Precision $\sin^2\theta_W$ and new PDF constraints from Drell-Yan Afb data in Hadron Colliders

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PDFs in Hadron Colliders

- PDFs are the basis of all measurements at the LHC and at the Tevatron. For some precision measurements at 8 TeV, the PDF errors at the LHC are larger than the statistical error. As the statistical error decreases (e.g. 13-14 TeV at the LHC), *PDFs become the dominant error.*

- New methods to further constrain PDFs are needed.

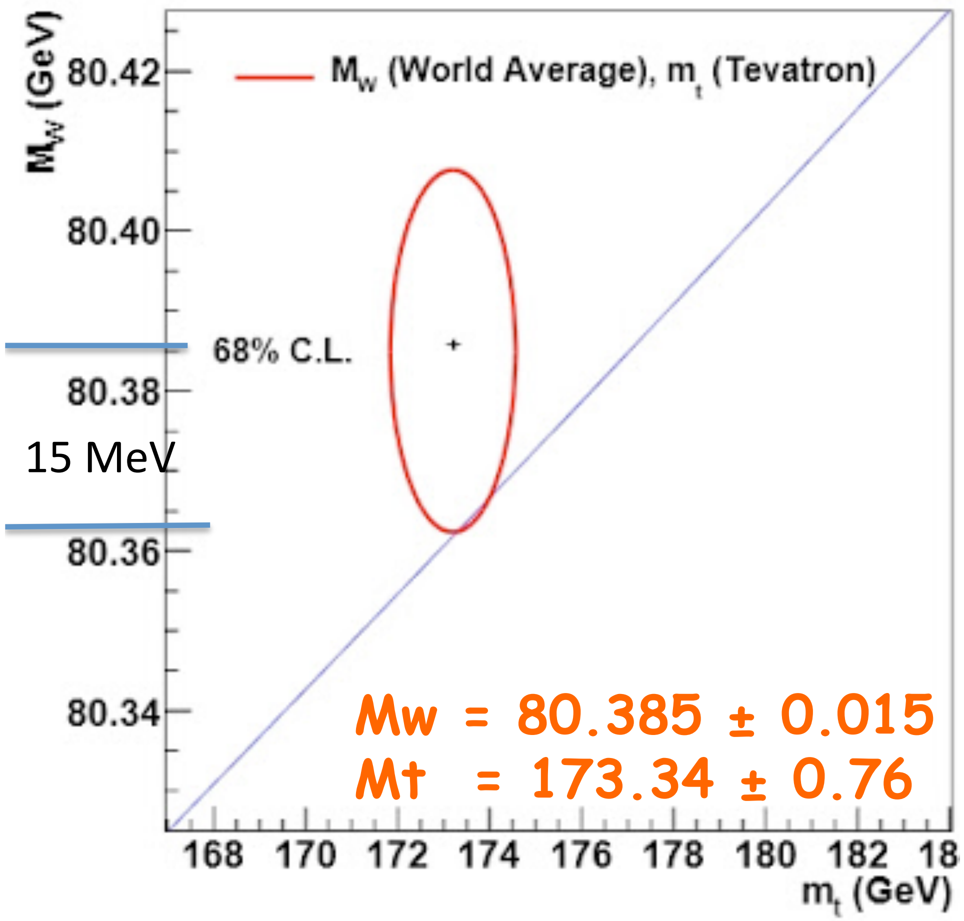
- We have investigated a new method to extract a precise determination of the EW mixing angle (**$\sin^2\theta_w$**)---- AND also greatly constrain PDFs ---- using **Drell-Yan Afb** data in Hadron Colliders (LHC and Tevatron)

- In addition to rreducung PDF errors in **$\sin^2\theta_w$**, these *Afb constrained PDFs* ----- *can* be directly applied to other precision =measurements, ----e.g. the W mass since the W's and Z's are in the same region of x.

Word average (CDF, Dzero, e+e-)   MW=80385±15 MeV

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 (as is being done at CDF)

