Measurements of the Electroweak Mixing Angle at High Energy Colliders Past, Present and Future

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Searching for Physics Beyond the Standard Models Using Charged Leptons

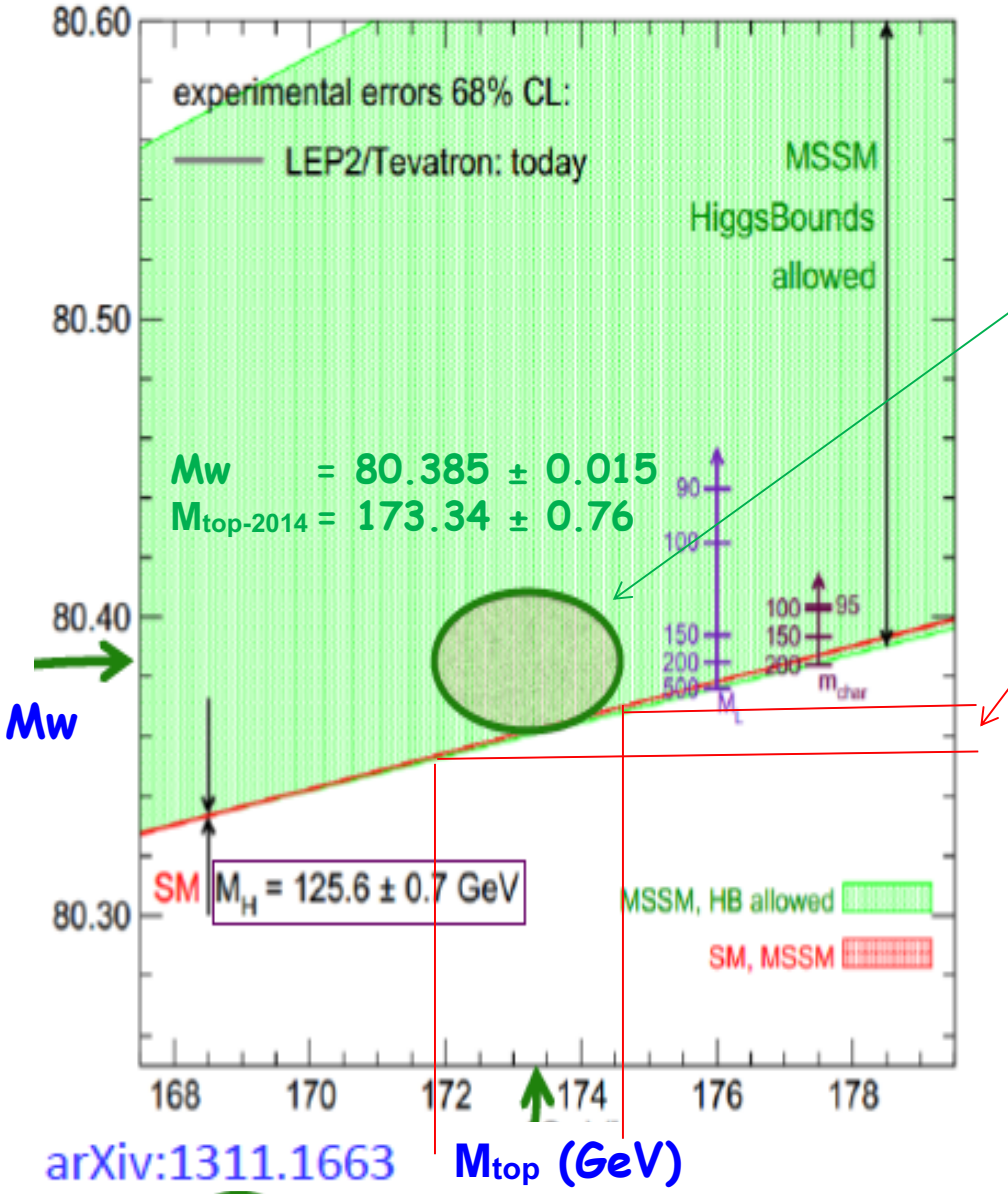
https://indico.cern.ch/event/660214/

21 May 2018, 09:00 → 26 May 2018, 17:00 America/Puerto_Rico

45 minutes talk and 15 minutes discussion 10:00 → 11:00 WEDNESDAY, 23 MAY

Testing the Standard Model

With a known Higgs mass, the SM is over-constrained. A better Measurement of M_W provi des more constraints on SM than a better measurement of M_{top}.



Average of TeV/ LEP direct measurement of **M_W is 1 sigma (15 Mev) higher than SM prediction.**

For a 0.7 GeV error in the measured value of M_T the error in the SM predicted value of M_W is 5 MeV

Alternatively:

Since M_H is known, if one includes radiative corrections, M_W can also be determined via

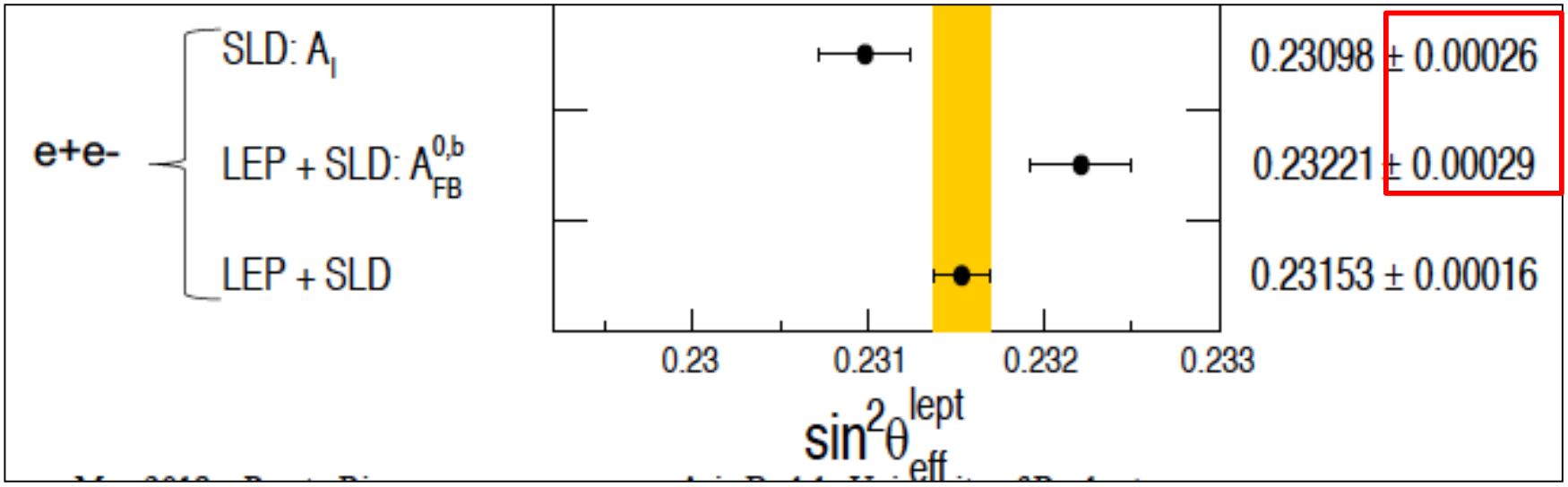
$$\sin^2\theta_W^{\text{on-shell}} = 1 - M_w^2 / M_z^2$$

Both $\sin^2\theta_W^{\text{on-shell}}$ and of $\sin^2\theta_W^{\text{eff}}$ can be extracted from the Drell-Yan forward-backward asymmetry (Afb) if one includes EW radiative corrections in the analysis. How well can we do?

An error of ± 0.00030 in $\sin^2\theta_w$ is equivalent to an indirect measurement of M_w to a precision of ± 15 MeV (which is the current uncertainty in the world average of direct measurements of M_w

This level of precision or better is needed to probe for physics beyond the Standard Model

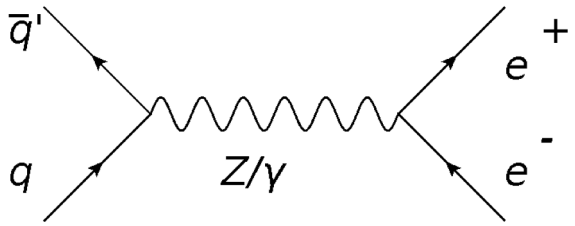
However, At this level of precision, the two most precise measurements from e+e- colliders differ by 3 standard deviations. Can Hadron colliders match this precision?



OUTLINE

- CMS RESULTS
- ATLAS RESULTS
- LHCB RESULTS
- D0 AND CDF TEVATRON
- TEVATRON COMBIATION
- CONSTRAINING PDF ERRORS
- FUTURE PROSPECTS AT LHC

Dilepton production at Hadron Colliders



The axial and vector neutral currents interfere

Weak neutral current strength related to $\sin^2\theta_{eff}$

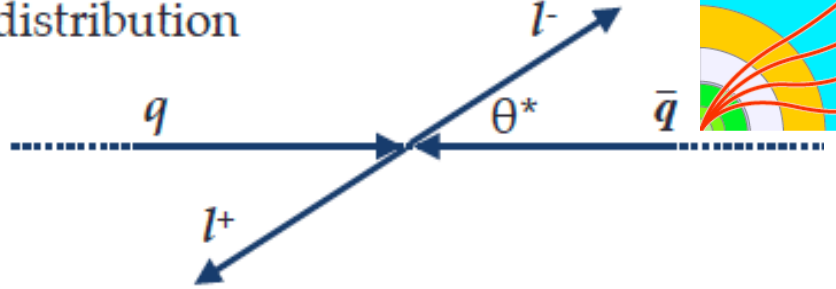
$\sin^2\theta_W = \sin^2\theta_W^{\text{on-shell}} = 1 - M_w^2 / M_z^2$

What is actually measured with dilepton events is the effective lepton EW mixing angle

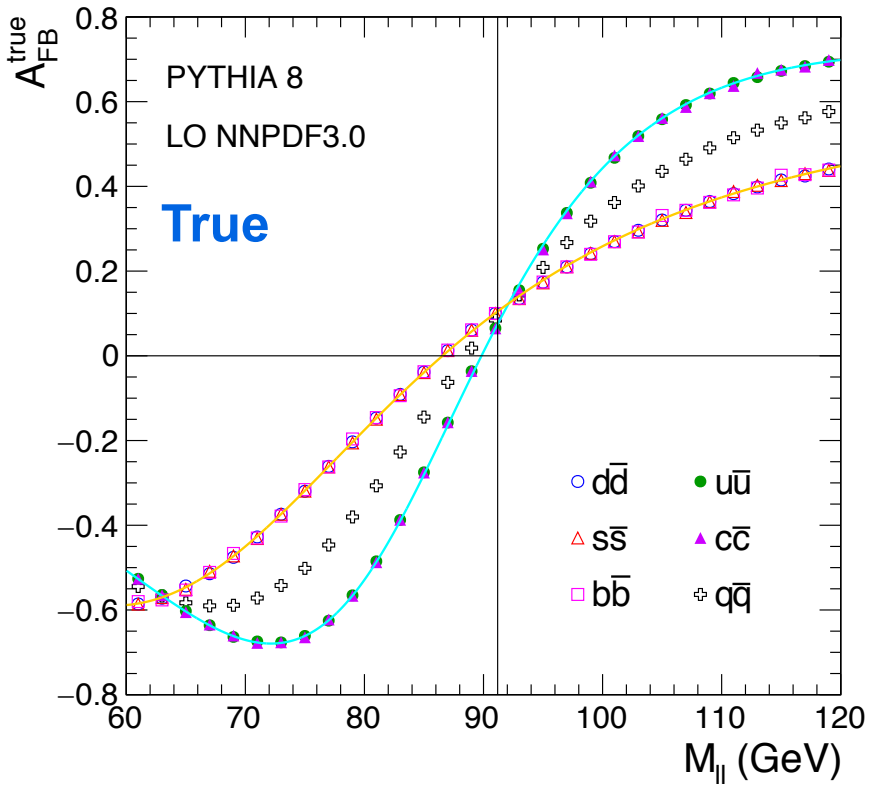
$$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$$

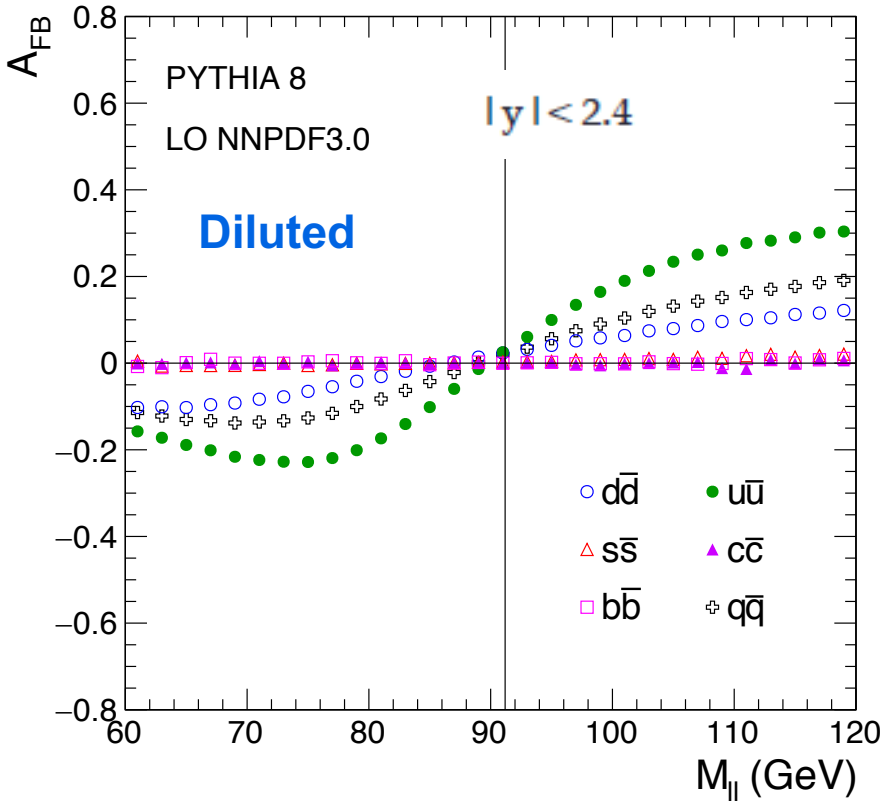
$$\hookrightarrow \approx 1.037$$

- Vector and axial couplings result in A_{FB} of $\cos\theta^*$ distribution
- A_{FB} near Z peak sensitive to leptonic $\sin^2\theta_{eff}$
- Mass dependence from Z/γ^* interference
- Observable A_{FB} in pp collisions based on ll boost
- A_{FB} dependence on PDFs:



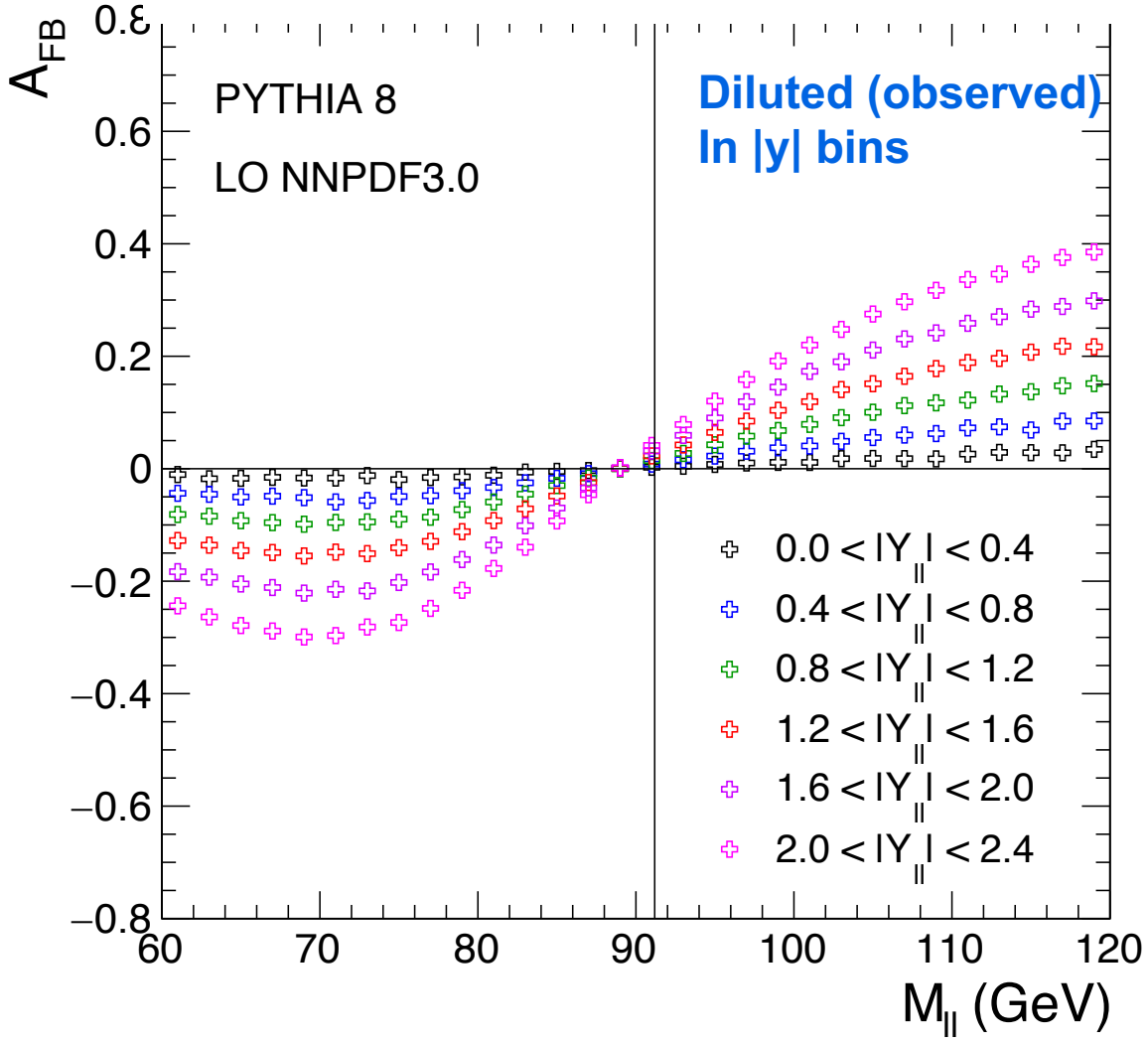
1. **Fraction of valence u vs. d**
2. **Dilution (y dependent) from high x antiquarks**





- 6 bins of $|y|$: 0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4
- 12 bins of m: 60, 70, 78, 84, 87, 89, 91, 93, 95, 98, 104, 112, 120

CMS



Dilution (y dependent). Therefore bin data in rapidity.

Extract $\sin^2\theta_{eff}$ by fitting the observed A_{FB} (as a function of M and |y|) to templates generated with different values of $\sin^2\theta_{eff}$.

