Measurement of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

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Electroweak precision measurements

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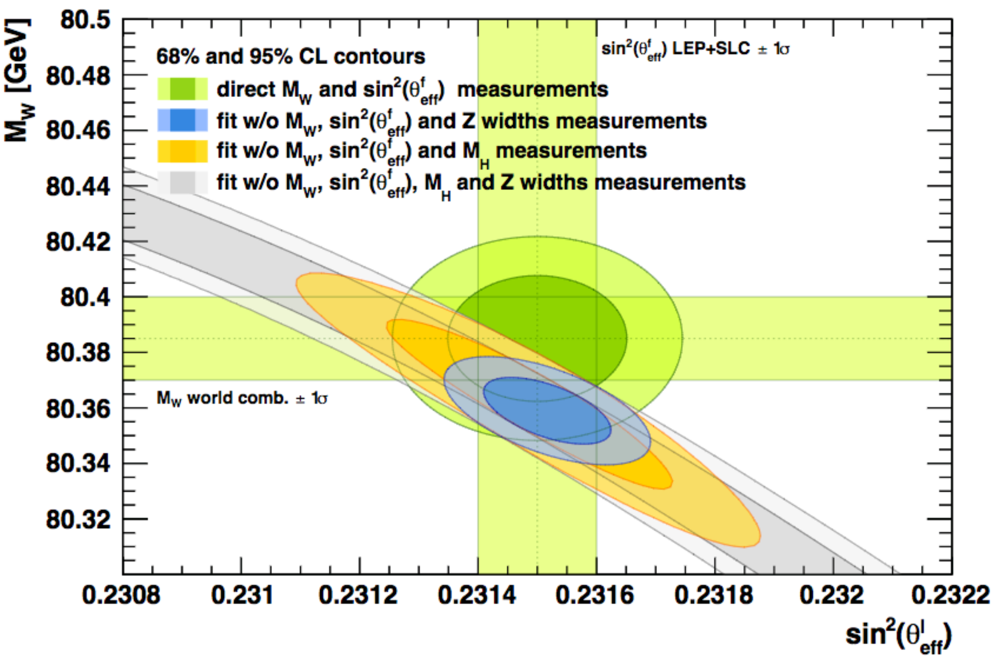
- Effective leptonic mixing angle and W mass are closely related
  $\sin^2\theta_{eff}^l = (1 - m_W^2/m_Z^2)\,\kappa_{RAD}$
  where κ_{RAD} is precisely known in standard model

- indirect measurement of W mass
- probe for contributions to κ_{RAD} from new physics particles

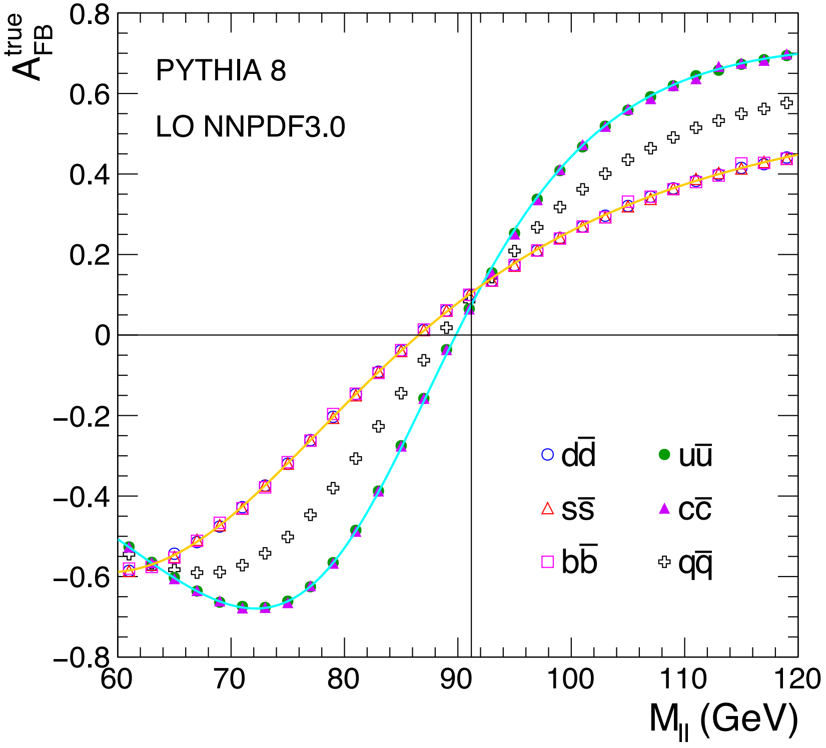


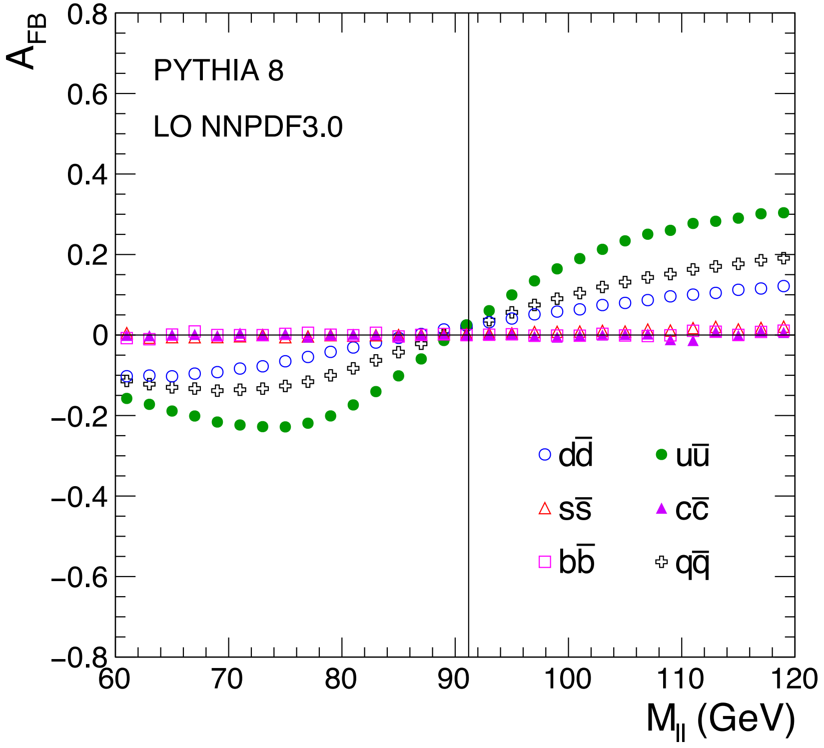
- Current world average dominated by LEP and SLD measurements

