Extraction of the EW mixing angle from precision measurements of A_{FB} in dilepton events at hadron colliders

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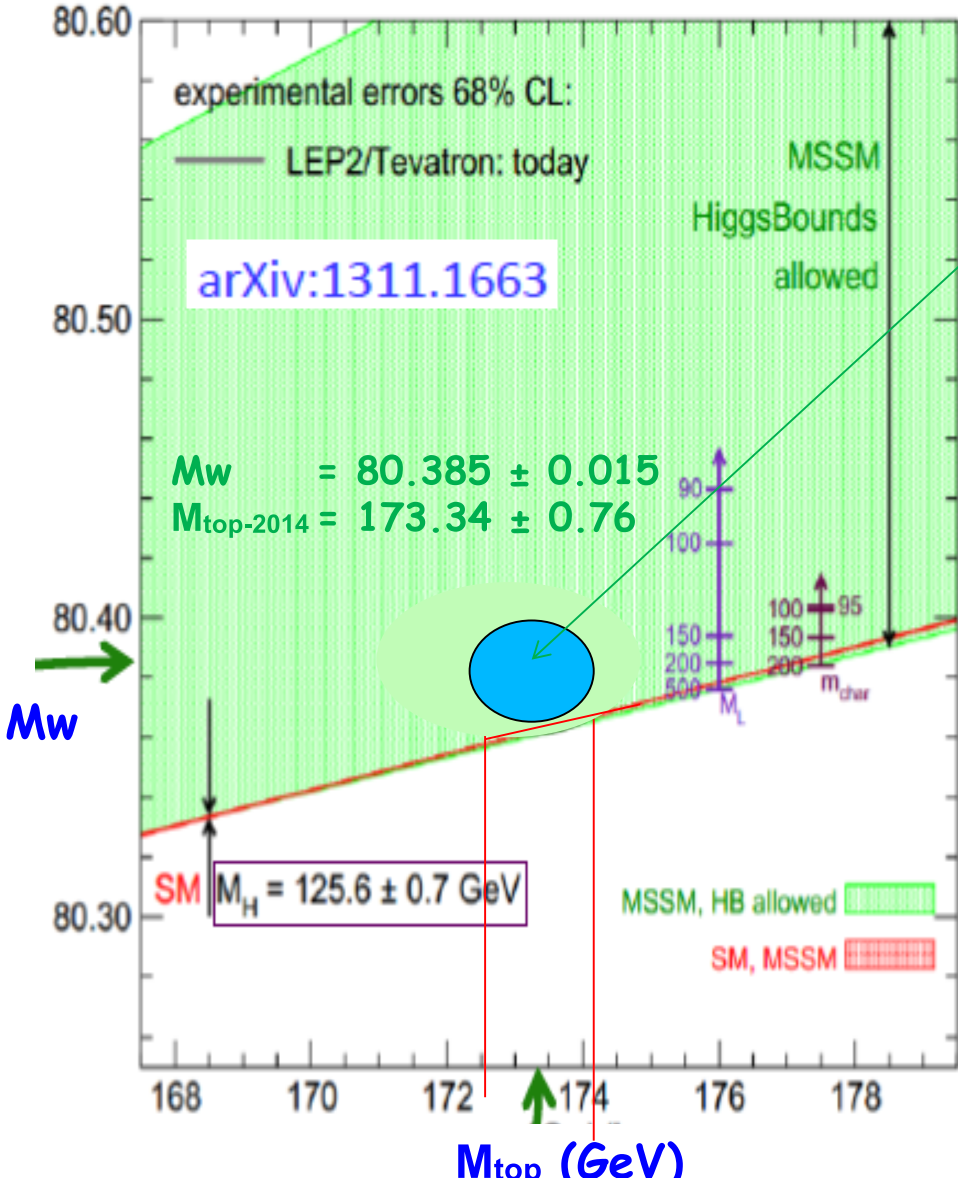
15:20-15:40

TSEI / PHE

TSEI Tests of Symmetries and the Electroweak Interaction
PHE Physics at High Energies
High Precision Extraction of *AFB* at the LHC

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.

Alternatively:

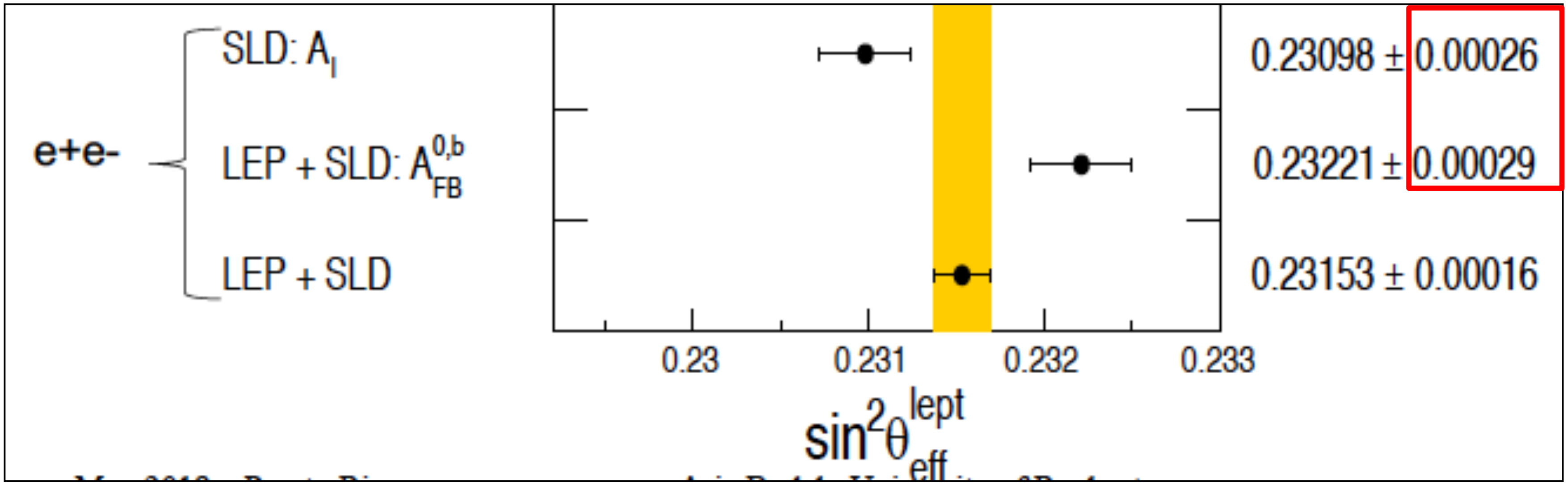
Since M_H is known, if one includes radiative corrections, M_W can also be determined via

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

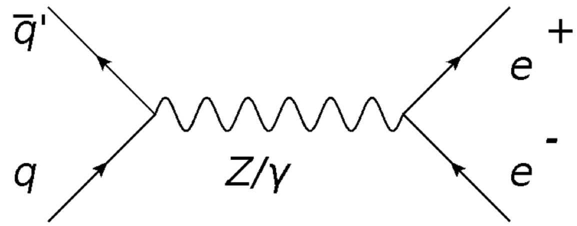
Both $\sin^2\theta_W^{on\text{-}shell}$ and of $\sin^2\theta_W^{eff}$ can be extracted from the Drell-Yan forward-backward asymmetry (Afb).

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)

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



Dilepton production at Hadron Colliders



The axial and vector neutral currents interfere

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

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

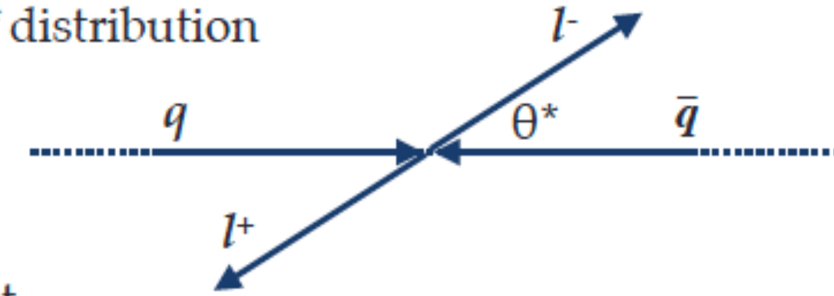
What is actually measured with dilepton events is the effective lepton EW mixing angle