Precision measurement at CMS and CDF using three new techniques:

1: Precise lepton momentum/energy scale (and modeling resolution)
Reduces contribution at to $\Delta\sin^2\theta_{eff}$ to ±0.00008

A. Bodek et al., "Extracting Muon Momentum Scale Corrections for Hadron Collider Experiments", *Eur. Phys. J.* **C72** (2012) 2194, doi:10.1140/epjc/s10052-012-2194-8, arXiv:1208.3710.

2: Angular Event weighting method for A_{FB} analyses:
systematic errors in acceptance & efficiency cancel: $\Delta\sin^2\theta_{eff}$ ±0.00008

A. Bodek, "A simple event weighting technique for optimizing the measurement of the forward-backward asymmetry of Drell-Yan dilepton pairs at hadron colliders", *Eur. Phys. J.* **C67** (2010) 321–334, doi:10.1140/epjc/s10052-010-1287-5, arXiv:0911.2850.

3: New PDF constraints using the same Drell Yan Data above and below the Z peak.

At CDF Reduced contribution of CDF error to $\Delta\sin^2\theta_{eff}$ from ±0.00023 to ±0.00017
At CMS: Reduced contribution of PDF error to $\Delta\sin^2\theta_{eff}$ from ±0.00054 to ±0.00030 at 8 TeV
(will be further reduced with more data in future)

A. Bodek, J. Han, A. Khukhunaishvili, and W. Sakumoto, "Using Drell-Yan forward-backward asymmetry to reduce PDF uncertainties in the measurement of electroweak parameters", *Eur. Phys. J.* **C76** (2016), no. 3, 115, doi:10.1140/epjc/s10052-016-3958-3, arXiv:1507.02470.

±0.00050 error in $\sin^2\theta w$ is equiv. to ±25 MeV error in Mw (indirect)

Precise Lepton Energy/Momentum calibration at CDF and CMS

CMS

Technique used for both $\mu^+\mu^-$ and e^+e^- for both data and MC.
Used in CDF and CMS for muons and electrons.

Step I : 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.

Step II: The Z mass used as a reference scale. The Z mass as a function of η, Φ, (and charge for $\mu^+\mu^-$) of each lepton be correct (done in bins of η, Φ).

•**Reference scale for muons:** Expected Z mass (post FSR) smeared by resolution (with acceptance cuts). (J/Ψ and ϒ are also used for tuning dE/dx).

•**Reference scale for electrons:** Expected Z mass post FSR with FSR photons clustered to form a dressed electron) **smeared** by resolution (with acceptance cuts).

In general: both data and MC are misaligned (or mis-calibrated for electrons). Corrections are extracted for both data and MC to agree with Z reference scale.

A. Bodek et al., "Extracting Muon Momentum Scale Corrections for Hadron Collider Experiments", *Eur. Phys. J.* C72 (2012) 2194,
doi:10.1140/epjc/s10052-012-2194-8, arXiv:1208.3710.

Mass distributions

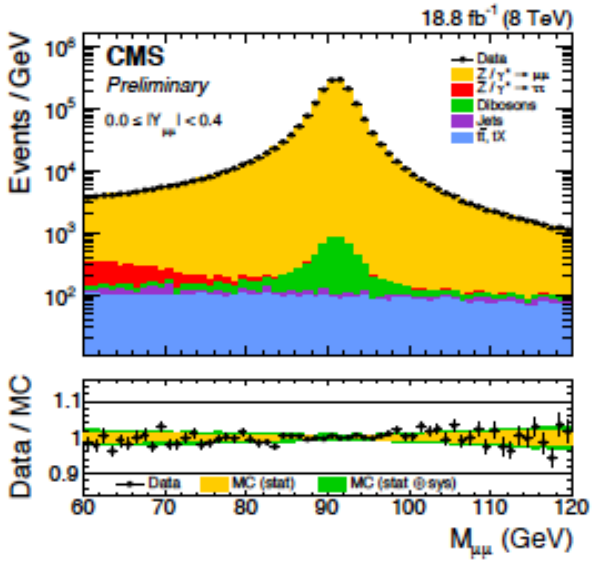
CMS

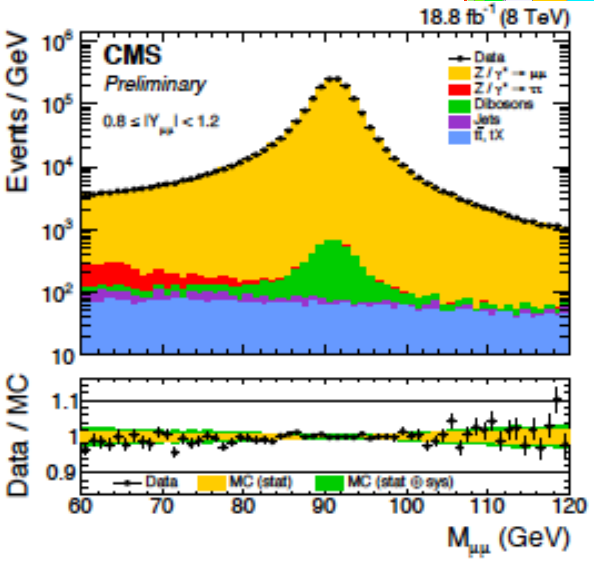
using Z-ll events to calibrate lepton momentum scale and resolution

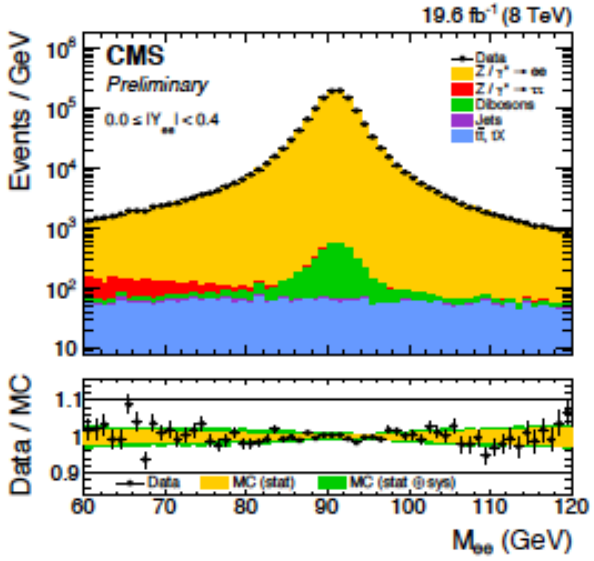
applied to data and simulation such that:

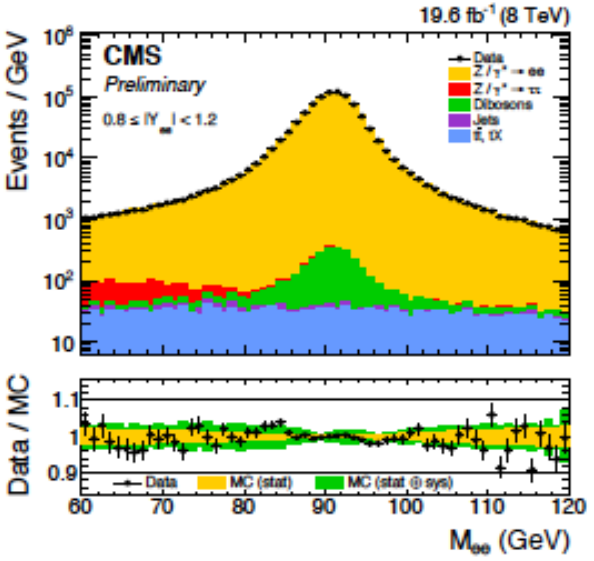
- scale matches true scale based on generated post-FSR (for muons) and dressed (for electrons electron) momenta

- resolution matches reconstruction resolution in data









Cosθ distributions

CMS

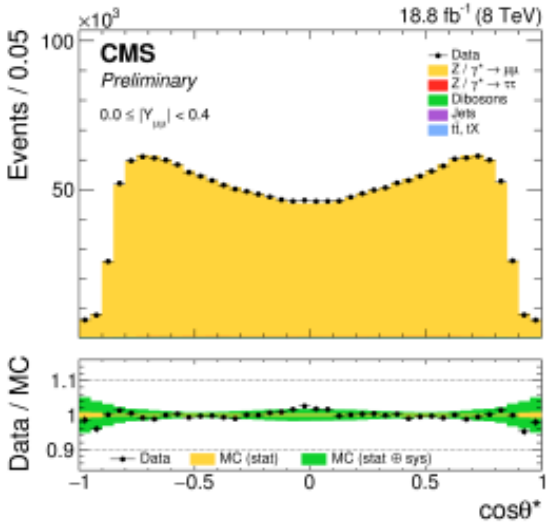
- Observable is weighted A_{FB}

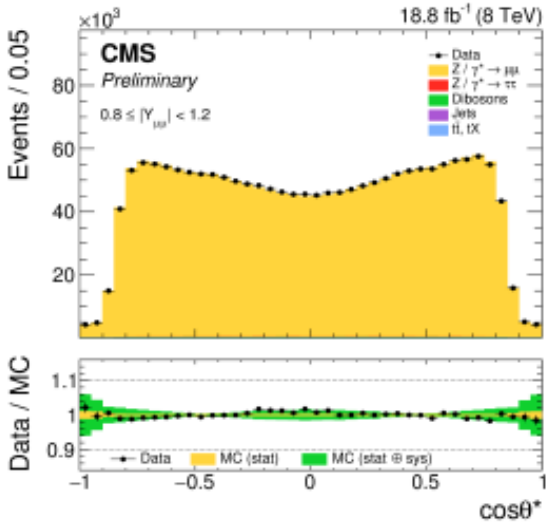
  A. Bodek, Euro. Phys. J. C67, 321(2010)

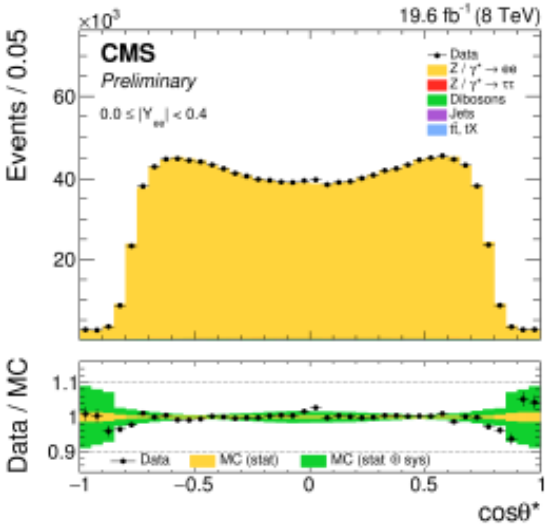
- Events weights based on cosθ* (0 at cosθ*=0)

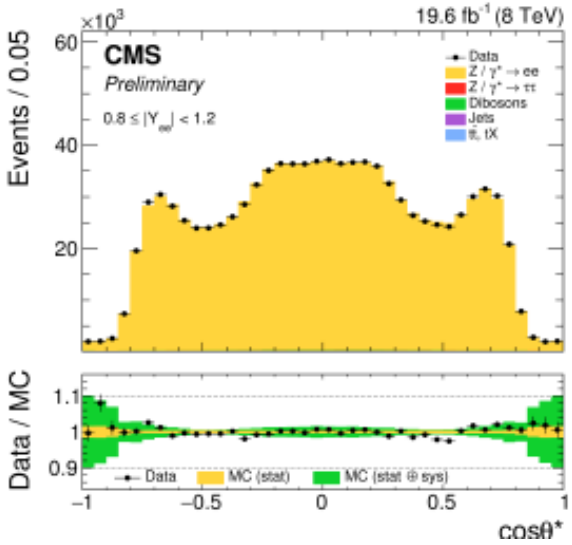
- $4\pi\ A_{FB}^{count} = 4\pi\ A_{FB}^{weight} = \text{fid}\ A_{FB}^{weight}$

- Less sensitive to acceptance
- Smaller statistical uncertainty









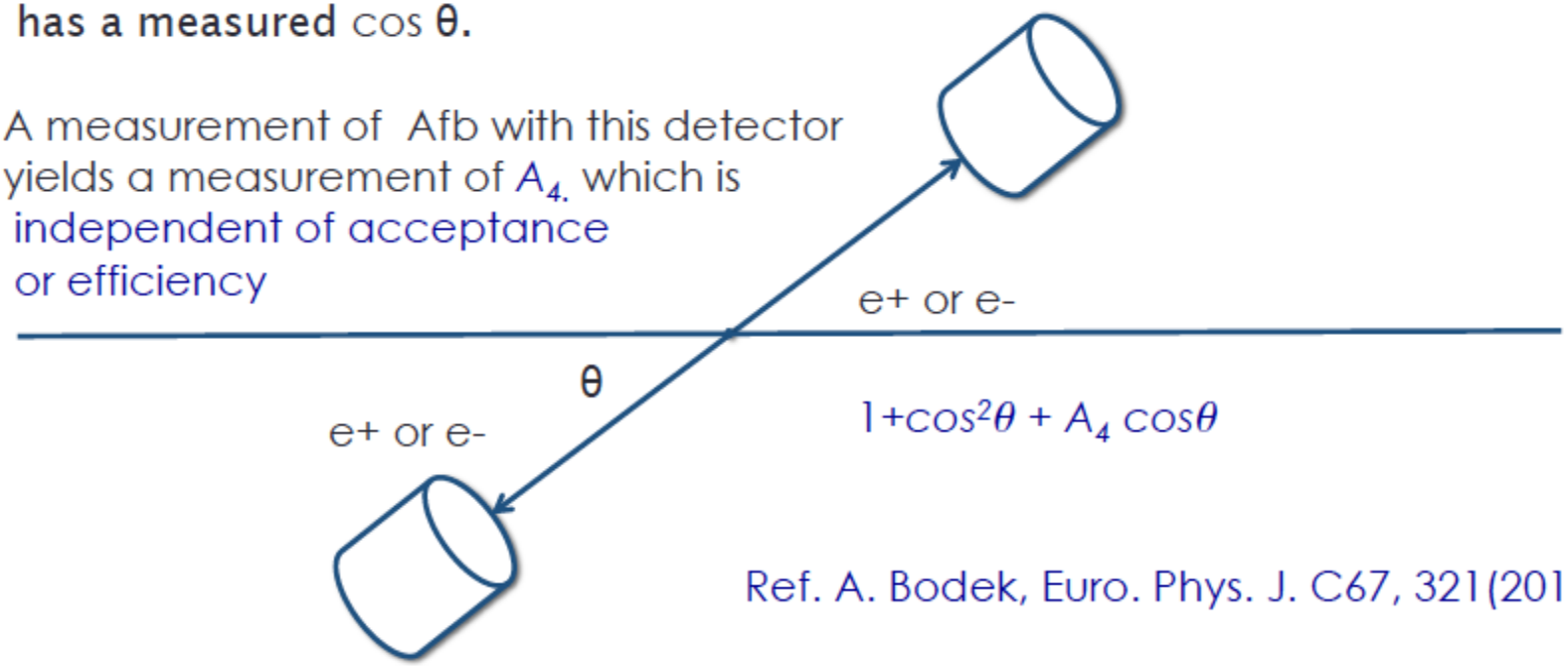
- At large cosθ acceptance sensitive to p_T modeling
- MiNLO has better A_0 modeling and improves description at central cosθ*
- Both have negligible effect on measurement

Details: Angular event weighting method (used in CMS and CDF)

Uncertainties in acceptance & efficiency cancel. Event weighted A_{FB} is the same as A_{FB} for full acceptance (but smeared by experimental resolution).

Imagine a detector with acceptance for only one value of cos θ. **Each event has a measured** cos θ.

A measurement of Afb with this detector yields a measurement of A_4, which is independent of acceptance or efficiency



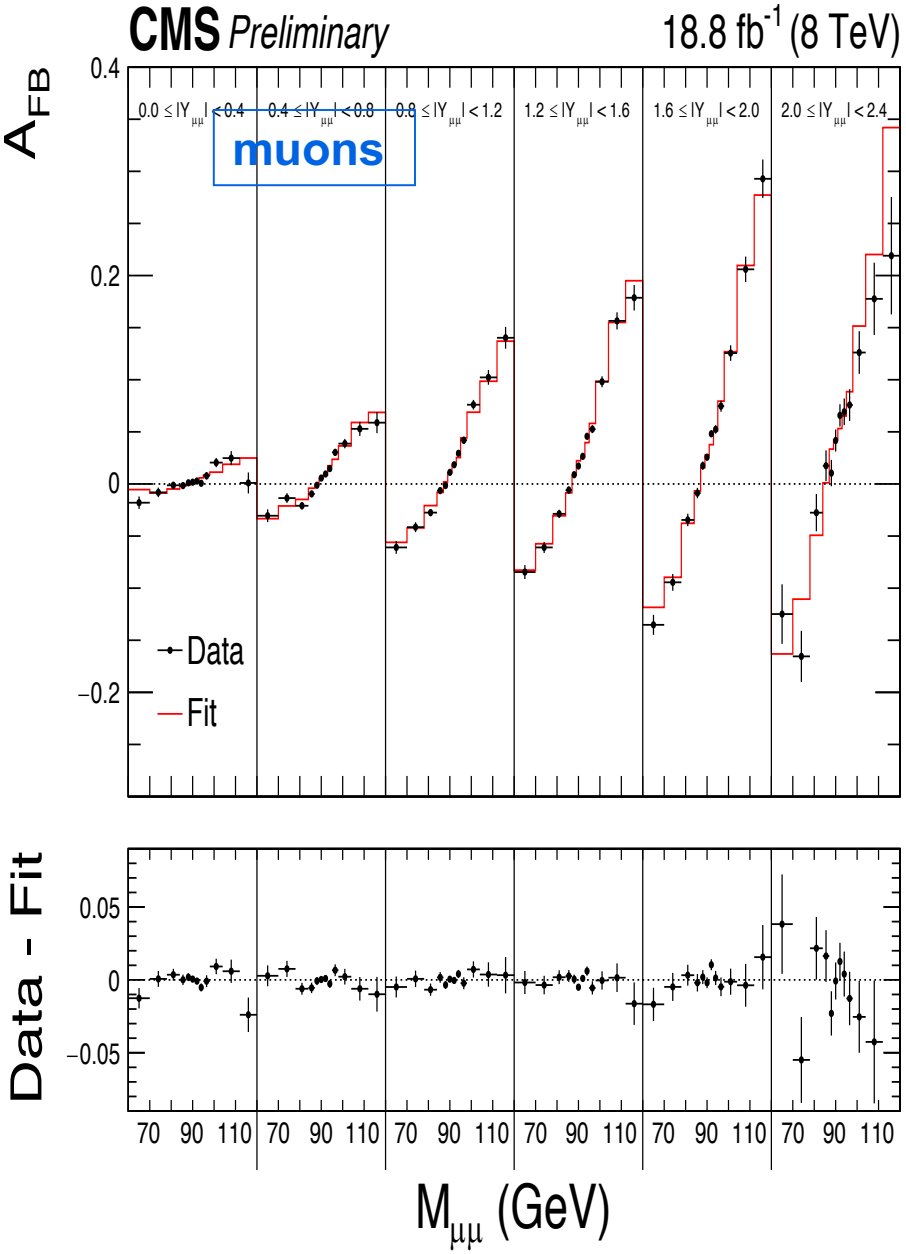
Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