- Best measurements at hadron colliders are still limited by statistical and PDF errors, both of which can be constrained with more data

- Lot of ~background-free *Z->ll* events produced at the LHC that can be used to precisely measure $\sin^2\theta_{eff}^l$

- A_{FB} distribution defined by the vector and axial couplings
- Near Z peak sensitive to $\sin^2\theta_{eff}^{l}$
- Mass dependence from Z/γ^* interference
- Definition of Forward/Backward in pp based on sign of y_{ll}
    - only valence quarks contribute
    - average depends on PDFs





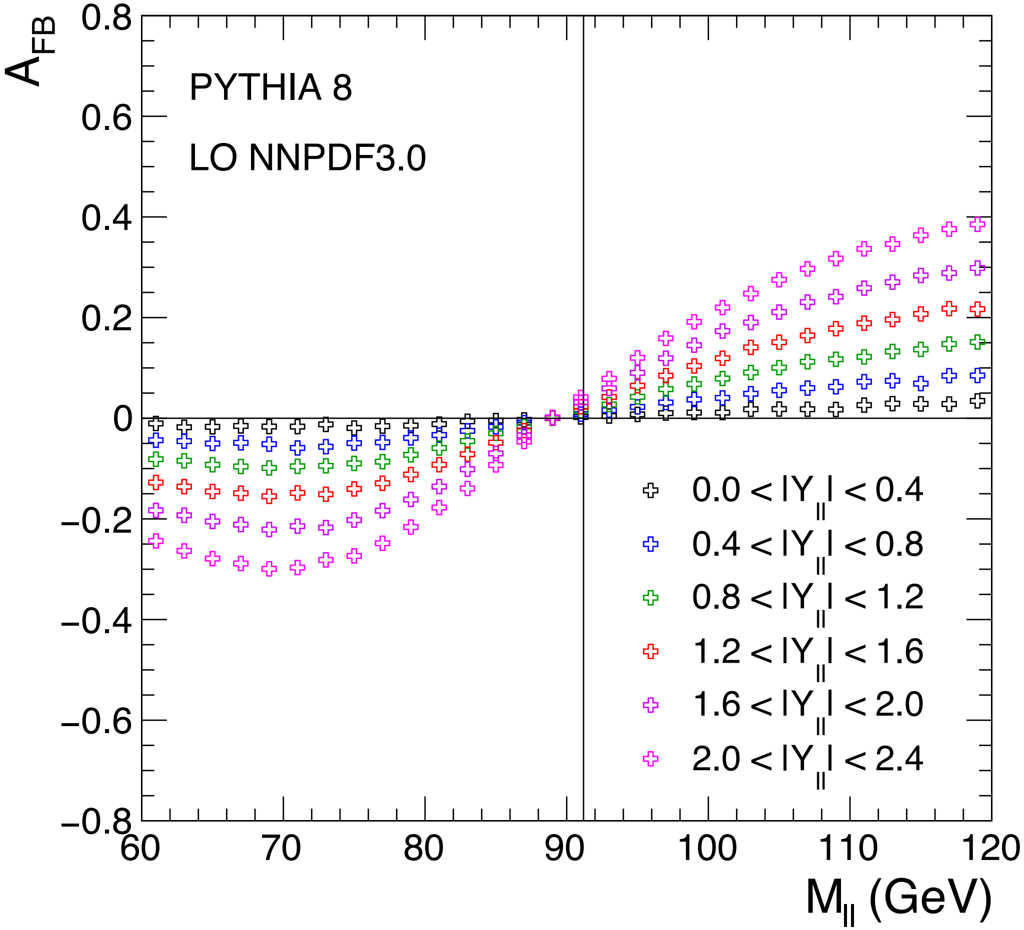
AFB in bins of mass and rapidity

- Definition of Forward / Backward in pp based on sign of y_{ll}
- dilution factor depends on rapidity
  - maximum / absolute dilution at y=0

AFB's measured in 72 bins of mass and rapidity:

- 6 equal | y | bins in [0-2.4]
- 12 mass bins in [60-120]

$\sin^2\theta_{eff}^{l}$ is extracted by fitting measured AFBs with different templates



Measurement strategy

- Fit AFB distribution in bins of mass and |y| with POWHEG $\sin^2\theta_{eff}$ templates