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

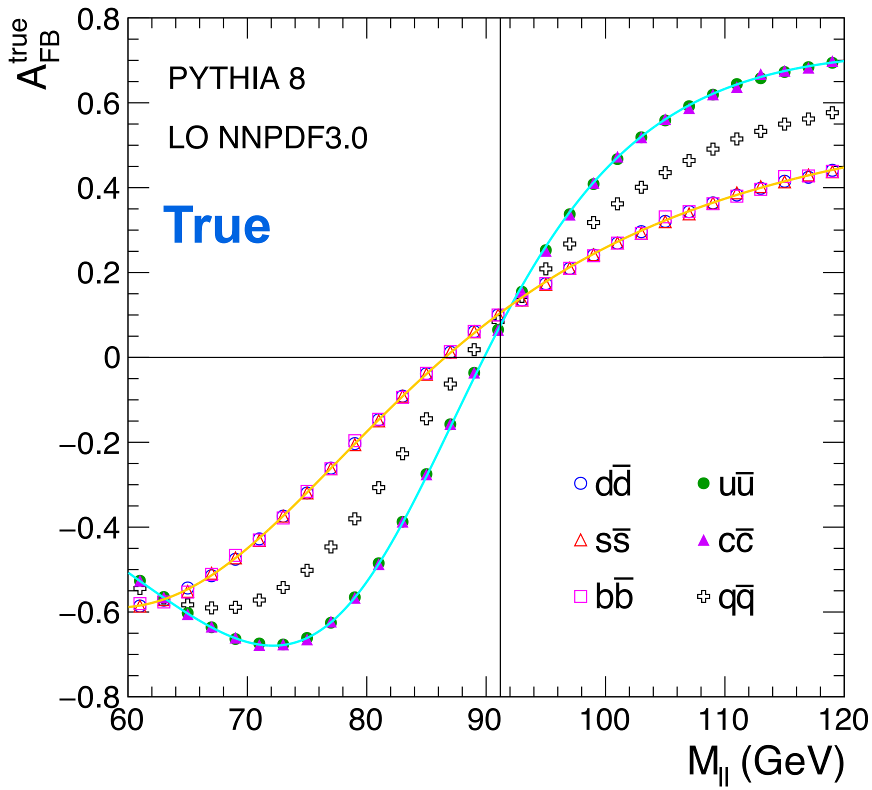
↳ ≈1.037

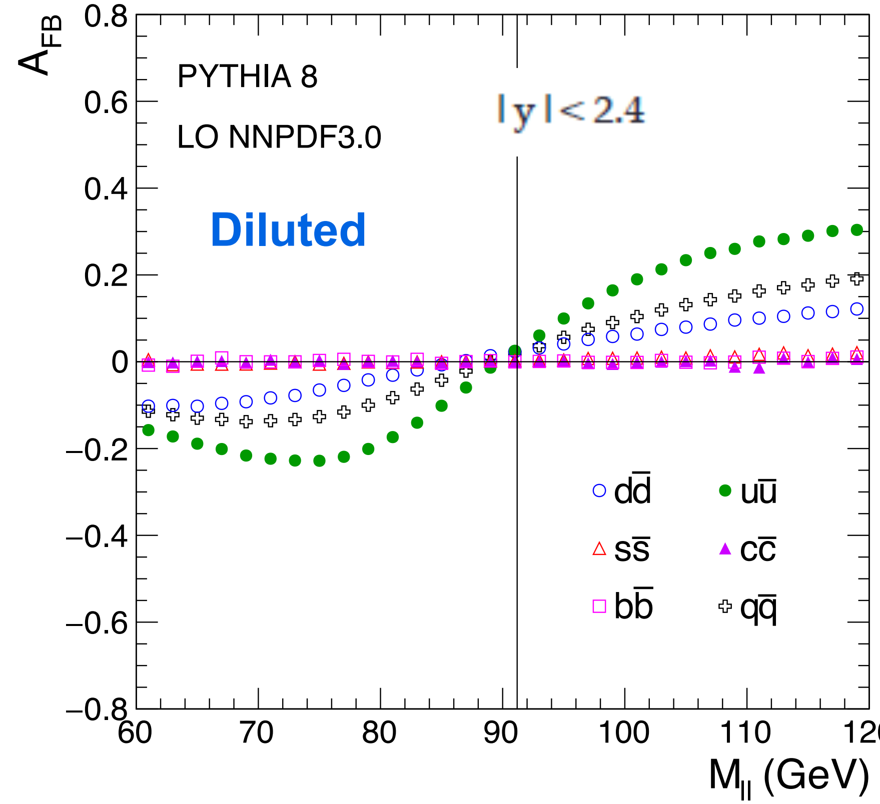
A_{FB} in dilepton events at LHC

- 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:



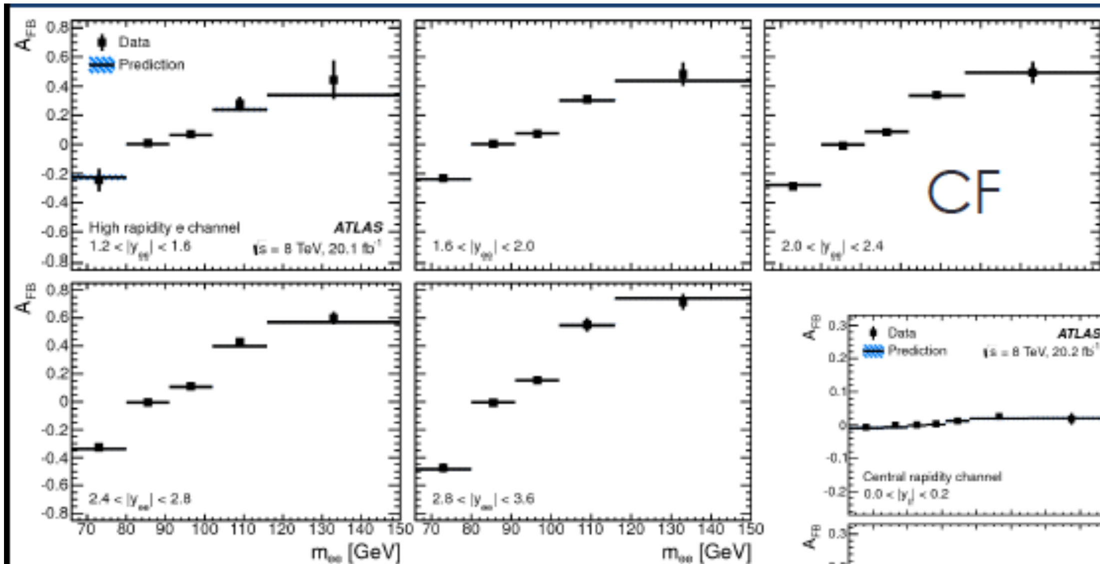
1. **Fraction of valence u vs. d**
2. **Dilution (y dependent) from high x antiquarks**

