Precision Measurements of Electroweak Parameters with Z Bosons at the Tevatron

($\sin^2\theta_W^{eff}$, $\sin^2\theta_W^{on\text{-}shell}$, $M_w^{indiret}$)

Arie Bodek, University of Rochester,

For the CDF and D0 Collaboration

Rencontres de Moriond
EW Interactions and Unified Theories

La Thuile, Aosta valley, Italy:
March 12th - 19th, 2016
20 min

UNIVERSITY of ROCHESTER

Dilepton forward backward asymmetry

$\rightarrow \sin^2\theta_{eff}^{leptonic}$

1. DØ e^+e^- (9.7 fb^{-1}) Phys. Rev. Lett. 115, 041801(2015)

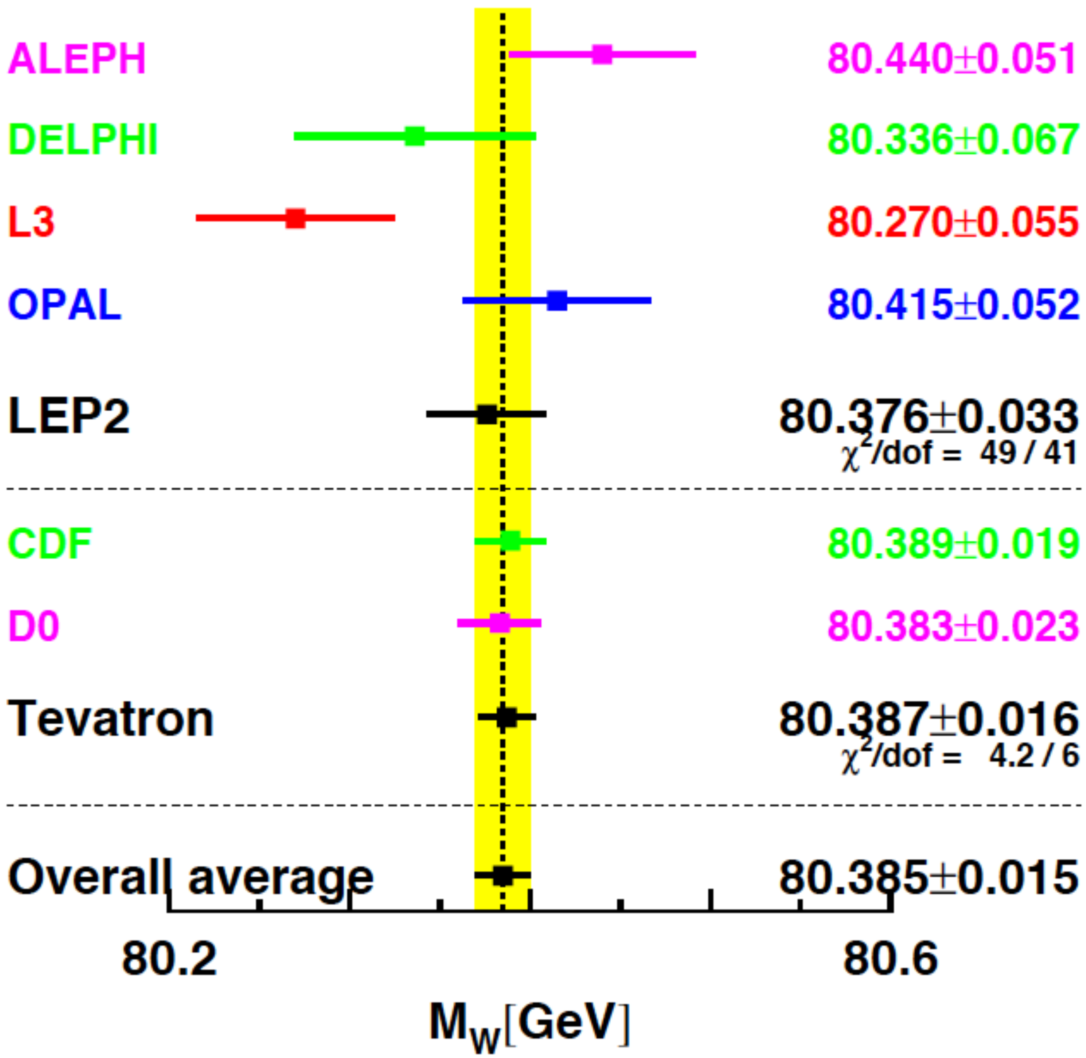
   measure **$\sin^2\theta_{eff}^{leptonic}$ (M_Z)**

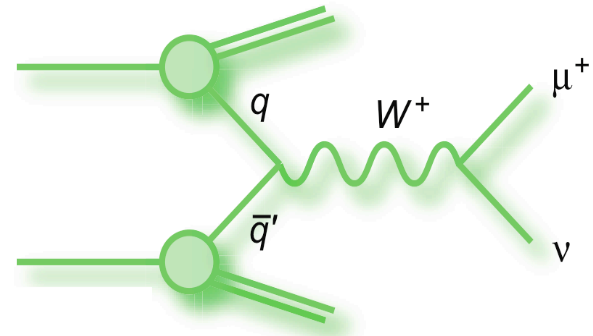
2. CDF $\mu^+\mu^-$ (9.2 fb^{-1}) Phys. Rev. D89, 072005(2014:
   CDF e^+e^- + $\mu^+\mu$ (9.4 fb^{-1}) submitted to Phys Rev D 2016

   measure **$\sin^2\theta_{eff}^{leptonic}$ (M_Z) & $\sin^2\theta_W^{on\text{-}shell}$, $M_W^{indirect}$**

3 A. Bodek et al arXiv:1507.02470 to be published in EPJC

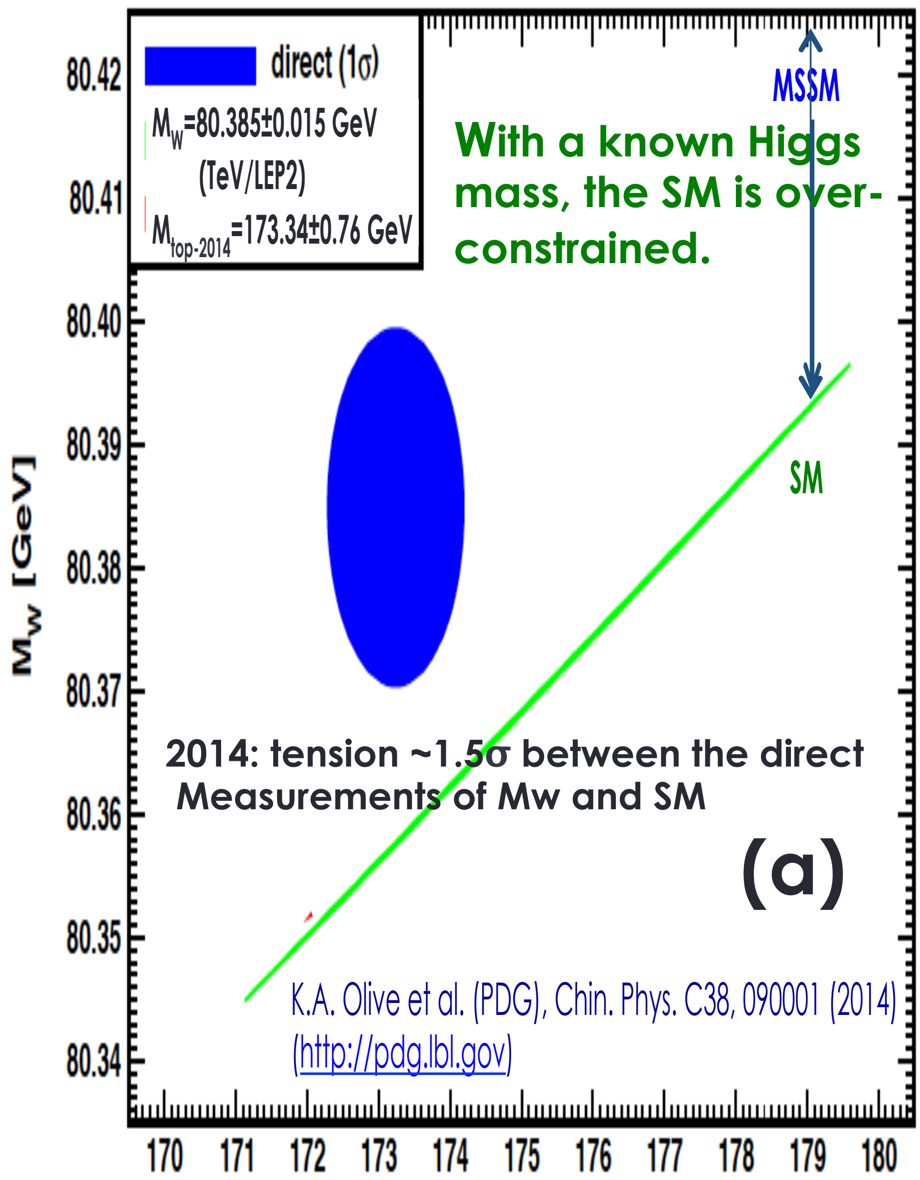
New method: PDF Constraints from Drell-Yan AFB http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf

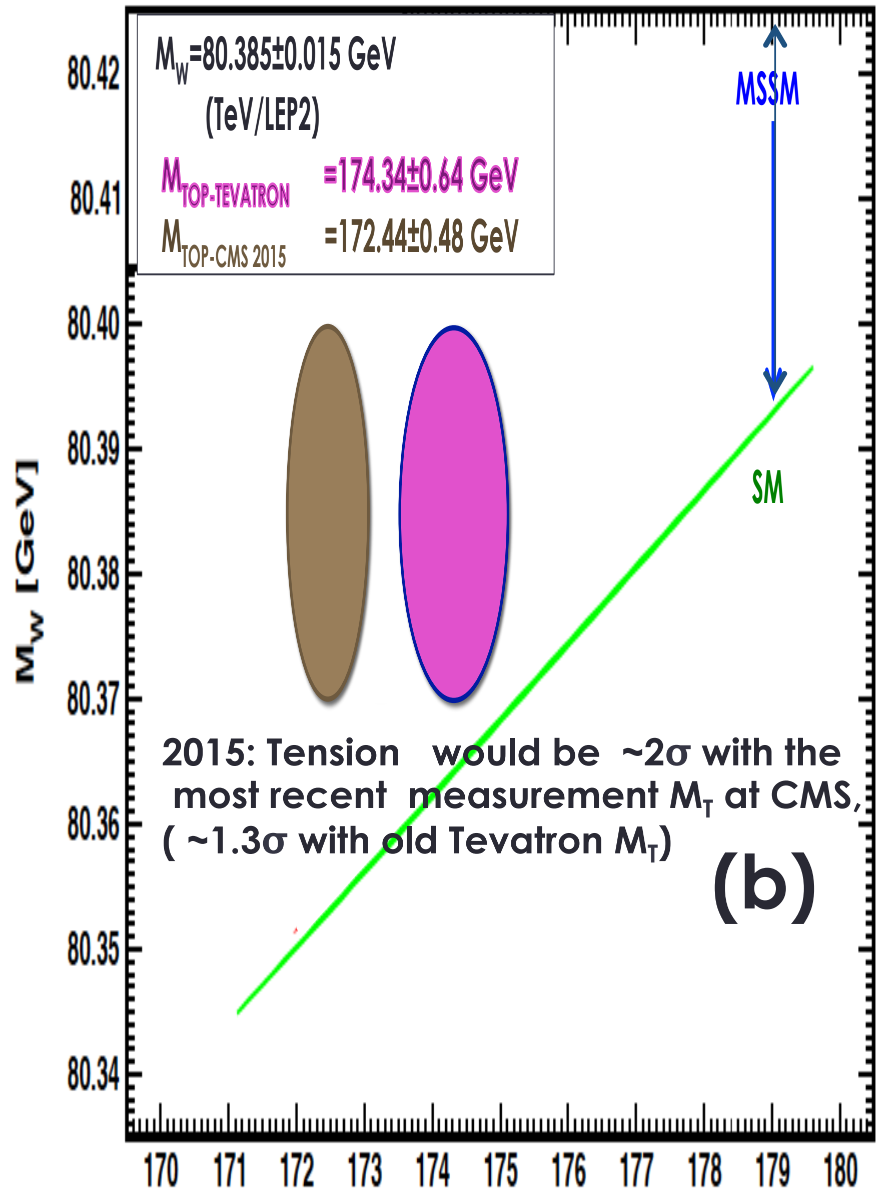




The most recent Tevatron measurements (CDF and Dzero) have errors of ~20 MeV

Standard Model vs Super symmetry





m_t [GeV] 15 MeV error in W mass m_t [GeV]