- 2012 8 TeV dataset — 19 /fb
- dimuon and dielectron channels

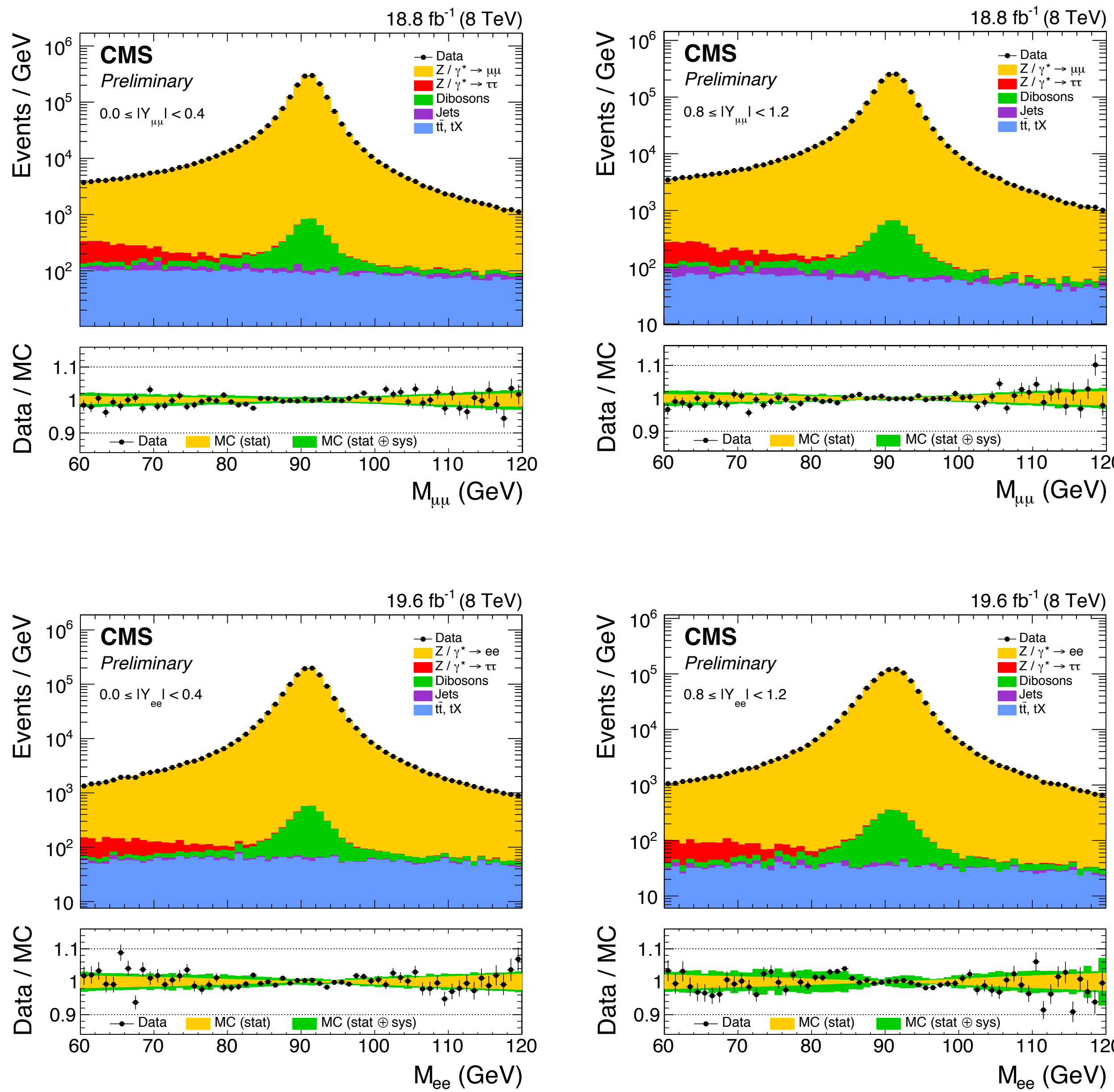
- Precise lepton momentum calibration using dilepton mass peak
- Event-weighting technique to calculate A_{FB}
- Constrain PDF uncertainties using AFB data

Mass distributions

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



Angular event-weighting

- Observable: weighted A_{FB} (Eur. Phys. J. C67, (2010) 321) (also used by CDF measurement)
- For each event with cosθ=c, define two weights:

$$w_D = \frac{1}{2}\frac{c^2}{(1+c^2+h)^3}, \qquad h = 0.5A_0(1-3c^2)$$

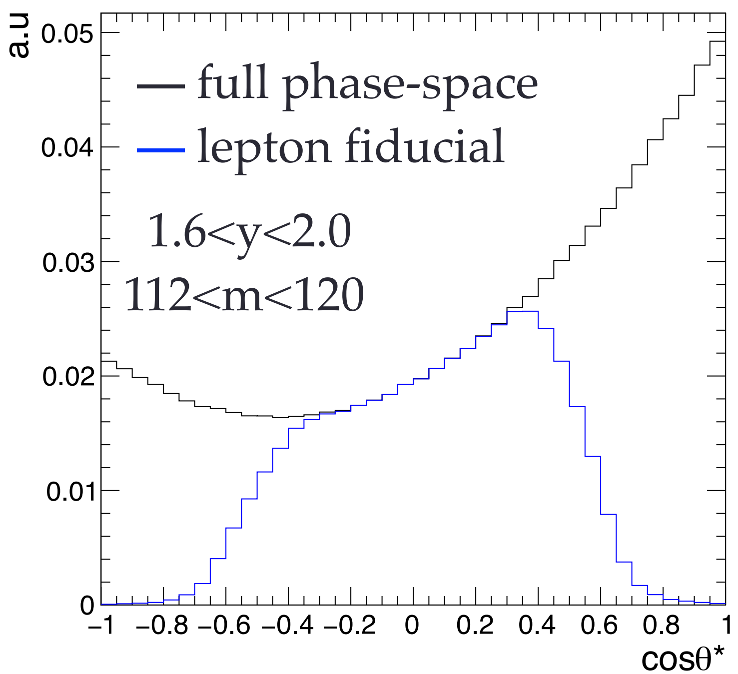
$$w_N = \frac{1}{2}\frac{|c|}{(1+c^2+h)^2}.$$

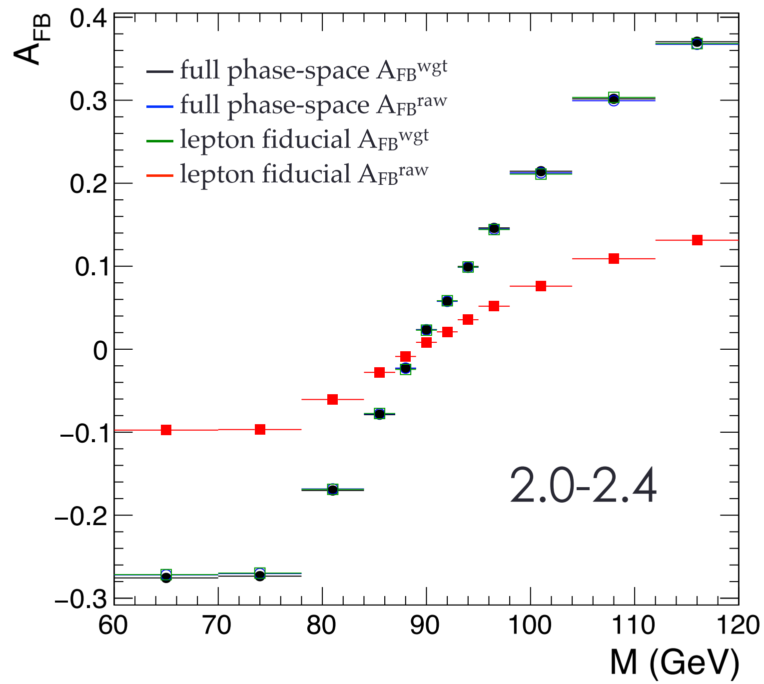
$$D_F = \sum_{c>0} w_D,\ D_B = \sum_{c<0} w_D.$$