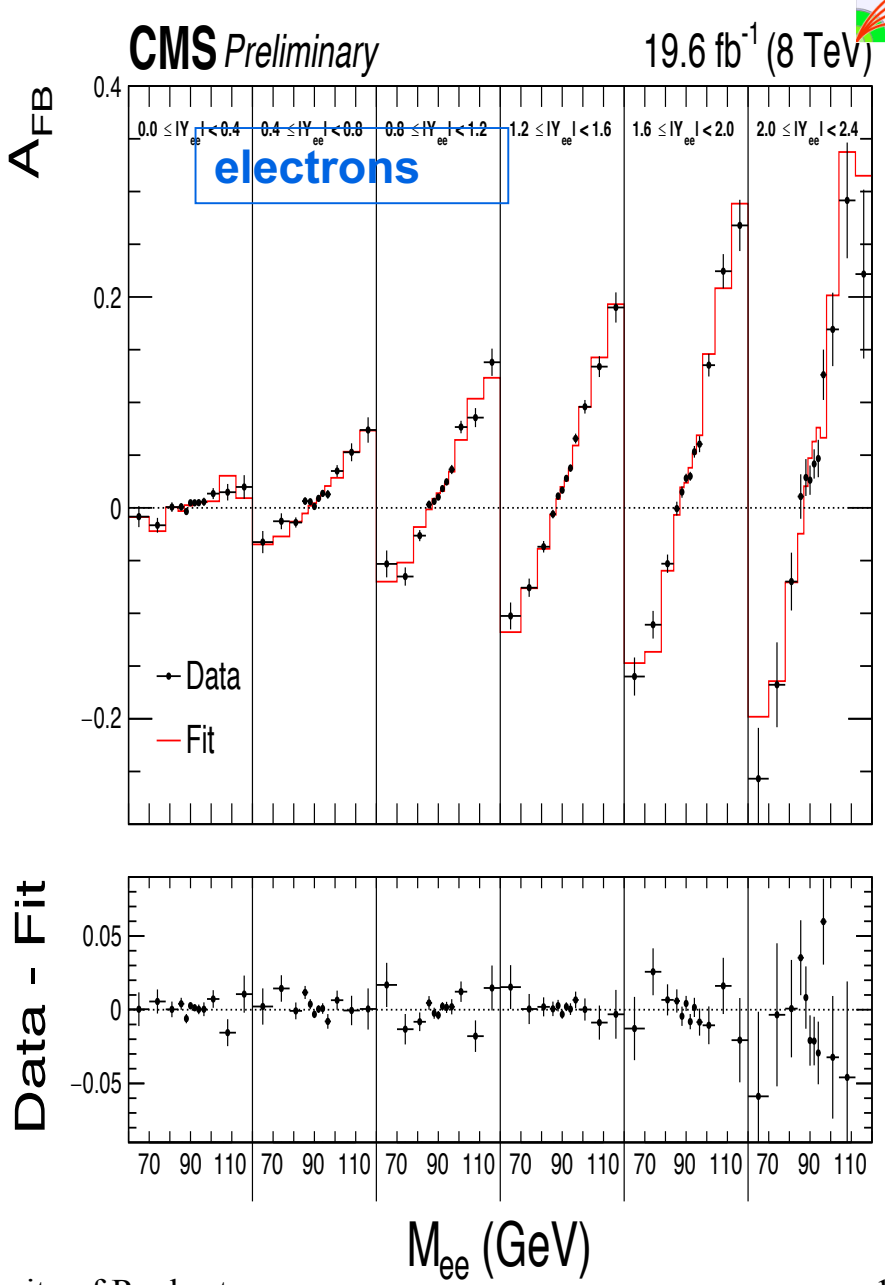
cos θ=1 **yields best** measurement of A_4. cos θ=0 **yields no measurement of** A_4

We can combine measurements of A_4 with different detectors at different values of by weighting events. Events with cos θ=0 **have zero weight.**
Events with cos θ=1 **have maximum weight. → obtain smaller statistical error.**
Afb (all cos θ) = (3/8) A_4 → **No acceptance corrections needed.**

- Weighted AFB in 6 dimuon rapidity x 12 mass measurement bins

CMS





channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

CMS

Combined **± 0.00036 (stat)**
8 TeV 19 fb-1

Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

Combined **± 0.00018 (syst)**
Dominated by MC statistics
Can be reduced with fast MC

model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} - \sin^2\theta_{\mathrm{eff}}^{\mathrm{u,d}}$)	0.00001	0.00001
Total	0.00015	0.00017

Combined **± 0.00016 (theory)**

Dominated by higher order QCD
Can be reduced in the future.

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory})$$

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory})$$

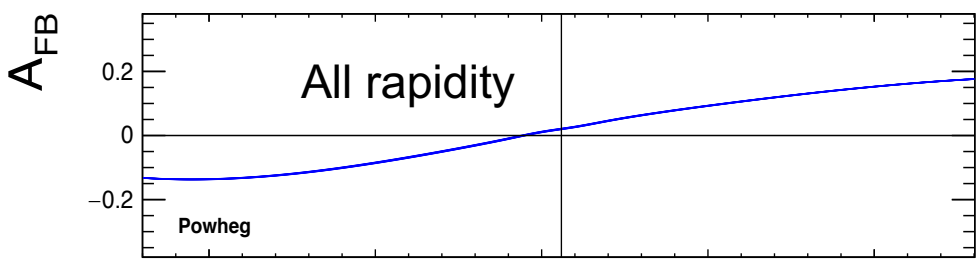
Channel	without constraining PDF
Muon	$0.23125 \pm 0.00048 \pm 0.00054$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$

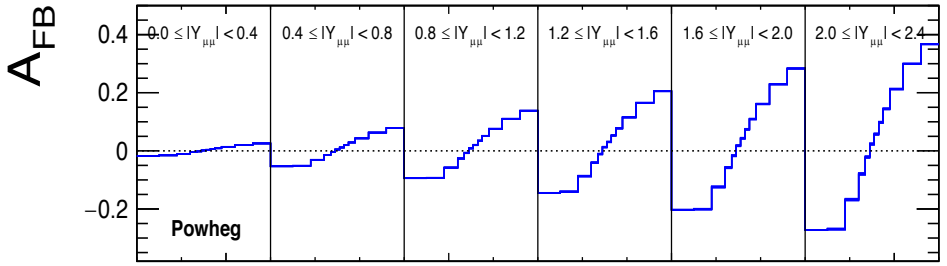
What about PDF error

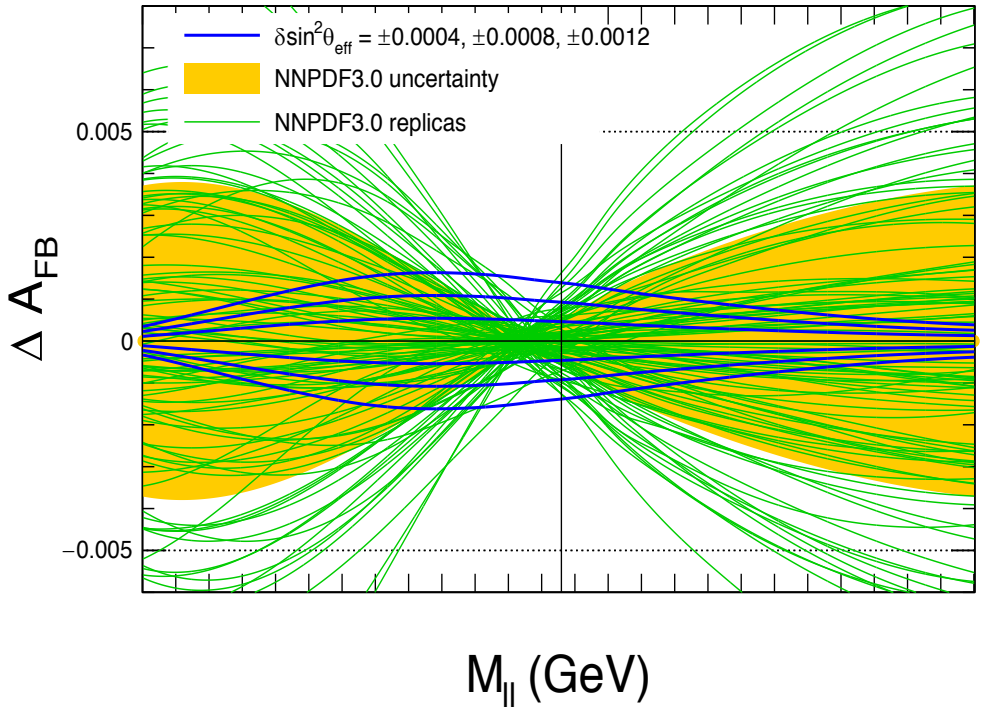
- Observed A_{FB} is very sensitive to PDFs
- Large in low and high masses, small near the peak (+ specific dependence on Y)

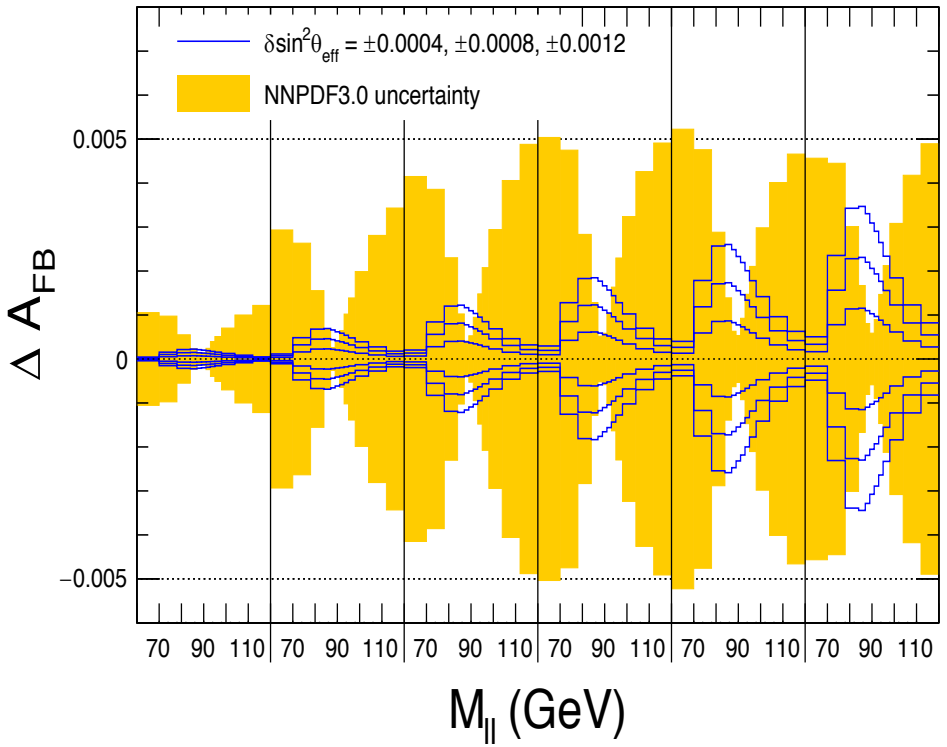
BLUE : Vary **$\sin^2\theta_{eff}$** for fixed PDF

ORANGE: Vary 100 NNPDF3.0 replicas for fixed **$\sin^2\theta_{eff}$** i









New Technique used by CMS and CDF

CMS

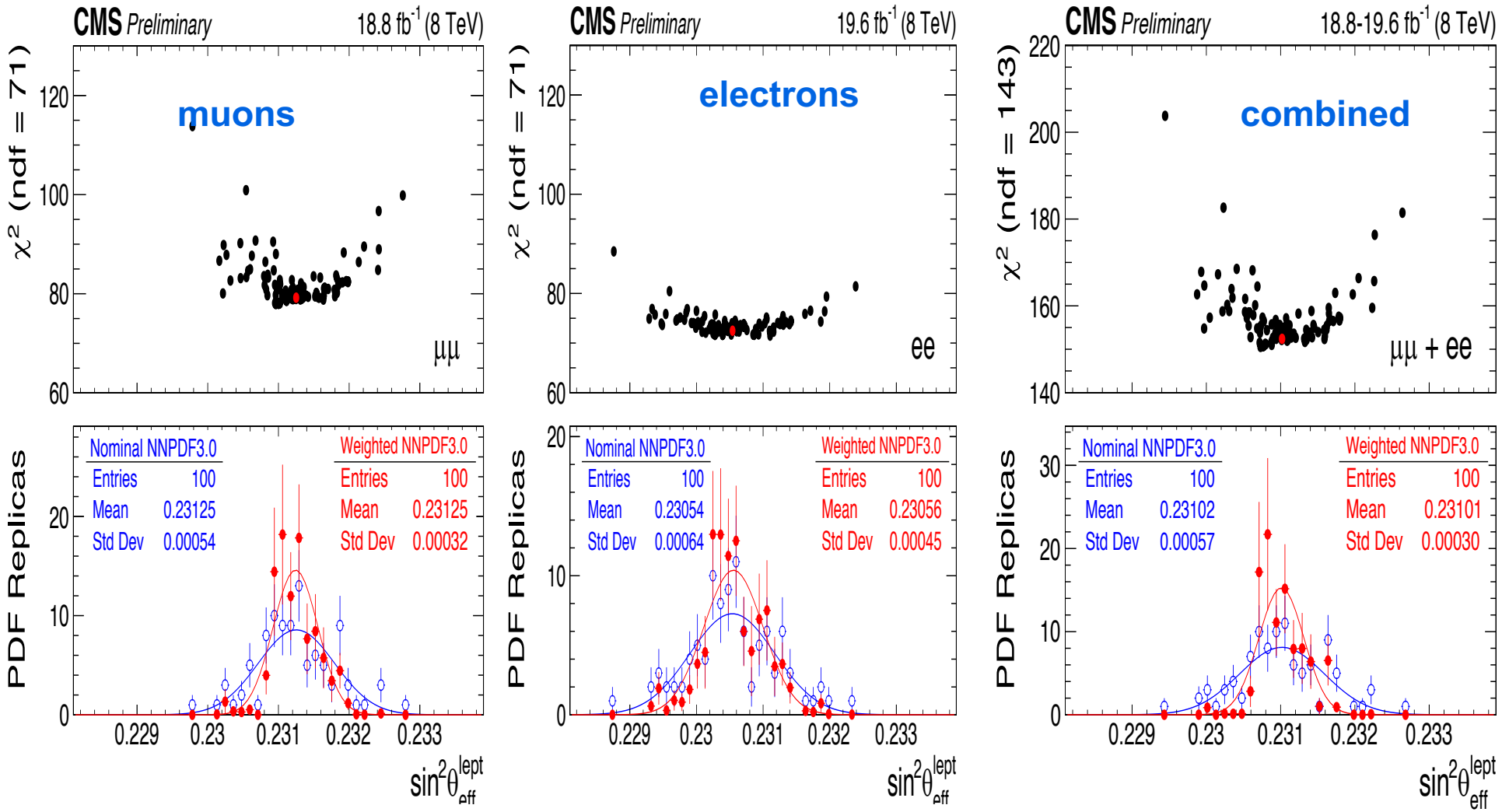
A. Bodek, J. Han, A. Khukhunaishvili, and W. Sakumoto, "Using Drell-Yan forward-backward asymmetry to reduce PDF uncertainties in the measurement of electroweak parameters", *Eur. Phys. J.* **C76** (2016), no. 3, 115, doi:10.1140/epjc/s10052-016-3958-3, arXiv:1507.02470.

- Perform $\sin^2\theta_{eff}$ fit for each PDF replica (by default we use NNPDF3.0)

- Weight each replica by

$$w_i = \frac{e^{-\frac{\chi^2}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2}{2}}}$$

Bayesian reweighting method: The weights are smaller for PDF replicas which give a bad Chi-square for the best fit **$\sin^2\theta_{eff}$**



Channel	without constraining PDF	with constraining PDFs
Muon	$0.23125 \pm 0.00048 \pm 0.00054$	$0.23125 \pm 0.00048 \pm 0.00032$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$	$0.23056 \pm 0.00069 \pm 0.00054$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

- Measured $\sin^2\theta_{eff}$ 8 TeV μμ and ee
- Statistical uncertainty dominates
- Followed by PDF (reduced with reweighting by ~50%)
- Experimental uncertainties small
  - MC statistics (dominates)
  - lepton calibration
  - lepton selection efficiencies
  - background estimate
  - pileup
- Modeling errors dominated by QCD

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00052.$$

(26 MeV error in Mw indirect)

PDF errors can be reduced with larger statistical samples !!!

Tests with other PDFs: If the PDF replicas truly describe the uncertainty in the PDF set, then the analysis should be independent of which PDF set is used.

Conversion of Hessian PDFs to Replica PDFs

We have also studied the PDFs represented by Hessian eigenvectors: CT10 [21], CT14 [50], and MMHT2014 [51]. This analysis is performed in the dimuon channel. First, we generate the replica predictions (i) for each observable O from the Hessian eigensets (k):

$$O_i = O_0 + \frac{1}{2}\sum_{k=0}^{n}(O_{2k+1} - O_{2k+2})R_{ik}, \tag{15}$$

where n is the number of PDF eigenvector axes, and the R_{ik} are random numbers sampled from the normal distribution with a mean of 0 and a standard deviation of unity. Then, the same technique is applied as in the case of the NNPDF set. The results of fits using different PDF sets are summarized in Fig. 8. After Bayesian χ^2 reweighting the central predictions for all PDFs are closer to each other, and the corresponding uncertainties are significantly reduced.