Indirect Measurement of W mass

M_W also can be determined indirectly via the relation

$$\sin^2\theta_W^{on\text{-}shell} = 1 - M_w^2 / M_z^2$$

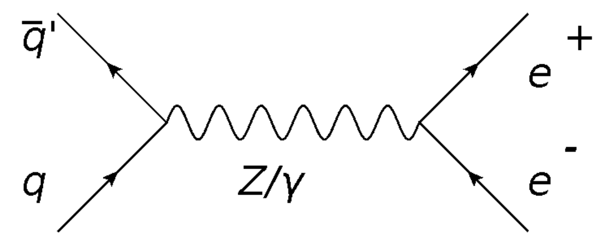
± 0.00040 error in $\sin^2\theta w$ is equiv. to ± 20 MeV error in Mw (indirect)

Both $\sin^2\theta_W^{on\text{-}shell}$ and $\sin^2\theta_{eff}^{leptonic}$ (M_z) can be extracted from Drell-Yan forward-backward asymmetry (Afb) if we include EW radiative corrections. $M_w^{indirect}$ can be extracted from $\sin^2\theta_W^{on\text{-}shell}$

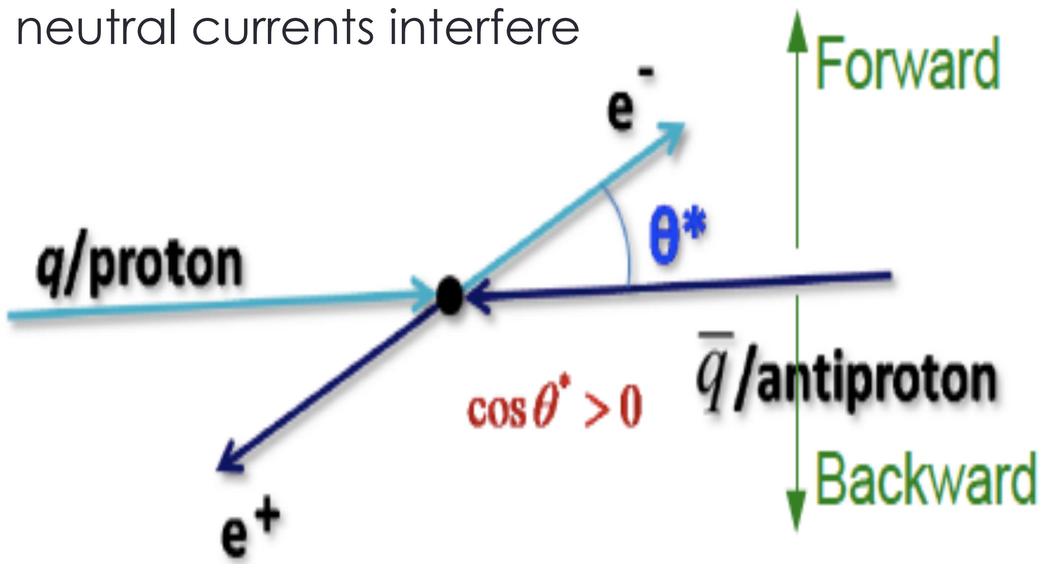
- If the SM is correct, then both direct and indirect measurements of M_W should agree. Deviations may imply the possibility of new physics.
- Similarly different measurements of $\sin^2\theta_{eff}^{leptonic}$ (M_z) should also agree and deviations may imply new physics.

As shown in this talk, for the full Run II 9.4 fb^{-1} Tevatron data, the uncertainties in direct and indirect measurements of M_w are now comparable.

A_{FB} for e^+e^- or $\mu^+\mu^-$ pairs in the Z boson Region is sensitive to the effective EW mixing angle $\sin^2\theta_{eff}$



The axial and vector neutral currents interfere



Define Forward-Backward asymmetry:

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

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

(*above relation is approximate*) one needs to include complex EW radiative correction form factors in the theory predictions for A_{FB} to extract the on-shell $\sin^2\theta_W$

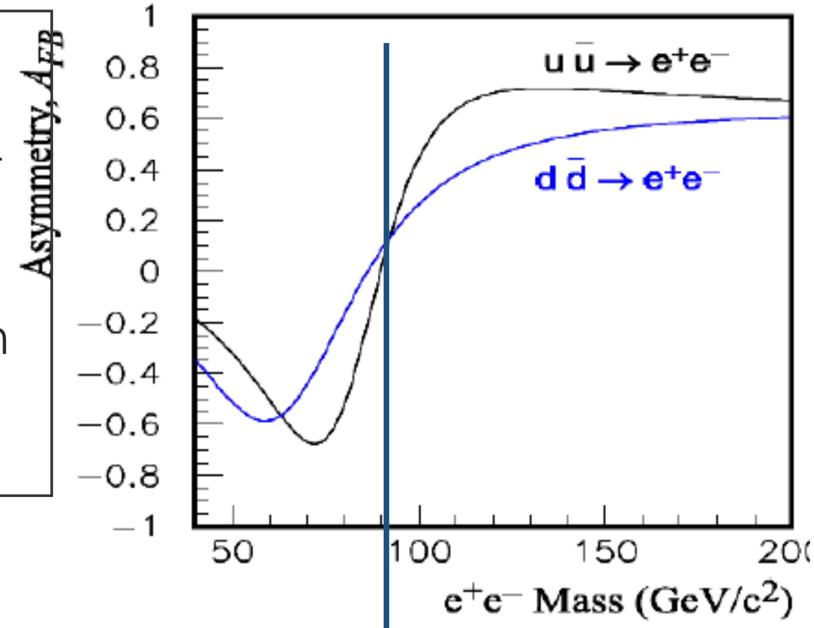
$$\sin^2\theta_W = 1 - M_W^2 / M_Z^2$$

Difference between u and d quarks

There is some dependence of the predicted Afb on the ratio of d/u PDFs since Afb for u and d type quarks is different

The d-quark valence PDF is smaller than the u- quark valence PDF.

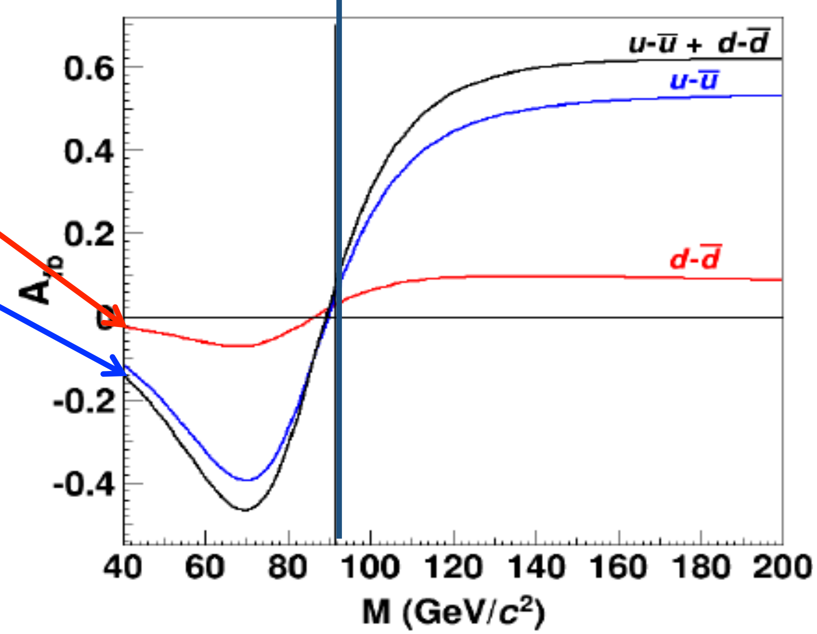
The result is that the d-dbar contribution to the asymmetry for proton-antiproton collisions is small.



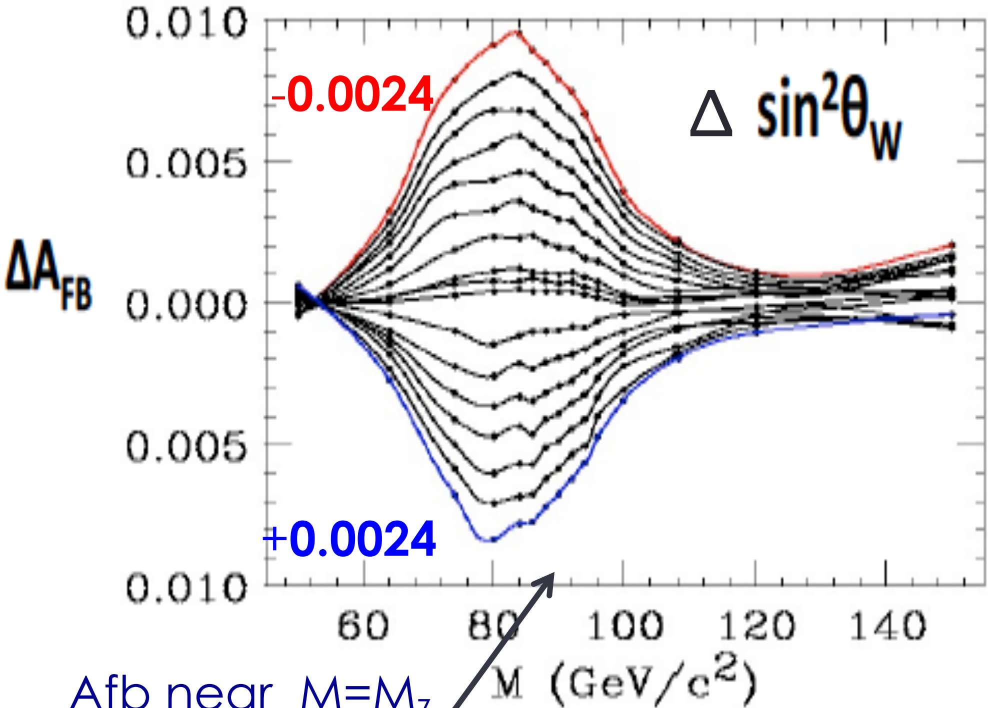
$$A_{FB}^{d-type} \approx \frac{(dd)_F - (dd)_B}{(dd)_F + (dd)_B + (uu)_F + (uu)_B}$$