$$N_F = \sum_{c>0} w_N,\ N_B = \sum_{c<0} w_N.$$

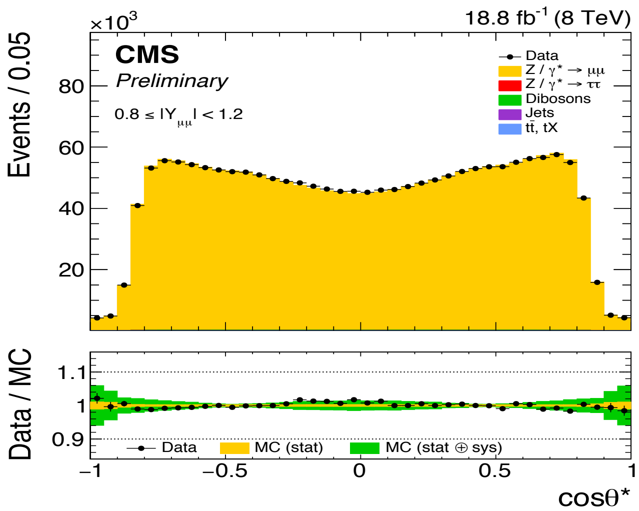
$$A_{FB} = \frac{3}{8}\frac{N_F - N_B}{D_F + D_B}$$

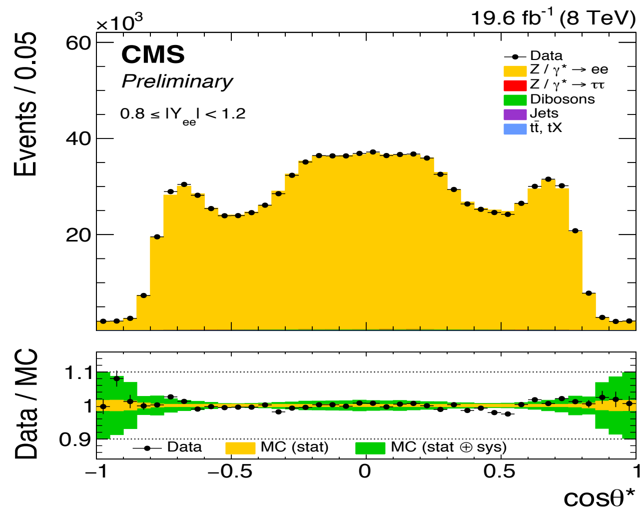
- **In 4π, Raw A_{FB} = Weighted A_{FB} = Weighted A_{FB} within lepton acceptance**
  => less sensitive to cosθ acceptance modeling
- Also, weighted A_{FB} yield smaller stat. uncertainty of extracted $\sin^2\theta_{eff}$