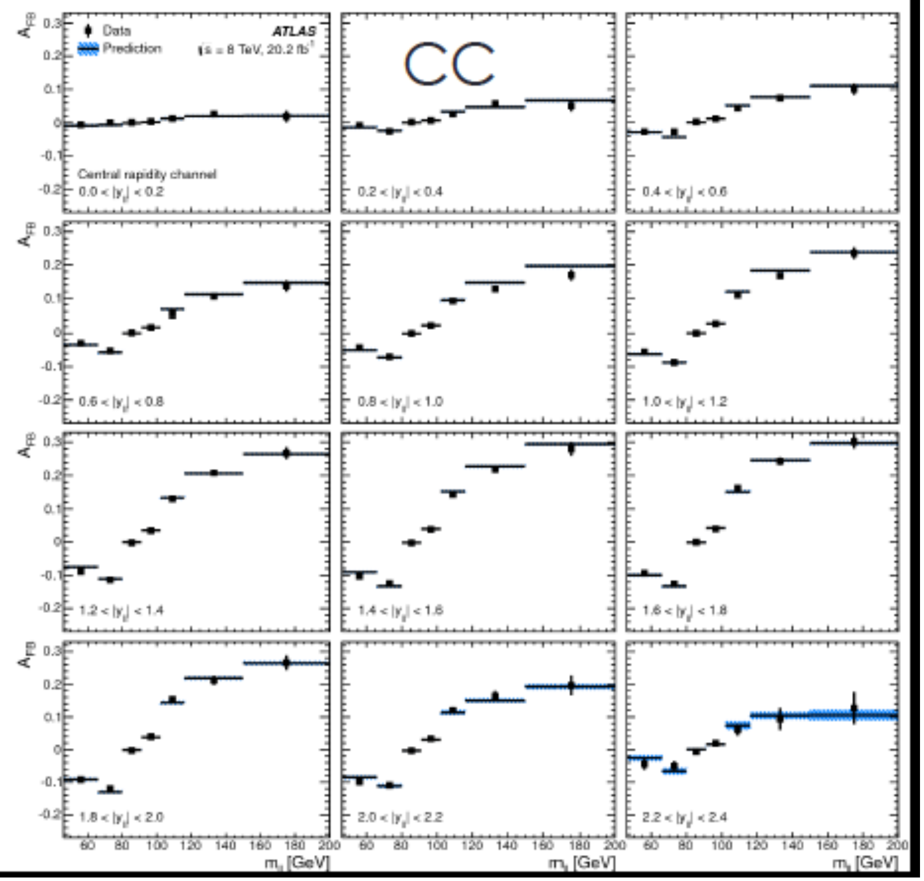




Weak mixing angle by ATLAS at 7 TeV PRD 84 (2011) 112002

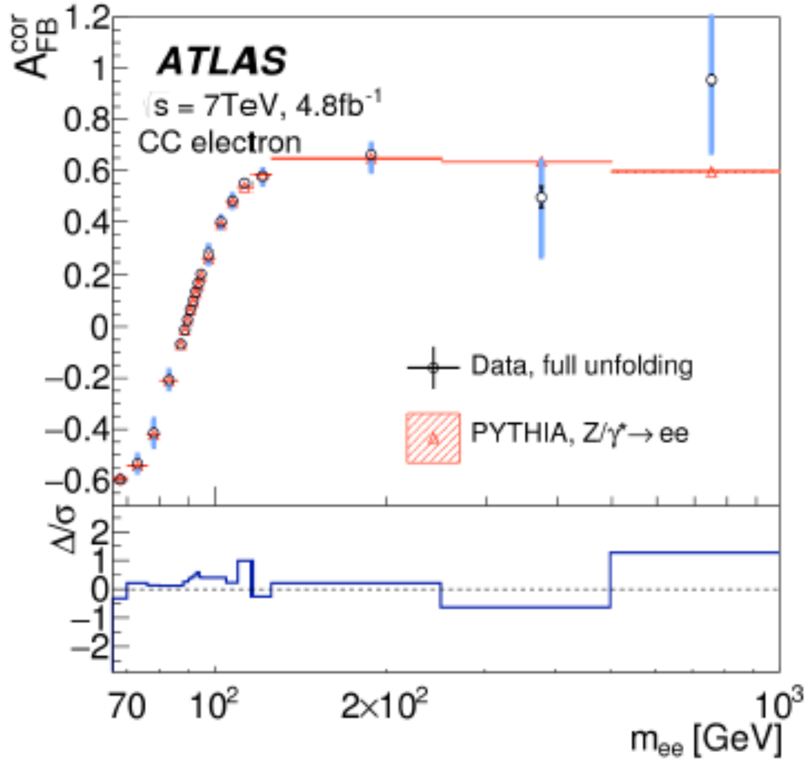
ATLAS 7 TeV
published 2011

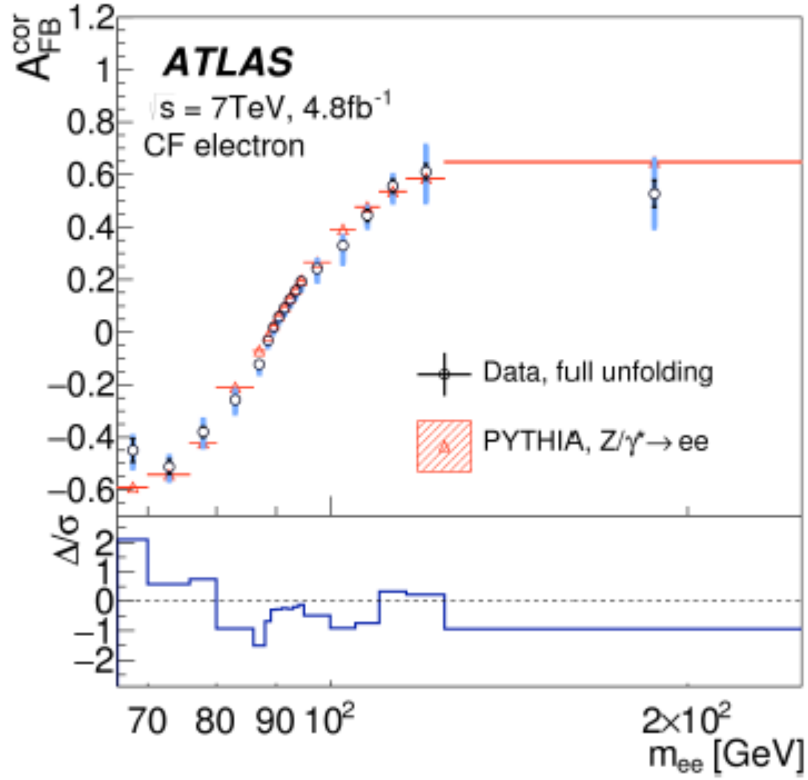




- Systematic errors cancel in AFB
- Dominated by statistical errors
- $\delta \sim 1\times10^{-3}$ in CC and 4×10^{-3} in CF
- Good description by theory
-

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





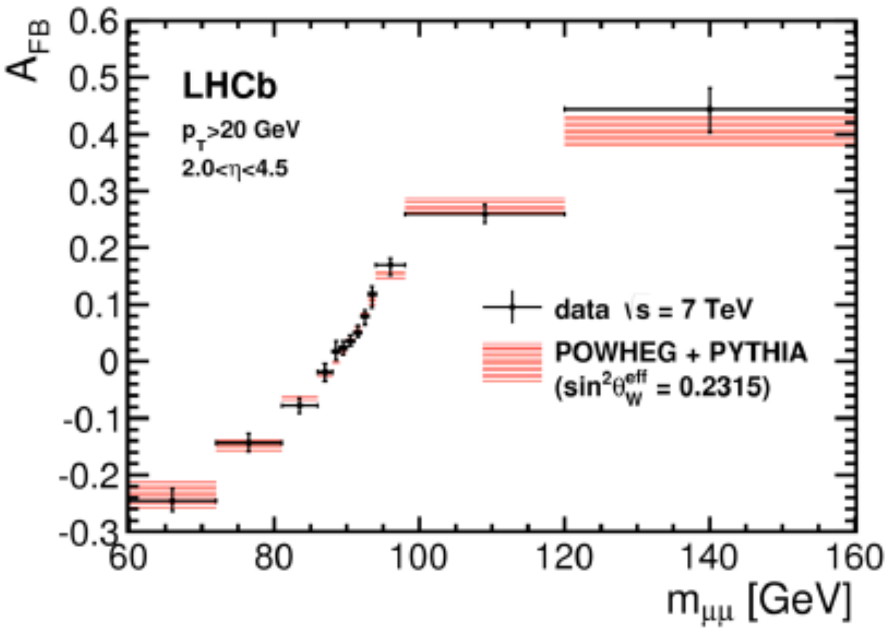
	$\sin^2\theta_{\rm eff}^{\rm lept}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.})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

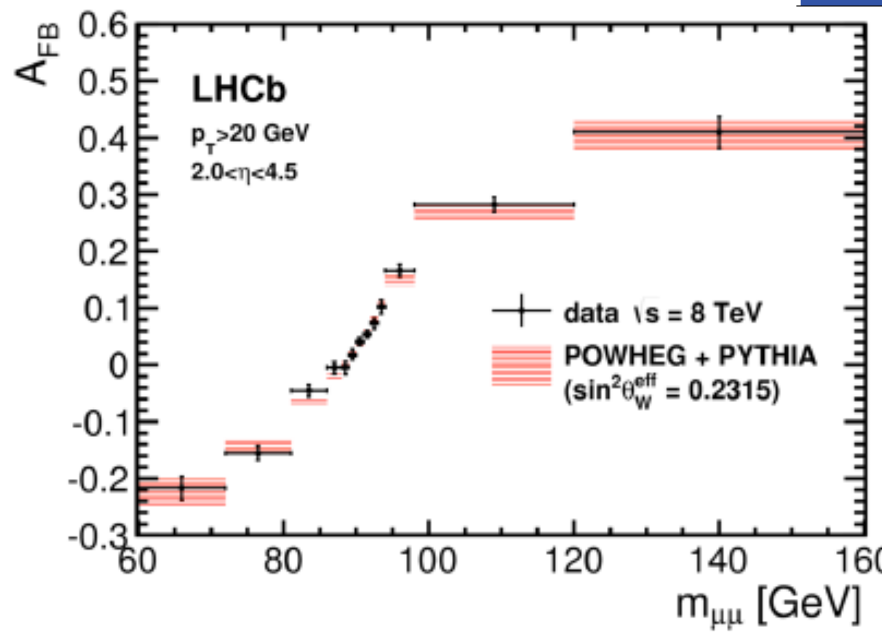
$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23080 \pm 0.00120$