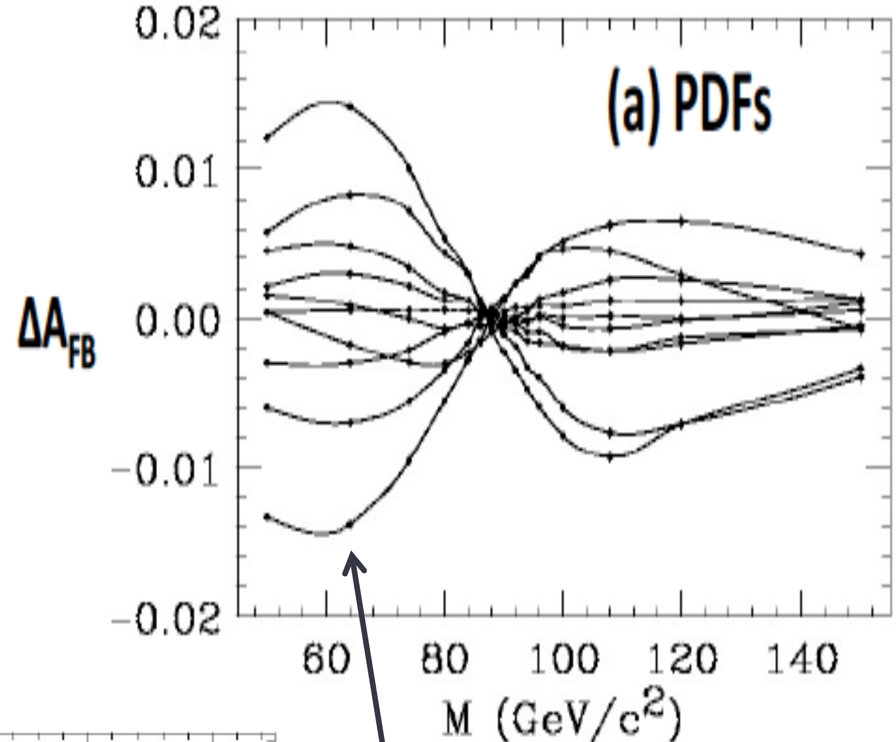
$$A_{FB}^{u-type} \approx \frac{(uu)_F - (uu)_B}{(dd)_F + (dd)_B + (uu)_F + (uu)_B}$$

Afb near $M=M_Z$ is related to $\sin^2\theta_W$



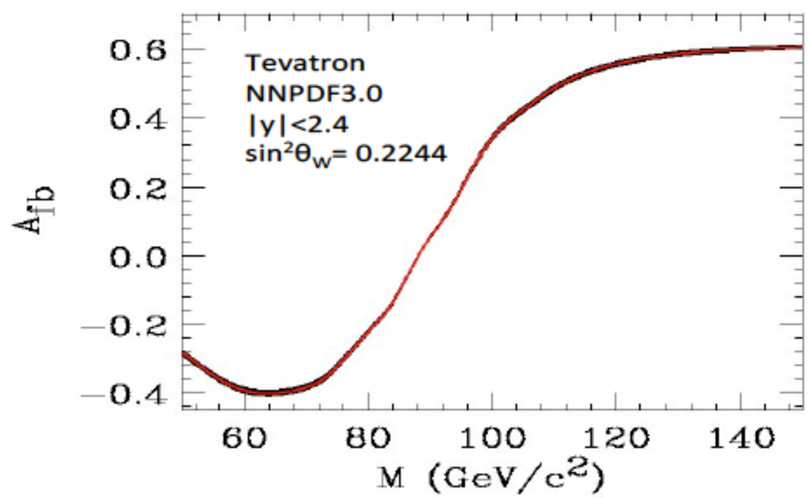
Change in Afb(M) with respect to Afb with $\sin^2\theta_W = 0.2244$





Afb near $M=M_Z$ is sensitive to $\sin^2\theta_W$

Afb at lower and higher mass is not sensitive to $\sin^2\theta_W$

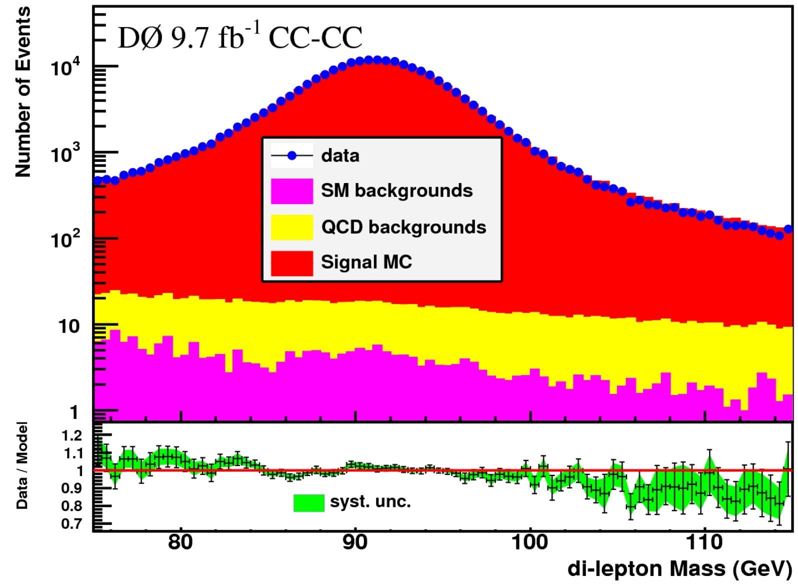


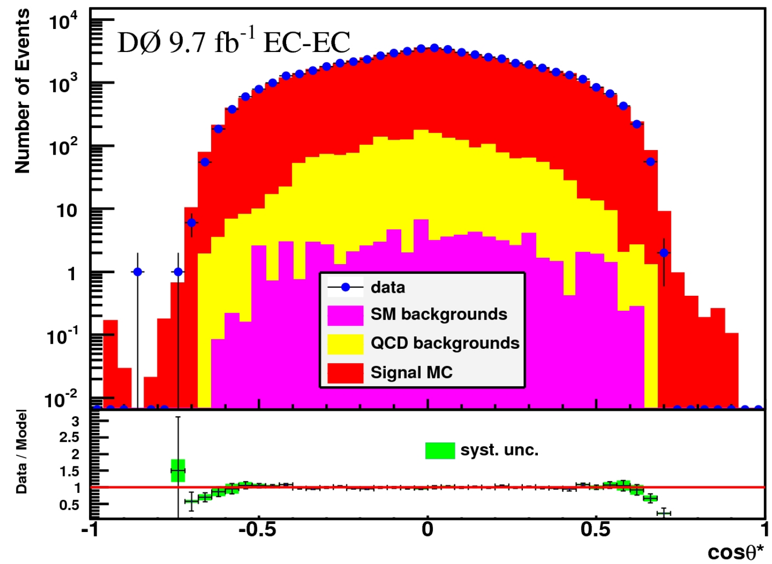
Afb at Low and high mass is sensitive to antiquark dilution.

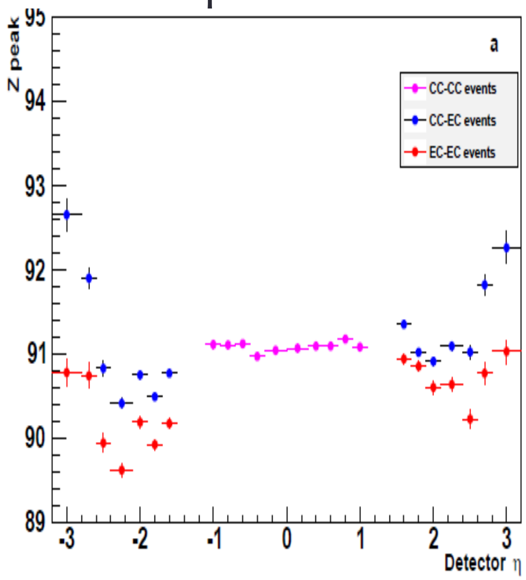
BAD PDFs have bad Chi2

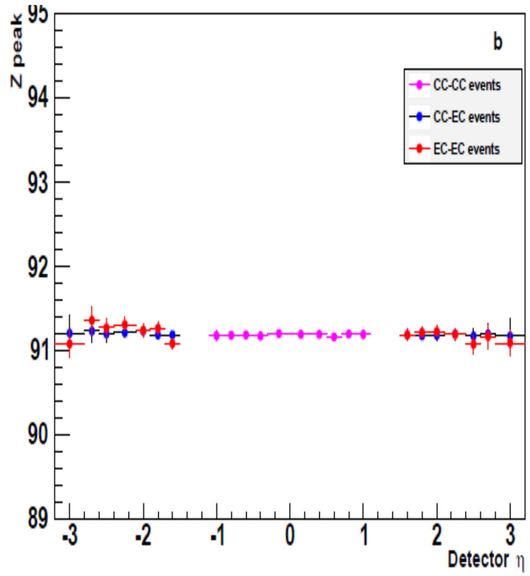
DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_W^{eff}$ analysis - I

- Require two electrons with p_T>25 GeV
  - Tight track match requirement
  - CC (|η|<1.1) and EC (1.5<|η|<3.2)
- Use 75<M_{ee}<115 GeV → 560k events
- New Lepton energy calibration similar to that used in CDF and CMS
  - Apply scale factor as a function of L_{inst} first and then η
  - M_{ee} peak scaled to LEP value in each bin
  - Separate calibrations for data and MC







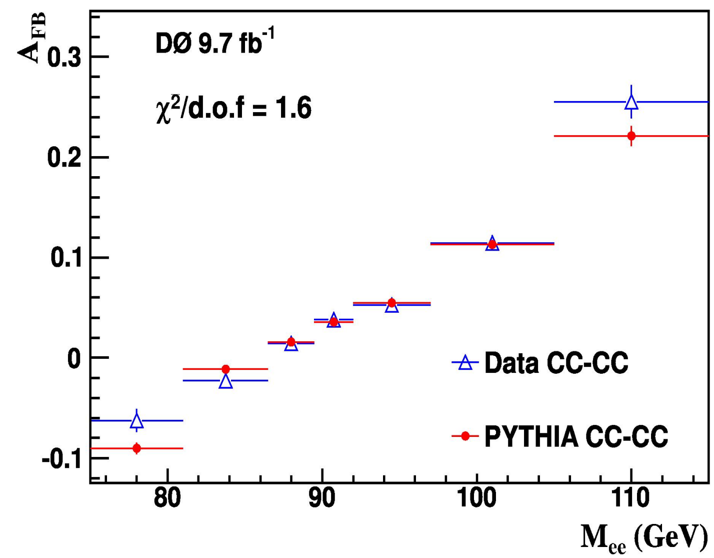


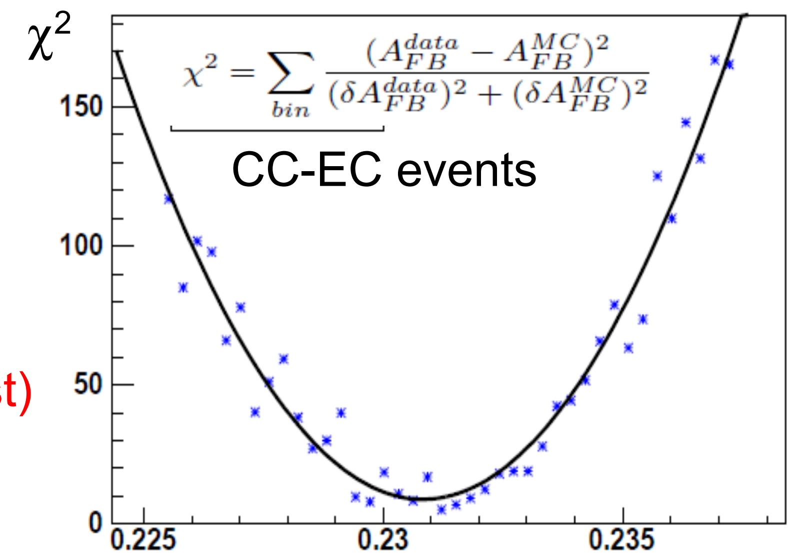
D0: Phys. Rev. Lett. 115, 041801 (2015)

DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_W^{eff}$ analysis - II

- Corrections are applied to MC to account for:
  - Smearing of electron energy
  - Efficiency corrections in $p_T(e)$, $\eta(e)$
  - L_{inst} and z_{PV} reweighting to match data
  - Higher order effects: NNLO Z p_T and y to match RESBOS
- Produce 2D templates of M_{ee} and $\cos\theta^*$ by reweighing default MC ($\sin^2\theta_{eff}$=0.232) as a function of $\sin^2\theta_{eff}$
- Extract $\sin^2\theta_{eff}$ by fitting raw A_{FB} to templates with different $\sin^2\theta_{eff}$ values
- No unfolding: MC is carefully corrected to describe the data

$\sin^2\theta_{efff}$ = 0.23138 ± 0.00043(stat) ± 0.00008(syst) ± 0.00017(NNPDF2.3 PDFs)
(no EW radiative corrections)

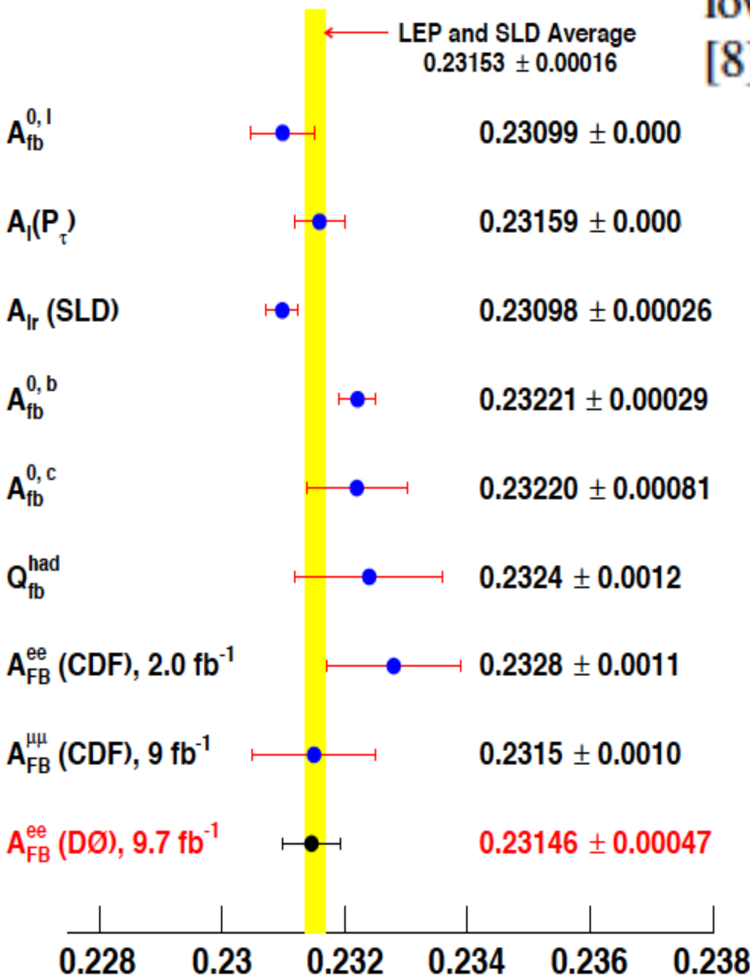




$\sin^2\theta_{eff}$

- D0: Phys. Rev. Lett. 115, 041801 (2015)

DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_W^{eff}$ analysis - III



An approximate way to correct for the flavor dependence of $\sin^2\theta_{\rm eff}$ from EW radiative corrections is used by the D0 collaboration. This is done by making the following corrections (proposed by Baur and collaborators [8]):

$$\sin^2\theta_{\rm eff}^{\rm u-quark} = sin^2\theta_{\rm eff}^{\rm lept} - 0.0001$$

$$\sin^2\theta_{\rm eff}^{\rm d-quark} = sin^2\theta_{\rm eff}^{\rm lept} - 0.0002$$

Change is +0.00008

Final results :**DØ ee**

$\sin^2\theta_{\rm eff}^{\rm leptonic}$ (Mz)

= 0.23146 ± 0.00043 (stat)

± 0.00008 (syst)

± 0.00017 (PDFs NNPDF2.3 NLO)

= 0.23146 ± 0.00047 (total)

- D0: Phys. Rev. Lett. 115, 041801 (2015)

CDF $\mu^+\mu^-$ & e^+e^- 9.7 fb^{-1} $\sin^2\theta_W$ analyses

Indirect measurement of W mass:

1st innovation: $\sin^2\theta_W$ is constant while $\sin^2\theta_{eff}^{lept}$ (M_{ee} ,flavor) is not. Implement Full ZFITTER EW radiative corrections, Enhanced Born Approximation (EBA), include full complex form factors implemented in private versions of RESBOS, POWHEG, and LO. *Ref Phys. Rev. D 88, 072002 (2013) Appendix A'.*

2nd innovation: Precise lepton momentum/energy scale for muons and electrons using a new method- (will also reduce scale error for M_W measurement) *Ref: A. Bodek et al. Euro. Phys. J. C72, 2194 (2012)*

3rd innovation: Event weighting method for A_{FB} analyses (systematic errors in acceptance and efficiencies cancel)-
Ref. A. Bodek. Euro. Phys. J. C67, 321 (2010)

4th innovation: Use Drell-Yan forward-backward asymmetry to constrain parton distribution functions - (will also reduce PDF errors for M_W measurement) *Ref A. Bodek et al arXiv:1507.02470v2 (2015)*

1. Implement ZFITTER EBA EW radiative corrections 13

$\sin^2\theta_W$ (on-shell) is a constant while $\sin^2\theta_{eff}^{lept}$ (M_{ee} ,flavor) is not.

Full ZFITTER EW radiative corrections, Enhanced Born Approximation (EBA), include full complex form factors implemented private versions of RESBOS, POWHEG, and LO) Phys. Rev. D 88, 072002 (2013) Appendix A'

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

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

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

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

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

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

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

- 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

Accounts for $\sin^2\theta_{eff}$ dependence on quark flavor and dilepton mass → get $\sin^2\theta_{eff}^{leptonic}(Mz)$ using Afb over a range of dilepton mass

2. Precise Energy/Momentum Scale corrections

New technique used for both $\mu^+\mu^-$ and e^+e^- for both data and hit level MC. (Ref A. Bodek et al. Euro. Phys. J. C72, 2194 (2012))

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 used as a calibration. The Z mass as a function of η,Φ, (and charge for $\mu^+\mu^-$) of each lepton be correct

- **Reference for muons:** Expected Z mass (post FSR) smeared by resolution (with acceptance cuts).
- **Reference for electrons:** Expected Z mass (post FSR + clustered FSR photons), smeared by resolution (with acceptance cuts).

3. Use event weighting Method

Event weighting method for A_{FB} analyses

Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

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

Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of $\cos\theta$, and averaging the results.

Events at large $\cos\theta$ provide better determination of A4, so they are weighted more than events at small $\cos\theta$.

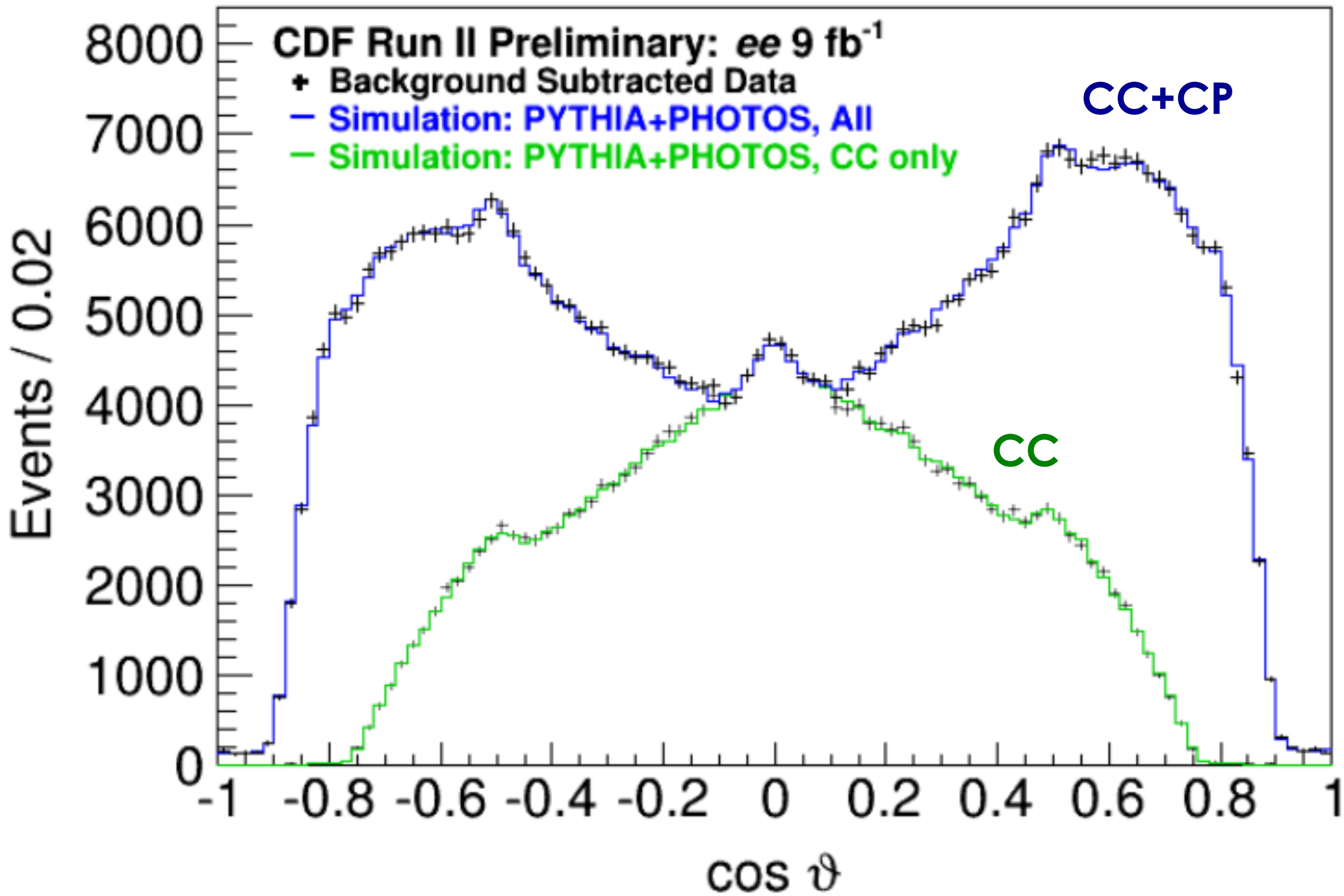
For each $\cos\theta$ acceptance and efficiencies cancel to first order and the statistical errors are 20% smaller. Then extract $A_{fb} = (3/8)A_4$

Event weighting does not correct for resolution smearing and final state radiation, which are included later in the unfolding.

The 4th innovation: Using Drell-Yan forward-backward asymmetry to constrain parton distribution functions is discussed at the end of the talk.