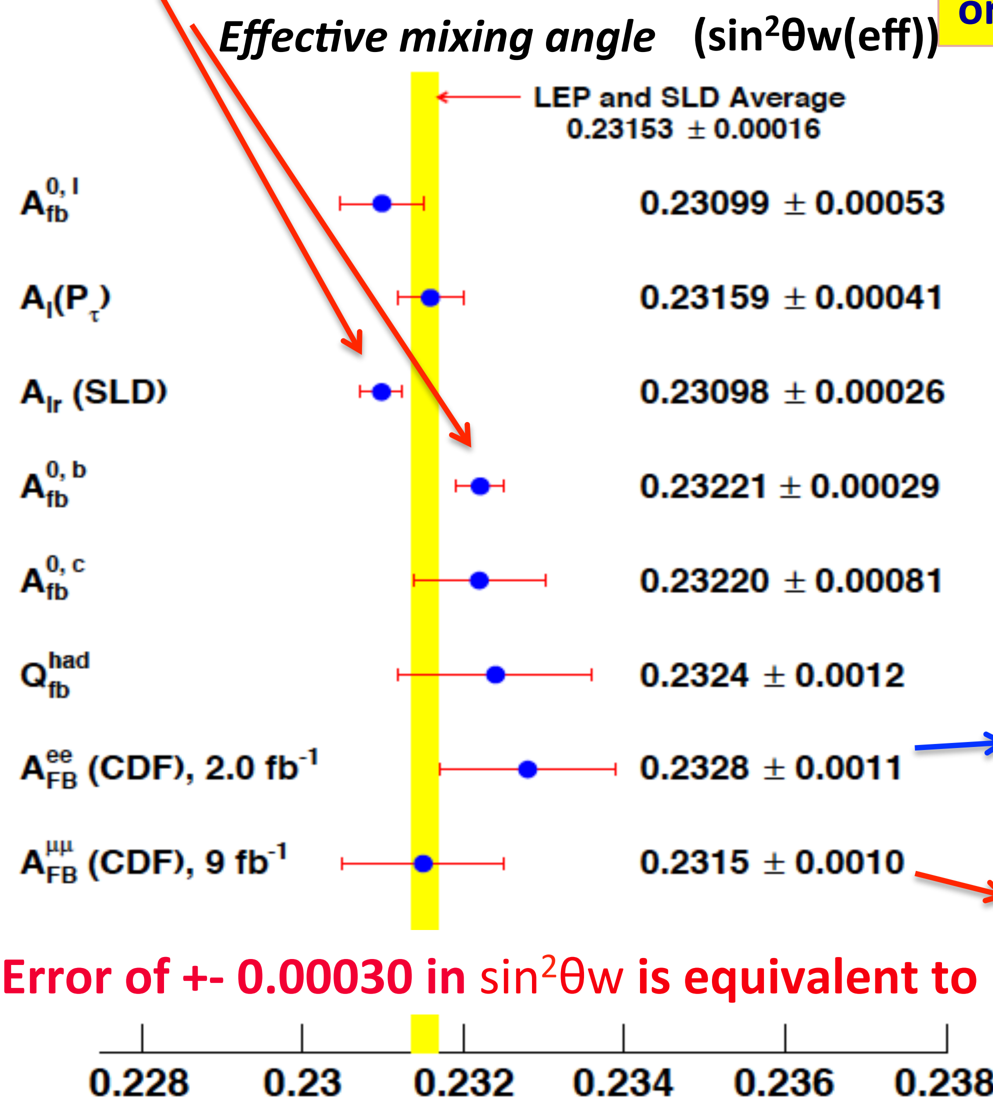
$$\sin^2\theta_w = 1 - M_w^2 / M_z^2$$

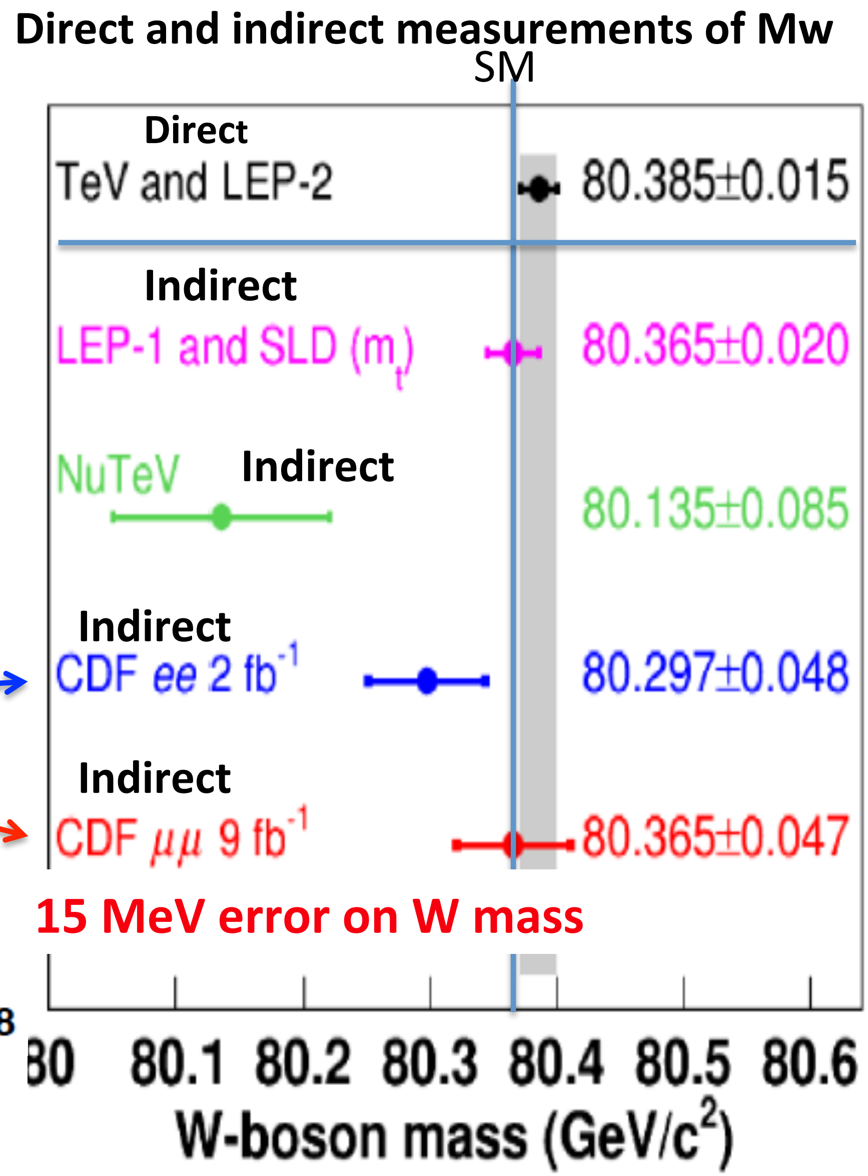
A error of ± 0.00030 in $\sin^2\theta_w$ is equivalent to an indirect measurement of M_w to a precision of ± 15 MeV Which is the error in the world average direct meas.

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

$\sin^2\theta_{eff}$ LEP SLD difference is 0.00122

Need **error of +- 0.00030 or better to resolve this.**





Error of +- 0.00030 in $\sin^2\theta$w is equivalent to 15 MeV error on W mass

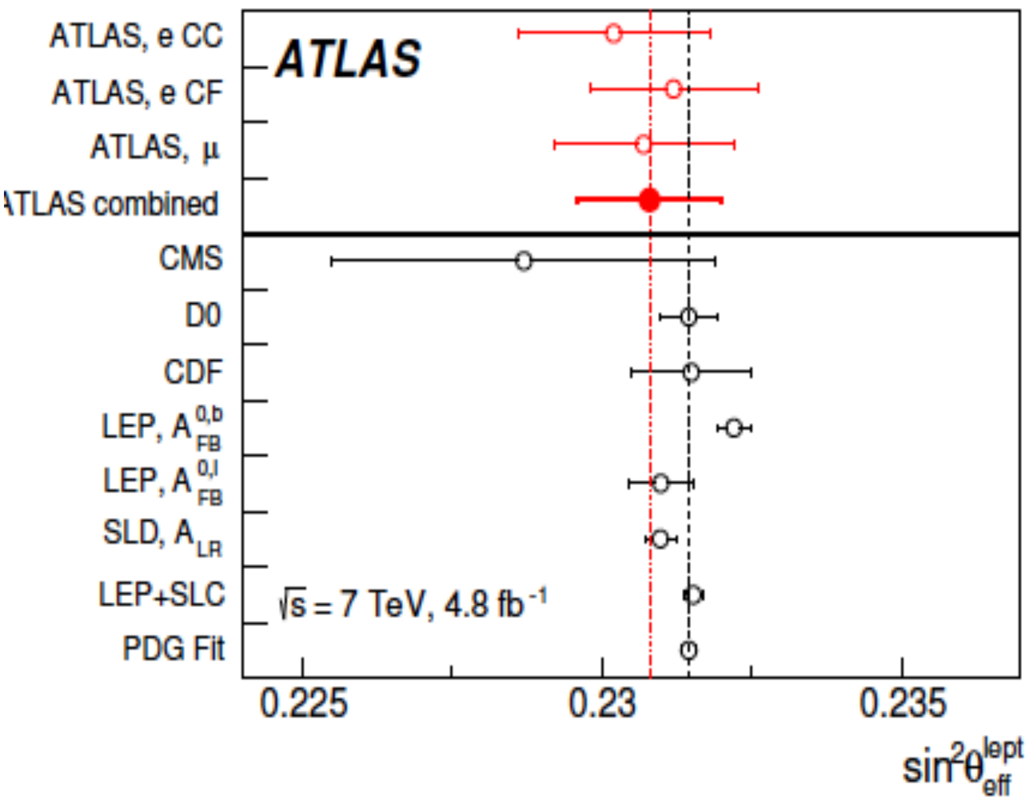
Above are published results

Include recent not yet published results

Current best LHC measurement of $\sin^2\theta_w$(eff). http://arxiv.org/abs/1503.03709 (March 2014)
ATLAS TeV from electron and muon Drell-Yan Afb data

$\sin^2\theta_{eff}$ (ATLAS) = 0.23080 +- *0.00050 (stat)* +-0.00060 (syst.) +-0.00090 (PDF)

This is a long way from +-0.00030. (we know of ways to greatly reduce the systematic errors). So ***PDF errors of 0.00090 dominate at the LHC. Need to be reduced using new methods.***



Dzero: http://arxiv.org/abs/1408.5016
Aug. 2014 (they use NNPDF2.3)

$\sin^2\theta_{eff}$ (Dzero) = 0.23135 +- *0.00043 (stat)* +-0.00008 (syst.) +-0.00017 (PDF)
??

Statistical errors for current LHC and Tevatron are the same, but PDF error at LHC much larger)

Need to reduce PDF errors at LHC using new methods

Start with summary of our new method

PDF errors of on $\sin^2\theta_{eff}$ ***+-0.00090 dominate at the LHC.***

Can be reduced to less than +- 0.00028 using a new method.

MC studies with a CDF like detector at the Tevatron & a CMS like detector at the LHC.

Technique can be appied to both Tevatron and LHC data.

1. **CDF-like detector:** Tevatron 10 fb-**1 ee and μμ MC data** (note real data now under analysis) (275K μμ y<1, and 500K ee y<2 events). (A Dzero-like detector will be similar)

Expected Stat error: ***0.00041*** **(CDF Tevatron)**

Expected PDF errors CT10 NLO: **0.00027 (CDF Tevatron)**

Expected PDF errors NNPDF3.0: **0.00027 (CDF Tevatron)**

New method Afb constrained NNPD3.0 NLO: 0.00018 (CDF Tevatron)

3. CMS-like detector: 19 fb-1 8 TeV MC **μμ MC data** (22M μμ y<2 events) (note real data now under analysis)

Ex**pected Stat error** ***0.00043*** **(CMS LHC)**

Expected PDF errors CT10 NLO**: 0.00077 (CMS LHC)**

Expected PDF errors NNPDF3.0: **0.00051 (CMS LHC)**

New method Afb Constrained NNPD3.0 NLO: 0.00026 (CMS LHC)

-->12 MeV indirect meas of W mass

13 an 14 TeV LHC samples will have negligible statistical errors. PDF errors will reduced even more using Afb constrained PDFs. → Precision EW measurements and greatly reduced PDF errors are now possible.

Two Asymmetries contribute to constraining PDF at the x region relevant to the production of W and Z boson. – We focus on reducing PDF errors for both **$\sin^2\theta_{eff}$** and for direct measurement of Mw,

W+- asymmetry originates from a difference between (u-dbar) and (d-ubar)

- *W Asymmetry constrains d/u and dbar/ubar*
- *Early LHC 7 TeV W+- asymmetry data is already used in PDF fits, but the more recent 8 TeV data are more precise and will provide additional constraints.*