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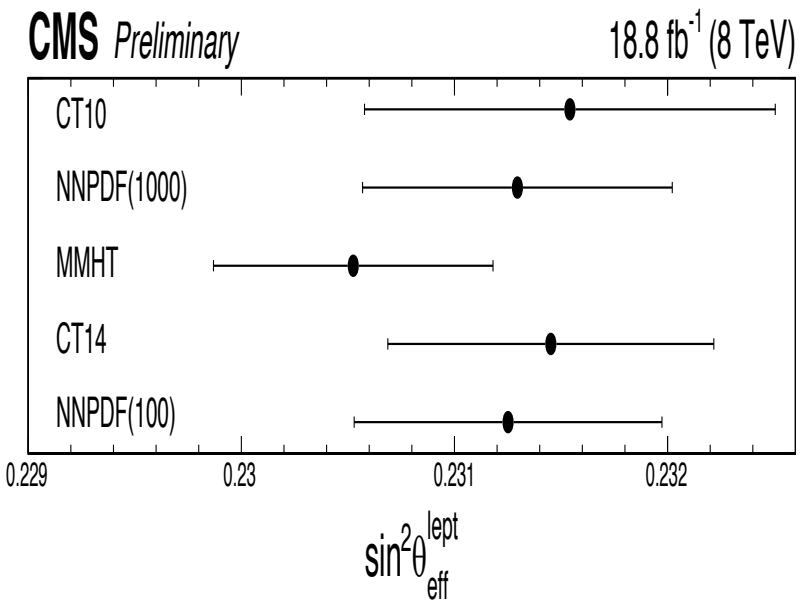
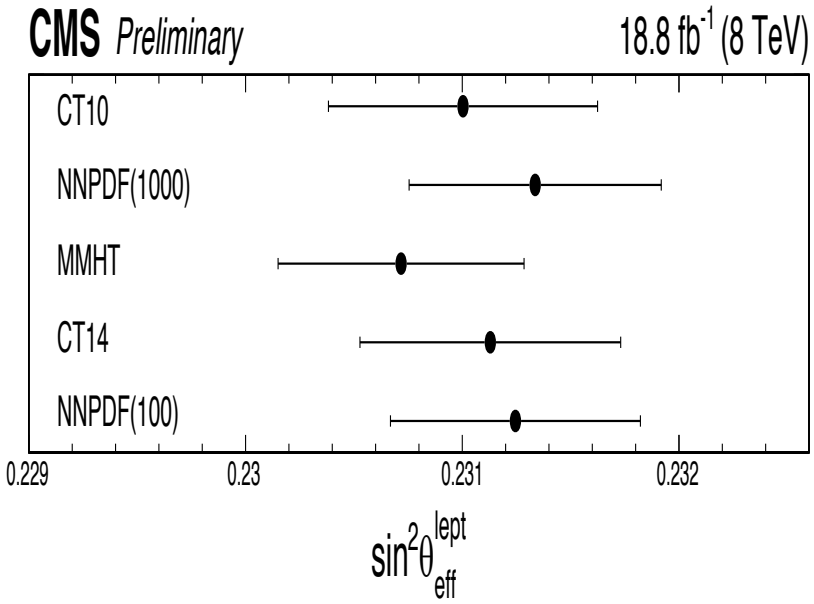
PDF nominal

PDF Weighted





Channel	without constraining PDF	with constraining PDFs
Muon	$0.23125 \pm 0.00048 \pm 0.00054$	$0.23125 \pm 0.00048 \pm 0.00032$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$	$0.23056 \pm 0.00069 \pm 0.00054$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

Two equivalent Methods of Constraining PDFs

As an additional check, for the Hessian PDFs we perform simultaneous fits by floating the pulls (ξ_k) along each of the PDF eigen-vector directions. The corresponding χ^2 that we minimize is defined as

$$\chi^2(s,\vec{\xi}) = (\boldsymbol{D} - \boldsymbol{T}(s,\vec{\xi}))^T \boldsymbol{V}^{-1} (\boldsymbol{D} - \boldsymbol{T}(s,\vec{\xi})) + \sum_{k=1}^{n} \xi_k^2, \tag{35}$$

where

$$\boldsymbol{T}(s,\vec{\xi}) = \boldsymbol{T_0}(s) + 0.5 \sum_{k=0}^{n} (\boldsymbol{T_{2k+1}}(s) - \boldsymbol{T_{2k+2}}(s)) \xi_k$$

for the hessian PDFs (CT10, CT14, MMHT), and

$$\boldsymbol{T}(s,\vec{\xi}) = \boldsymbol{T_0}(s) + \sum_{k=1}^{n} (\boldsymbol{T_k}(s) - \boldsymbol{T_0}(s)) \xi_k$$

for the sym-Hessian NNPDF. Smooth dependence of $A_{\rm FB}$ on s is achieved by linear interpolation between the two neighboring templates of $\sin^2\theta^{\rm l}_{\rm eff}$.

Results from all the Hessian and Replica PDFs considered, with their corresponding uncertainties obtained with the constrained fits and Bayesian reweighting, respectively, are summarized in Table 8. As one can see, for all the native Hessian PDFs, the two approaches give the same result. Additionally, the test validates that the sym-hessian NNPDFs and 1000-replica NNPDFs are equivalent (they are used as provided by the authors, in constrast to replica CT10, CT14, and MMHT predictions, which are generated on-the-fly in this analysis).

DRAFT

Same results are obtained from the two equivalent Methods.

The technique can also be used for Hessian PDFs.

Table 8: Extracted $\sin^2\theta^{l}_{eff}$ for different PDF sets and corresponding uncertainties obtained with and without PDF constraints. The central value of $\sin^2\theta^{l}_{eff}$ is blinded by shifting all templates by X. The CT10, CT14 and MMHT replicas are generated "on-the-fly", as described in the text. The PDFs represented with MC replicas are constrained with the Bayesian reweighting procedure. The Hessian PDF uncertainties are constrained by simultaneous fit minimizing χ^2 of Eq. 35 with floating $\sin^2\theta^{l}_{eff}$ and $\vec{\xi}$.

	without constraining PDFs		after Bayesian reweighting		
PDF replicas	$(\sin^2\theta^{l}_{eff}+X)\pm\delta_{stat}\pm\delta_{pdf}$	n_{tot}	$(\sin^2\theta^{l}_{eff}+X)\pm\delta_{total}$	$\pm\delta_{stat}\pm\delta_{pdf}$	n_{eff}
CT10	$0.13554\pm0.00049\pm0.00084$	1000	0.13499 ± 0.00062	$\pm0.00049\pm0.00039$	307
CT14	$0.13545\pm0.00049\pm0.00059$	1000	0.13510 ± 0.00060	$\pm0.00049\pm0.00036$	375
MMHT	$0.13452\pm0.00049\pm0.00044$	1000	0.13470 ± 0.00057	$\pm0.00049\pm0.00030$	578
NNPDF(1000)	$0.13528\pm0.00049\pm0.00055$	1000	0.13529 ± 0.00058	$\pm0.00049\pm0.00033$	596
NNPDF(100)	$0.13523\pm0.00049\pm0.00054$	100	0.13521 ± 0.00057	$\pm0.00049\pm0.00031$	56
Hessian PDFs	without constraining PDFs		from simultaneous fit		
CT10	$0.13554\pm0.00049\pm0.00084$		0.13494 ± 0.00060		
CT14	$0.13545\pm0.00049\pm0.00060$		0.13508 ± 0.00059		
MMHT	$0.13452\pm0.00049\pm0.00044$		0.13471 ± 0.00057		
NNPDF	$0.13529\pm0.00049\pm0.00056$		0.13528 ± 0.00059		

Summary of CMS results

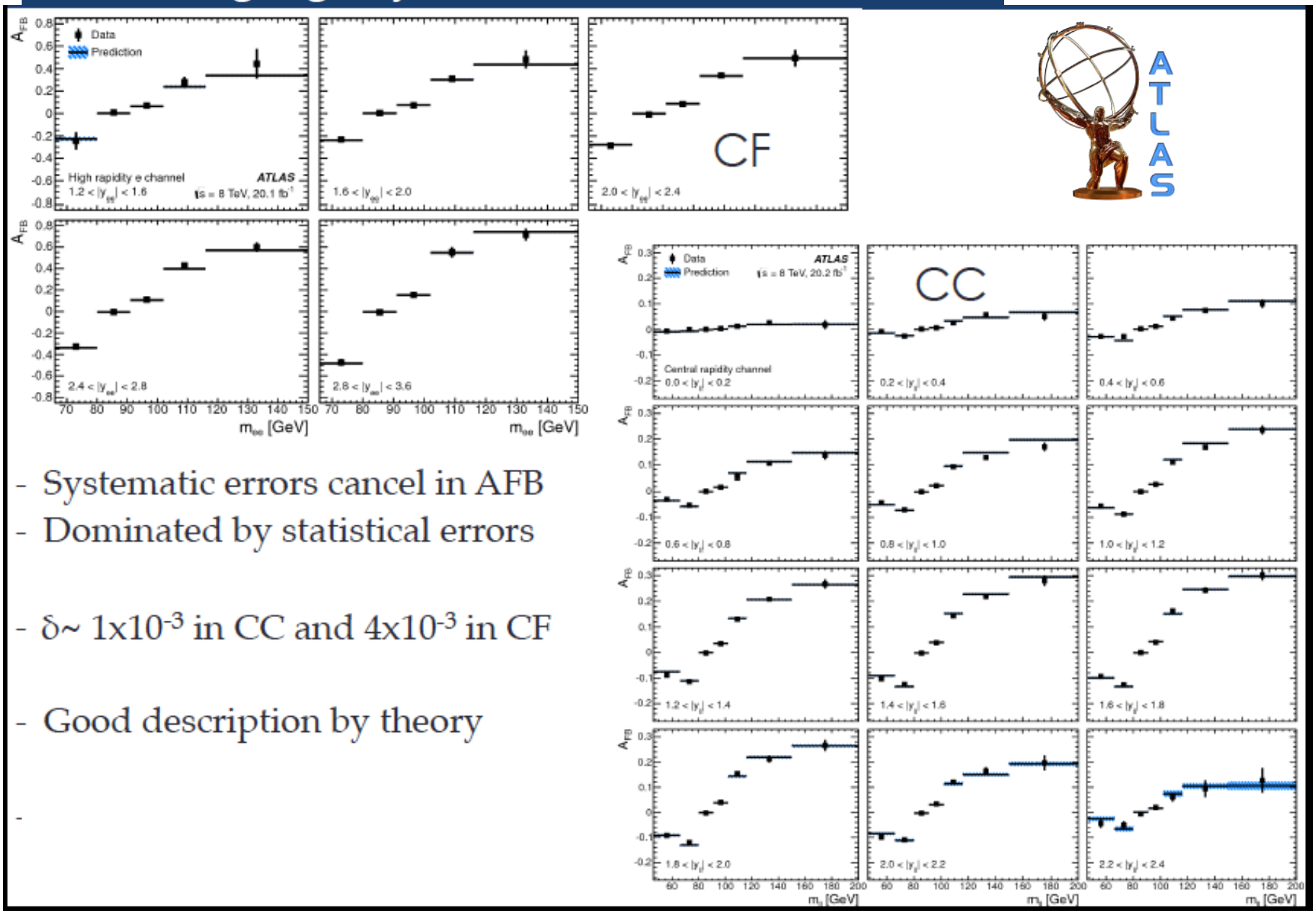
$$\sin^2\theta^{lept}_{eff} = 0.23101 \pm 0.00052$$

With larger statistical samples and new analysis techniques (including **precise lepton scale calibration,** **angular event weighting,** and **additional PDF constraints**) the errors in the EW mixing angle are significantly reduced:

Lesson: or precision measurements at the LHC such as **the electroweak mixing angle and direct measurement of the mass of the W Boson,** there is great advantage in using the same data sample to further constrain the PDFs, and use PDF replicas with weights,

The weights can come just from Afb data or one can also add additional data (e.g W asymmetry) to reduce PDF errors in the direct measurement of the W mass.

Weak mixing angle by ATLAS at 7 TeV PRD 84 (2011) 112002



- Systematic errors cancel in AFB
- Dominated by statistical errors

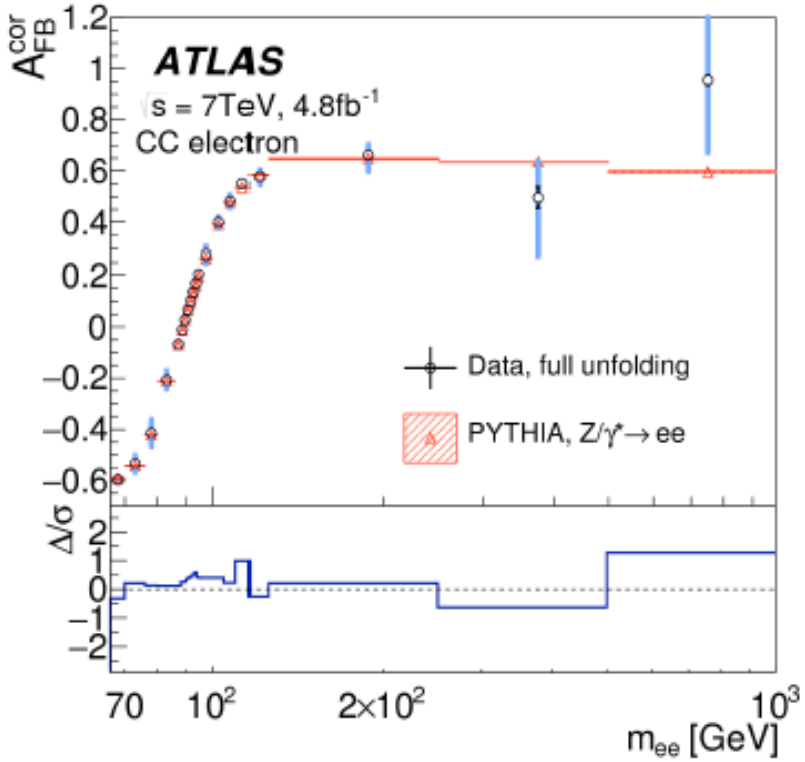
- $\delta \sim 1 \times 10^{-3}$ in CC and 4×10^{-3} in CF

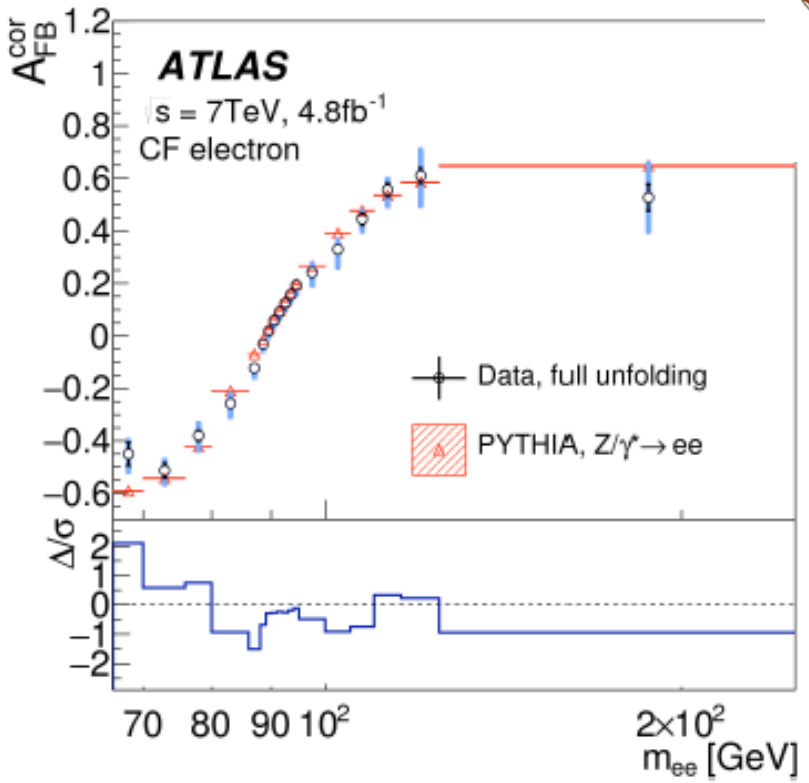
- Good description by theory

-

ATLAS sw2 extraction from 7 TeV (4.8/fb) measurement

8 TeV analysis in progress





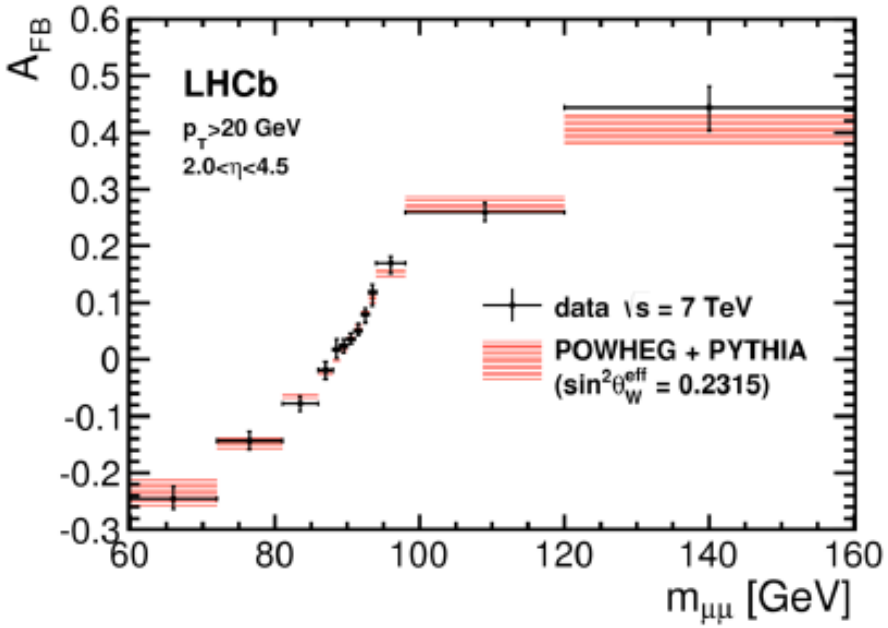
	$\sin^2\theta_{\rm eff}^{\rm lept}$		
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.})$	$\pm 0.0010(\text{PDF})$	$= 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.})$	$\pm 0.0010(\text{PDF})$	$= 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.})$	$\pm 0.0009(\text{PDF})$	$= 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.})$	$\pm 0.0010(\text{PDF})$	$= 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.})$	$\pm 0.0009(\text{PDF})$	$= 0.2308 \pm 0.0012$

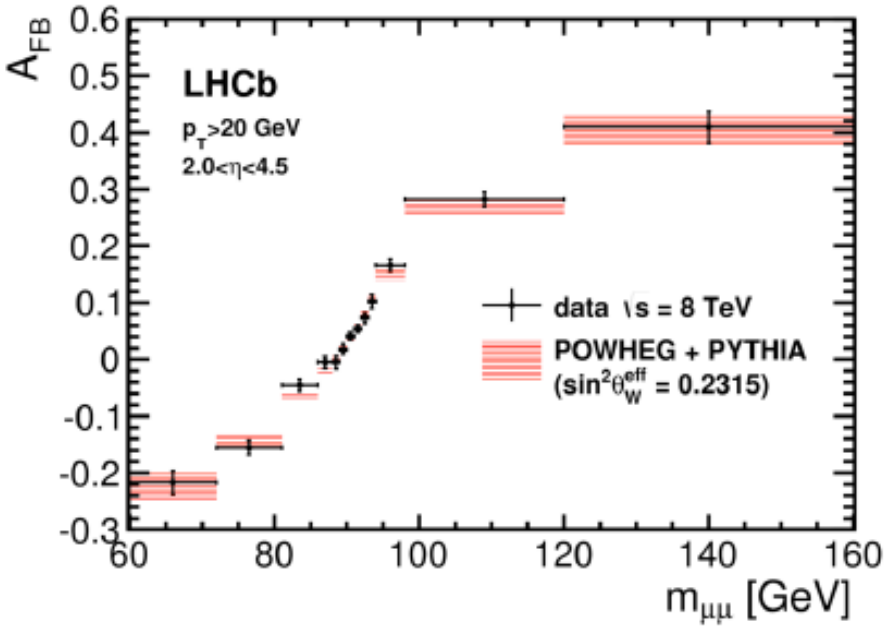
$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23080 \pm 0.00120$