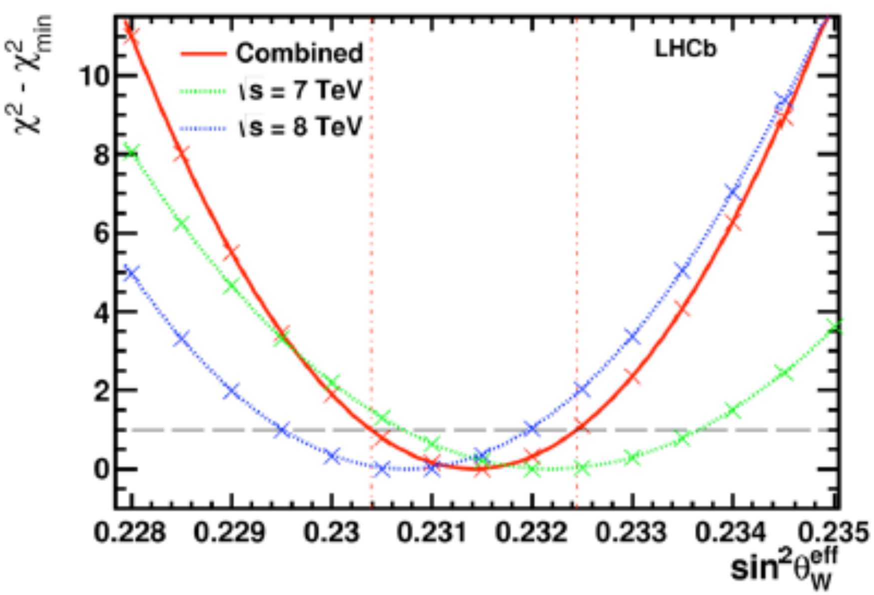
Standard PDF errors

Weak mixing angle by LHCb

JHEP 1511(2015) 190







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

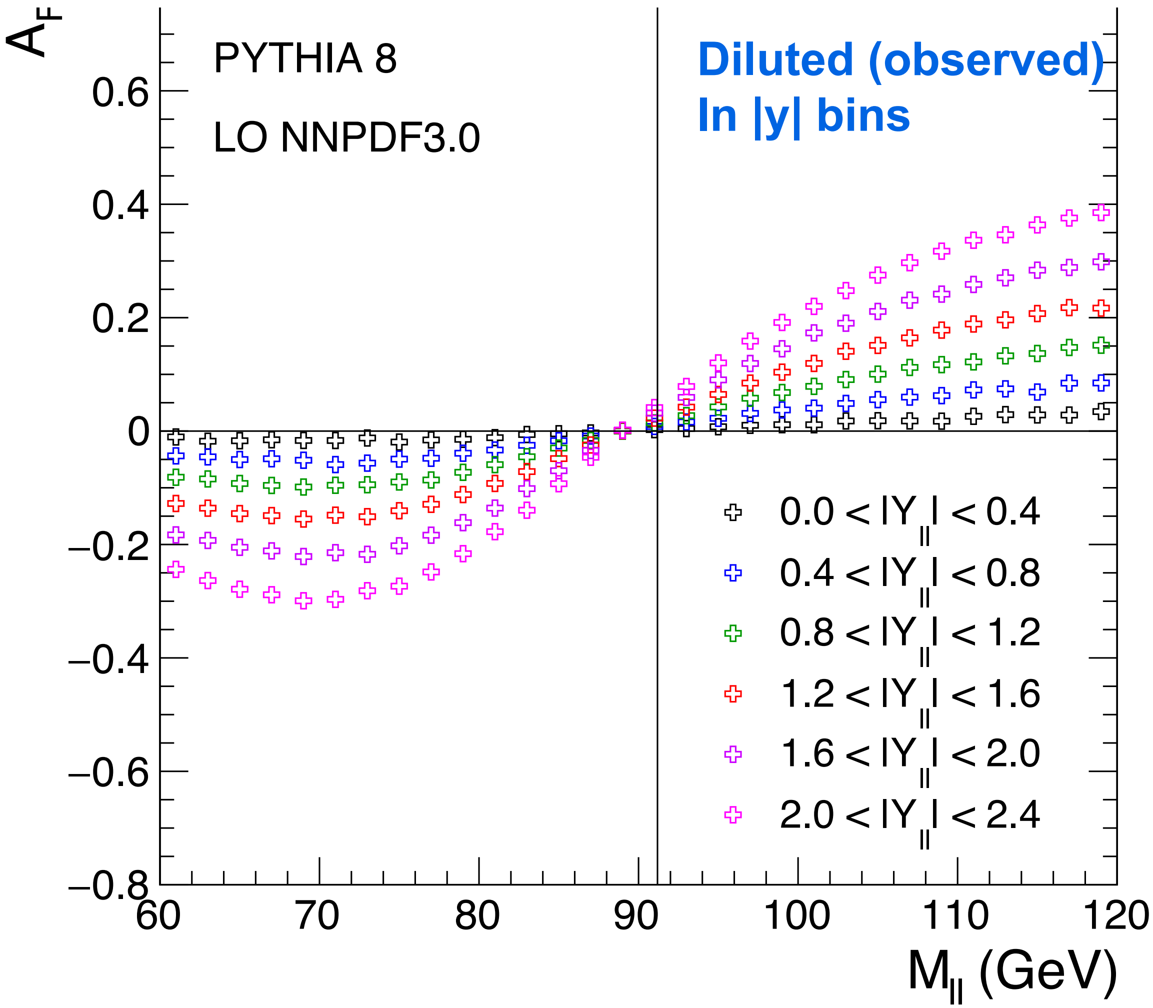
$$\sin^2\theta_W^{eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$

(stat) (syst) (th+pdf)

0.23142 ± 0.00106 Standard PDF errors

CMS PAS SMP-16-007

- 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



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 $\sin^2\theta_{eff}$.

To be submitted for publication

Precision measurement at CMS 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)