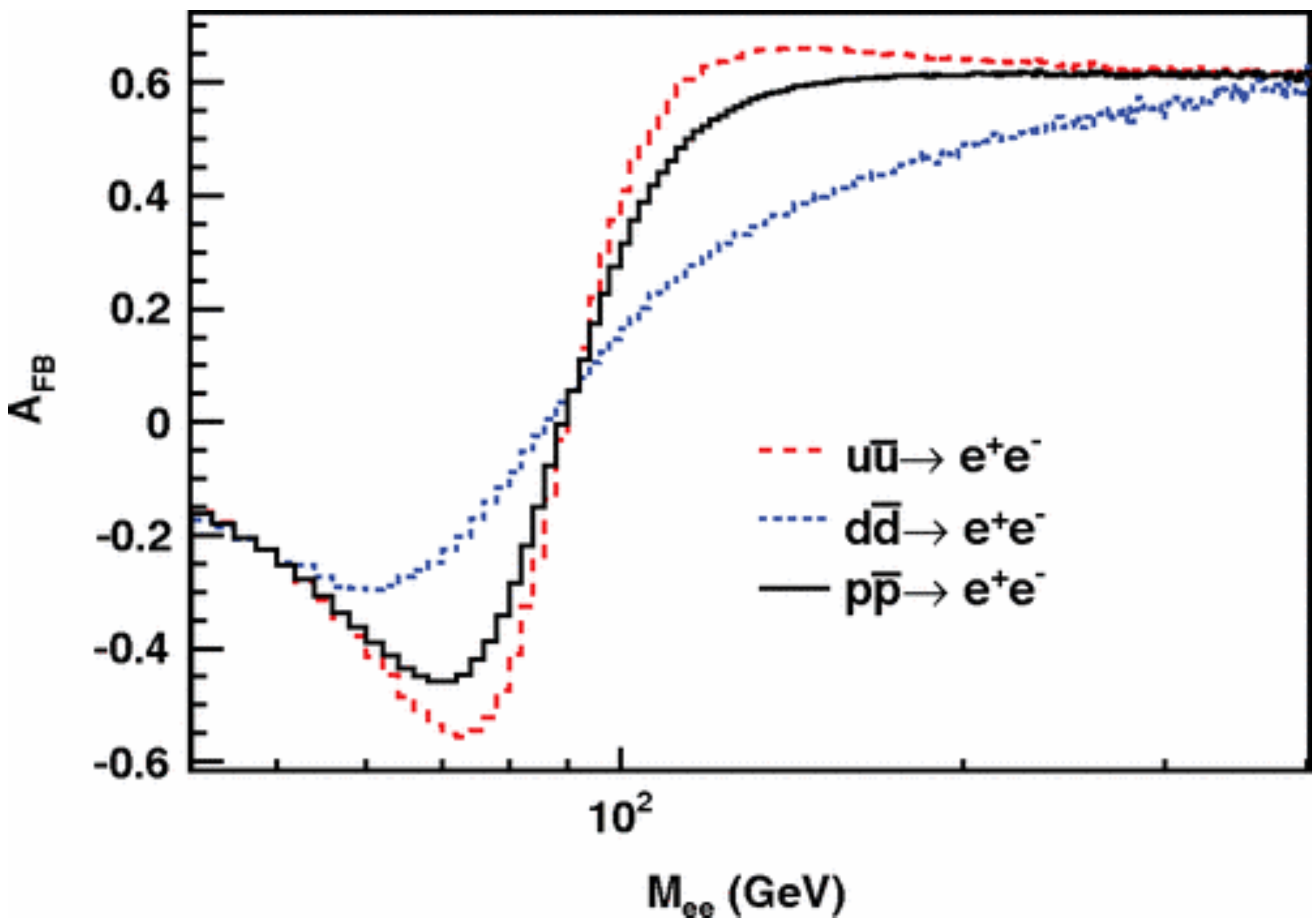
Drell-Yan Afb sample originates from (u-ubar) and (d-dbar) for which the quark is at higher x than the antiquark.

- *Afb is diluted because Afb for u-quark and d-quark are different.*
- *Afb is diluted by events where the antiquark is at higher x than the quark (Afb for such events is in the opposite direction → dilution).*
- *Afb is also diluted by s-sbar, c-cbar which have no asymmetry.*

Therefore, measurement of the dilution of Afb provides information on antiquarks and on the d and u quark distributions.

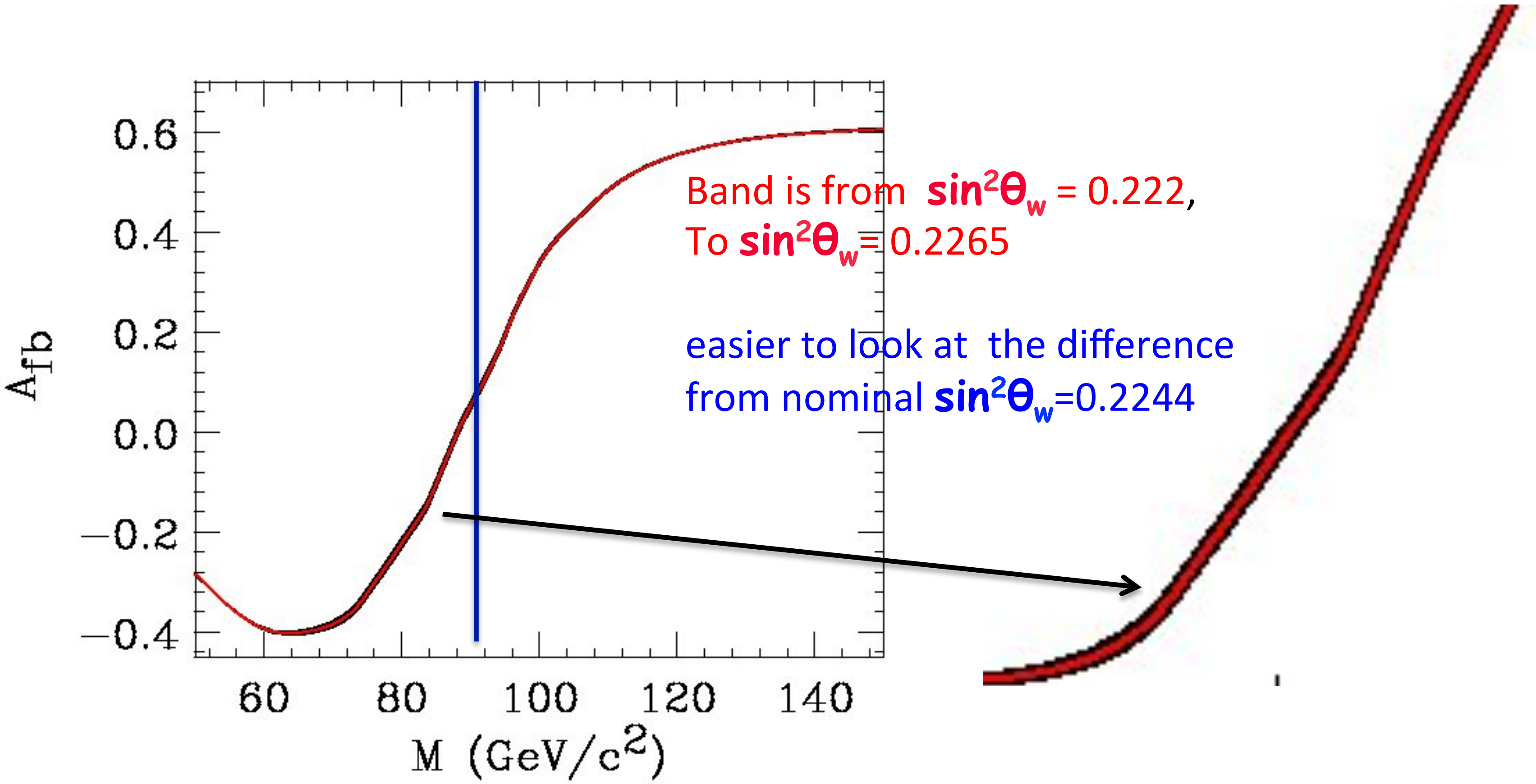
NOTE: For Asymmetries, NNLO K factors (For Drell Yan data) NNLO and scale QCD uncertainties are small.

Example, sensitivity of Afb to to u and d ratio at the Tevatron



Afb is sensitive to both $\sin^2\theta_{eff}$ and PDFs, so how do we get information on both?