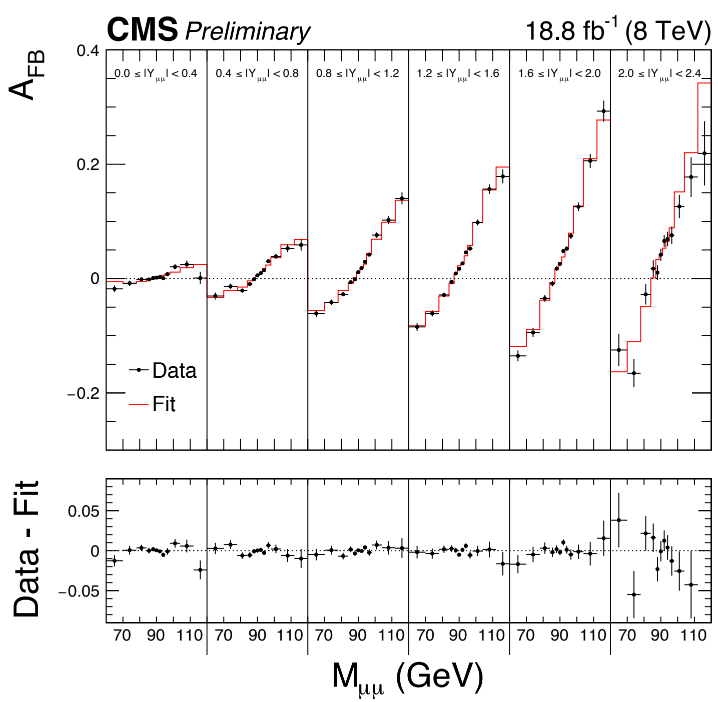


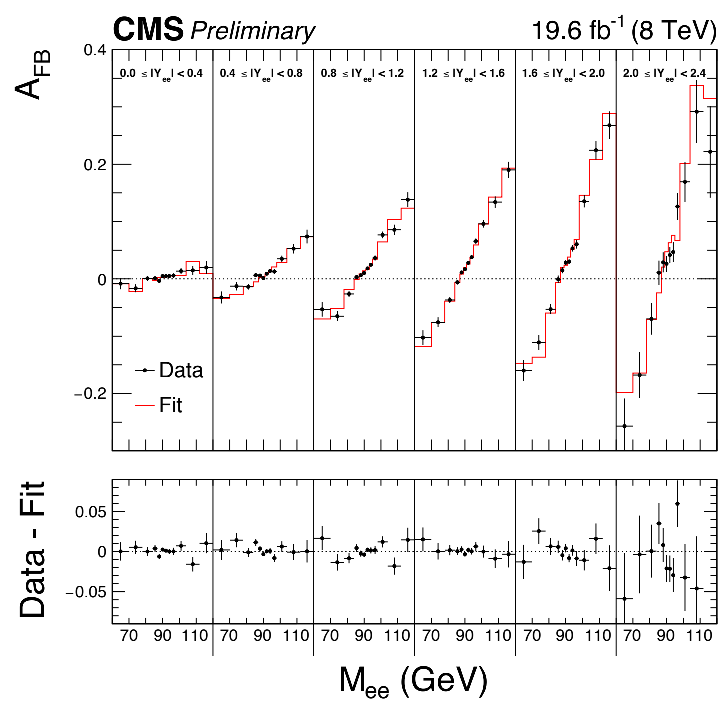


CosTheta and AFB









Statistical and experimental uncertainties

- Statistical uncertainties dominate
  - include stat. uncertainties in lepton calibration & efficiencies
- Evaluated with bootstrapping to take into account correlations

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

- Experimental uncertainties are small
- Biggest contribution coming from limited MC statistics

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

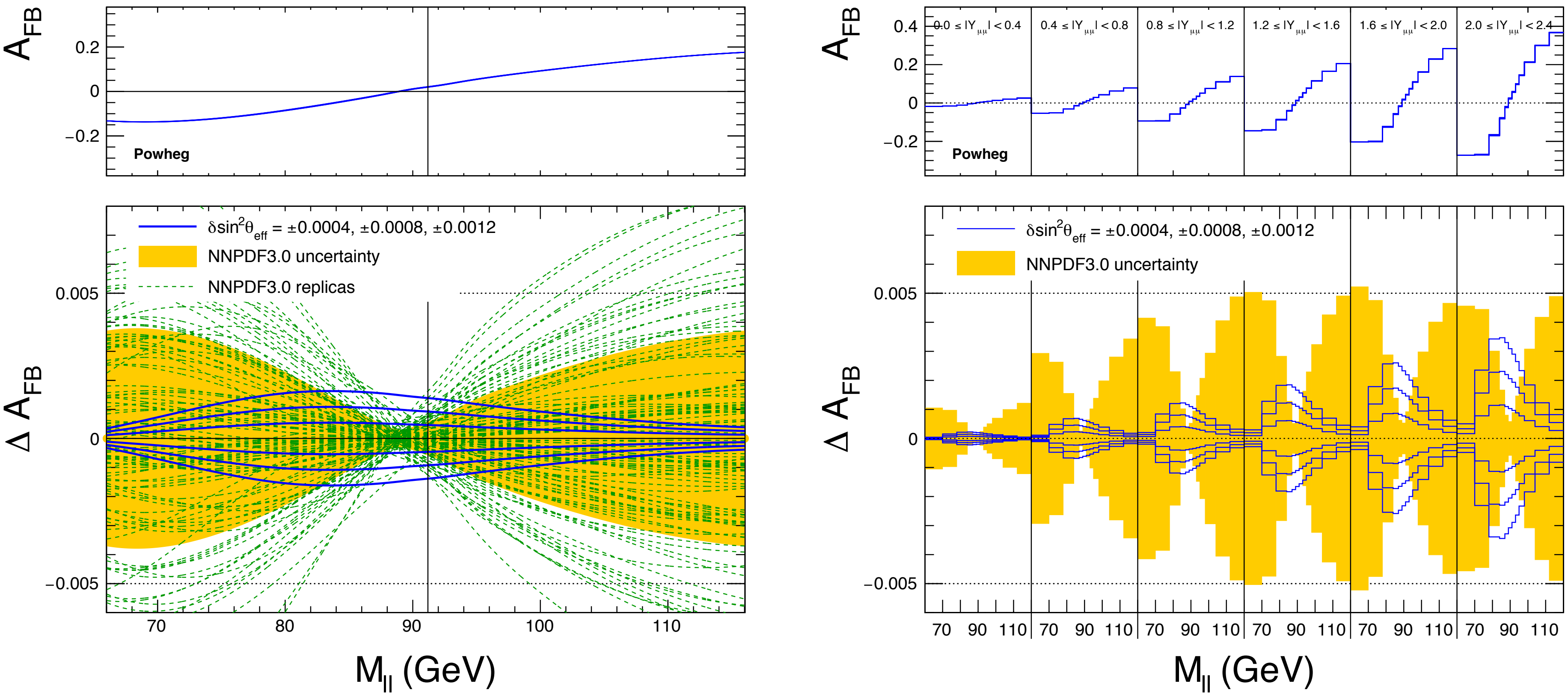
Modeling uncertainties

Following variations are considered to estimate template modeling uncertainties:
- raw vs weighted (to data) boson pt distribution
- QCD $\mu_{R/F}$ scales varied by factor of 2 independently excluding two opposite variations
- POWHEG MiNLO Z+j vs NLO Z process
- UE tune parameters within their uncertainties
- u and d quark $\sin^2\theta_{eff}$ values are changed w.r.t. leptonic ones by 0.0001 and 0.0002

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

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***)

