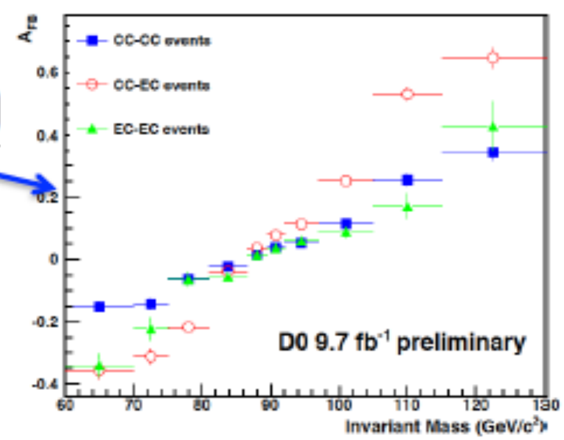


Predicted $A_{FB}(s) = (3/8)\, A_4(s)$

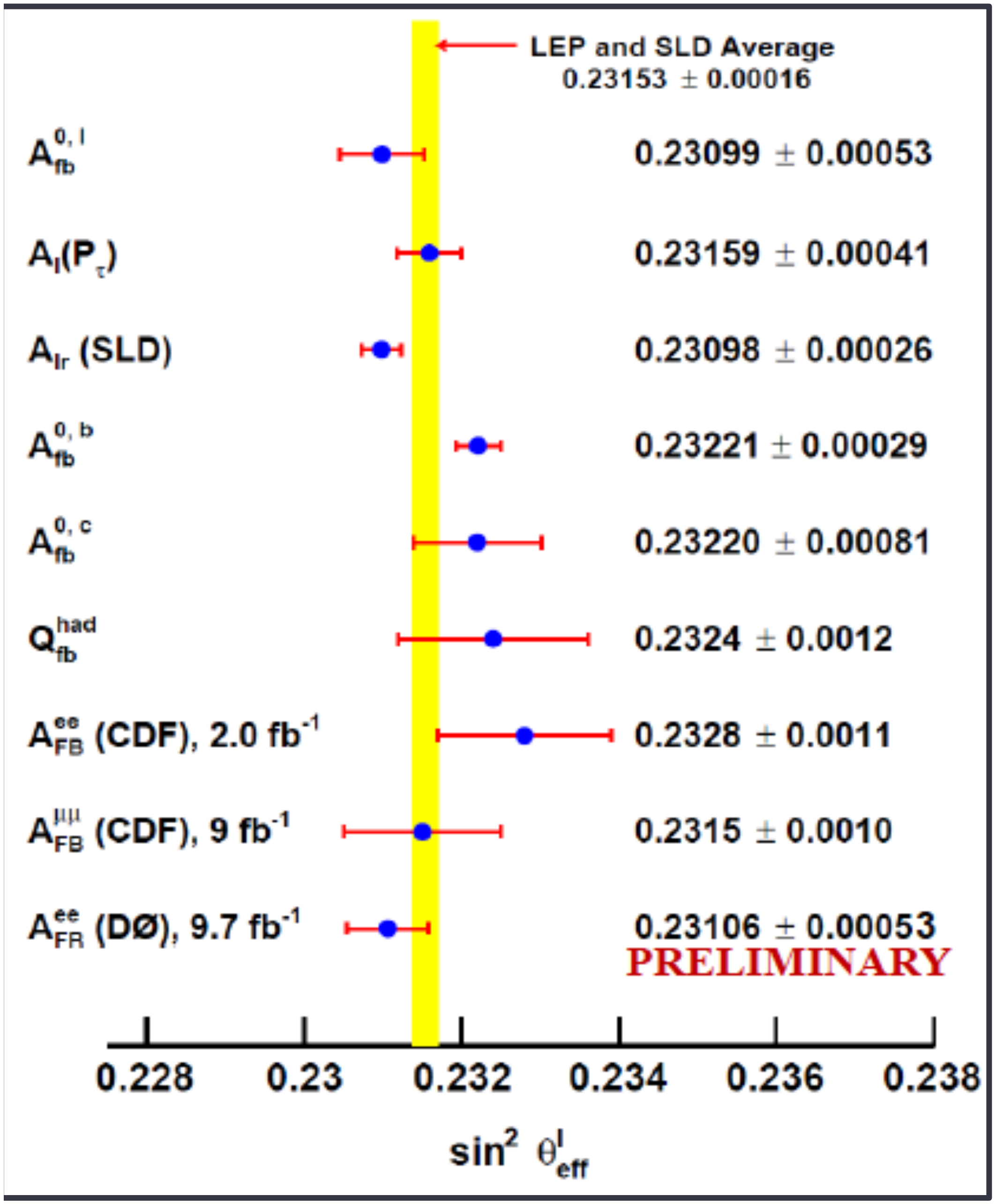


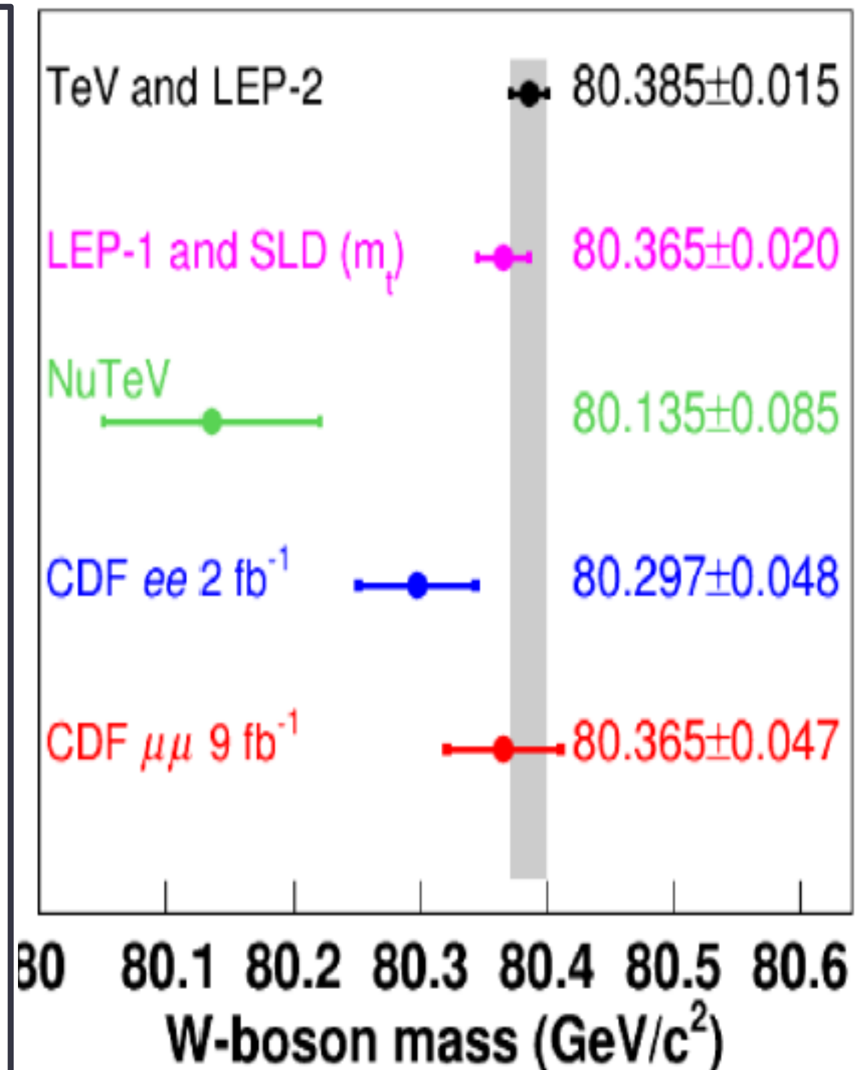
Use PHYTIA MC (weighted to look like RESBOS) +FSR.
Simulate experimental cuts, resolutions, acceptance.
Get prediction for experimental Afb by topology

Compare to $A_{FB}(s)$ observed by experiment for different topologies to get $\sin^2\theta_{eff}^{\,leponic}(av)$ that describes The data best +(correct for PYTHIA RESBOS difference)



Since most of the statistics is at the Z mass the measured $\sin^2\theta_{eff}^{\,leponic}(av)$ Is taken to be the measured D0 $\sin^2\theta_{eff}^{\,lept}$ (Mz)


LEP and SLD Average
0.23153 ± 0.00016
A fb 0, l 0.23099 ± 0.00053
Al(Pτ) 0.23159 ± 0.00041
Alr (SLD) 0.23098 ± 0.00026
A fb 0, b 0.23221 ± 0.00029
A fb 0, c 0.23220 ± 0.00081
Q fb had 0.2324 ± 0.0012
A FB ee (CDF), 2.0 fb-1 0.2328 ± 0.0011
A FB μμ (CDF), 9 fb-1 0.2315 ± 0.0010
A FB ee (DØ), 9.7 fb-1 0.23106 ± 0.00053
PRELIMINARY
0.228 0.23 0.232 0.234 0.236 0.238
sin2 θl eff


TeV and LEP-2 80.385±0.015
LEP-1 and SLD (mt) 80.365±0.020
NuTeV 80.135±0.085
CDF ee 2 fb-1 80.297±0.048
CDF μμ 9 fb-1 80.365±0.047
80.1 80.2 80.3 80.4 80.5 80.6
W-boson mass (GeV/c2)