Start with CDF like Tevatron Afb MC data ***as an example*****.**

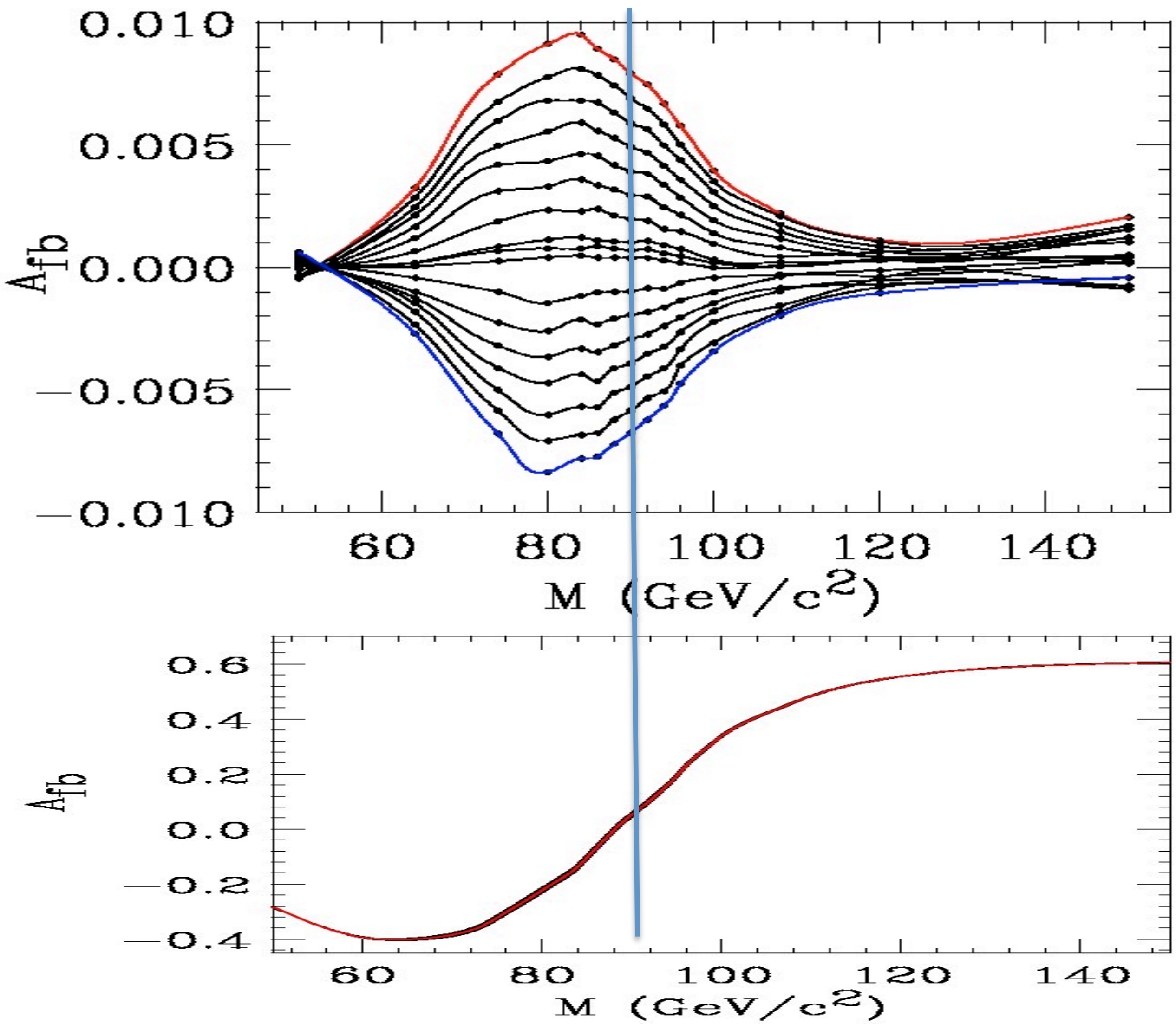


Afb pseudo data calculated at Tree level with default NNPDF3.0 for different values of $\sin^2\theta_{eff}$ .For real data, such templates are compared to AFB data to extract a value of $\sin^2\theta_{eff}$.

Difference plot of Afb(M,$\sin^2\theta_w$)−Afb(M,$\sin^2\theta_w$=0.2244). **(Tevatron)** For NNPDF3.0 261000

Red is $\sin^2\theta_w$ = 0.222, blue is $\sin^2\theta_w$= 0.2265

Different values of $\sin^2\theta_w$ raise or lower Afb in the region between 70 to 100 GeV

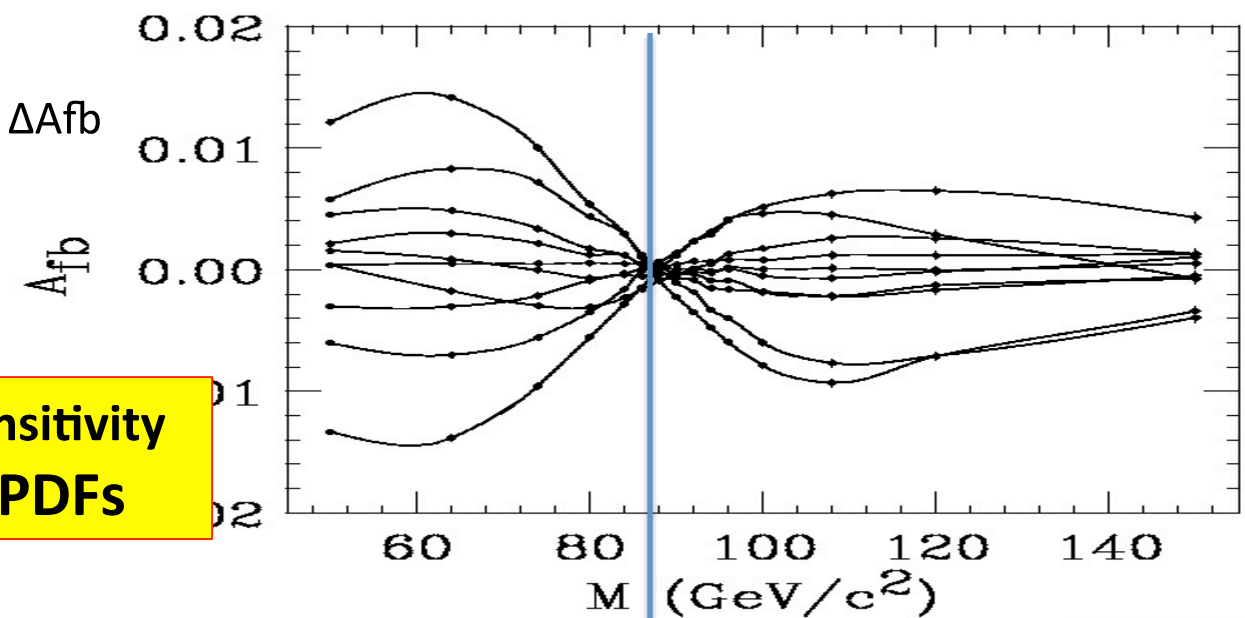


Difference from nominal Afb for $\sin^2\theta_w$=0.2244

All sensitivity is from M=-70 to M=100

$\sin^2\theta_w$ changes Afb in the Z region, where Afb is small. It does not change Afb at low or high mass where Afb is large

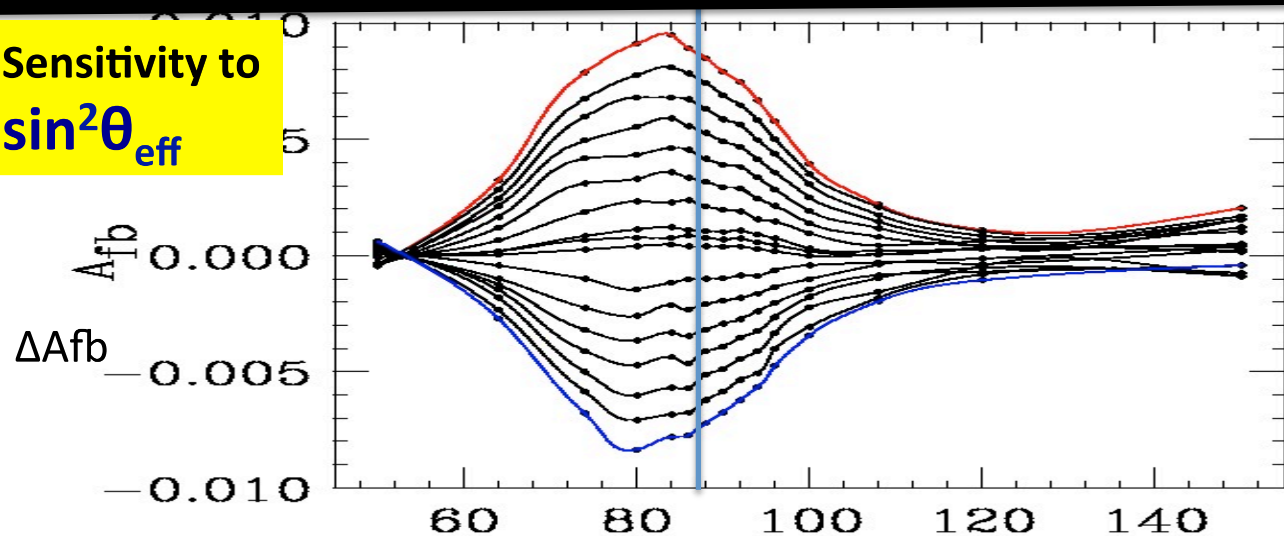
ΔAfb = Afb(M,PDF)−Afb(M,261000) **(Tevatron)**



Sensitivity to PDFs

Different d/u and different level of antiquarks lead to different amount of dilution

Incorrect PDF leads to bad Chis-quare. This cannot be compensated by a different value of **$\sin^2\theta_w$**



Sensitivity to $\sin^2\theta_{eff}$

Different values of $\sin^2\theta_w$ raise or lower Afb in the region between 70 to 100 GeV.