(Ref A. Bodek et al arXiv:1507.02470v2 (2015))

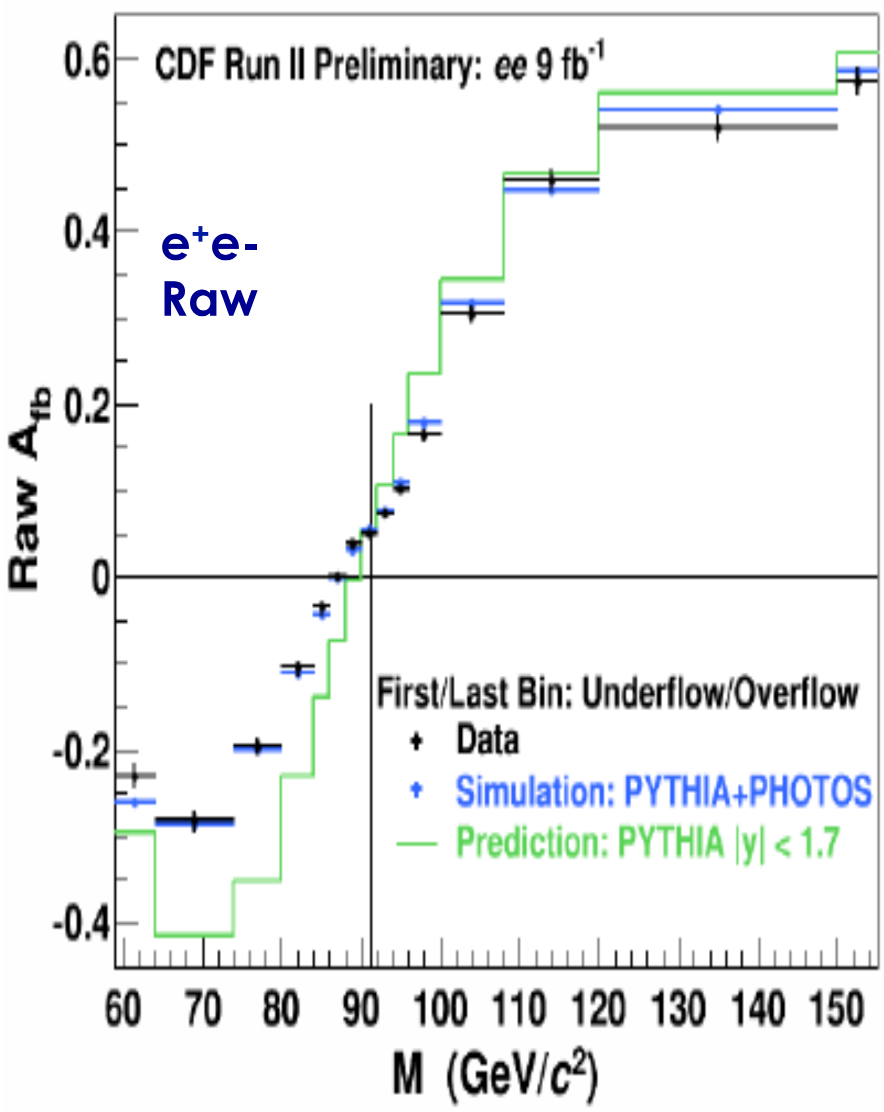
Why use event weighting Method

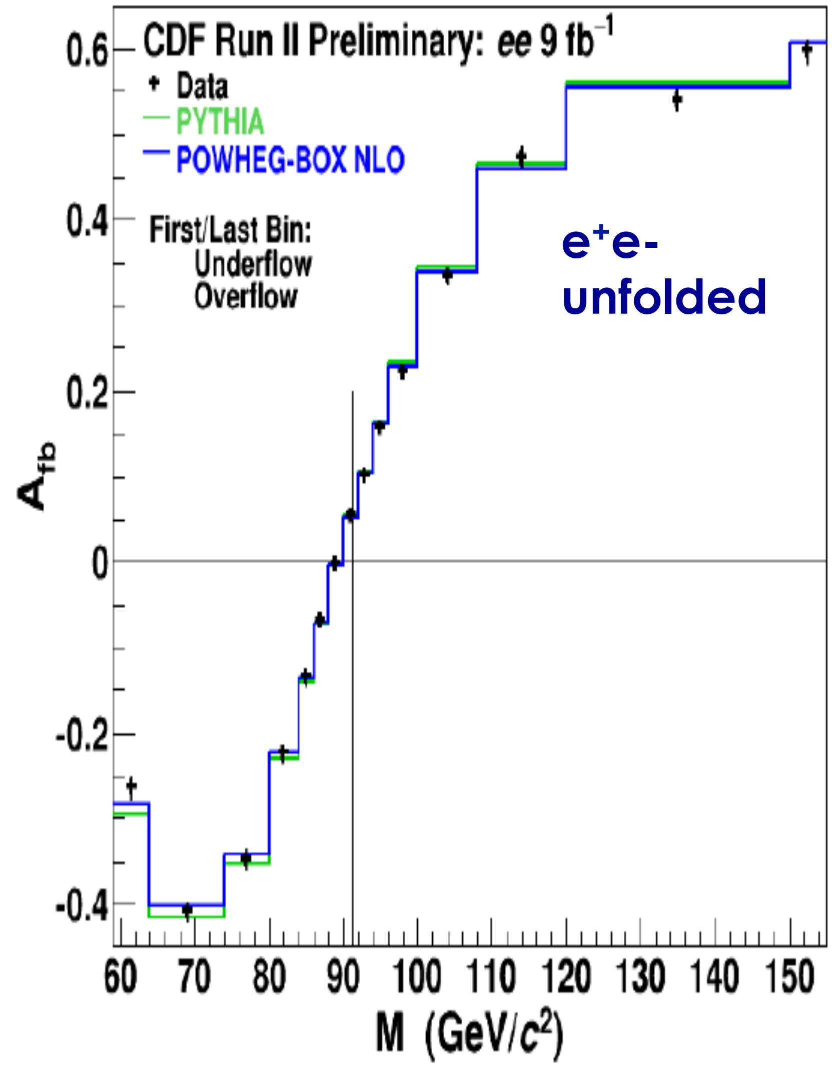


The error in **Afb** is reduced if we have more acceptance at large **cosθ**,
Standard Afb method requires precise knowledge of acceptance and efficiencies.

Measure A_4 → A_{FB}

CDF e^+e^-: unfolding for Resolution and FSR





e^+e^-: Afb Background subtracted
Raw no corrections

e^+e^- Afb: Afb unfolded
fully corrected

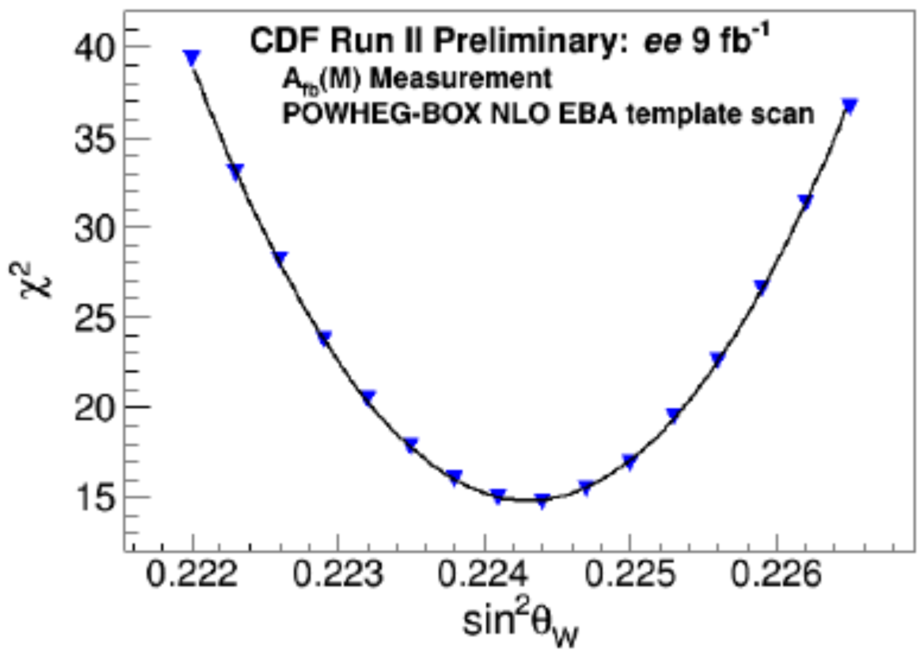
CDF e^+e^-: $\sin^2\theta_W$ extraction using templates

Comparisons of A_{fb} Measurement to Calculations

- Comparison χ^2: $\Sigma_M \Delta A_{fb}(M)^{\sim} \bullet E \bullet \Delta A_{fb}(M)$
  - Measurement: Fully corrected $A_{fb}(M)$
  - Calculated templates: $A_{fb}(M,\sin^2\theta_w)$ for 16 values of $\sin^2\theta_w$
  - E: Measurement error matrix

Example $\sin^2\theta_w$ template scan using data

- Afb template: Powheg-Box NLO + default PDF of NNPDF 3.0 (261000)
- Fit of scan points to a parabola: $\chi^2_{min} + (\sin^2\theta_w - \sin^2\theta_{w\,min})^2/\sigma_{min}^2$



This analysis is repeated with
1. POWEG ,2. RESBPOS
3. Tree-Level LO

For the POWHEG analysis, the extraction is repeated 100 times for all 100 NNPDF3.0 replicas to get PDF error.

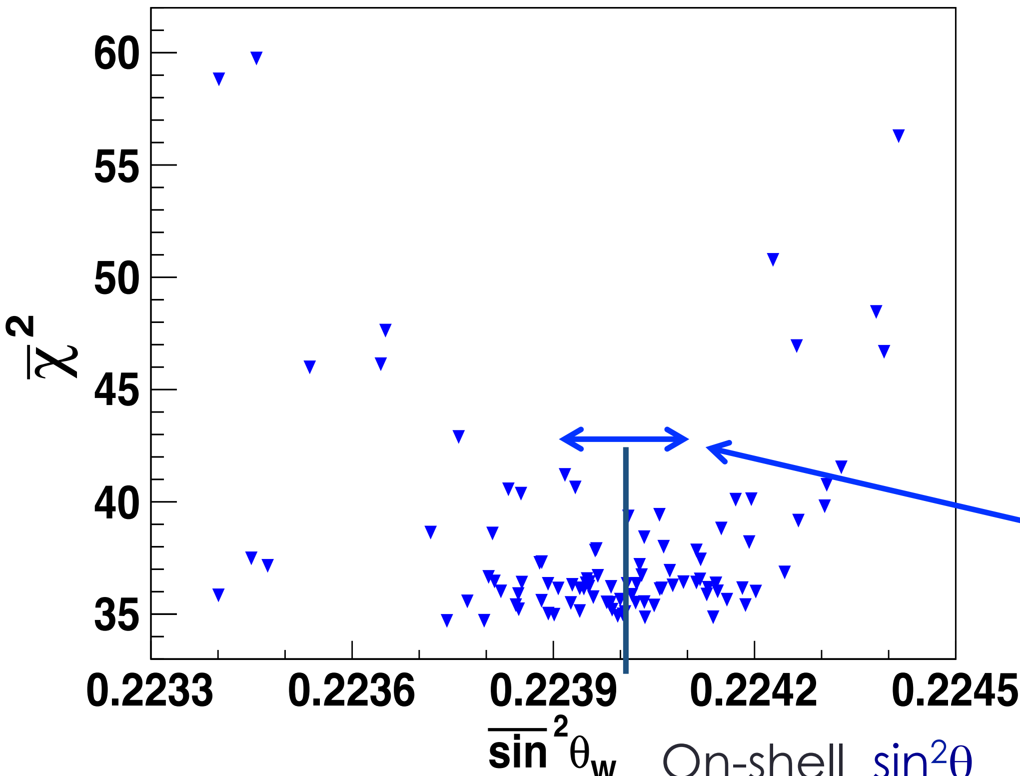
CDF $\mu^+\mu^-$ & e^+e^- : $\sin^2\theta_W$ PDF errors

- NNPDF 3.0 ensemble measurement of $\sin^2\theta_w$
  → Powheg-Box NLO and Tree (LO) Afb templates calculated with NNPDF
  → Example:
  Each entry is the $\sin^2\theta_w$ fit value for an ensemble PDF

15 Mass bins. This plot indicates that the NNPDF3.0 PDFs are consistent with the CDF Afb (M) data

CDF Run II Preliminary:

100 NNPDF 3.0 (NNLO) replicas



100 replicas NNPDF 3.0 (NNLO)
In the replica method
The RMS is the P**DF error**
RMS= ± 0.00020