CMS 8 TeV Analysis
To be submitted for publication

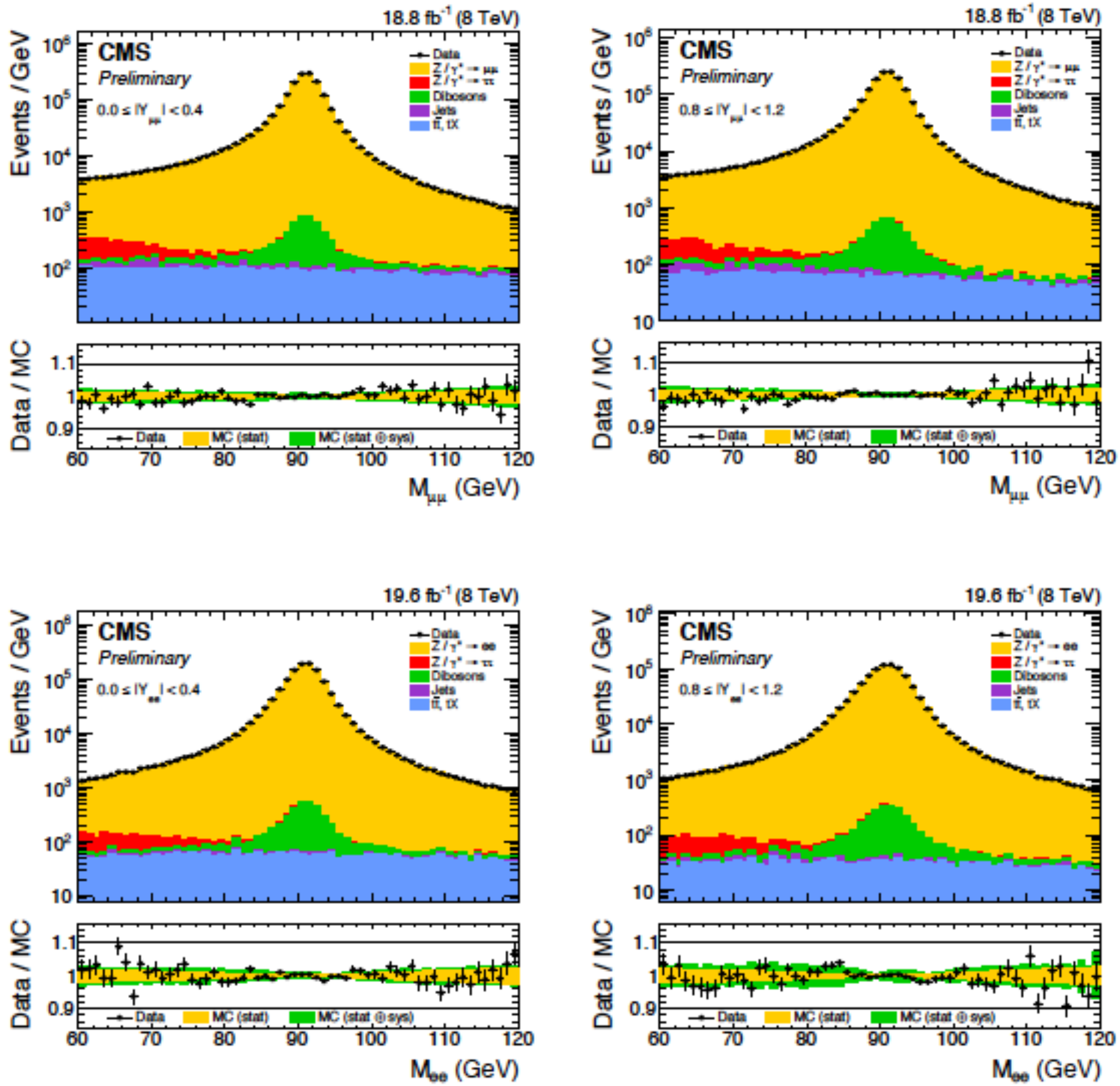
Mass distributions

CMS PAS SMP-16-007

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

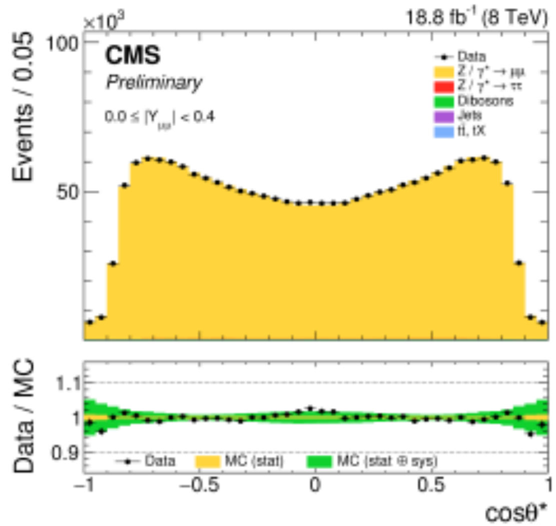


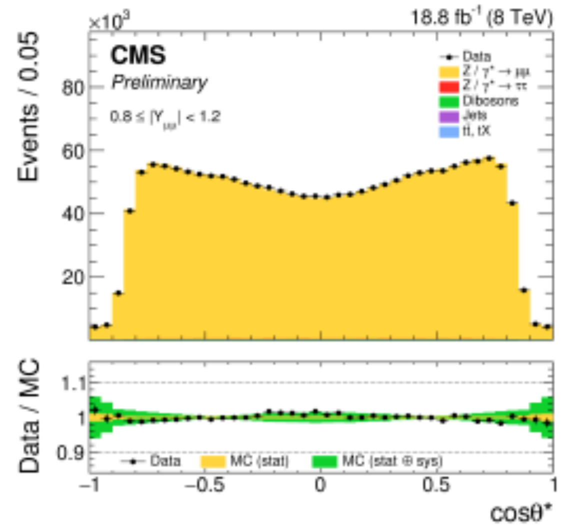
CMS 8 TeV Analysis
To be submitted for publication

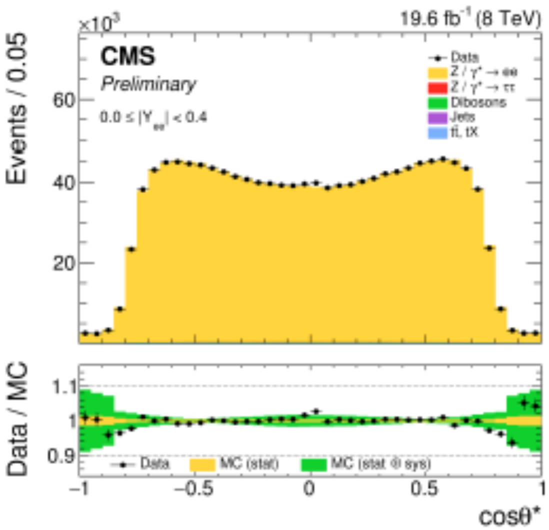
Cosθ distributions

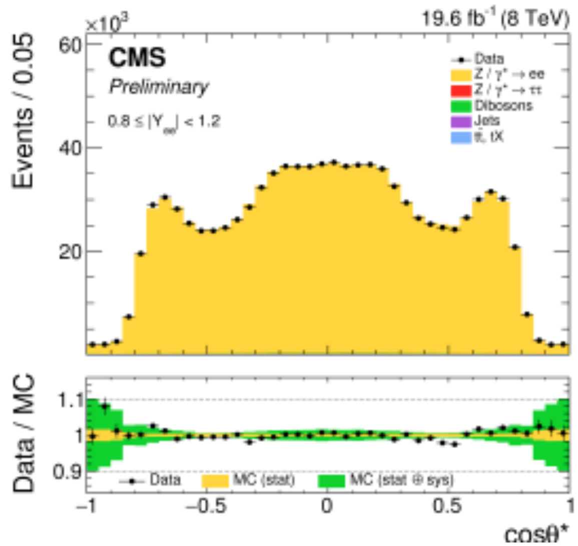
CMS PAS SMP-16-007

- 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

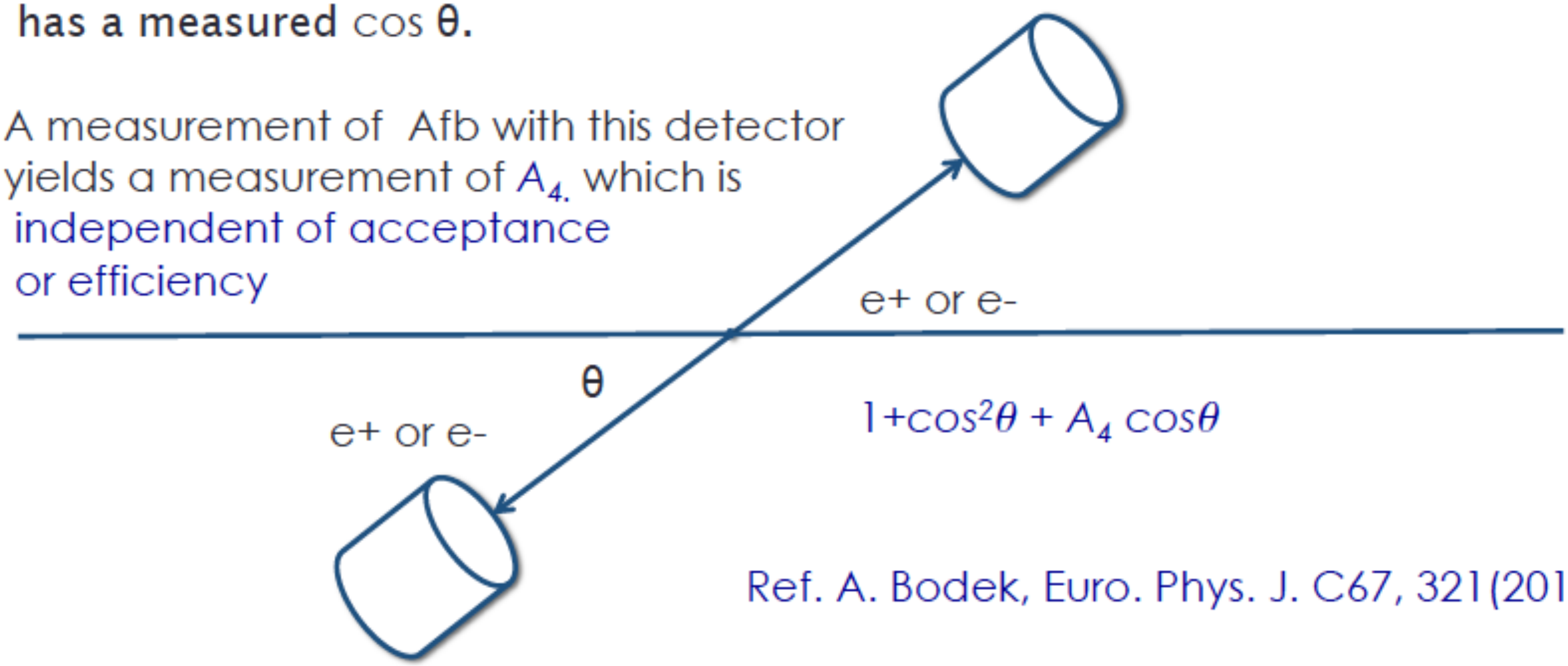
CMS 8 TeV Analysis
To be submitted for publication

Details: Angular event weighting method (used in CMS)