Compare

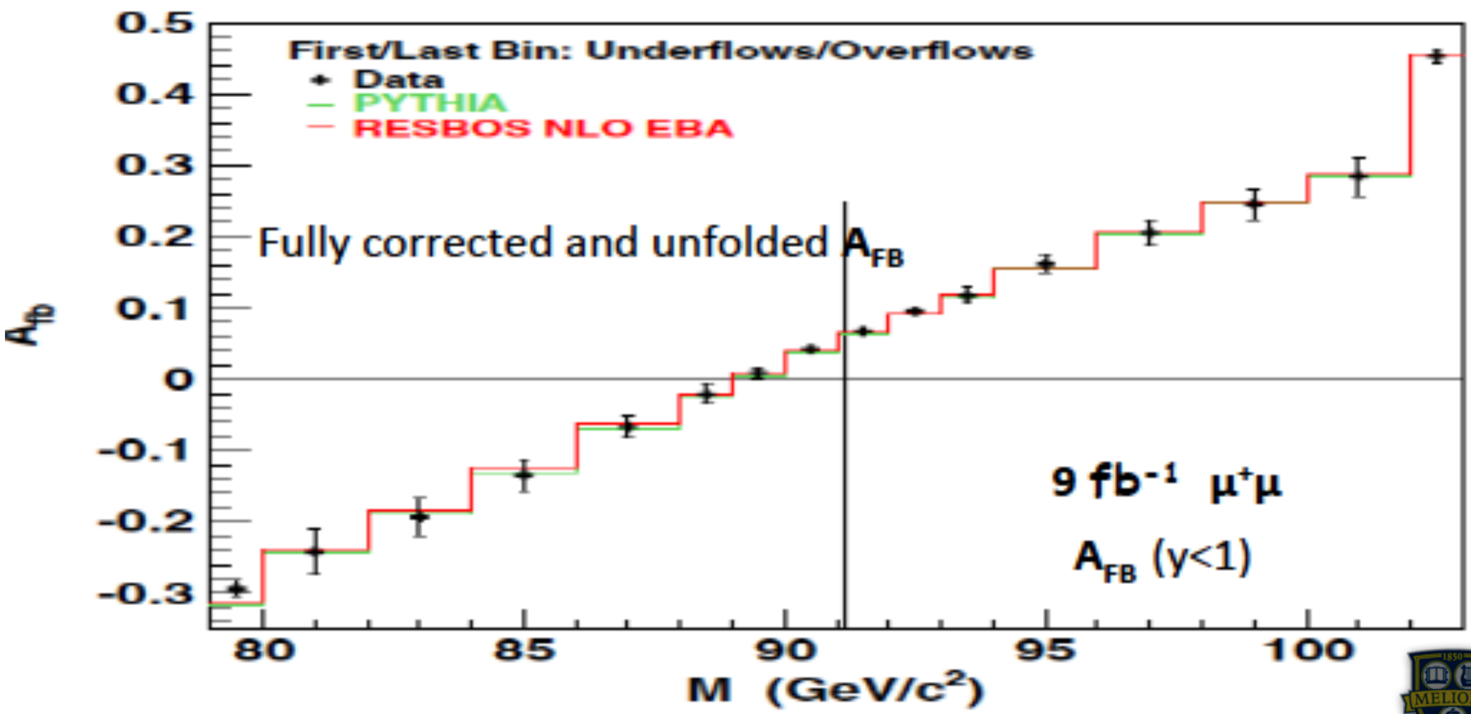
CDF SM analysis with Full Zfitter EBA rad corrections analogous to LEP analysis

Extract $\sin^2\theta_{eff}^{lept}$ (Mz)

CDF data analyzed With a D0 type analysis (partial rad corrections)

Extract $\sin^2\theta_{eff}^{leponic}$(ave)

Extracted $\sin^2\theta_{eff}^{lept}$ (Mz) ≈ $\sin^2\theta_{eff}^{leponic}$(ave) + 0.00032



Summary

* CDF ($\mu^+\mu^-$ 9 fb^{-1}) : Mw(indirect) = 80.365 ± 0.045 GeV (2014)

* CDF ($\mu^+\mu^-$ 9 fb^{-1}) : $\sin^2\theta_{eff}$ = 0.23150 ± 0.00100 (2014)
  D0 (e+e- 9.7 fb^{-1} Preliminary) $\sin^2\theta_{eff}$ = 0.23106 ± 0.00053 (2014)

  + 0.00032 ?
  (with full ZFITTER EBA EW rad cor?)

LEP/SLD	0.23153 ± 0.00016
LEP	0.23221 ± 0.00029
SLD	0.23098 ± 0.00026

LEP SLD difference is 0.00122

* CDF will reduce its errors by a factor of 2 with the run II 9 fb^{-1} e+e- sample (results expected fall 2014).
  The combined CDF/D0 error in $\sin^2\theta_{eff}$ will match LEP and SLD errors. Error in indirect MW will be close to the error in the direct measurement of MW

Incorporating LHC data into updated PDF fits will PDF error
(current PDF error ± 0.00029)