However, the Afb chi-square can be used to further constrain PDFs **and reduce PDF error** to Weighted **RMS**
± 0.00016

On-shell $\sin^2\theta_W$ =0.23400 ± 0.00043(stat)

DØ ee

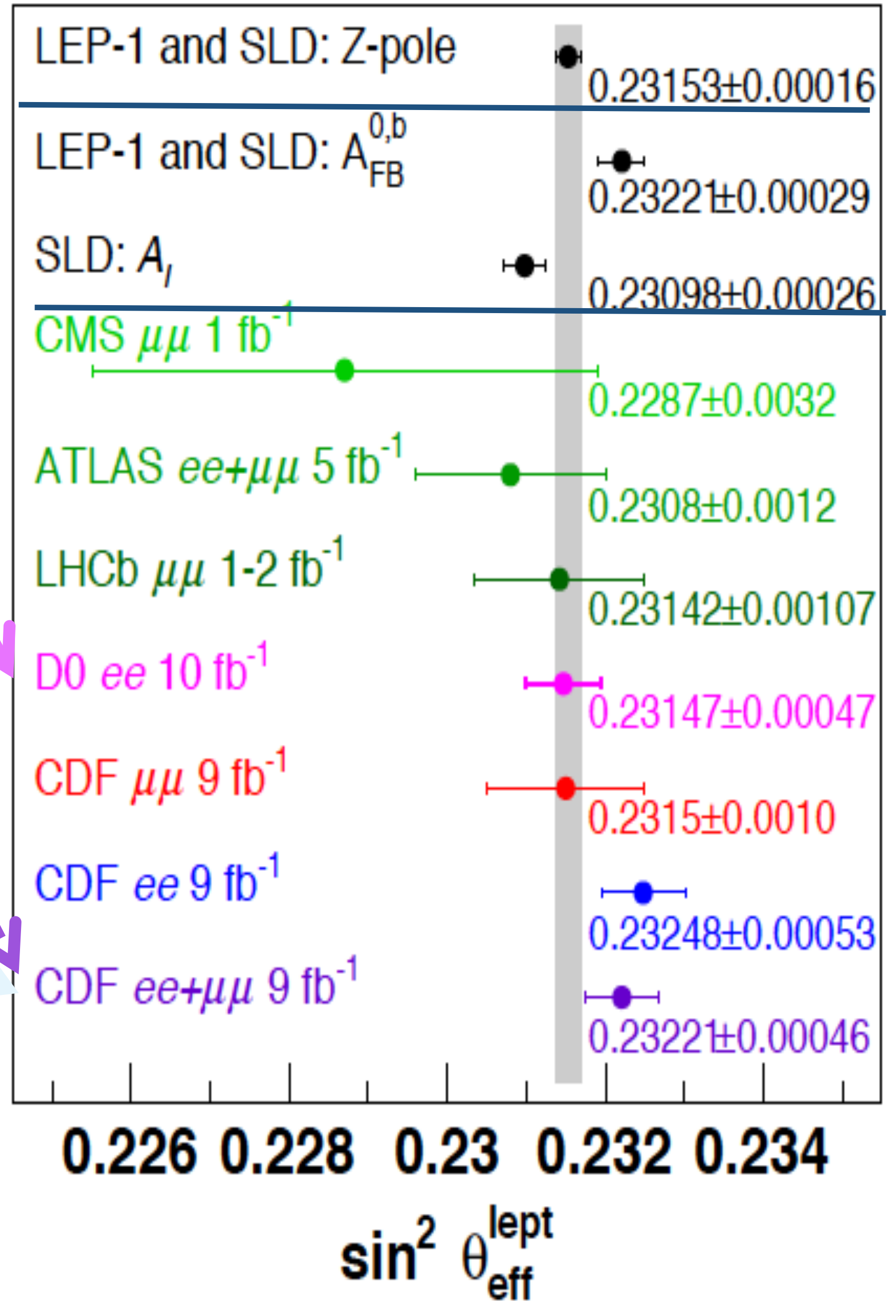
$\sin^2\theta_{efff}$ = 0.23146 ± 0.00043(stat)
± 0.00008(syst)
±0.00017 (NNPDF2.3 PDFs NLO)

$\sin^2\theta_{efff}$ = 0.23146 ± 0.00047 (total)

CDF ee & μμ

$\sin^2\theta_{eff}$ =0.23221 ± 0.00043(stat)
± 0.00005(syst)
±0.00016 (NNPDF3.0 PDFs NNLO)

$\sin^2\theta_{efff}$ = 0.23221 ± 0.00046 (total)



Differences between D0 and CDF Analyses

1. CDF uses NNPDF 3.0 PDFs (NNLO) which include LHC data and supersede the NNPDF2.3 (NLO) used by D0
2. CDF uses full EBA EW rad correction. D0 uses partial Zgrad EW rad corr.

Need to resolve these issues before The two results can be combined.

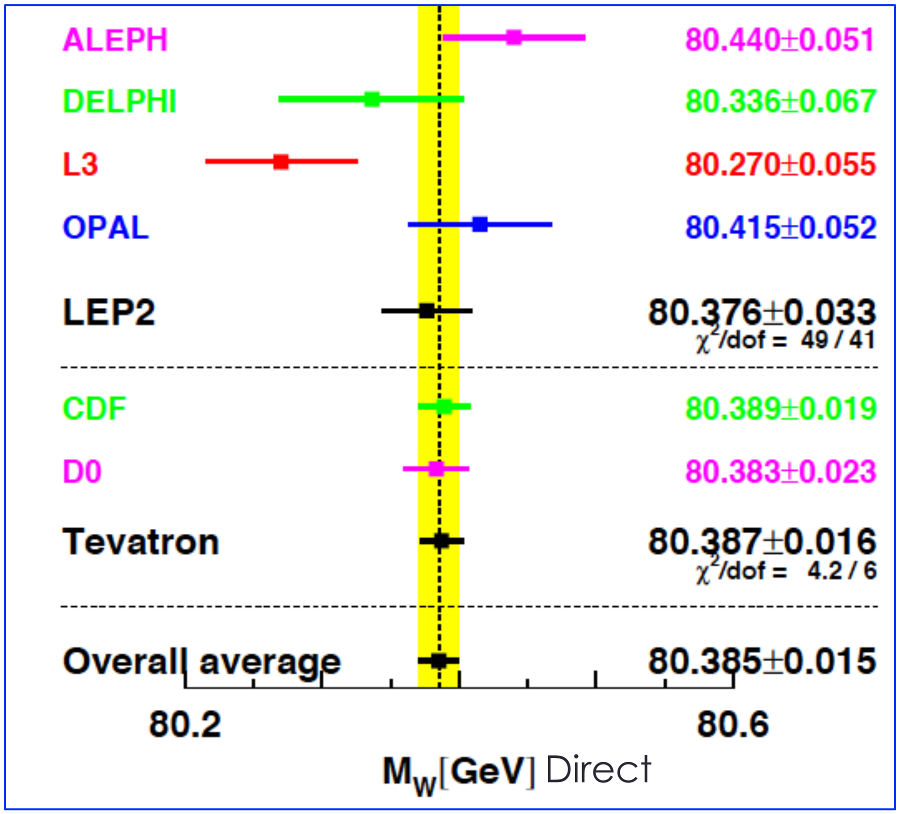
CDF ee & μμ 9 fb^{-1} Indirect M_W measurement

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23221 \pm 0.00046$$

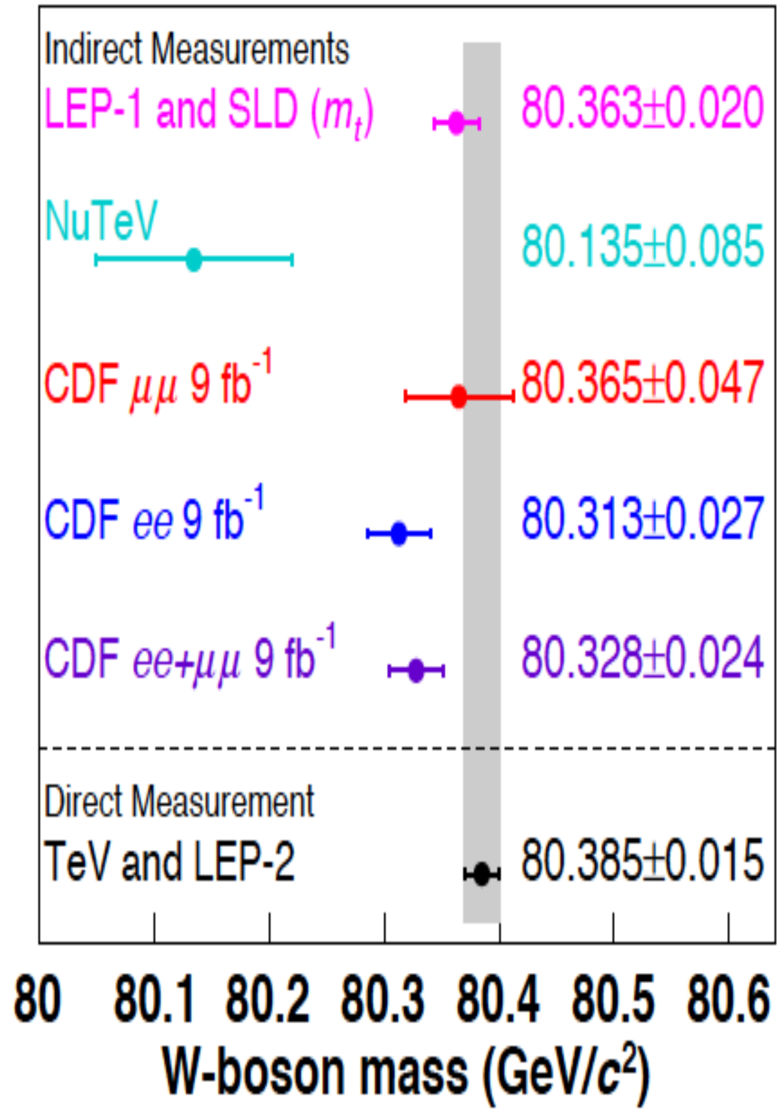
On-shell $\sin^2\theta_W = 0.22400 \pm 0.00045$