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.**

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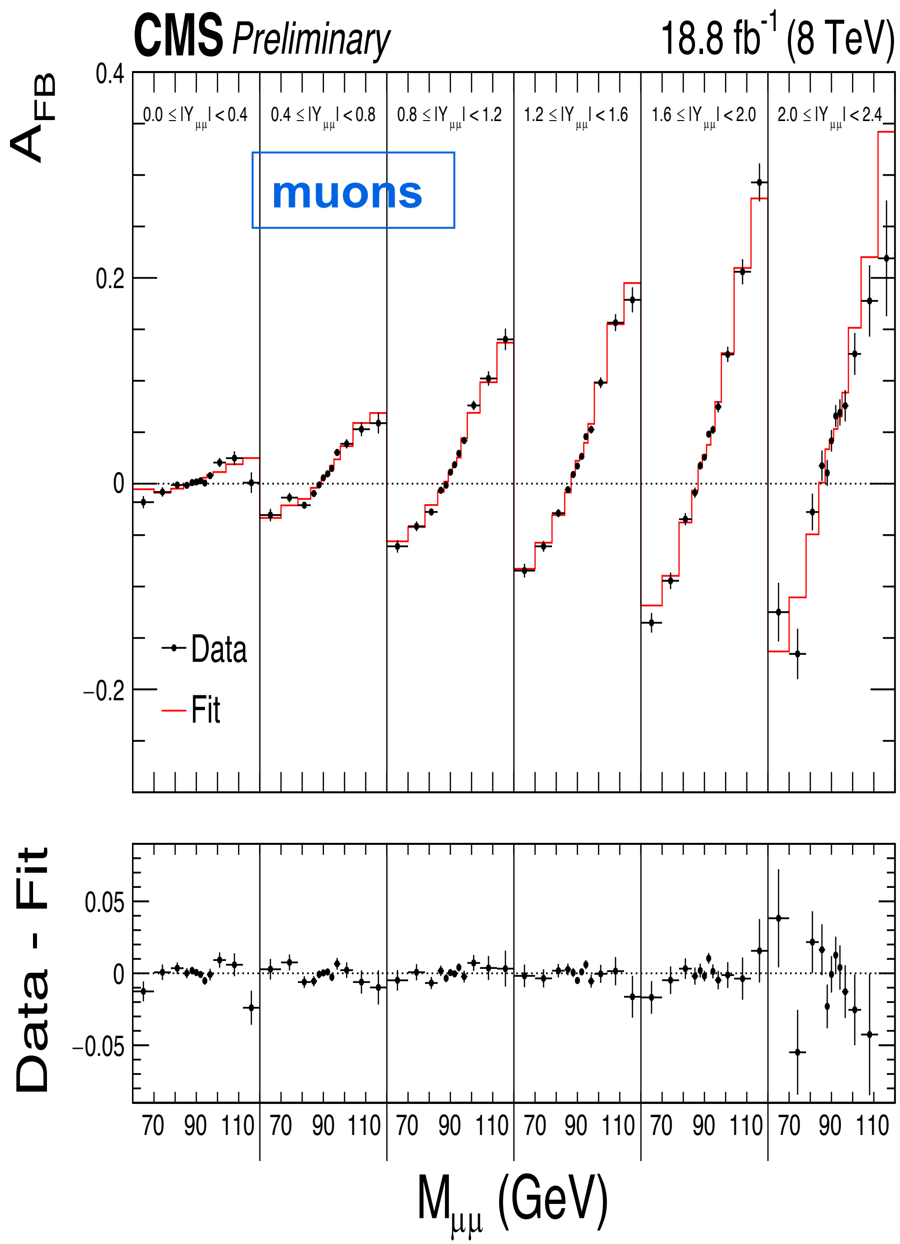
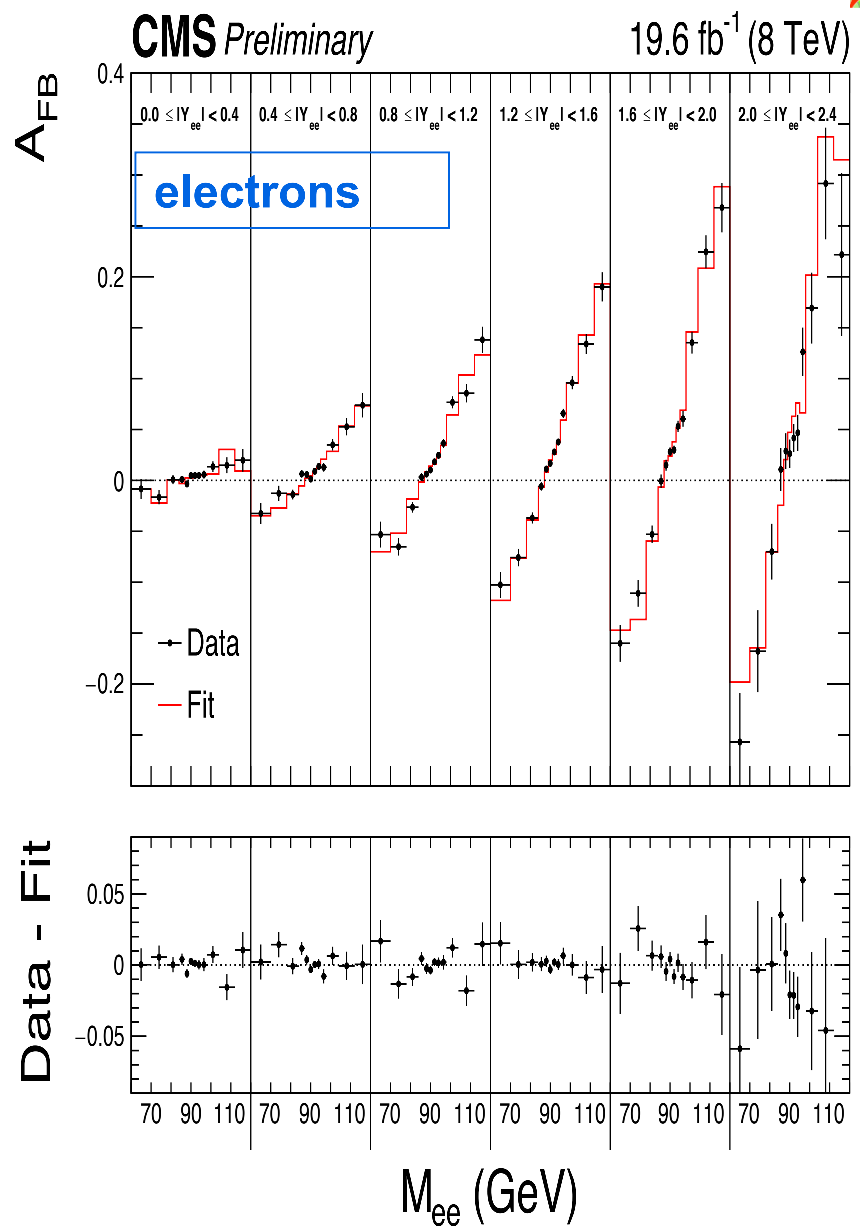
- Weighted AFB in 6 dimuon rapidity x 12 mass measurement bins





CMS 8 TeV Analysis
To be submitted for publication

CMS PAS SMP-16-007

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

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 ($\sin^2\theta^{lept}_{eff} - \sin^2\theta^{u,d}_{eff}$)	0.00001	0.00001
Total	0.00015	0.00017

Combined ± **0.00016 (theory)**

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

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

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)