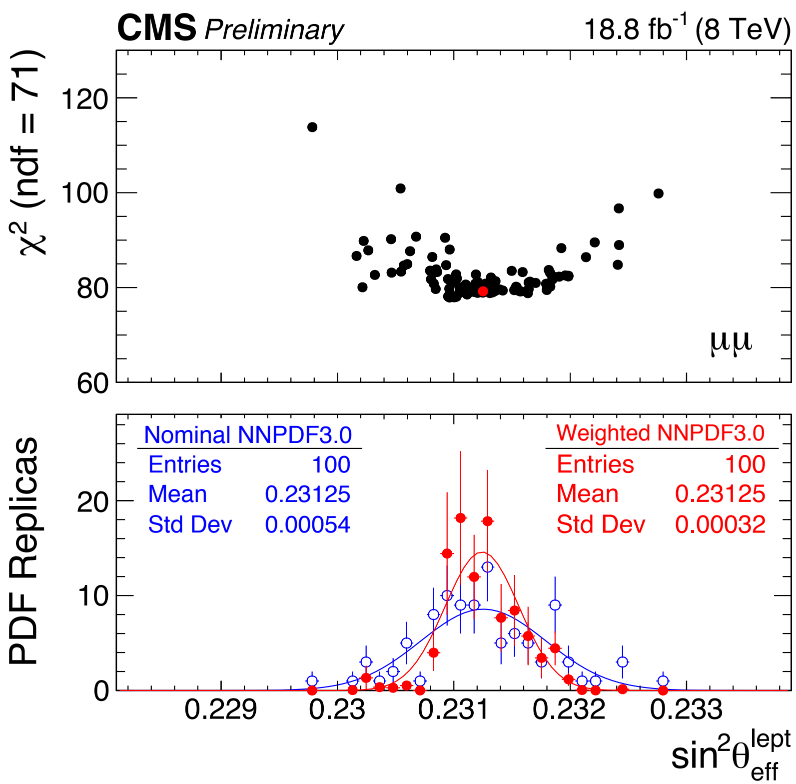


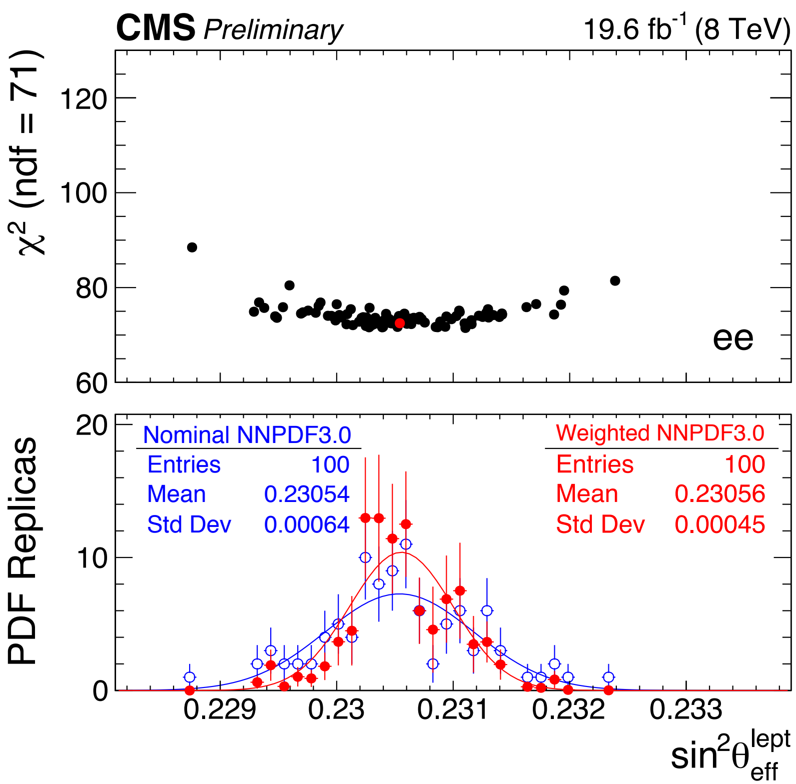
- Perform $\sin^2\theta_{eff}$ fit for each PDF replica (by default we use NNPDF3.0)
- Weight each replica (i) by $w_i(\chi^2_{min})$

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

A. Bodek et al Euro. Phy. J. C76:115 (2016)

PDF uncertainties



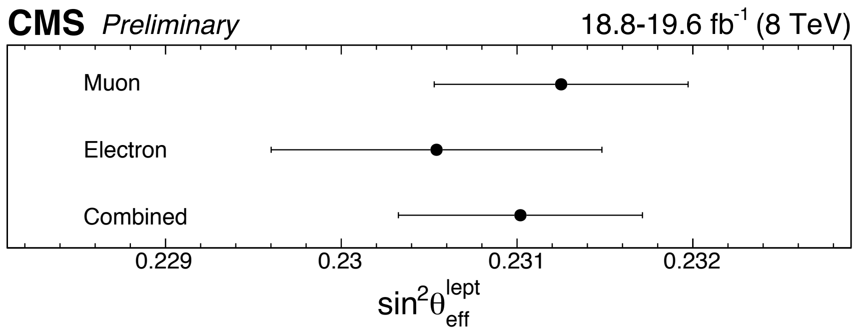


— replicas that poorly describe data (with corresponding best-fit $\sin^2\theta_{\mathrm{eff}}$) get smaller weights

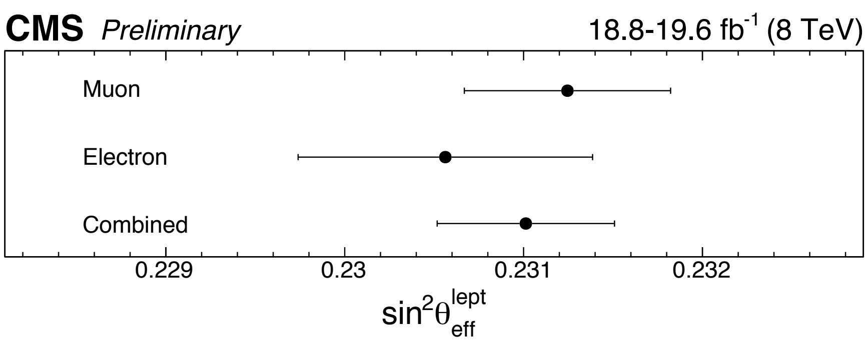
— extreme replicas from both sides are disfavored by both dimuon and dielectron data