$$M_W(\text{indirect}) = 80.328 \pm 0.024 \text{ GeV}/c^2 .$$

CDF Mw 24 MeV Indirect Mw error is similar to CDF 19 MeV direct Mw error

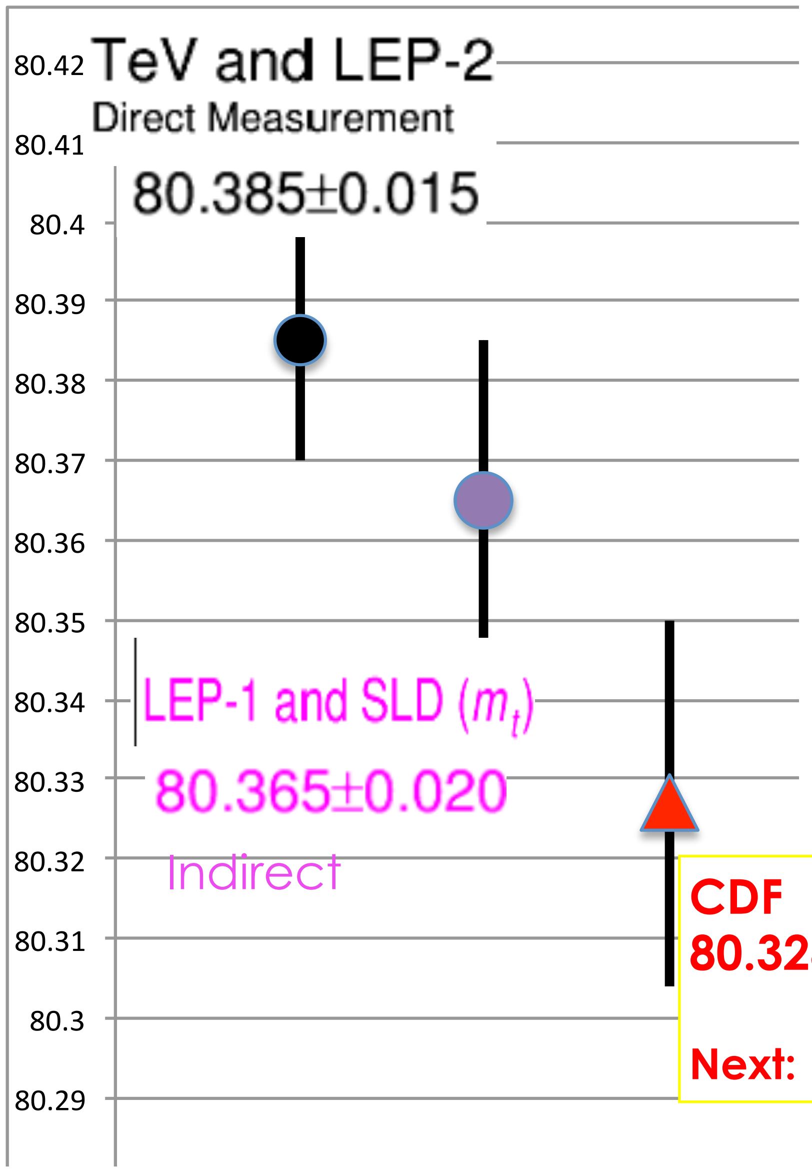


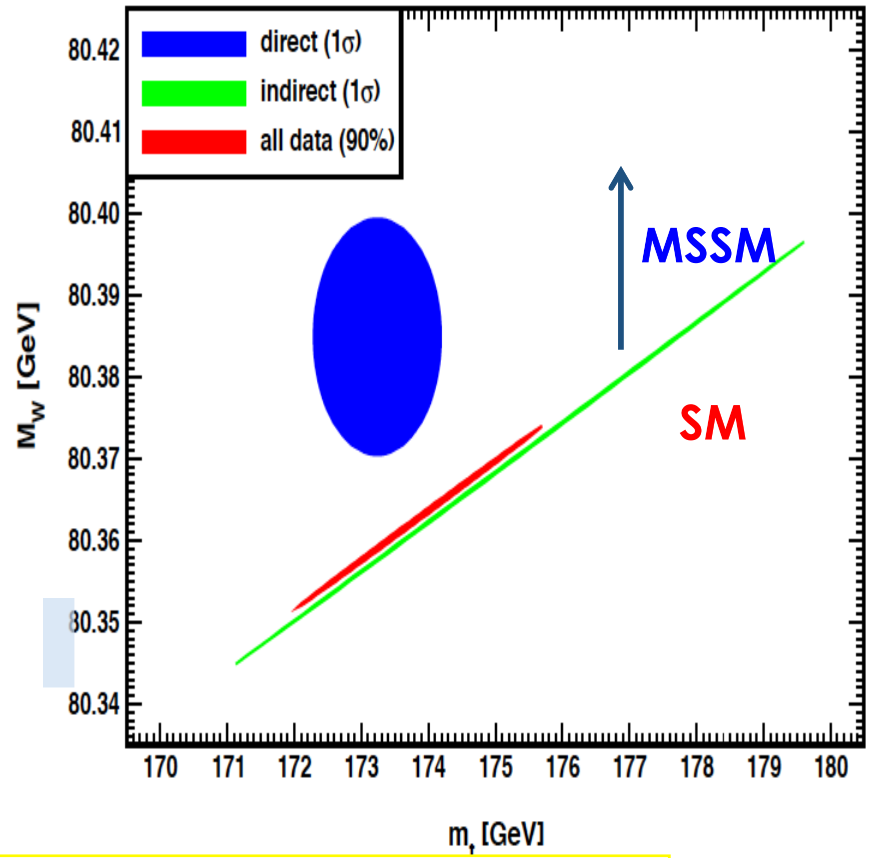
http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf



CDF ee & μμ 9 fb^{-1} Indirect M_W measurement

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-standard-model.pdf
K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014) (http://pdg.lbl.gov)





CDF ee & μμ
80.328 +- 0.024

Next: CDF-D0 combination (in future)

Conclusions Tevatron Legacy 23

An Error of +- 0.00040 in $\sin^2\theta w$ is equiv. to +-20 MeV error in Mw.

Currently the Tevatron direct (L= 2.2 fb^{-1}) and indirect (L=9.4 fb^{-1}) measurements of Mw have similar errors. (~ 20 MeV per experiment)

Tevatron Run II Legacy measurements of $\sin^2\theta w$ and $M_W^{indirect}$ are in good agreement with SM predictions from M_H and M_T. (no hint of super-symmetry). $A_{FB}(M)$ data can also be used to put additional constraints on PDFs. These constraints will help reduce PDF errors in the ongoing Tevatron Run II Legacy (L=9.4 fb^{-1}) direct measurement of Mw.

Extra slides:

Moving on to the LHC: With these new techniques, as the statistical errors in Afb become smaller, there is a corresponding reduction in both the statistical errors and PDF errors in the measurements of of $\sin^2\theta w$ and $M_W^{indirect}$.

With current 8 TeV data, LHC can match CDF errors.
With 13 and 14 TeV LHC data, the errors can be reduced by a factor of 2.

Extra Slides

Replica PDFs

- New measurements can be incorporated into the ensemble without refits
  - Ensemble PDFs are reweighted

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$

χ^2_k: between new measurement and prediction with ensemble PDF k

This is clear for new data (e.g. new W asymmetry data)

However, How can we get both $\sin^2\theta_{eff}^{lept}$ AND constrain PDFs from the same Afb data ?

18. G. Watt and R. S. Thorne (MRST), JHEP 08:052 (2012) (arXiv:1205.4024)
19. https://mstwpdf.hepforge.org/random/
20. Walter T. Giele, and Stephane Keller, Phys.Rev. D58 (1998) 094023 (arXiv:hep-ph/9803393).
21. Nobuo Sato, J. F. Owens, Harrison Prosper, Phys. Rev. D 89, 114020 (2014) (arXiv:1310.1089)
22. Hannu Paukkunen, Pia Zurita, "PDF reweighting in the Hessian matrix approach", http://arxiv.org/abs/1402.6623
23. Richard D. Ball, Valerio Bertone, Francesco Cerutti, Luigi Del Debbio, Stefano Forte, Alberto Guffanti, Jose I. Latorre, Juan Rojo, Maria Ubiali, Nucl.Phys.B849, 112 (2011) arXiv:1012.0836.

Constraining PDF replicas

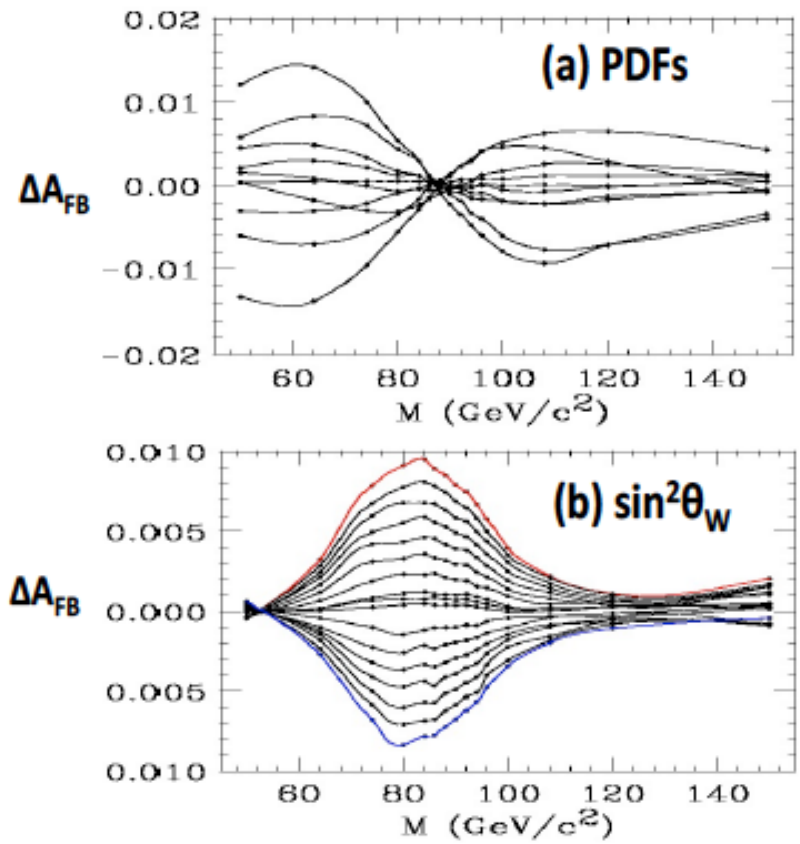
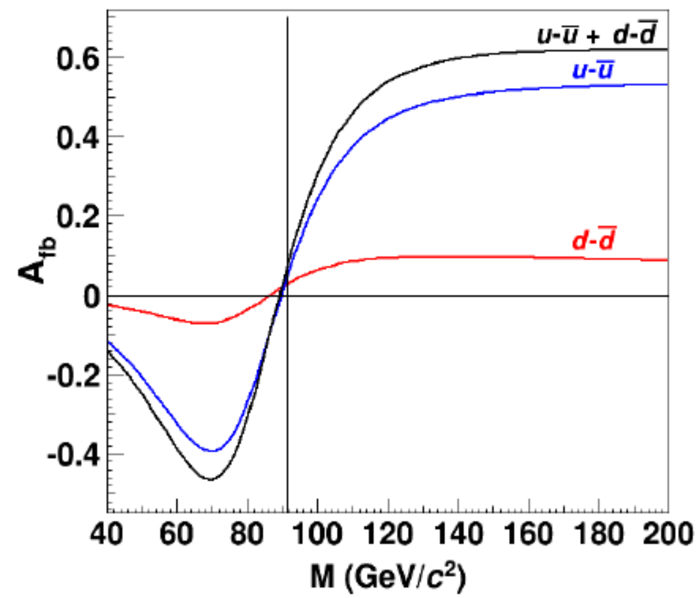


Fig. 3. Tevatron: (a) The difference between $A_{FB}(M)$ for 10 NNPDF3.0 (NNLO) replicas and $A_{FB}(M)$ calculated for the default NNPDF3.0 (NNLO) (261000). Much of the difference originates form the different dilution factors for each of the NNPDF replicas. Here $\sin^2\theta_W$ is fixed at a value of 0.2244. (b) The difference between $A_{FB}(M)$ for different values of $\sin^2\theta_W$ ranging from 0.2220 (shown at the top in red) to 0.2265 (shown on the bottom in blue), and $A_{FB}(M)$ for $\sin^2\theta_W$ =0.2244. Here $A_{FB}(M)$ is calculated with the default NNPDF3.0 (NNLO).