$\sin^2\theta_w$ changes Afb where Afb is small. Wrong PDFs change Afb more where Afb is large. **If we constrain dilution, we reduce PDF error on $\sin^2\theta_w$**

ΔAfb =Afb(M,**$\sin^2\theta_w$**)−Afb(M,**$\sin^2\theta_w$**=0.2244).
Red is **$\sin^2\theta_w$** = 0.222, blue is **$\sin^2\theta_w$**= 0.2265

Standard Extraction of $\sin^2\theta_{eff}$

(and on- shell $\sin^2\theta_w$)

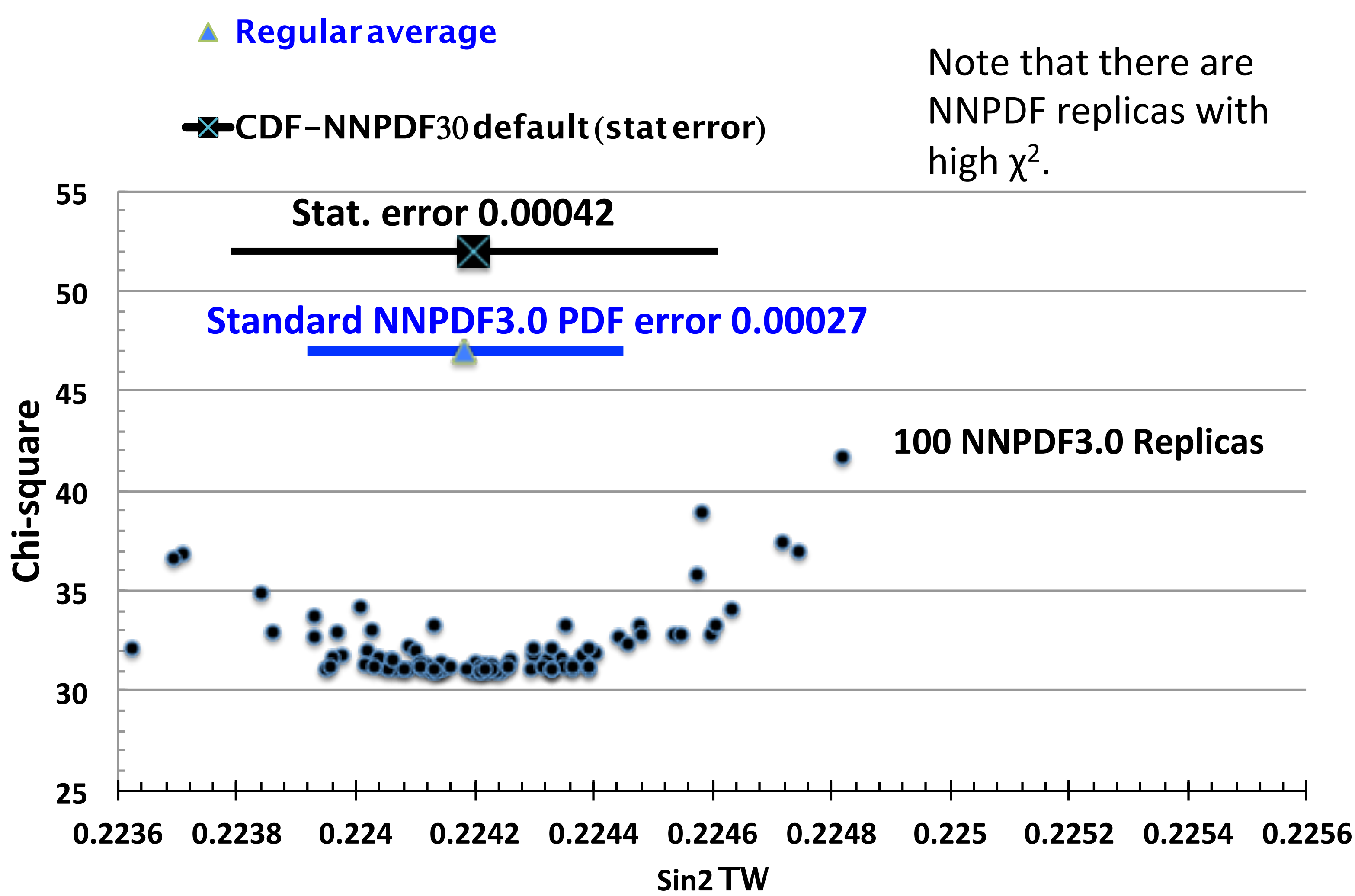
- For every one of the 100 (or 1000) set of PDF replicas for NNPDF3.0 find the $\sin^2\theta_w$ that gives the best fit to Afb

Note: NNPDF3.0 PDFs include LHC data.

(NNPDF2.3 PDFs do not include LHC data and are not as good).

- Without any additional constraints, all 100 PDF sets of NNPDF3.0 are equally likely. Therefore, the **average** value of the 100 (or 1000) determination of $\sin^2\theta_w$ is the measurement, and the RMS of the $\sin^2\theta_w$ from all 100 (or 1000)NNPDF3.0 replicas is the PDF error.

Central NNPDF3.0 NLO taken as Pseudo Data. **CDF-like detector**. Number of events, same as CDF run 2 10 fb^{-1} sample. Here we extract **$\sin^2\theta_W$** (on shell) from pseudo data using each of the 100 NNPDF3.0 replicas (*one experiment*)



However we can do better by using the chi-square values for each of the 100 (or 1000) best fits

NNPDFs can be modified by incorporating new additional data without doing a new global fit.

- Procedure is to assign weights to each of the 100 (or 1000) PDFs according to the chi-square value of the PDF agreement with ANY new data.

- PDFs which give a bad χ^2 are assigned lower **weights.**

- The **new average value** of **$\sin^2\theta_w$** (or any other parameter) is the **weighted average** of the values for the 100 PDFs, and the PDF error is the RMS of the values for the 100 weighted PDFs. The PDF error will be reduced since PDFs with bad χ^2 will not contribute to the new weighted average of $\sin^2\theta w$.

- Since the mass dependence of Afb to PDF and to $\sin^2\theta w$ is different, DY Afb data can be used to do both: better constrain PDFs AND the better constrained PDFs can be used to yield a reduced PDF error in $\sin^2\theta w$ (or any other SM parameter)

The procedure is more general

- Updated weighted PDFs can be used to reduce the PDF errors in other measurements (e.g. W mass). This is because the x range of the Z data is the same as the x range for the W mass data, so the Afb constrained PDFs should also be good for W mass.

- In addition, any new measurements (e.g. W asymmetry) can also be incorporated. The weights of the updated PDFs can include the χ^2 information from both the Afb data and the new W asymmetry data. This should work since all these measurements are at the same range of x

.

- Example of other new precise measurements that can be incorporated is *more precise data on Z rapidity distributions*, and dσ/dη for μ+ and μ- leptons from W decays (not yet measured) (but here, we need to include NNLO K factors).

What is the relation between weights and χ^2

- The NNPDF paper has a prescription, of how to do it: http://arxiv.org/pdf/1012.0836v4.pdf

Weight = $[\chi^2]^{(n-1)/2}\,[\exp(-\chi^2/2)]$

- Giele and Keller (GK), published previously, have a different prescription http://arxiv.org/pdf/hep-ph/9803393v1.pdf

Weight = $[\exp(-\chi^2/2)]$

- Sato et. al. discusses the difference between the two and concludes that the GK method is unbiased and will yield smaller errors.

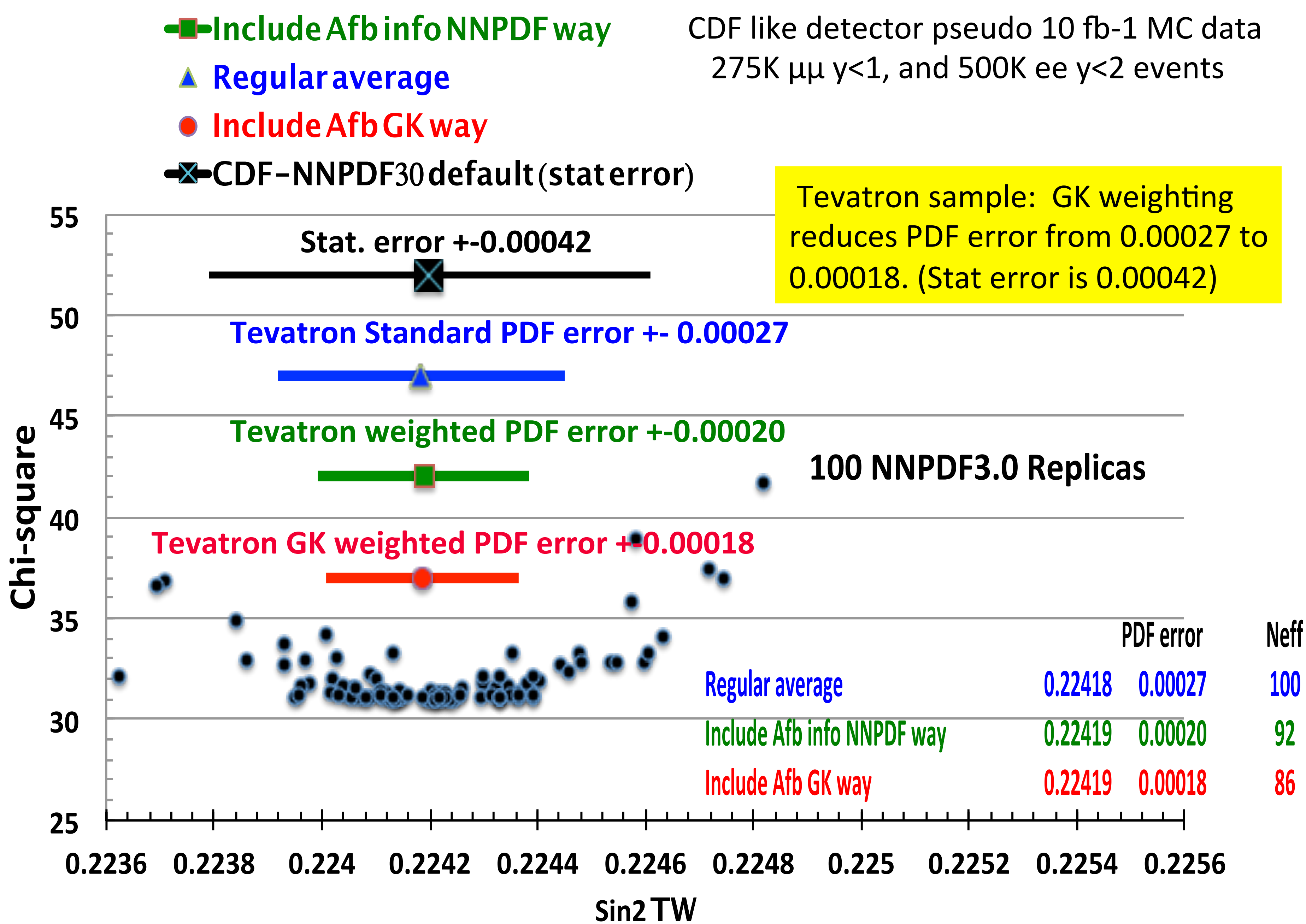
  http://arxiv.org/pdf/1310.1089v1.pdf

Compare three estimates of the NNPDF3.0 errors to fits to Afb to get $\sin^2\theta_W$. *Number of Afb points =n.*

1. **The average** of results using 100 NNPDFs is the best value and the RMS of the 100 results is the PDF error.