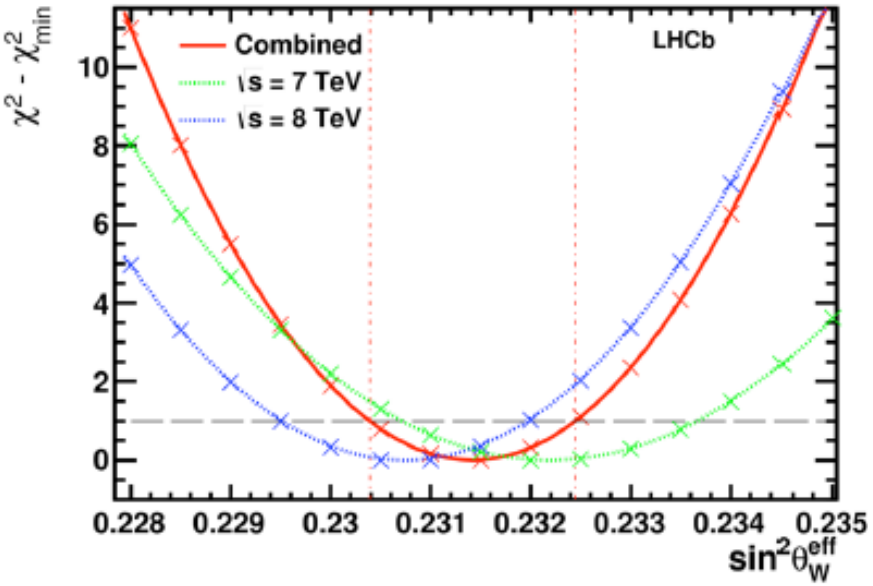
unconstrained PDF errors

Weak mixing angle by LHCb

JHEP 1511(2015) 190





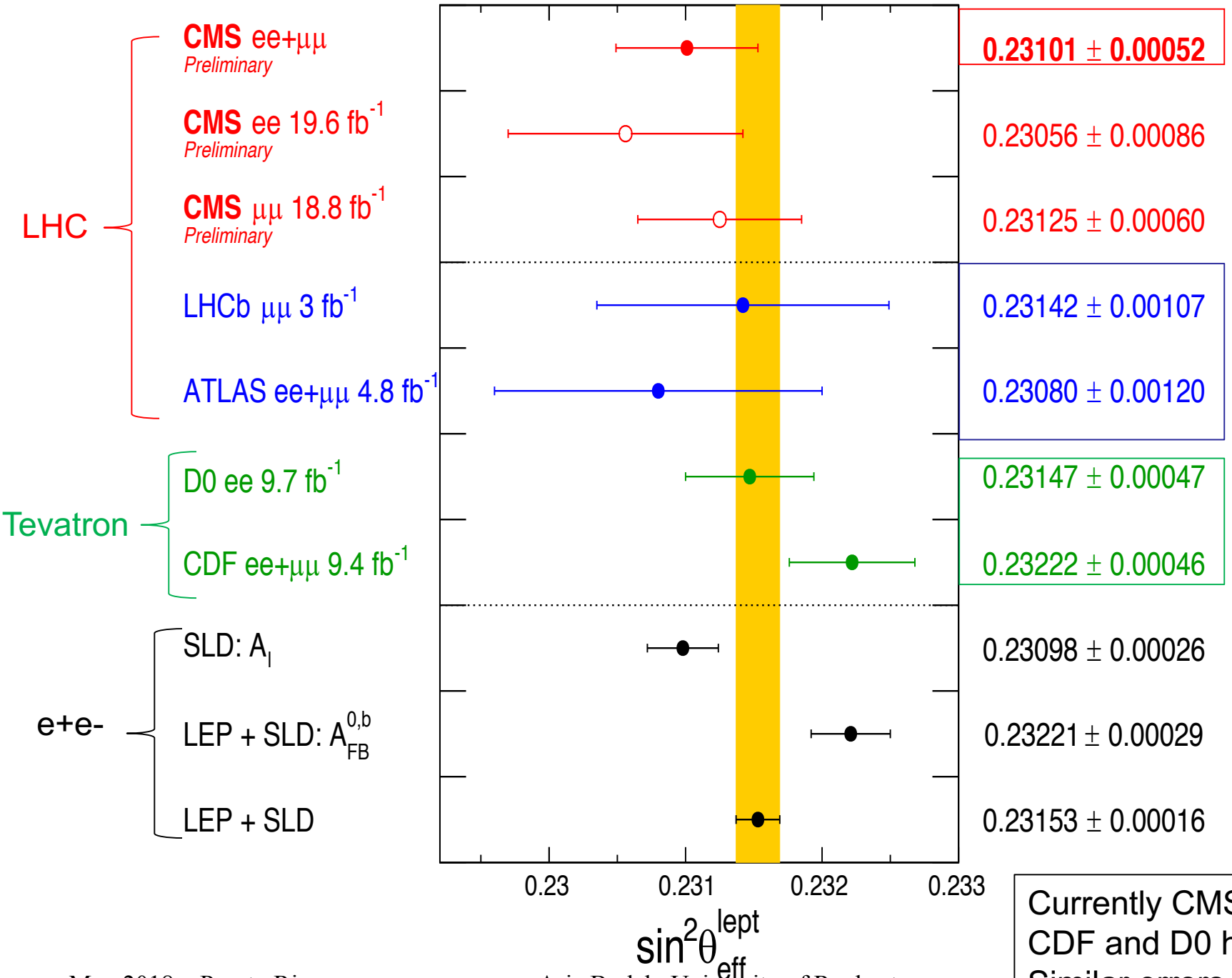


- Combined 7 and 8 TeV measurement
- Limited by statistical uncertainties

$$\sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$

0.23142 ± 0.00106 (stat) (syst) (th+pdf)

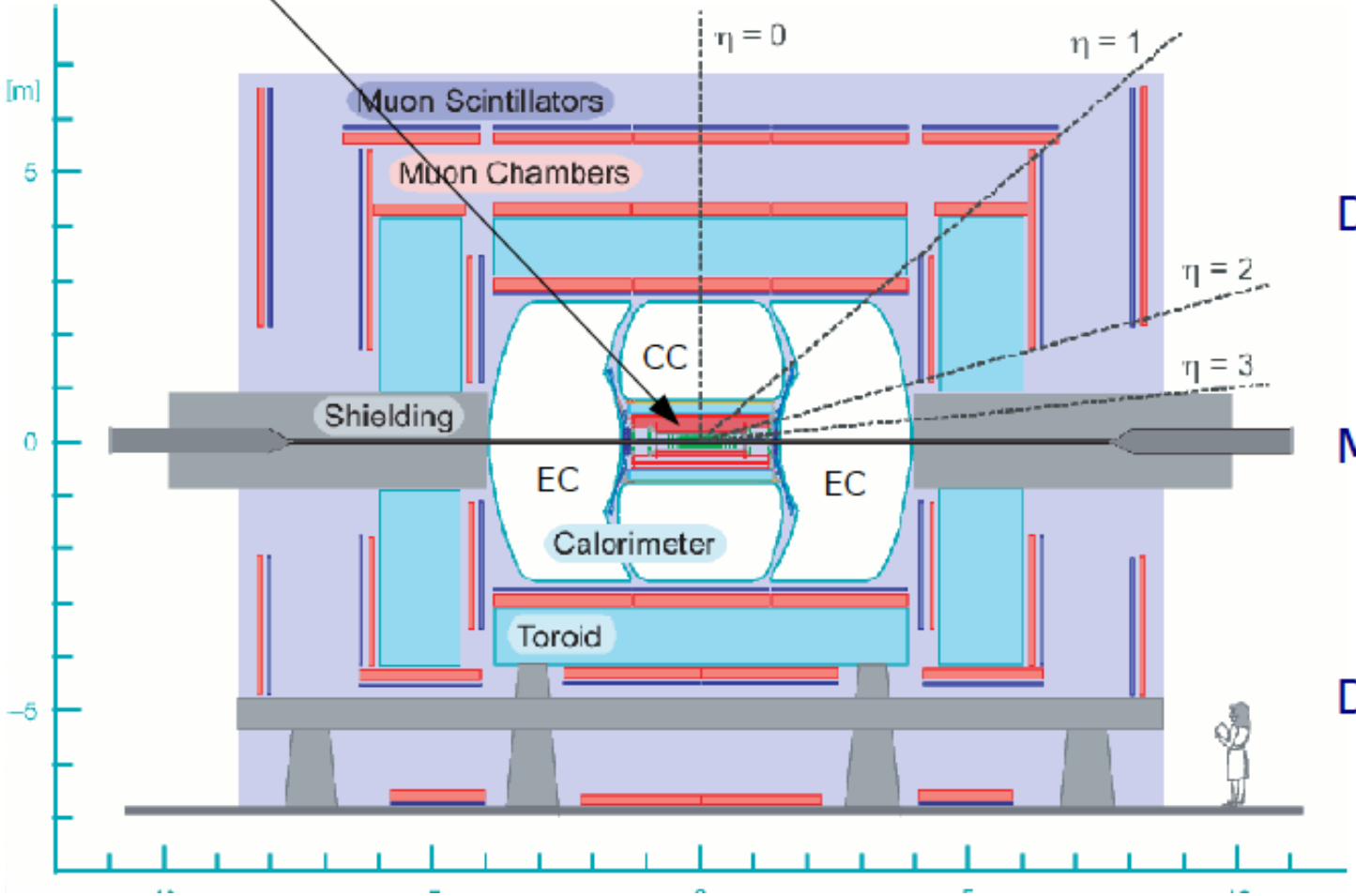
unconstrained PDF errors



Currently CMS, CDF and D0 have Similar errors.

D0 A_{fb} dataset selection

Precision tracking
Solenoid field 1.9 T
Fiber tracker |η| < 2
Silicon tracker |η| < 3



Electrons: CC + EC

P_T > 25 GeV/c
CC: |η| < 1.1
EC: 1.5 < |η| < 3.2

Dielectrons

CC-CC: 248K events
CC-EC: 241K events
EC-EC: 71K events

Muons

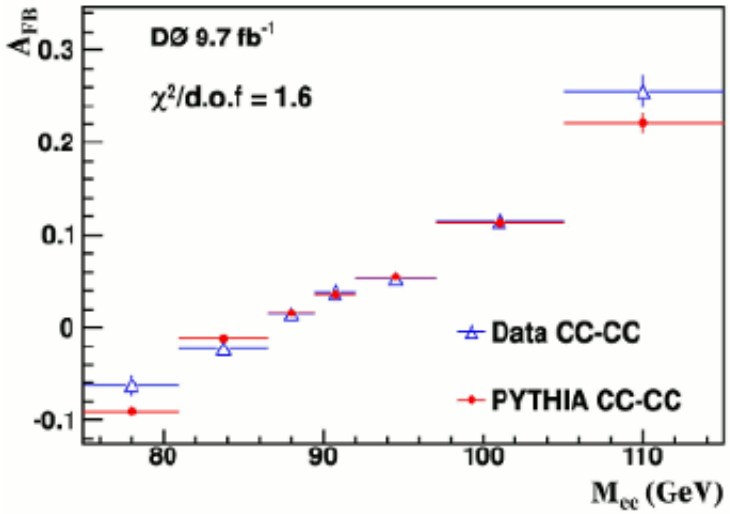
P_T > 15 GeV/c
Muon 1: |η| < 1.6
Muon 2: |η| < 1.8

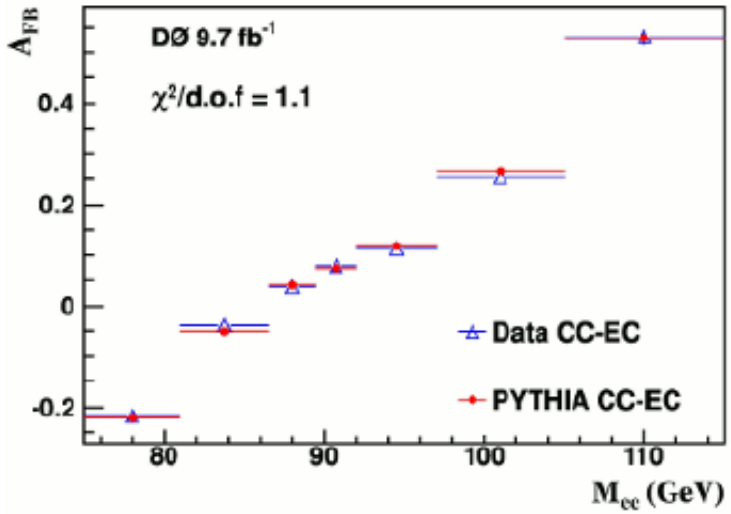
Dimuons

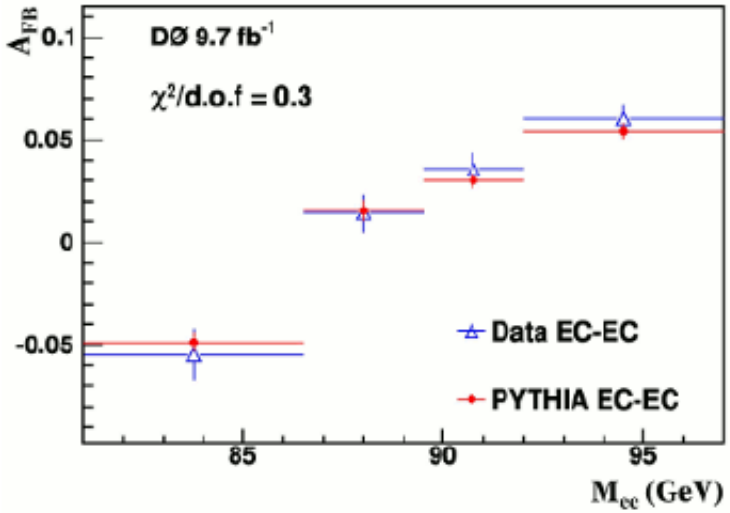
481K events

A_{fb} measurements: ee

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







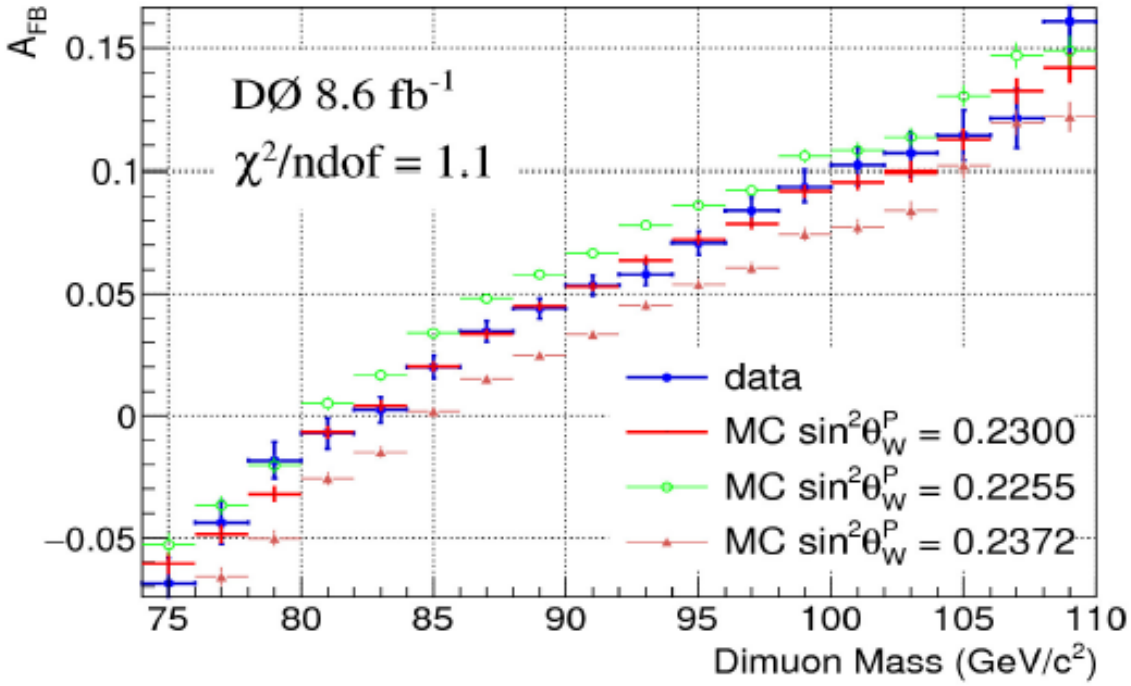
Inputs:

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

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

Tevatron Results

A_{fb} measurement: μμ



Inputs: D0 conference note 6499 (2017)

- 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 2.3(ee) 3.0(μμ) 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