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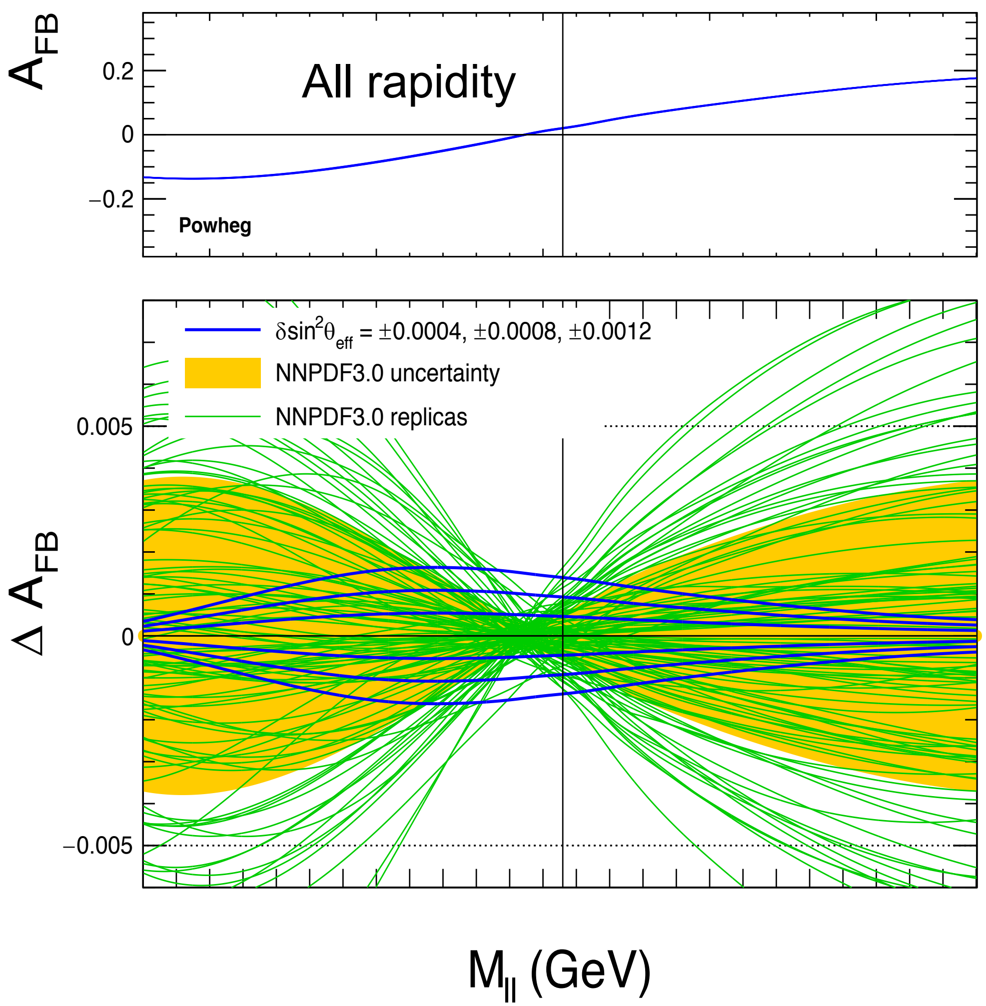
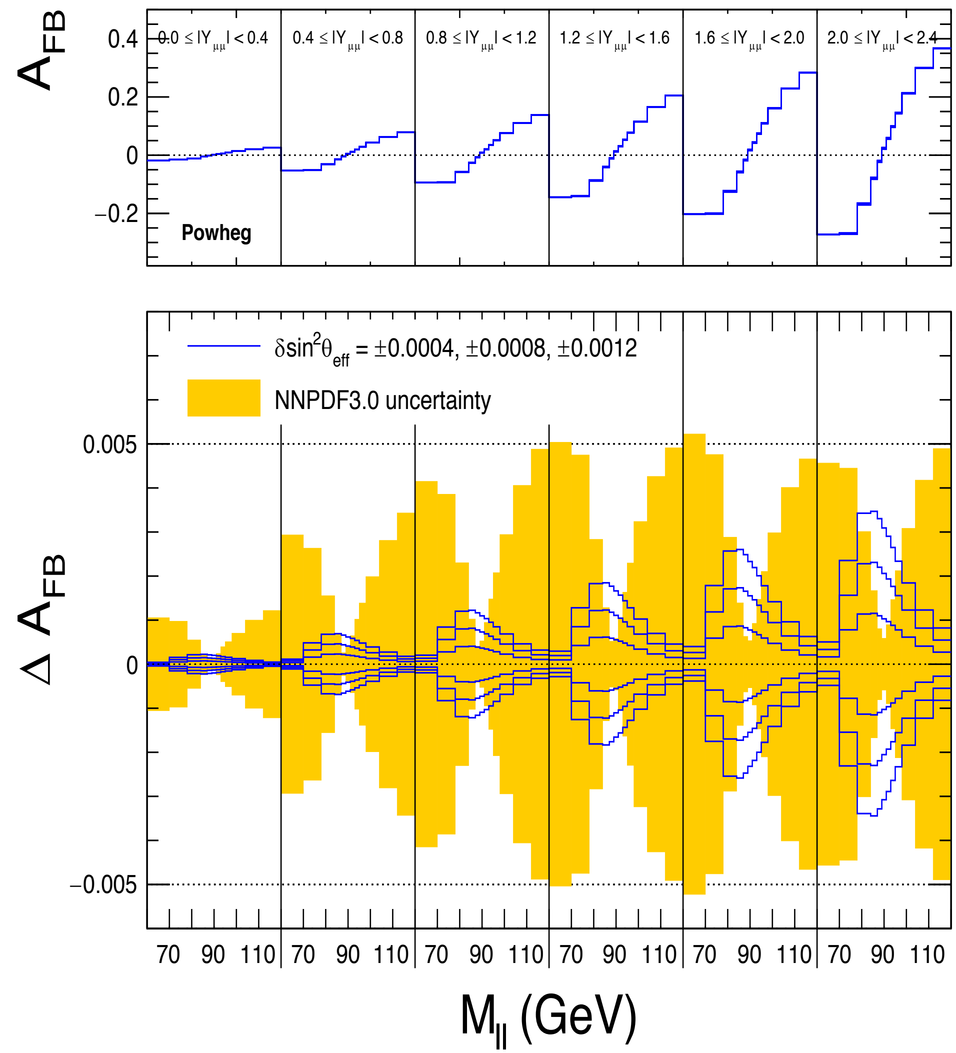
BLUE : Vary **$\sin^2\theta_{eff}$** for fixed PDF

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





CMS PAS SMP-16-007

New Technique used by 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 $\sin^2\theta_{\mathrm{eff}}$ 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 **$\sin^2\theta_{\mathrm{eff}}$**