Now we can reduce the error by using the information of how well does each PDF fit the Afb data.

2. **NNPDF method**, weight each NNPDF with a weight which is proportional to $[\chi^2]^{(n-1)/2}[\exp(-\chi^2/2)]$. (n is the number of Afb data points). Take average and RMS of the results using the 100 weighted PDFs
3. **GK method** , weight each NNPDF with a weight which is proportional to $[\exp -(\chi^2/2)]$. Take average and RMS for the results using the 100 weighted PDFs (Sato et al paper says this weighting is optimal)



Include Afb info NNPDF way
Regular average
Include Afb GK way
CDF-NNPDF30 default (stat error)
CDF like detector pseudo 10 fb-1 MC data
275K μμ y<1, and 500K ee y<2 events
Tevatron sample: GK weighting reduces PDF error from 0.00027 to 0.00018. (Stat error is 0.00042)
Stat. error +-0.00042
Tevatron Standard PDF error +- 0.00027
Tevatron weighted PDF error +-0.00020
100 NNPDF3.0 Replicas
Tevatron GK weighted PDF error +-0.00018
PDF error
Neff
Regular average 0.22418 0.00027 100
Include Afb info NNPDF way 0.22419 0.00020 92
Include Afb GK way 0.22419 0.00018 86
Chi-square
55
50
45
40
35
30
25
0.2236
0.2238
0.224
0.2242
0.2244
0.2246
0.2248
0.225
0.2252
0.2254
0.2256
Sin2 TW

A quick study using Tree Level analysis.
Pseudo-data = CTEQ6.6 PDF + Resbos

Pseudo-Experiment *Tevatron* $10\ fb^{-1}$ $500K\ e^+e^-$ events	ResBos CTEQ 6.6	ResBos CTEQ 6.6
$\sin^2\theta_W$ input	0.22420	0.22420
statistical error $\Delta\sin^2\theta_W$	±0.00042	±0.00042
PDF error (*CT10 PDFs*)	±0.00026	±0.00026
Tree-level Analysis replicas NNPDF set	100 NNPDF3.0	100 NNPDF2.3
extracted $\sin^2\theta_W$ bias *PDF error RMS* Average method	0.22425 +0.00005 ±0.00027 $N_{eff} = 100$	0.22469 +0.00049 ±0.00027 $N_{eff} = 100$
extracted $\sin^2\theta_W$ bias *PDF error weighted* (*NNPDF method*)	0.24425 +0.00005 ±0.00024 $N_{eff} = 99.2$	0.24462 +0.00042 ±0.00025 $N_{eff} = 94.6$
extracted $\sin^2\theta_W$ bias *PDF error weighted* (*GK method*)	0.22425 +0.00005 ±0.00020 $N_{eff} = 91.3$	0.22452 +0.00032 ±0.00021 $N_{eff} = 70.5$

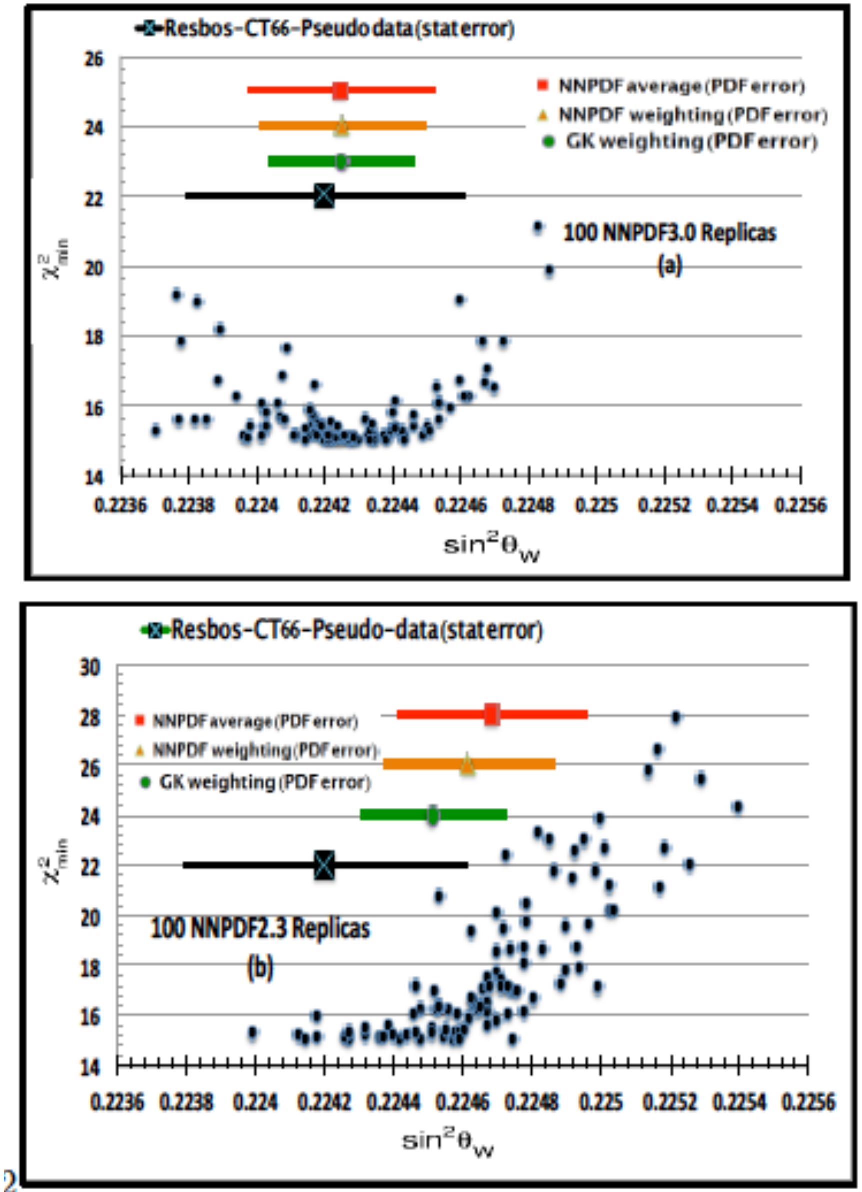


Fig. 5. Tevatron: (a) Analysis of pseudo experiment generated with CTEQ 6.6 PDF and $\sin^2\theta_W$=0.22420 with ResBos. The analysis is done using 100 NNPDF3.0 replicas. (b) The same pseudo experiment, but here the analysis is done using 100 NNPDF2.3 replicas.

8 TeV LHC pseudo data

Afb data at the LHC provides much more information on PDFs.
P-P collisions have much larger level of dilution from antiquarks, and the dilution is a function of rapidity y and dilepton.

Afb is measured as a function of mass in several rapidity bins all of which should have the same SW2.

We do a MC pseudo-data study for CMS like detector with 15M dimuon events at 8 TeV.