To be discussed

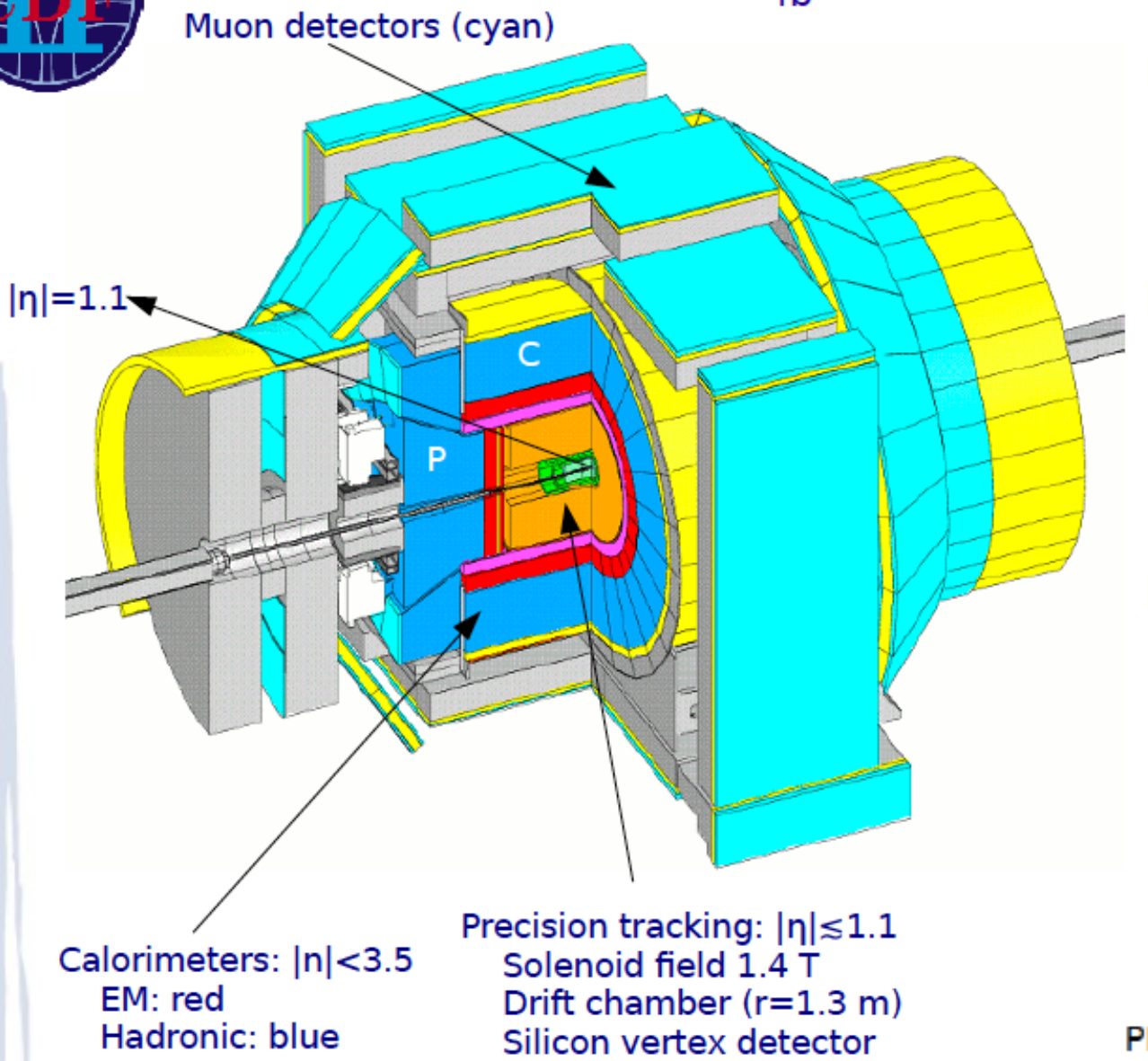
- Result

	ee	μμ
$\sin^2\theta_{eff}^{lept}$ = 0.23147 ± 0.00047 (total)		0.22996 ± 0.00064 (total)
statistics:	0.00043	0.00059
PDF:	0.00017	0.00024
other systematics:	0.00008	0.00005

D0 $ee+\mu\mu$ 10 fb^{-1} 0.23095±0.00040

CDF

CDF A_{fb} dataset selection



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

Phys. Rev. D93, 112016 (2016)

CDF

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 2nd order angular-weighting bias corrections (few percent)
- Mass bins
  - Electron and muon channel binning differ
  - Bins of variable widths

Both CMS and CDF analyses were done at Rochester

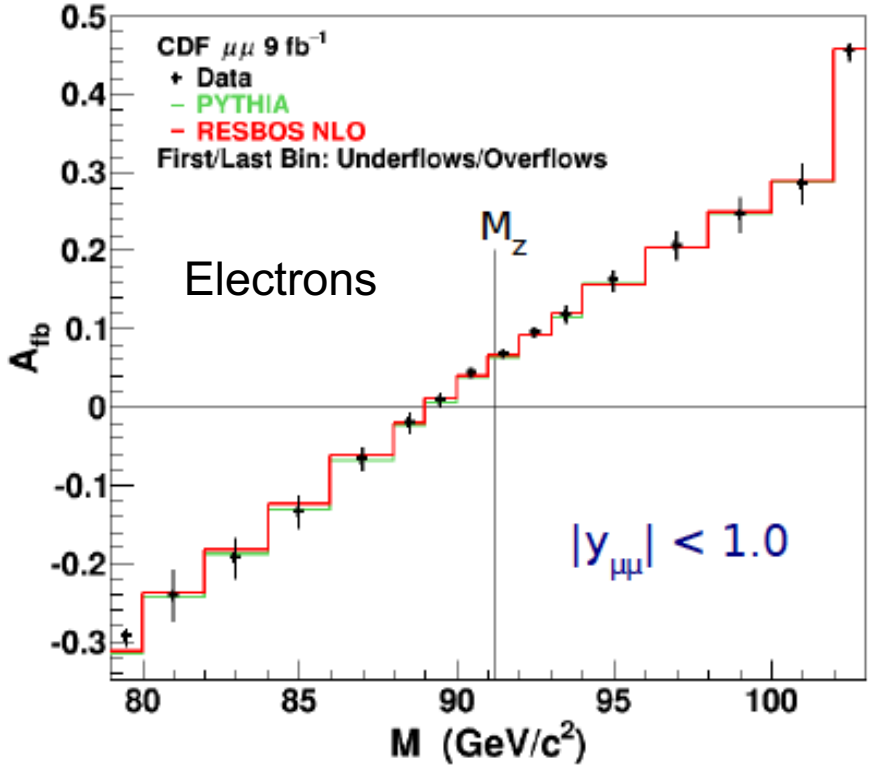
Phys. Rev. D93, 112016 (2016)

CDF

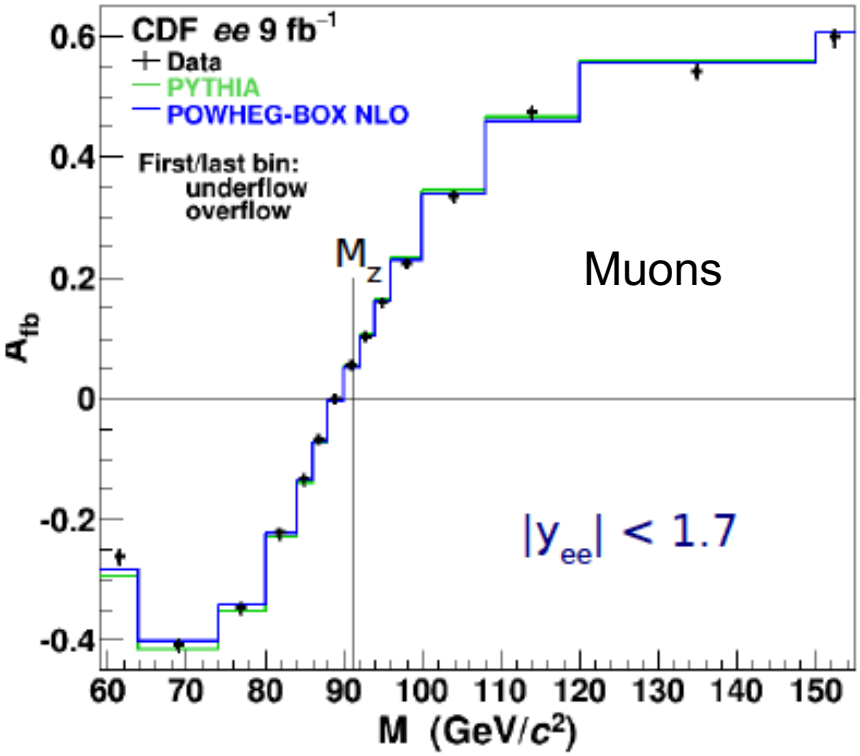
Unfolded

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

Phys. Rev. D93, 112016 (2016)

CDF

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) with 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

https://arxiv.org/abs/1801.06283
Jan 9, 2018

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

- Input observable values
  - D0 ee⊕μμ value : 0.23095±0.00035 (stat) ± 0.00023 (syst)
  - CDF ee⊕μμ value : 0.23221±0.00043 (stat) ± 0.00018 (syst)

arXiv:1710.03951 [hep-ex]

Phys. Rev. D93, 112016 (2016)

- Input uncertainty categories
  - Statistics: CDF: 0.00043, D0: 0.00035
  - PDF: CDF: 0.00016, D0: 0.00019 (100% correlated)
  - Other systematics: CDF: 0.00007, D0: 0.00007 (uncorrelated)
- Results of BLUE method

  - $\sin^2\theta_{eff}^{lept}$ = 0.23148 ± 0.00027 (stat) ± 0.00020 (syst)
  - Combination: 2.6% probability
  - Uncertainties
    - Statistics: 0.00027
    - PDF: 0.00018
    - Other systematics: 0.00005

TeV combined: CDF+D0 0.23148±0.00033

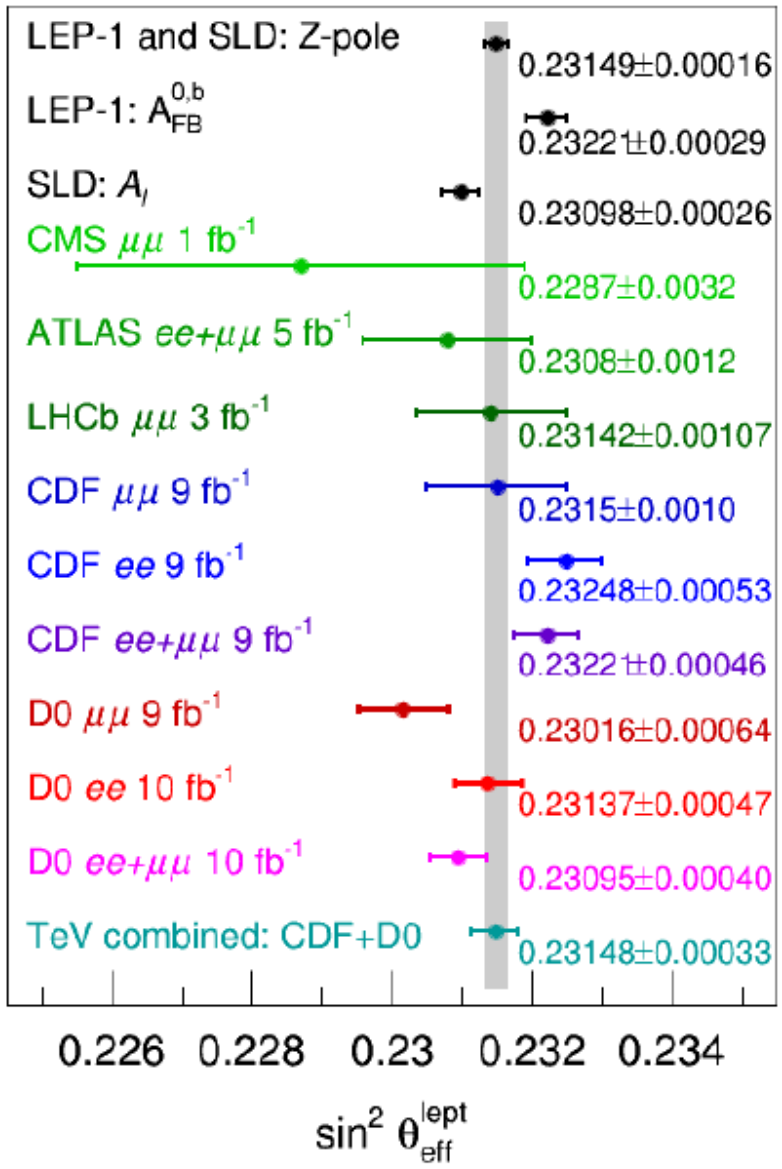
The value of Dzero measurement was adjusted for the change from NNPDF2.3 to NNPDF3.0 used by CDF.

Adjust for Electroweak radiative corrections (used in CDF)

It just happened that the two adjustments are in opposite direction and of similar magnitude.

CDF+Dzero combination uncertainty of 0.00033 is close to the LEP/SLD error of 0.00029

Band is LEP/SLD average



Tevatron combination

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

Phys. Rev. D84, 11202 (2011)

J. High Energy Phys. 09 (2015) 049

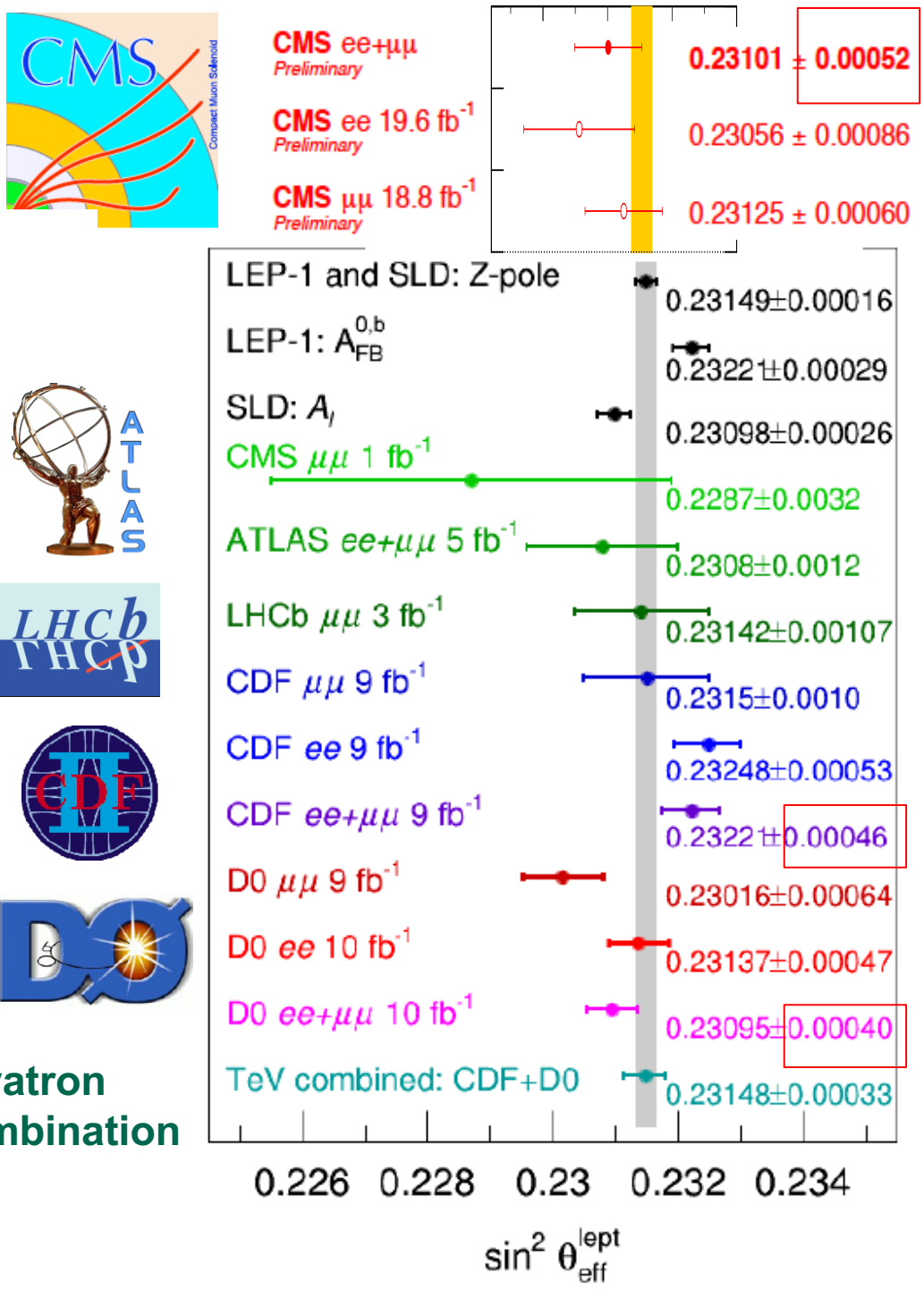
J. High Energy Phys. 11 (2015) 190

Phys. Rev. D89, 072005 (2014)

Phys. Rev. D93, 112016 (2016)

arXiv:1710.03951 [hep-ex]

https://arxiv.org/abs/1801.06283
Jan 9, 2018



Tevatron combination

Band is LEP/SLD average

CDF, D0, CMS have similar errors ~0.00045

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)

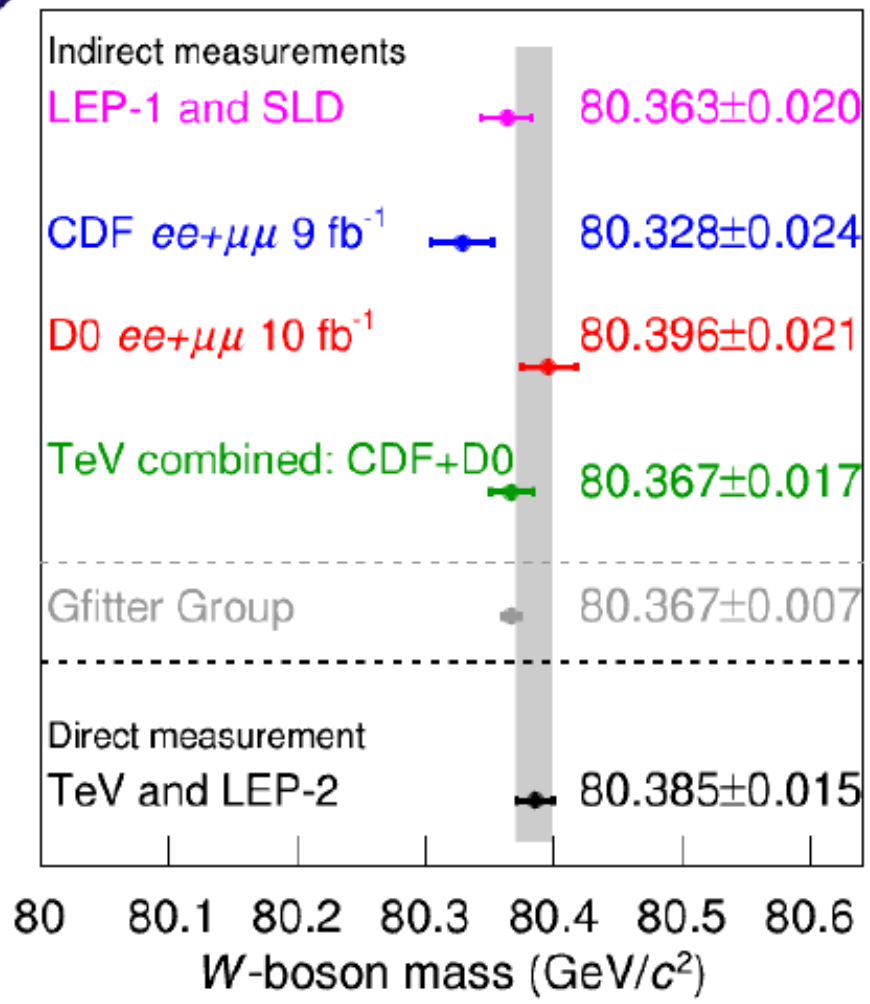
arXiv:1710.03951 [hep-ex]

https://arxiv.org/abs/1801.06283
Jan 9, 2018

$\sin^2\theta_w$ / M_w interpretations

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



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

Before M_H was measured

Phys. Rev. D89, 072005 (2014)
Phys. Rev. D93, 112016 (2016)