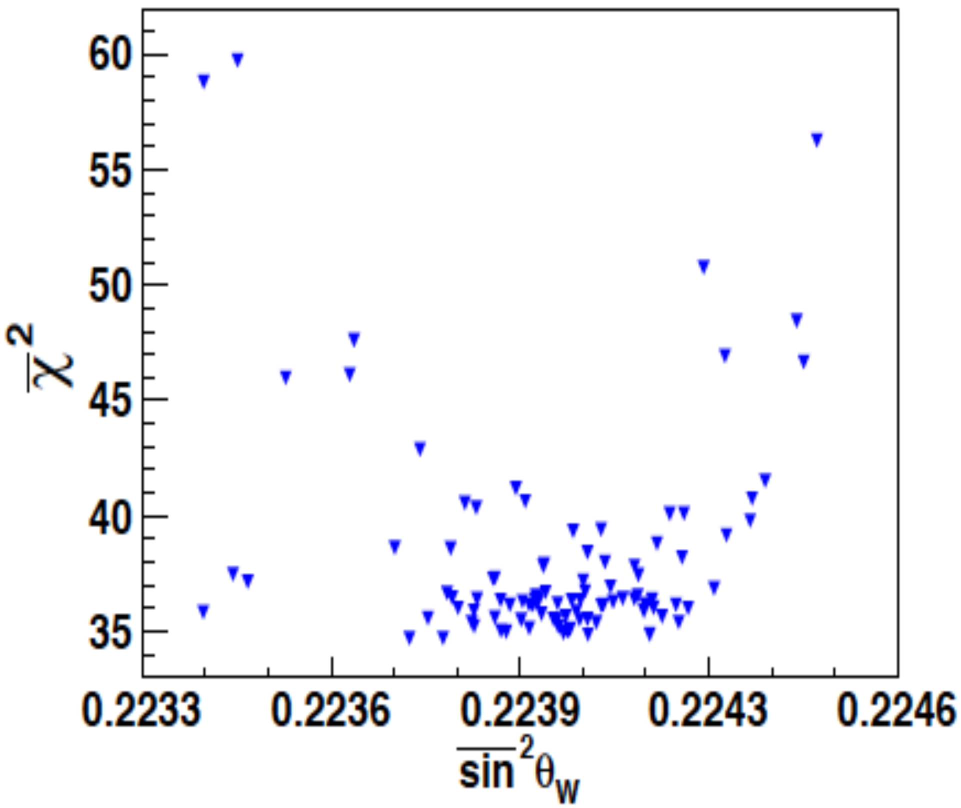


For details see:
A. Bodek. J. Han A. Khukhunaishvili, W. Sakumoto:" Using Drell-Yan forward-backward asymmetry to constrain parton distribution functions"
arXiv:1507.02470

Constraining PDFs & reducing PDF errors 27

χ^2_{min} versus $\sin^2\theta_W$ for each ensemble PDF:

100 NNPDF 3.0 (NNLO) replicas



CDF e+e Afb Data is compatible with NNPDF3.0 PDFs

In addition "Ensemble PDF can be constrained by reweighting"

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$

Technique can be used with any PDF set.

LHC A_{FB} data can also be used to constrain PDFs

See: A. Bodek arXiv:1507.02470

LHC CMS like Pseudo-Experiment LHC 15 fb^{-1} 8 TeV $6.7M$ $\mu^+\mu^-$ reconstructed events	input POWHEG Default NNPDF 3.0 (NLO) (261000)
$\sin^2\theta_{eff}$ input	0.23120
statistical error	±0.00050
$\Delta\sin^2\theta_{eff}$ CT10 PDF error	± 0.00080
Analysis replicas NNPDF set Templates	100 NNPDF 3.0 (NLO) POWHEG
Average method	$N_{eff}=100$
extracted $\sin^2\theta_{eff}$	0.23121
Standard PDF error RMS	±0.00051
(uncertainty in PDF error)	(0.00004)
χ^2_{Afb} weighting	$N_{eff}=37$
extracted $\sin^2\theta_W$	0.23119
χ^2_{Afb} weighted PDF error RMS	±0.00029
(uncertainty in PDF error)	(0.00003)
$\chi^2_{Afb}+\chi^2_{Wsym}$ weighting	$N_{eff}=15$
extracted $\sin^2\theta_W$	0.23122
Weighted PDF error RMS	±0.00026
(uncertainty in PDF error)	(0.00005)

ATLAS (e+μ) 4.5 fb^{-1}
0.23080 ±0.00050(stat)
± 0.00060(syst)
± 0.00090(pdf)→need to reduce

With the existing 8 TeV μμ Afb sample from one LHC experiment the PDF errors on $\sin^2\theta_{efff}$ can be reduced From the current CT10 PDF error of **+- 0.00090 to to +-0.00026.**

The constrained PDFs can also be used to reduce PDF errors on the direct measurement of M_W at the LHC

The PDF errors can be **further reduced** with larger statistical samples at 13 TeV.

LHC 8 TeV pseudo data

NNPDF3.0 pseudo data

A. Bodek arXiv:1507.02470

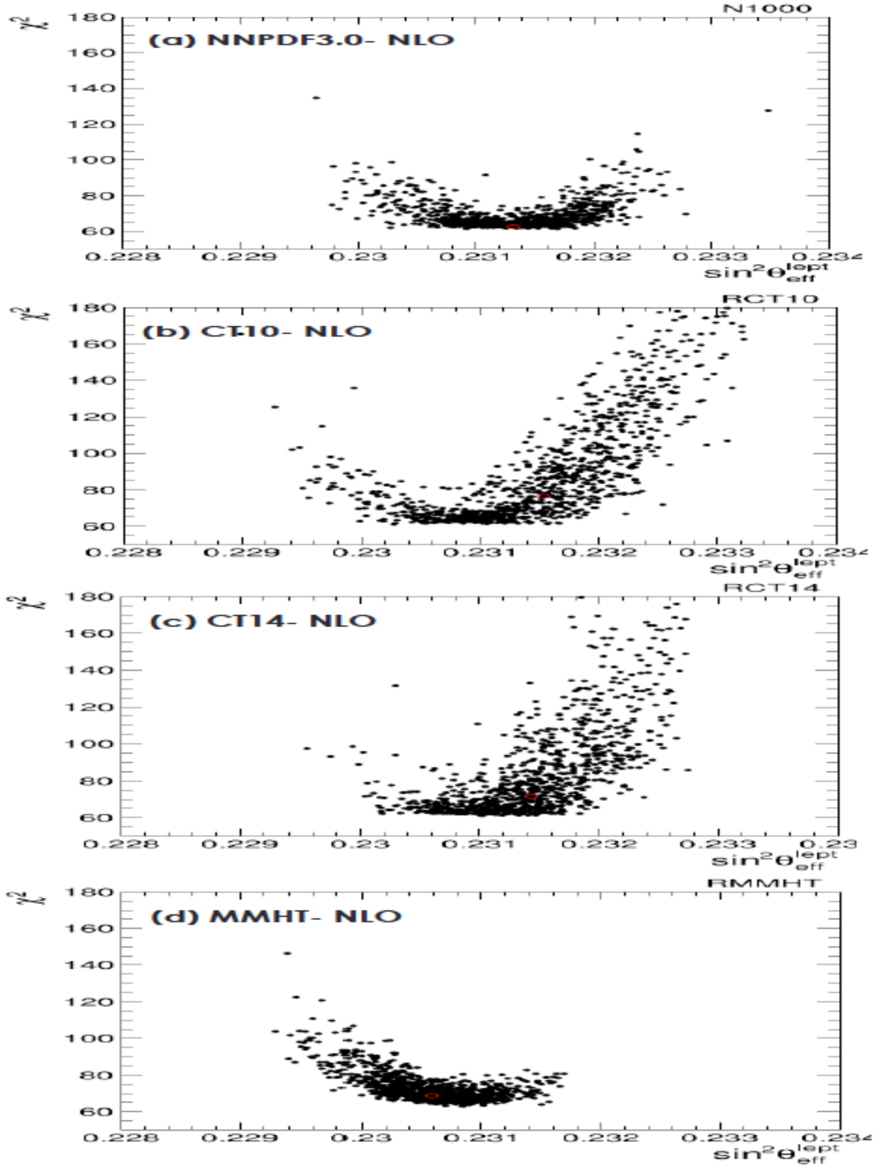


Fig. 9. Scatter plots of χ^2_{Afb} values versus $\sin^2\theta_{eff}$ for one of the 64 LHC pseudo experiments. Here templates are gener-

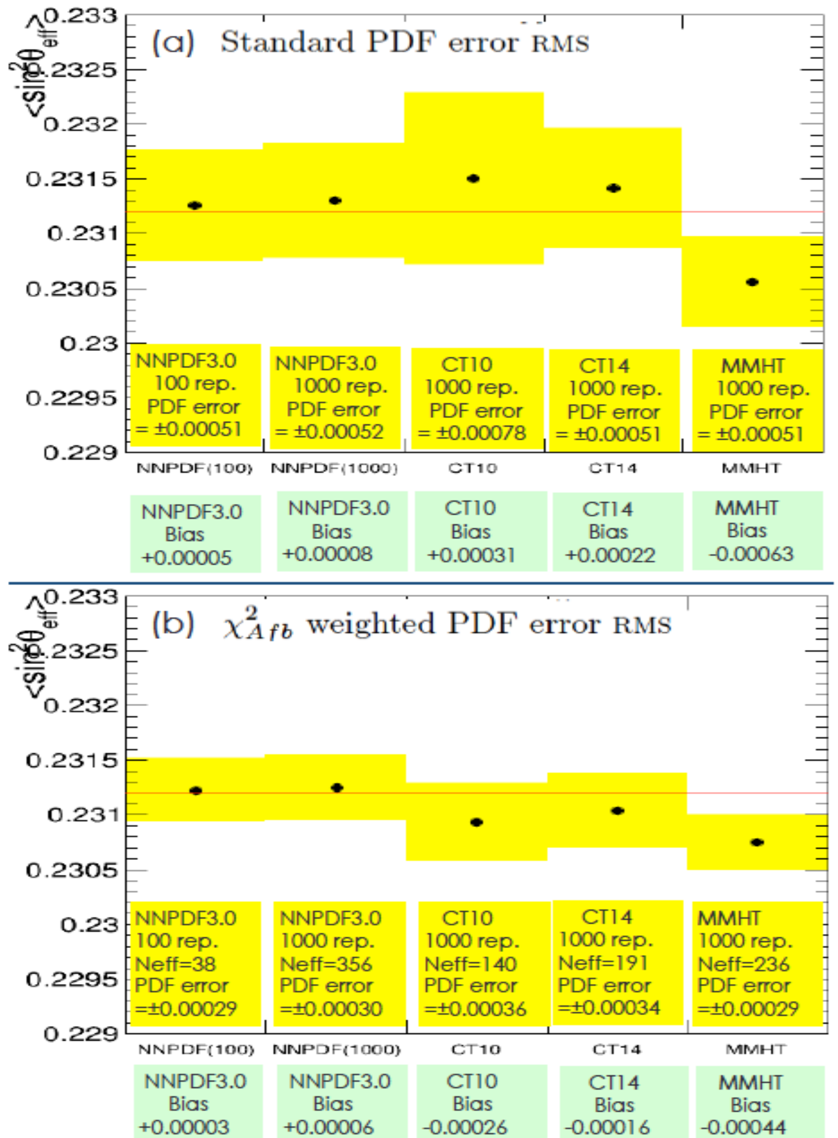


Fig. 10. The average of the results from the analyses of the 64 LHC pseudo experiments. Each pseudo experiment is analyzed

A. Bodek arXiv:1507.02470

CMS like detector	2016 sample	2017-18 sample
Energy	8 TeV	13-14 TeV
Number of reconstructed events	8.2M $\mu^+\mu^-$ 6.8M e^+e^-	120M $\mu^+\mu^-$ -
$\Delta \sin^2 \theta_W$		
Statistical error	$\pm$ 0.00034	$\pm$ 0.00011
Weighted PDF error	$\pm$ 0.00022	$\pm$ 0.00014
(Stat+PDF) error	$\pm$ 0.00040	$\pm$ 0.00018
$\Delta M_W^{indirect}$	MeV	MeV
Statistical error	$\pm$17	$\pm$5
weighted PDF error	$\pm$11	$\pm$7
(Stat+PDF) error	$\pm$20	$\pm$9