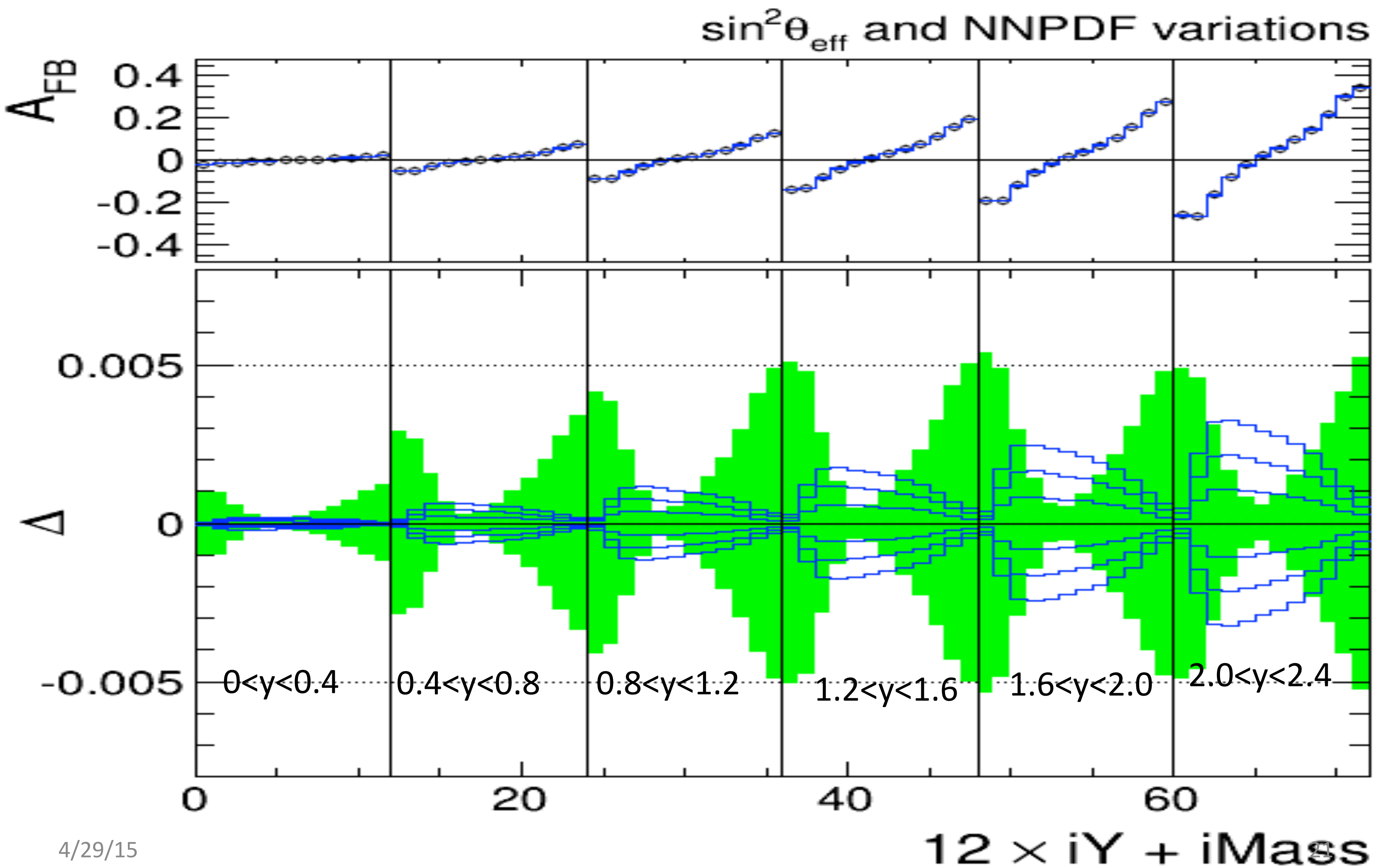
MC sample is similar to current CMS 8 TeV sample (18.8 fb-1 for MC vs 22M events for data).

Repeat this study for 64 pseudo experiments.

CMS Like detector: **Green band is RMS variation from different PDFs.**

Blue lines are variation from different EW mixing angles SW2.

(note that dilution decreases for higher rapidity y).

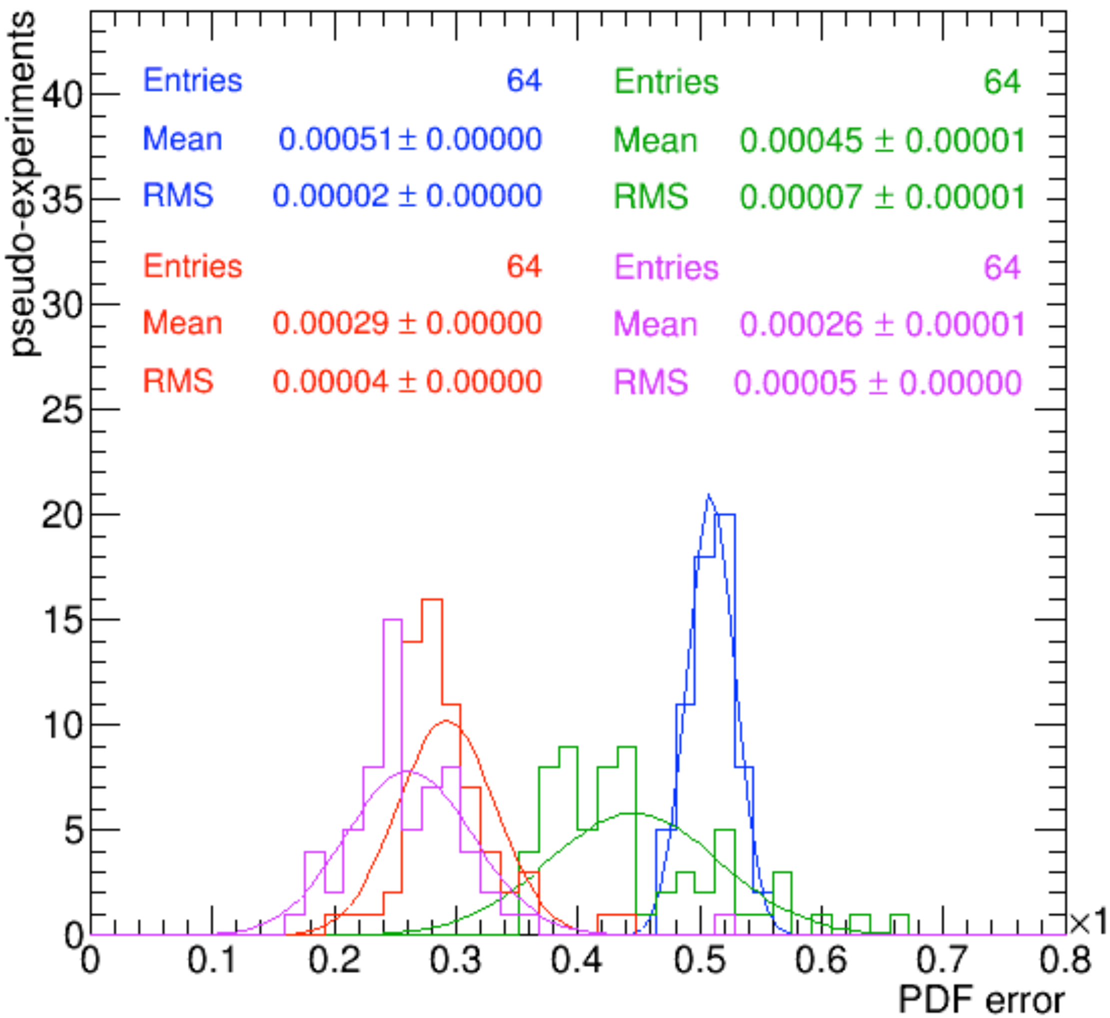


MC study of CMS like detector

- MC pseudo Data: NNPDF3.0 NLO with LHC data Central PDF. Generated with Effective EW mixing angle of 0.23120.
- Statistics a little less than the current CMS 8 TeV muon data. (error in EW mixing angle of 0.00047 (vs data stat error is 0.00043). Each pseuodo experiment has 15 M events vs data which has 22 M events)
- Do the analysis with 100 NNPDF3.0 NLO replicas (these PDFs include LHC data).
- Investigate what happens if we also include new 8 TeV W asym pseudo data and its corresponding statistics in the analhsis
- Do 64 pseudo-experiments look at distributions and take the mean of the results.

PDF errors for **unconstrained** and constrained NNPDF3.0
For the 64 pseudo-experiments (8 TeV CMS muon sample)