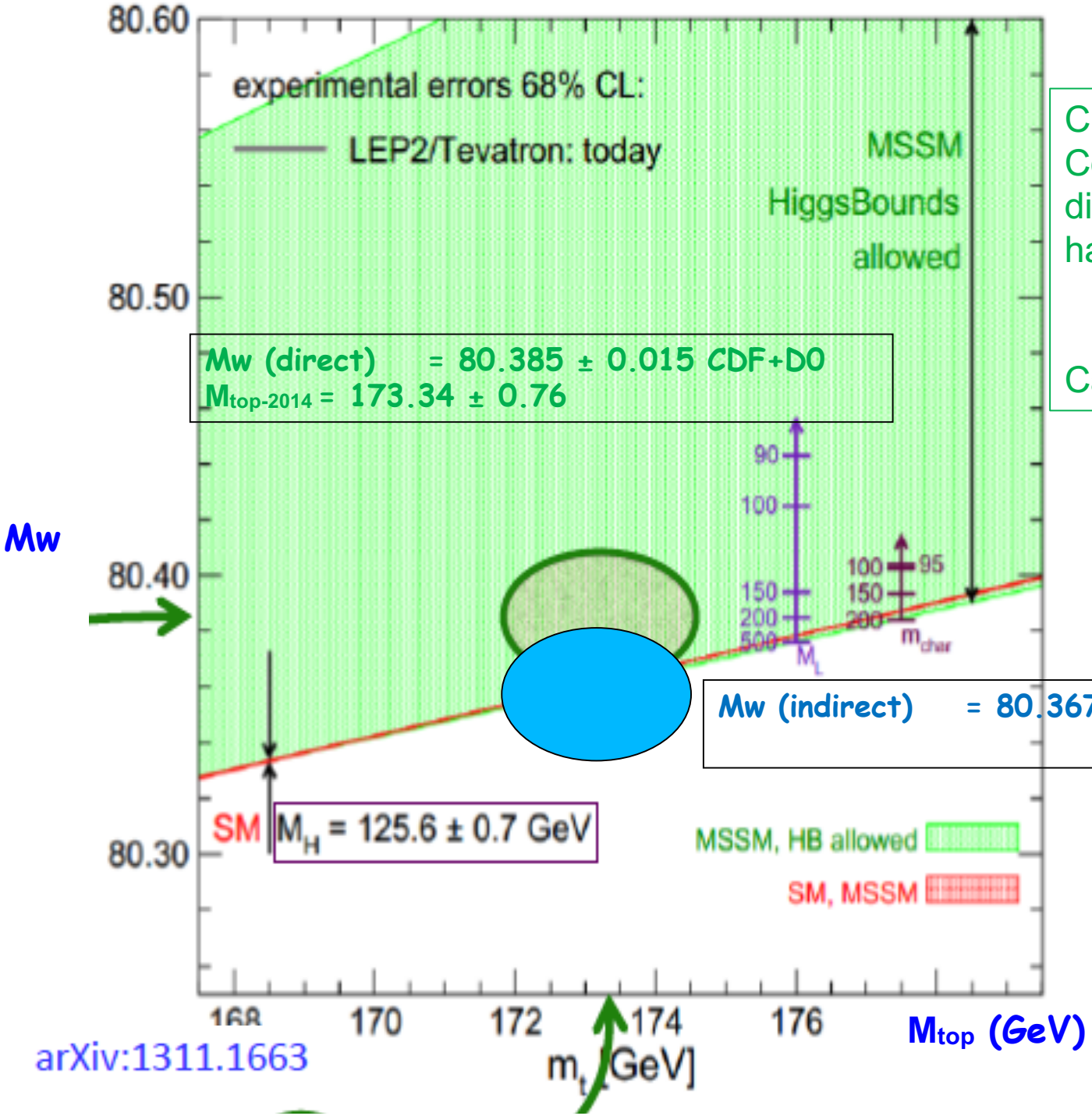
Includes M_H value

https://arxiv.org/abs/1801.06283 Jan 9, 2018

Eur. Phys. J. C72 2205 (2012)
SM prediction (m_h=125.7±0.4 GeV)
... with apologies to the ZFITTER group

Phys. Rev. D88, 05218 (2013)

Current Tevatron Combination Indirect and direct measurements of Mw have similar errors ~15 MeV



Current Tevatron Combination Indirect and direct measurements of Mw have similar errors ~15 MeV

Can we do better at the LHC?

A proposal for the measurement of the weak mixing angle at the HL-LHC

CMS-PAS-FTR-17-001

Setup

- Generate ~100M POWHEG dimuon events with m>50 GeV
- 8 TeV, 13 TeV and 14 TeV, with different $\sin^2\theta_{eff}^{lept}$ and NNPDF weights
- PYTHIA8 for parton showering, hadronization and QED FSR

Table 1: Setup for MC study for $\sin^2\theta_{\rm eff}^{\ell}$ extraction

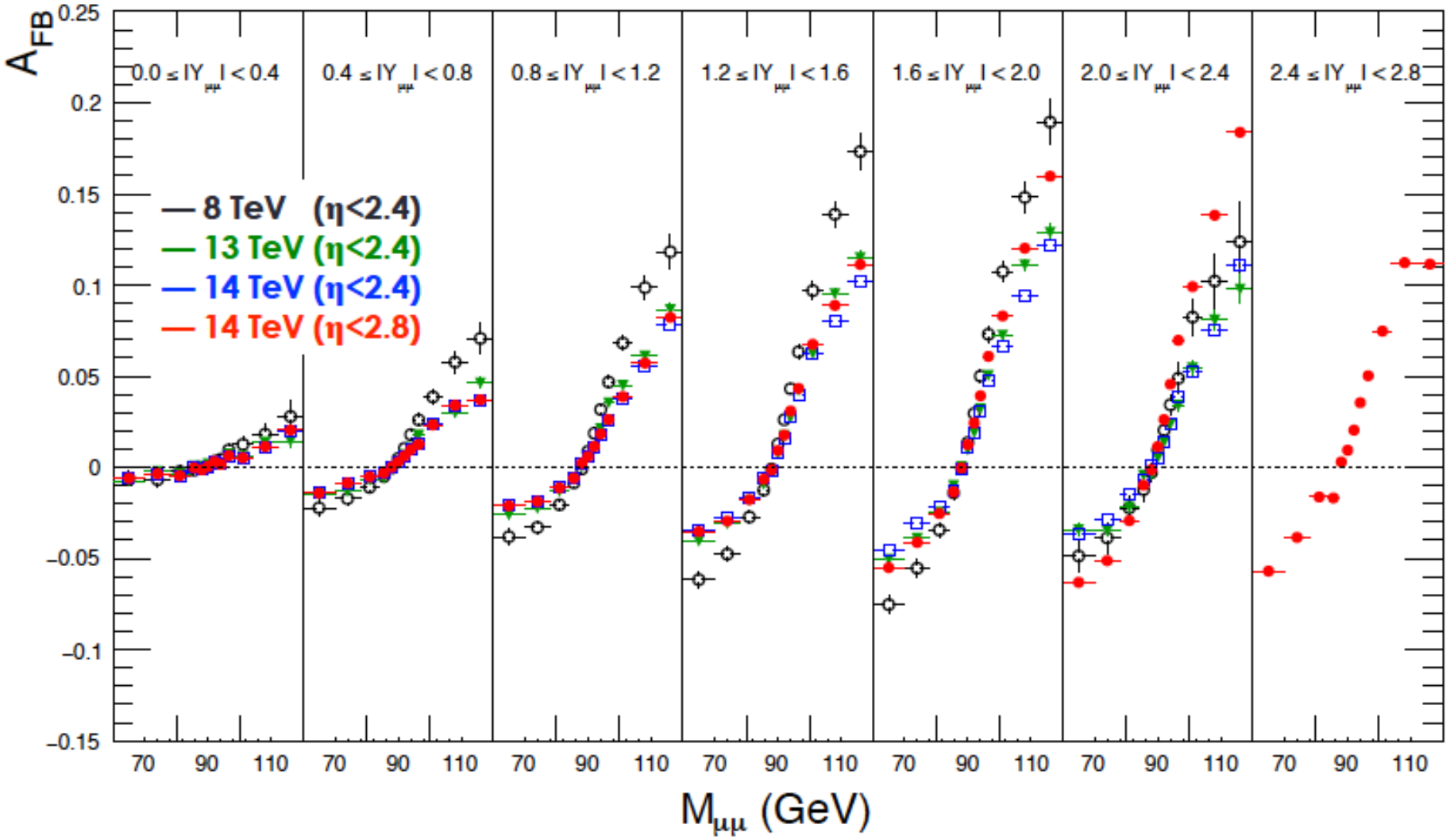
$\sqrt{s}$ (TeV)	events (million)	σ (pb)	L_{equiv} (fb^{-1})	L_{target} (fb^{-1})
8	251.0	1177	213	20
13	99.5	1922	50	100
14	99.8	2072	48	1000

- Generator-level study (no efficiency loss or resolution smearing)
- Lepton acceptance cuts: $p_T^{0\,(1)}$>25 (15) GeV
- $|\eta| < 2.4$ (2.8)
- Uncertainties are scaled from effective to target integrated luminosity
- Fits are performed to A_{FB} in bins of mass and rapidity:

  6(7) bins of $|y|$: 0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4 (,2.8)

  12 bins of m: 60, 70, 78, 84, 87, 89, 91, 93, 95, 98, 104, 112, 120

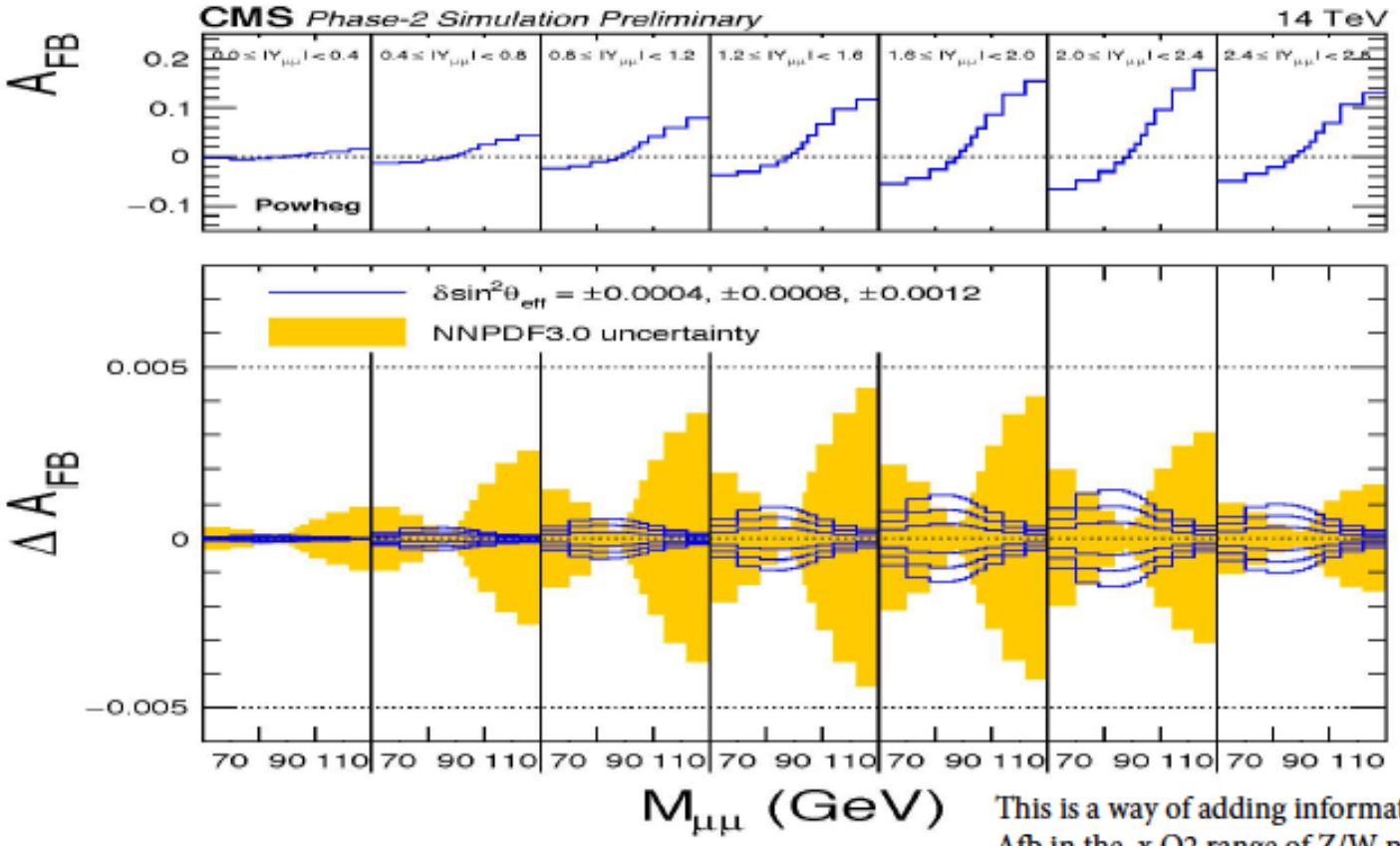
AFB



- larger dilution for higher sqrt(s) due to less contribution from valence quarks at lower x
- extending η coverage to 2.8 significantly reduces both stat. and pdf errors (next slide)

PDF uncertainties

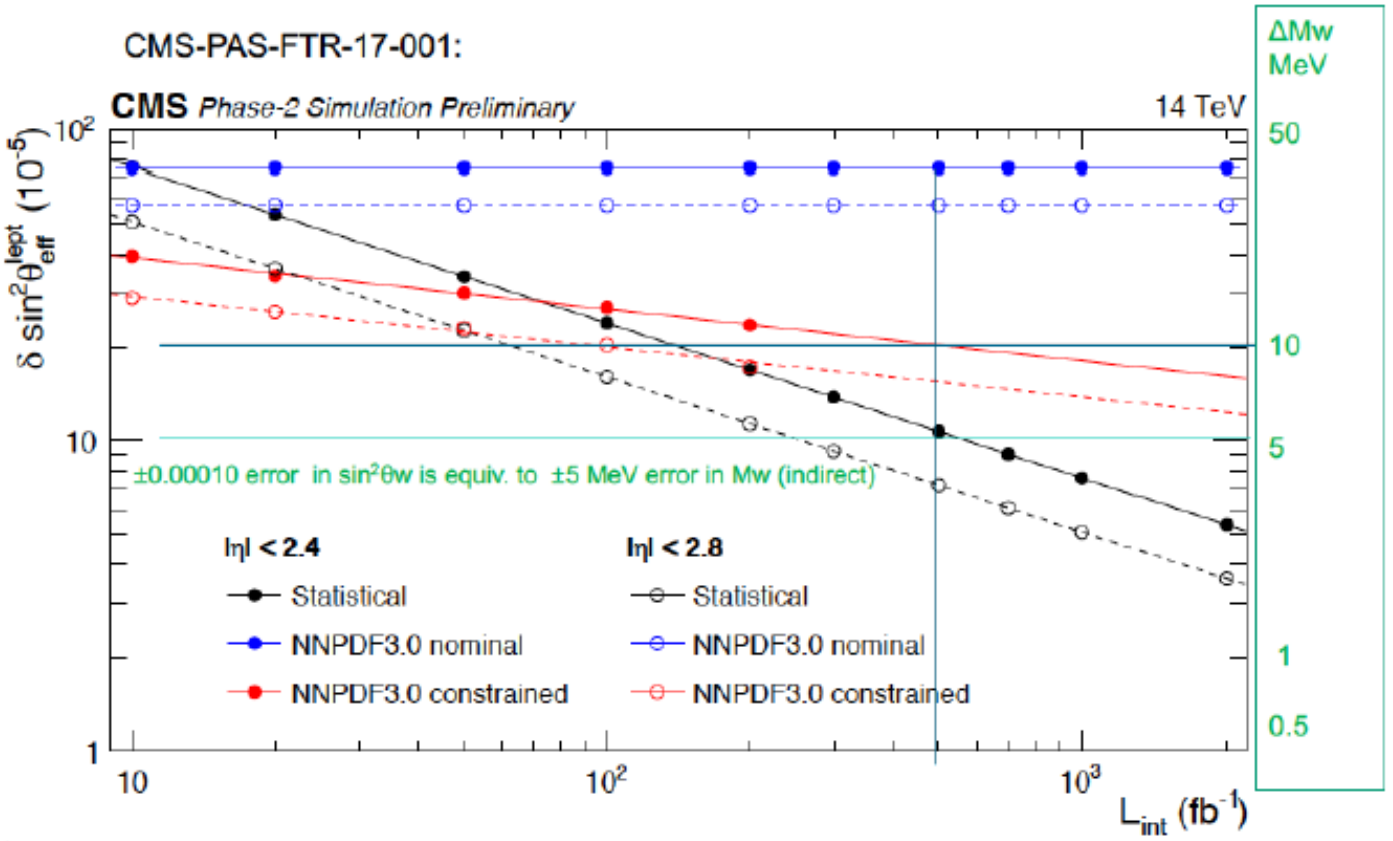
- Observed A_{FB} is very sensitive to PDFs (size of dilution, ratio of u and d to total)
- Large in low and high masses, small near the peak (+ specific dependence on y)



This is a way of adding information from Afb in the x,Q2 range of Z/W produciton

- Perform $\sin^2\theta_{eff}$ fit for each PDF replica (by default we use NNPDF3.0)
- Weight each replica (i) by $w_i(\chi^2_{min})$

$$w_i = \frac{e^{-\frac{\chi^2_{min}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{min}}{2}}}$$



14 TeV

L_{int}	$\delta_{stat}[10^{-5}]$		$\delta^{nominal}_{nnpdf3.0}[10^{-5}]$		$\delta^{constrained}_{nnpdf3.0}[10^{-5}]$		PDF err constrained (Mw indirect error)
(fb^{-1})	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$	
10	76	51 (25)	75	57	39	29	(15 MeV)
100	24	16 (8)	75	57	27	20	(10 MeV)
500	11	7 (3,5)	75	57	20	16	(8 MeV)
1000	8	5 (2.5)	75	57	18	14	(7 MeV)
3000	4	3 (1,5)	75	57	15	12	(6 MeV)
8 TeV 19	43 MC		49 MC		27 MC		
19 (from [1])	44 data		54 data		32 data		

Compare to CMS 8 TeV data

Summary

- Studied prospects for $\sin^2\theta_{eff}^{lept}$ measurement with large integrated luminosity and extended muon pseudorapidity coverage

- Two main conclusions:

1000 fb-1k CMS detector only.

EW mixing angle PDF error 0.00014 which corresponds to 7 MeV uncertainty in indirect measurement of Mw.

- With limited acceptance ($\eta<2.4$) statistical (PDF) uncertainties are **50% (30%)** larger compared to extended ($\eta<2.8$) acceptance regardless of int. luminosity and for both nominal or constrained PDF errors

- With 1000 / fb a single measurement will have ~negligible stat. errors and PDF errors can be constrained to improve current precision of $\sin^2\theta_{eff}^{lept}$

Vs. Current Tevatron combination mixing angle error 0.00033 which corresponds to 17 MeV uncertainty in indirect measurement of Mw.