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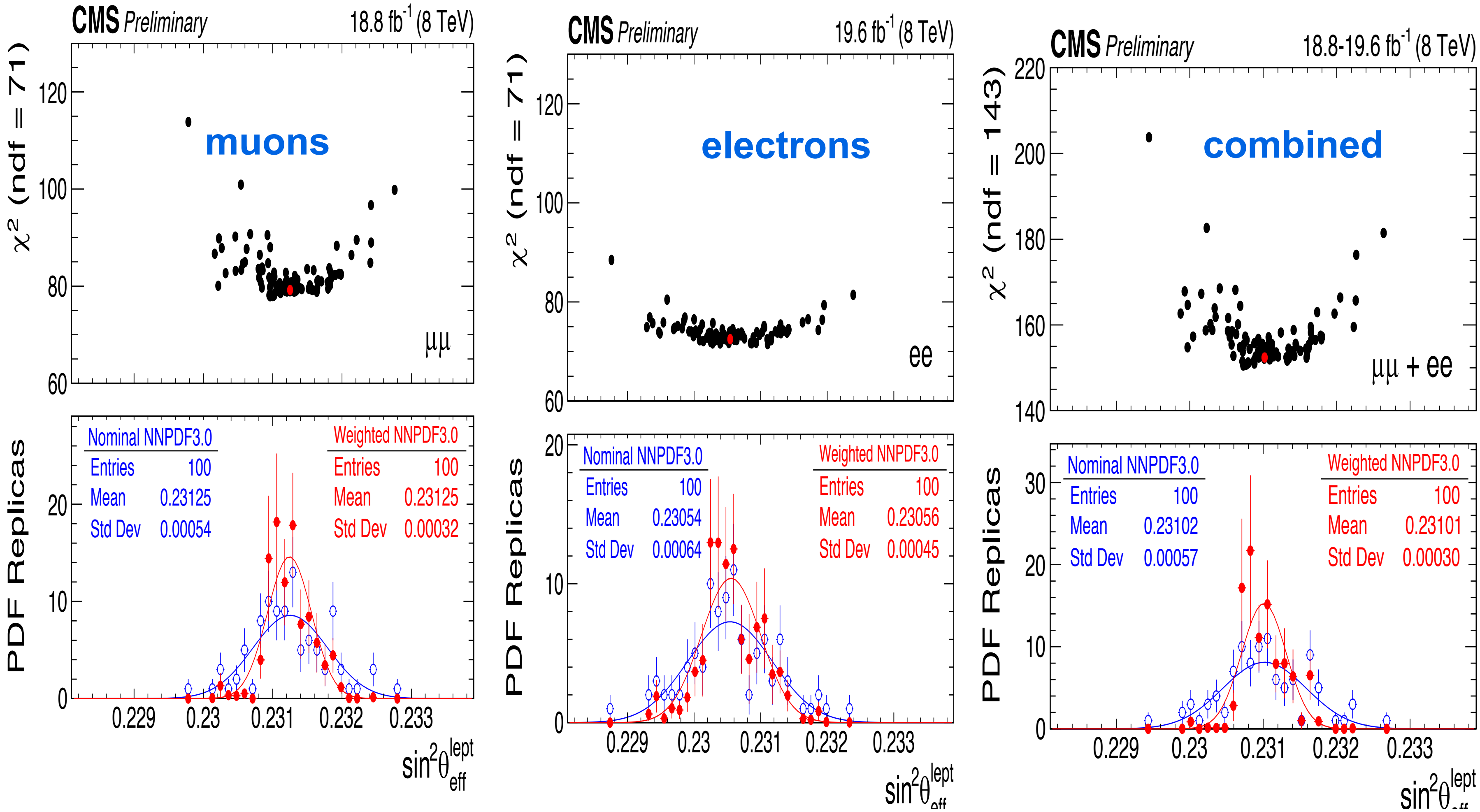
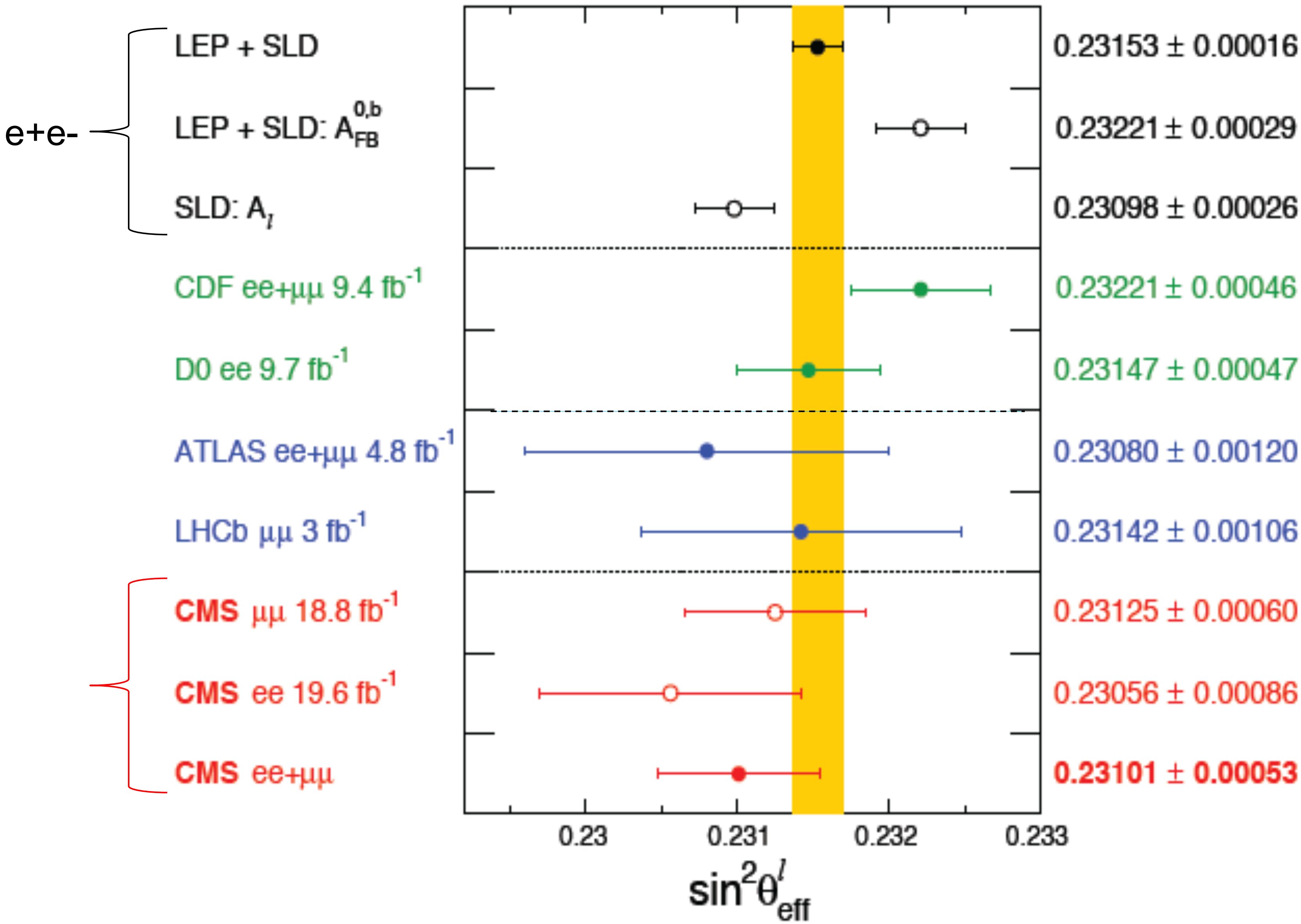


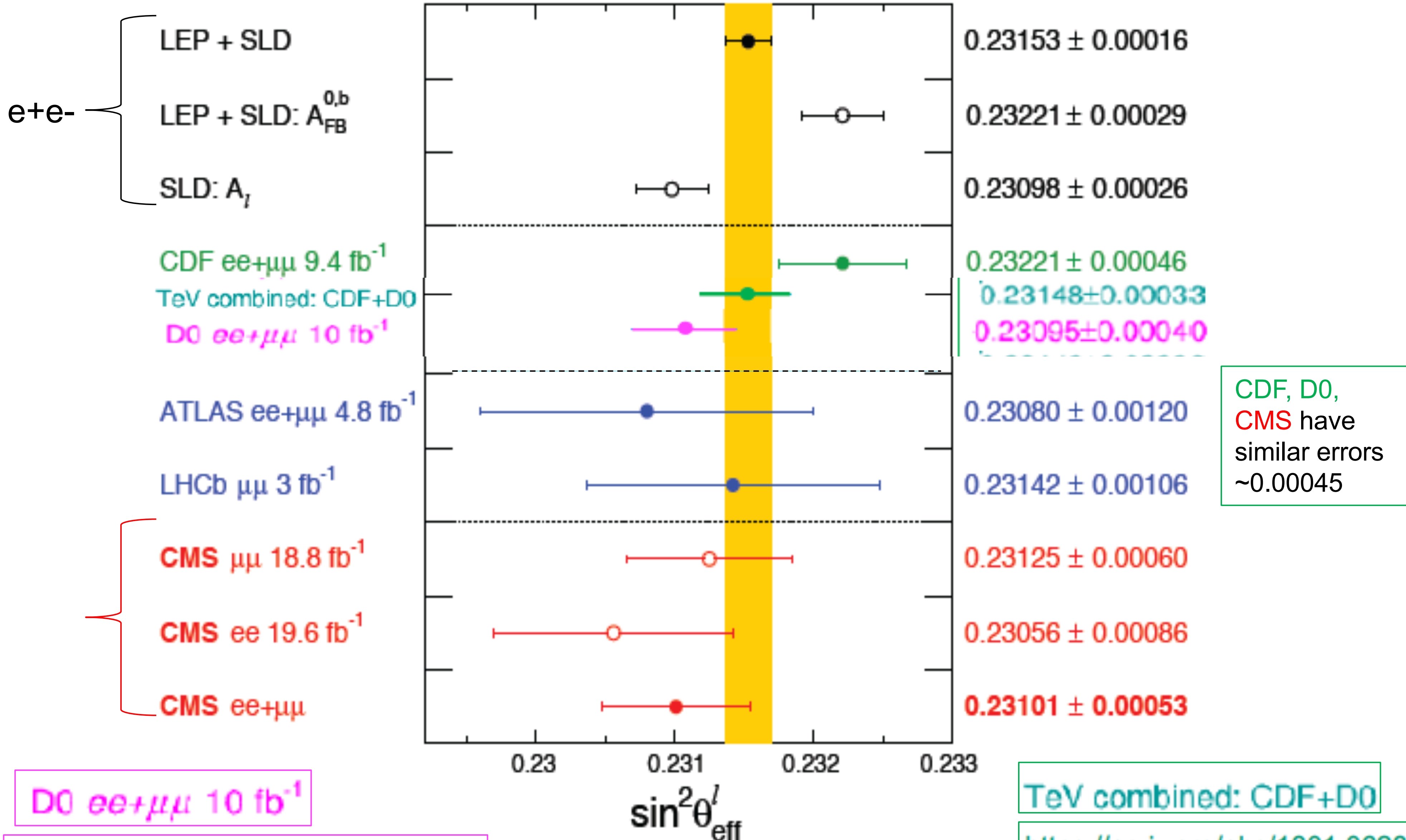
Channel	without constraining PDF	with constraining PDFs
Muon	$0.23125 \pm 0.00048 \pm 0.00054$	$0.23125 \pm 0.00048 \pm 0.00032$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$	$0.23056 \pm 0.00069 \pm 0.00054$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

CMS PAS SMP-16-007



CDF, D0, CMS have similar errors ~0.00045

CMS PAS SMP-16-007



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

arXiv:1710.03951 [hep-ex]

Add: Tevatron combination

TeV combined: CDF+D0

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

Outlook for the future at the LHC *CMS-PAS-FTR-17-001*

Current Tevatron combination 10 fb-1:

Total EW mixing angle error 0.00033 which corresponds to 17 MeV uncertainty in indirect measurement of Mw.

Current CMS 8 TeV results 20 fb-1:

Total EW mixing angle error 0.00052 which corresponds to 26 MeV uncertainty in indirect measurement of Mw.

Future LHC 14 TeV 1000 fb-1

Each LHC detector will have negligible statistical error.
PDF EW mixing angle constrained to 0.00014 which corresponds to 7 MeV uncertainty in indirect measurement of Mw.