Stat error 0.00050
CT10 PDF error 0.00077



Method ***PDF error***

AFB data
Unconstrained NNODF3.0
100 replicas σ_{PDF}= +- 0.00051

AFB data
Constrained NNPDF3.0
Weighting σ_{PDF}= *+- 0.00045*

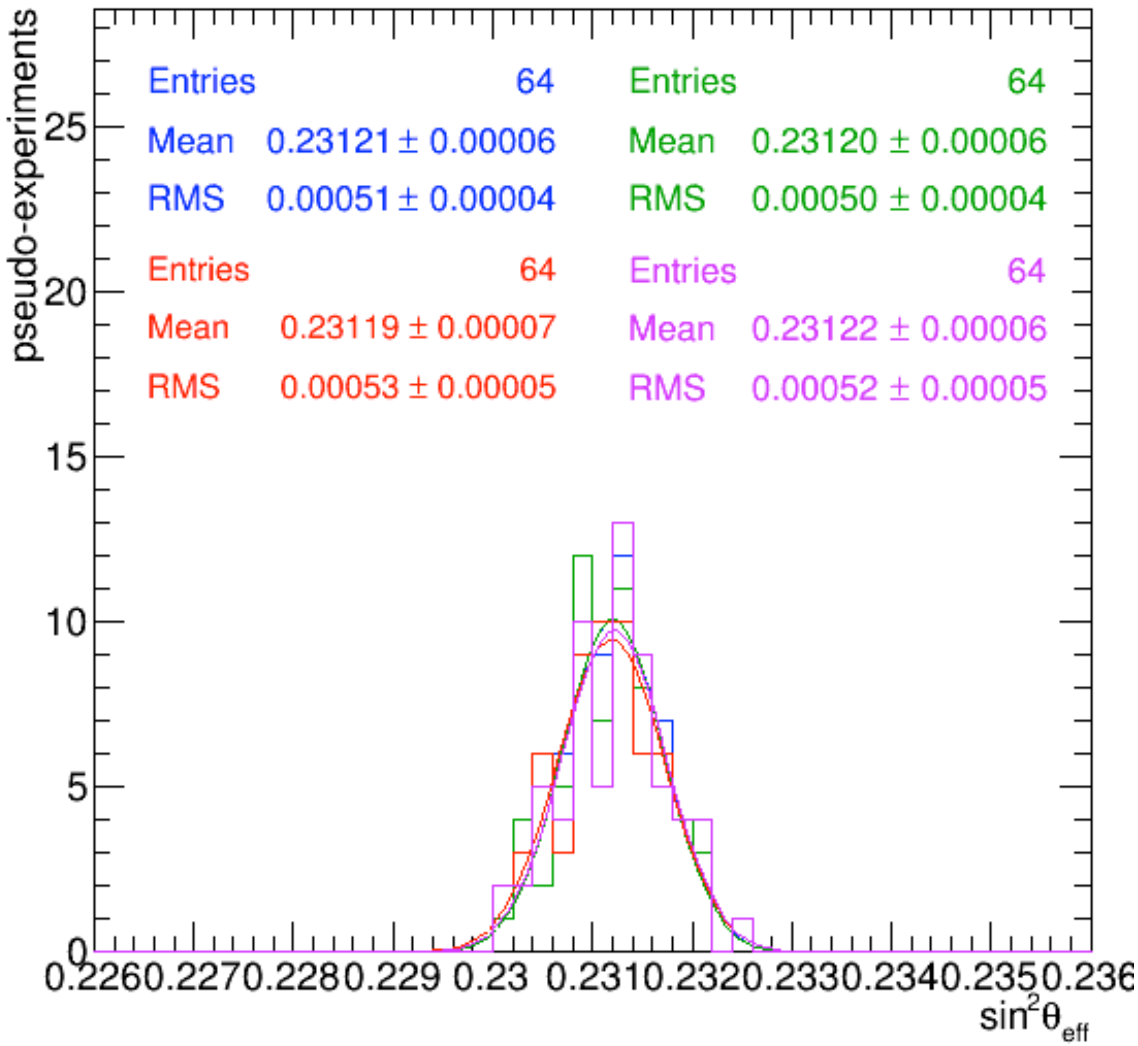
AFB data
NNPDF3.0 Constrained
GK weighting σ_{PDF}= +- 0.00029

AFB data
GK Constrained Plus also
8 TeV W asym data
Weighting σ_{PDF}= +- 0.00026

*At 8 TeV, Afb and new W asym data reduce PDF errors to +- **0.00026.** **Factor of 3 smaller than CT10. PDF errors no longer dominate. Statistical errors dominate (but will become very small with 13-14 TeV data)***

Check for Bias from input value of SW2 for **unconstrained** and constrained NNPDF3.0 for the 64 pseudo-experiments

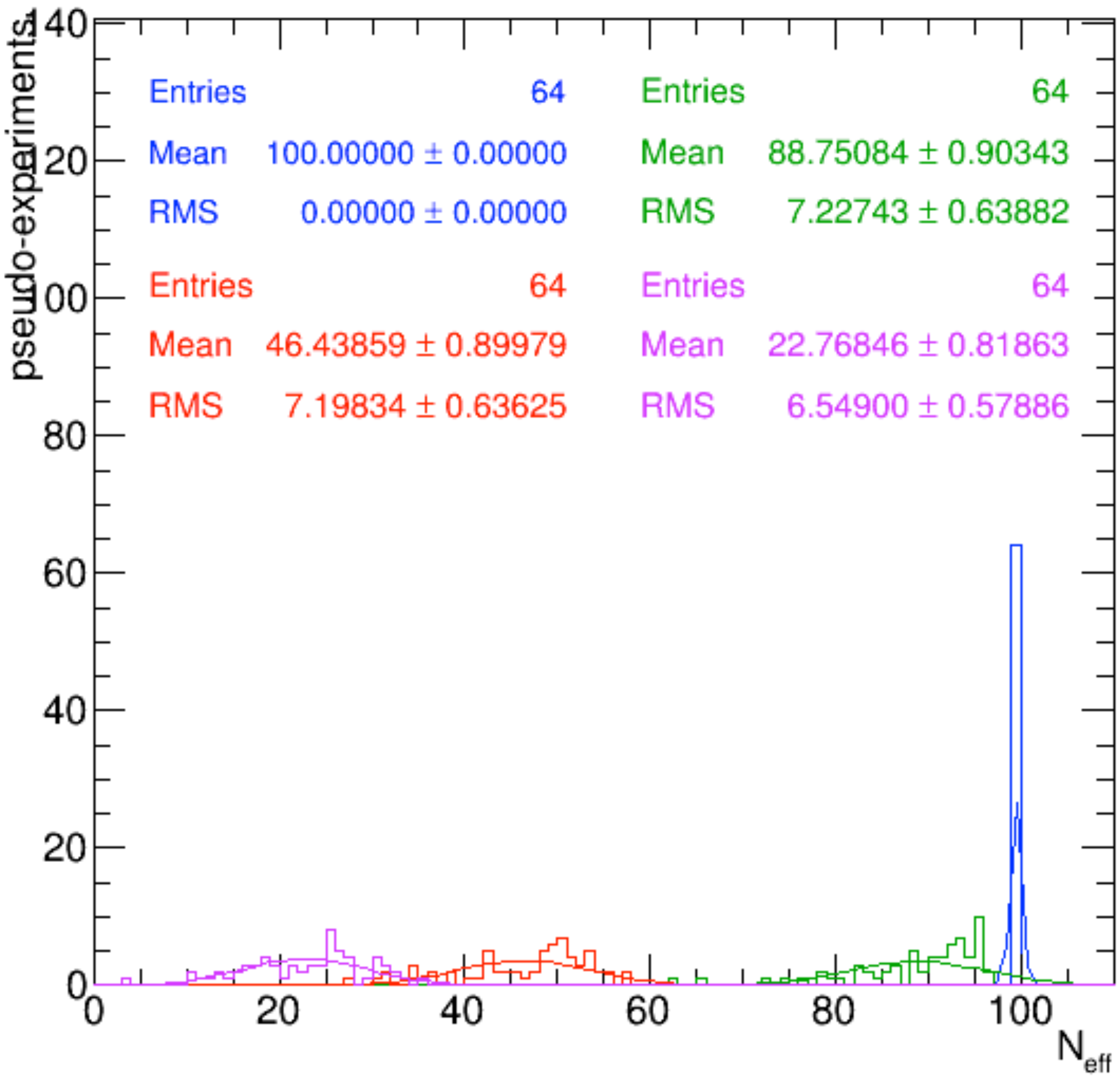
Input $\sin^2\theta_w$ = 0.23120



Method	Extracted EW mixing angle
AFB data Mean of 100 replicas	0.23121+-0.00006
AFB data NNPDF Weighting	0.23120+-0.00006
AFB data GK weighting	0.23119+-0.00007
AFB data Plus W asym Data GK Weighting	0.23122+-0.00006

We use central NNPDF3.0 pdf as pseudodata, and use 100 NNPDF3.0 pdf replicas to do the analysis. All method yields same central value.

What is the number of effective replicas for for **unconstrained** and constrained NNPDF3.0 for various levels of constraints.



Method	# of effective replicas
AFB data Mean of 100 replicas	100
AFB data NNPDF Weighting	89
AFB data GK weighting	46
AFB data Plus W asym Data GK Weighting	23

Method will work better with 1000 replicas (will soon be available for NNPDF3.0)

Conclusions

- LHC Drell-Yan Afb data with current 8 TeV statistics (and 8 TeV W asymmetry data) can be used to reduce PDF errors by a factor of about 3 with respect to CT10.

- These improved PDFs can be use to reduce PDF errors for precision SM parameters measurements with W and Z Bosons (e.g. $\sin^2\theta_{eff}$, $\sin^2\theta_W$ and W mass)

- The NNPDF replica method allows LHC experiments to further constrain PDFs using any new data without having to wait for new PDF fits. The constrained PDF sets are obtained by reweighting of the most recent NNPDF set. Therefor, they can be used several analyses.

- Higher statistics at 13 and 14 TeV, Afb data can be used to further constrain PDF. Just as the error in $\sin^2\theta_{eff}$ and $\sin^2\theta_W$ becomes smaller, the constraints on PDFs also improve with more statistics. At 13-14 TeV the statistical error on $\sin^2\theta_{eff}$ and $\sin^2\theta_W$ become negligible.

- Precision measurements of EW parameters at the LHC are possible because the PDF errors can be brought under control. Error on the indirect measurement of the W mass with 13-14 TeV can be smaller than 10 MeV. (Note that unlike Afb, the W mass measurement can only be done with low luminosity (due to pileup)).