We could get a factor of 2 better than TeV combination (or LEP/SLD)

TeV combined: CDF+D0 0.23148±0.00033 CMS 8 TeV 0.23101 ± 0.00052

However

CMS, ATLAS AND LHCB ANALYSIS HAVE NOT APPLIED EW CORRECTION

Tevatron

CDF: Applying a private implementation of the full EW corrections in POWHEG, RESBOS or PHYTHIA increases the extracted EW mixing angle by **+0.00022 (full EW corrections)**

Dzero: Accounting only for the difference in the mixing angles between leptons and u and d quarks increases the extracted EW mixing angle by: **+ 0.00007 (partial EW corrections)**

LHC

ATLAS: Applying preliminary private version of full EW corrections results in a **very small effect** on the extracted EW mixing **(full EW corrections)**

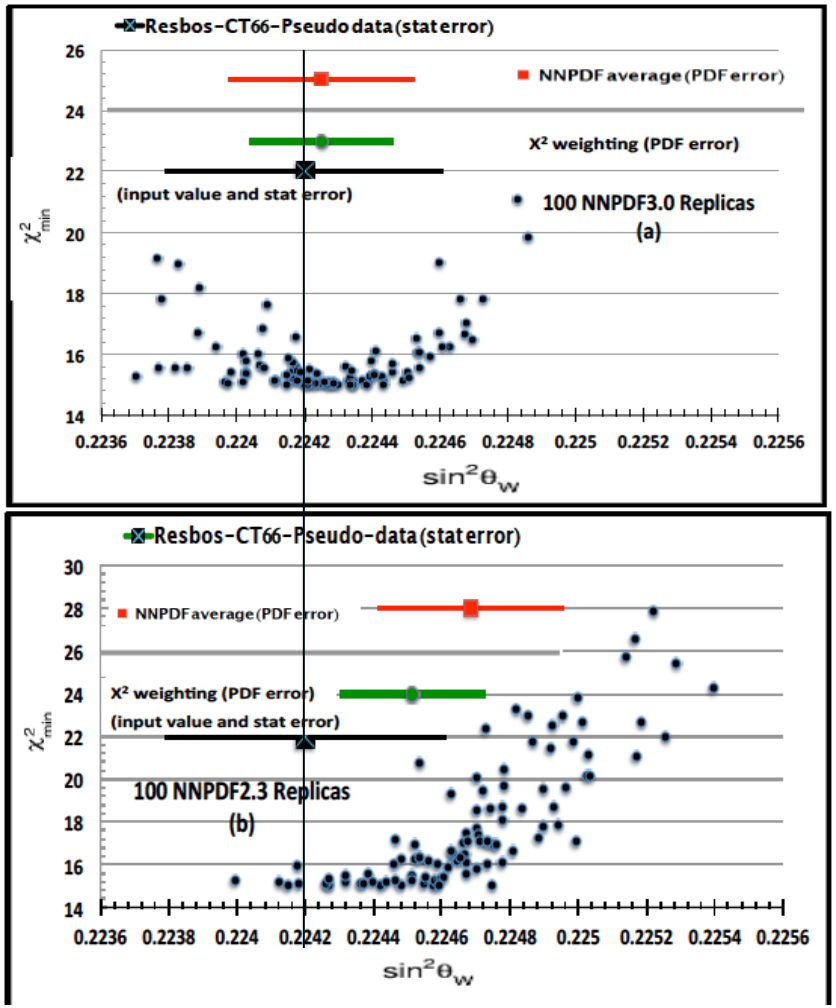
CMS: Accounting only for the difference in the mixing angles between leptons and u and d quarks in POWHEG has a negligeable effect (**<0.00001**) on the extracted EW mixing angle. **(partial EW corrections)**

How to resolve this?

*CMS finds that the **official POWHEG with EW corrections** is in disagreement with the measured Drell-Yan mass distributions. This is being investigated*. Hope to resolve soon.

Additional studies with MC samples

A. Bodek, J. Han, A. Khukhunaishvili, and W. Sakumoto, "Using Drell-Yan forward-backward asymmetry to reduce PDF uncertainties in the measurement of electroweak parameters", *Eur. Phys. J.* **C76** (2016), no. 3, 115, doi:10.1140/epjc/s10052-016-3958-3, arXiv:1507.02470.



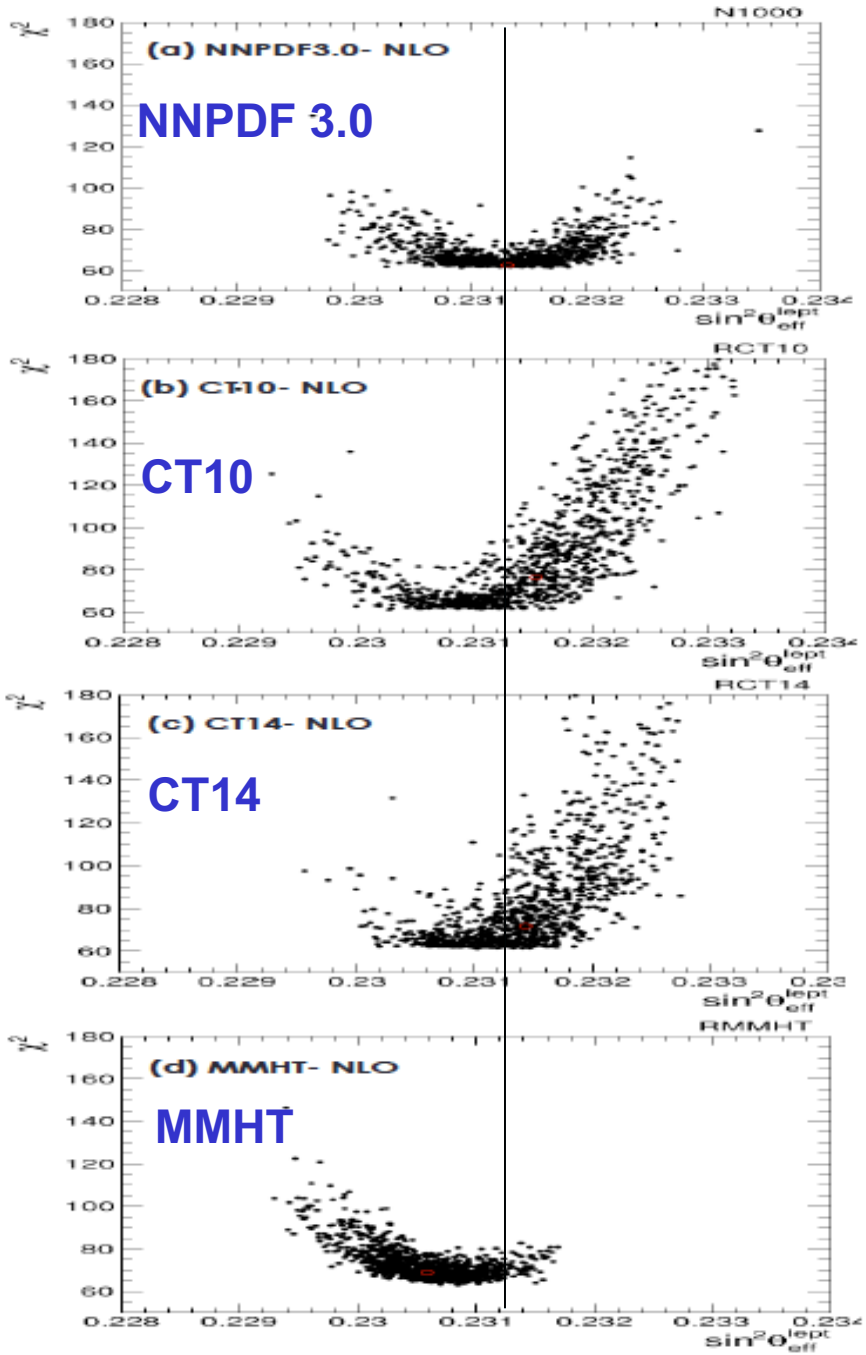
MC study Tevatron Run II MC Sample GENERATED with central NNPDF3.0 PDF with on-shell $\sin^2\theta_W = 0.2242$

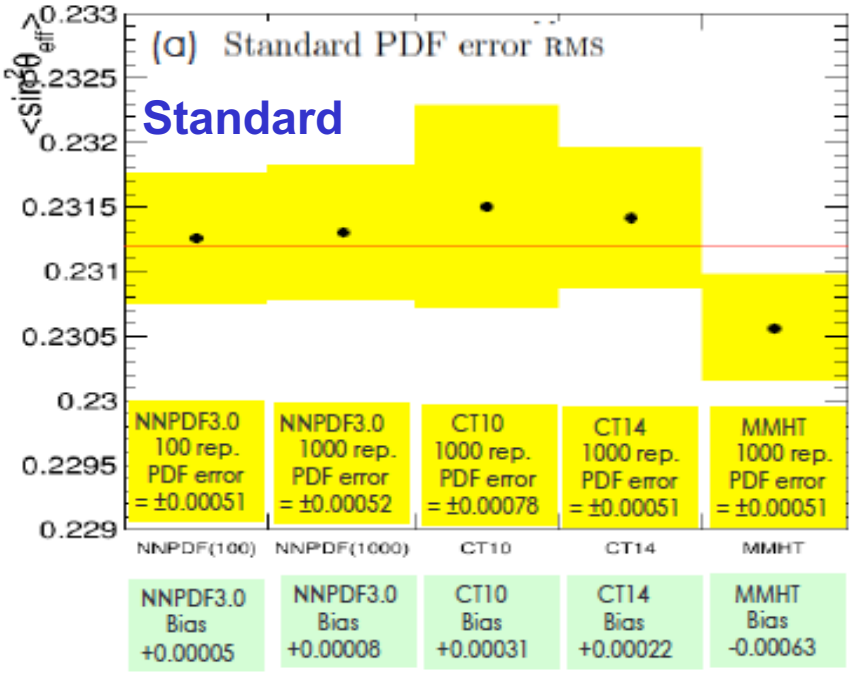
Chi-squares for 100 NNPDF3.0 replicas are symmetric with respect to the central PDF.

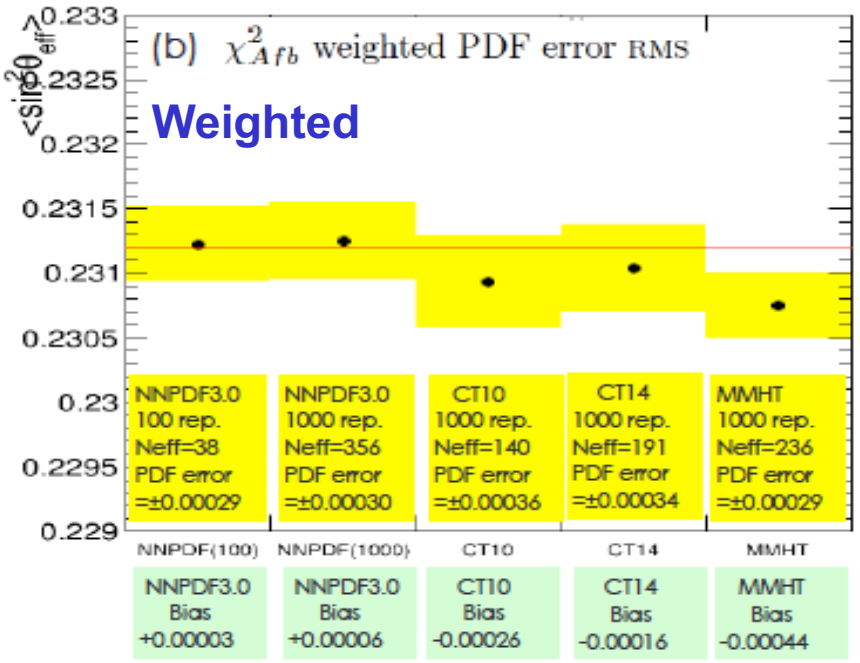
NNPDF2.3 is not consistent with NNPDF3.0 generated sample. Asymmetric distribution.

What about at the LHC

MC study: **Generated** LHC MC Sample with **central NNPDF 3.0** and **$\sin^2\theta^{lept}_{eff} = 0.2312$**







[40] W. T. Giele and S. Keller, "Implications of hadron collider observables on parton distribution function uncertainties", *Phys. Rev. D* **58** (1998) 094023, doi:10.1103/PhysRevD.58.094023, arXiv:hep-ph/9803393.

[41] N. Sato, J. F. Owens, and H. Prosper, "Bayesian Reweighting for Global Fits", *Phys. Rev. D* **89** (2014) 114020, doi:10.1103/PhysRevD.89.114020, arXiv:1310.1089.

Also

Hannu Paukkunen[a,b], and Pia Zurita[c]

paper, we conclude that both methods are statistically equivalent in the limit when the prior densities are well constrained by the data and the new evidence does not provide significant information. We have shown using a numerical example that, if the uncertainties in the prior distribution are larger compared to the uncertainties obtained by the inclusion of new data, the method proposed by the NNPDF collaboration is less efficient than the method proposed by [1]. Moreover, the latter yields results that are significantly closer to those obtained from global fits.

$$\omega_k^{\mathrm{GK}} = \frac{\exp\left[-\chi_k^2/2\right]}{(1/N_{\mathrm{rep}})\sum_{k=1}^{N_{\mathrm{rep}}}\exp\left[-\chi_k^2/2\right]},$$

$$\omega_k^{\text{chi-squared}} = \frac{\left(\chi_k^2\right)^{(N_{\mathrm{data}}-1)/2}\exp\left[-\chi_k^2/2\right]}{(1/N_{\mathrm{rep}})\sum_{k=1}^{N_{\mathrm{rep}}}\left(\chi_k^2\right)^{(N_{\mathrm{data}}-1)/2}\exp\left[-\chi_k^2/2\right]}.$$

[1] W. T. Giele and S. Keller, Phys. Rev. D **58**, 094023 (1998).
[2] R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J. I. Latorre, J. Rojo, and M. Ubiali (NNPDF Collaboration), Nucl. Phys. **B849**, 112 (2011); **B854**926 (2012); **B855**927 (2012).
[3] R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, and J. I. Latorre, J. Rojo, and M. Ubiali, Nucl. Phys. **B855**, 608 (2012).

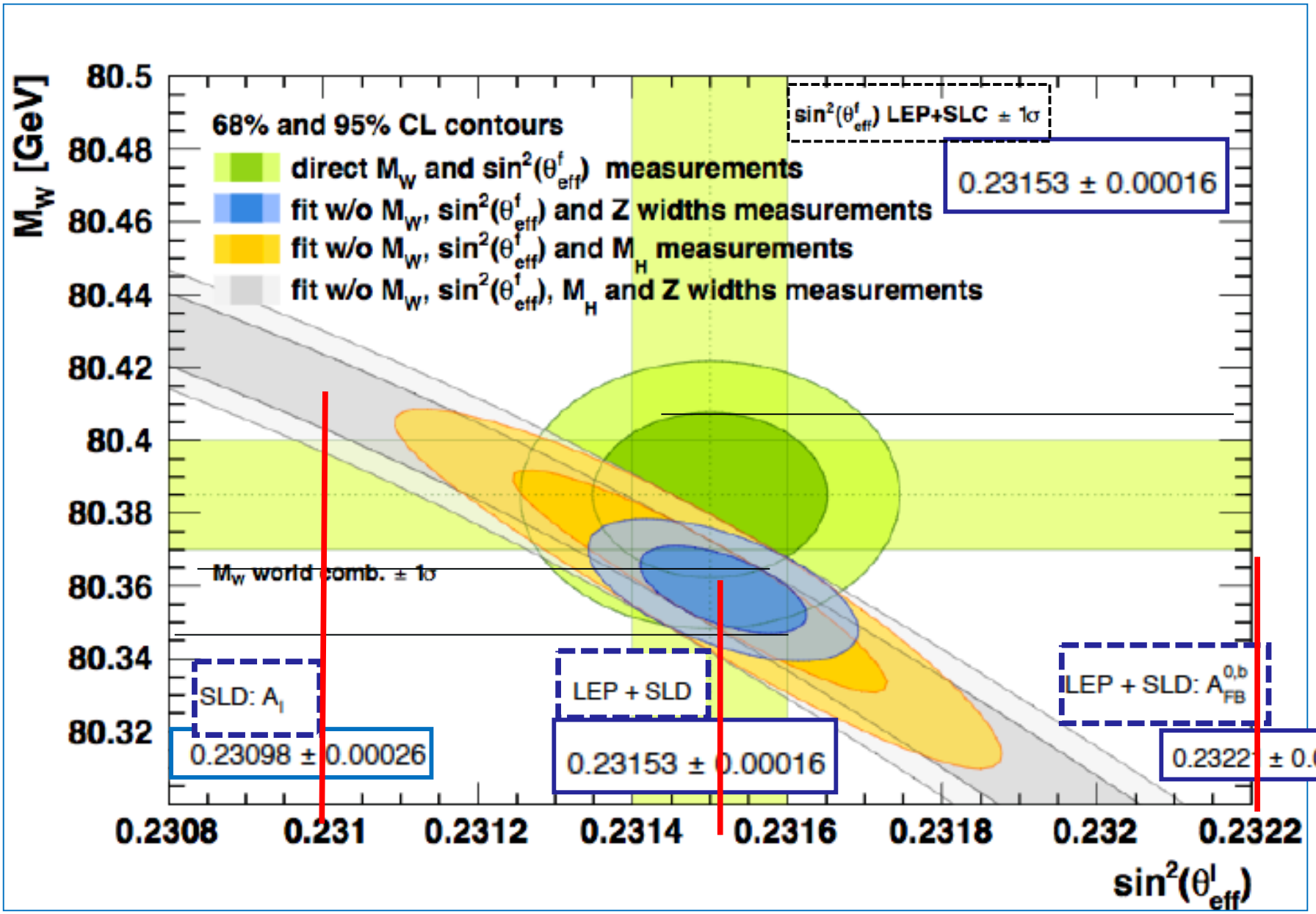
They Conclude: GK method and Hessian method are equivalent

Paukkunen and Zurita, JHEP 1412 (2014) 100

Hannu Paukkunen, Pia Zurita
arXiv:1408.4572 [hep-ph]

We have found out that this is indeed true.

Old plot


68% and 95% CL contours
direct M_W and $\sin^2(\theta^f_{eff})$ measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$ and Z widths measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$ and M_H measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$, M_H and Z widths measurements
$\sin^2(\theta^f_{eff})$ LEP+SLC ± 1σ
0.23153 ± 0.00016
M_W world comb. ± 1σ
SLD: A_l
0.23098 ± 0.00026
LEP + SLD
0.23153 ± 0.00016
LEP + SLD: $A^{0,b}_{FB}$
0.2322 ± 0.00029
M_W [GeV]
80.5
80.48
80.46
80.44
80.42
80.4
80.38
80.36
80.34
80.32
0.2308
0.231
0.2312
0.2314
0.2316
0.2318
0.232
0.2322
$\sin^2(\theta^l_{eff})$