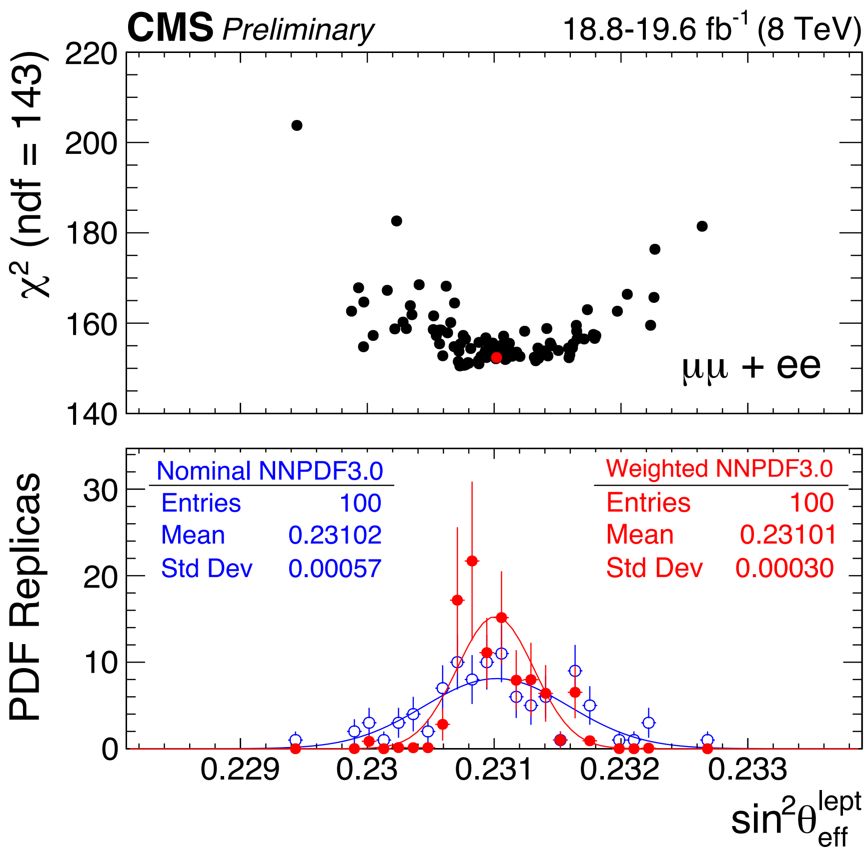
PDF uncertainties

Nominal PDF Errors



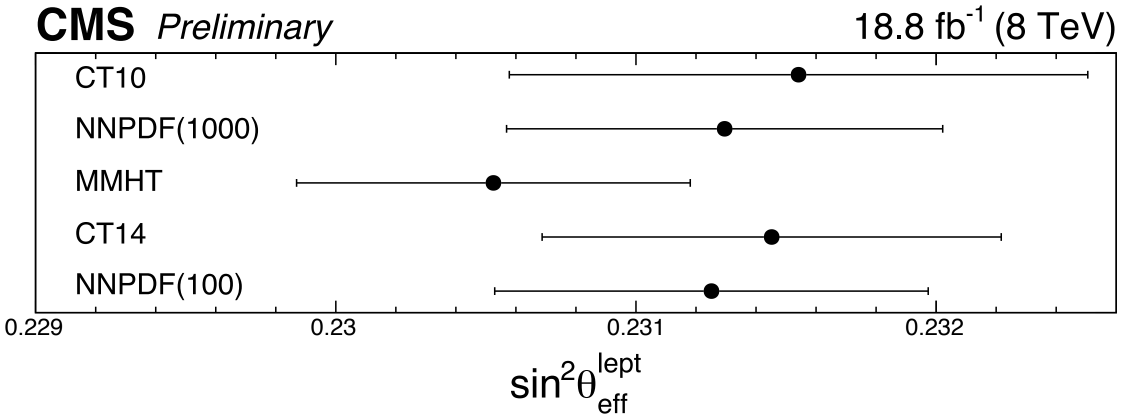
Constrained PDF Errors

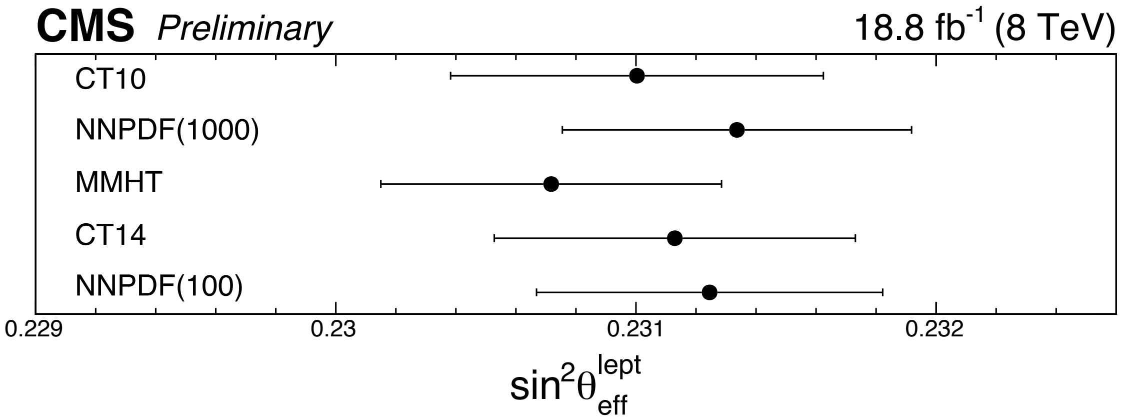




- Good consistency between electron and muon results
- PDF uncertainties reduced by about factor of two

study done with muons





- From Hessian PDFs first generate 1000 replicas:

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

- then apply same PDF reweighting

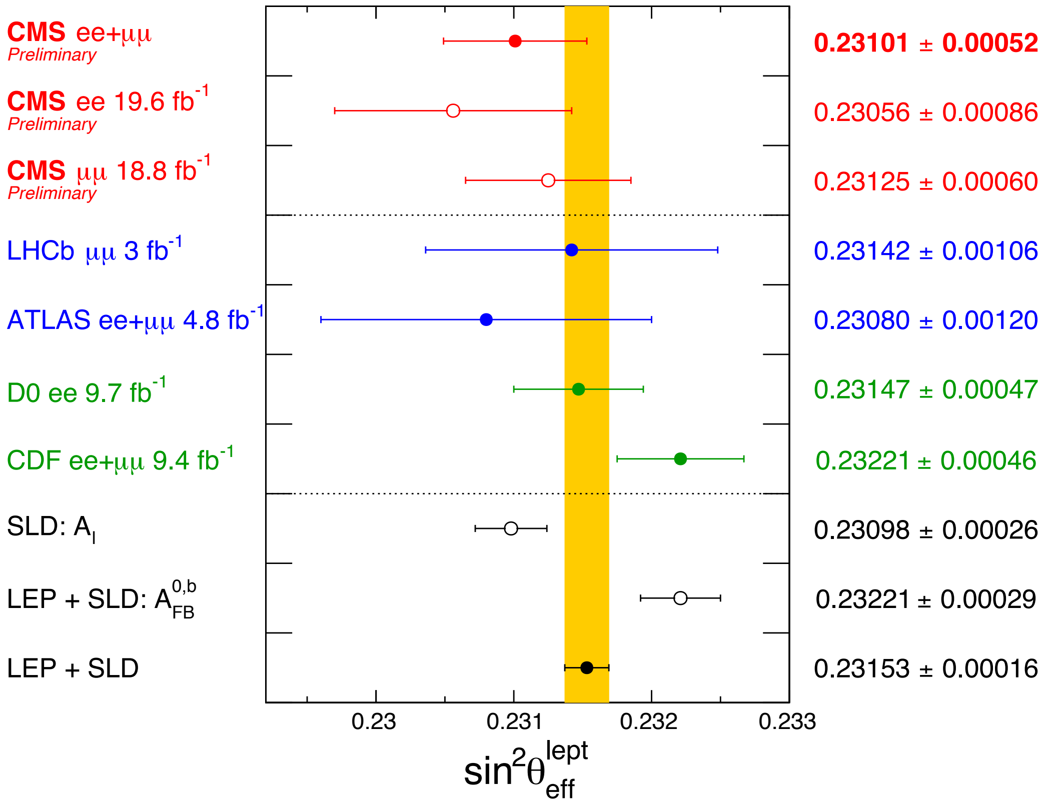
- also did simultaneous fit directly using Hessian PDFs
- also cross-checked with Hessian NNPDFs

=> both central values and uncertainties are ~identical to those obtained with replicas

- PDF uncertainties reduce
- Spread of central values reduce

Result

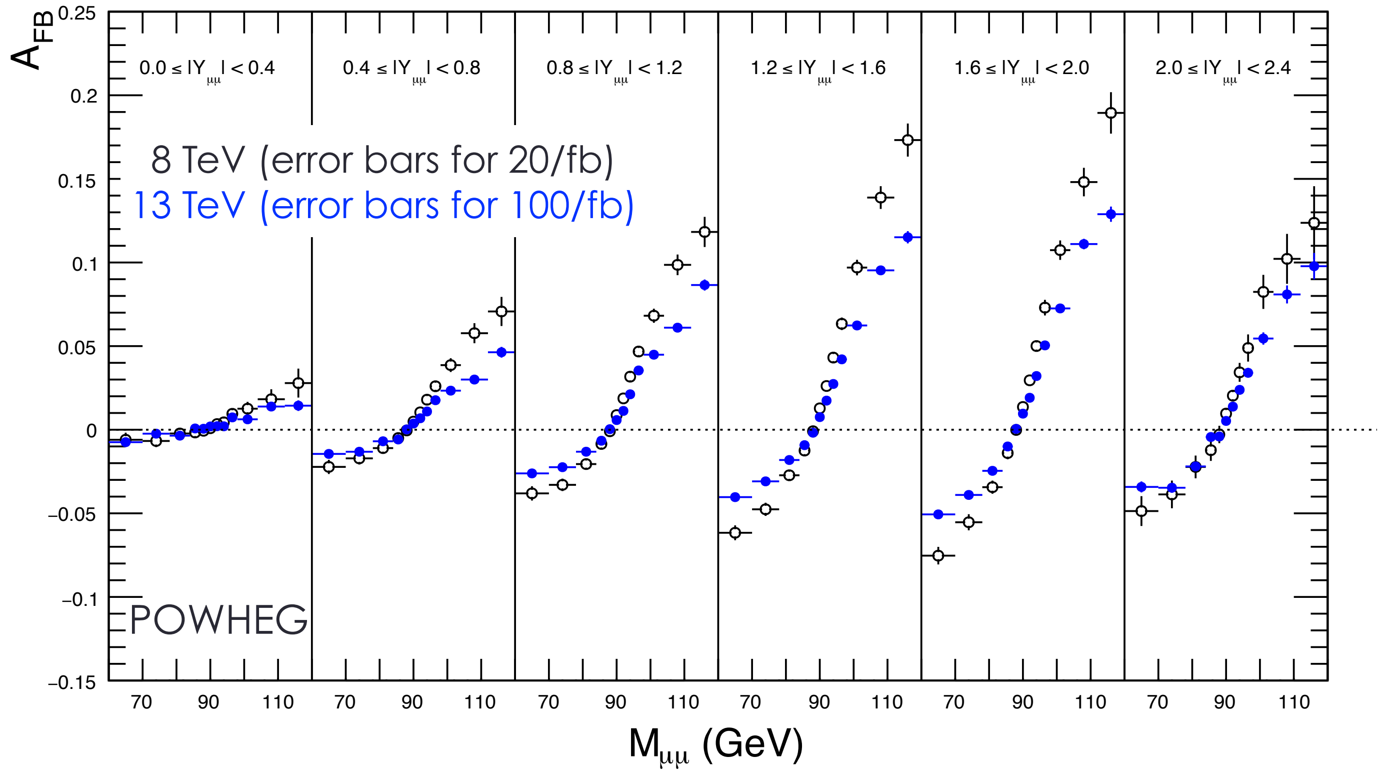
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00052.$$



- Statistical uncertainties still dominate
- PDF uncertainties constrained significantly using same AFB distributions
- Experimental uncertainties are small (MC statistical uncertainties will be reduced for more precise data)
- Modeling uncertainties, dominated by QCD scale variations, are small compared to *current* statistical errors

What to expect from Run2 (and beyond)

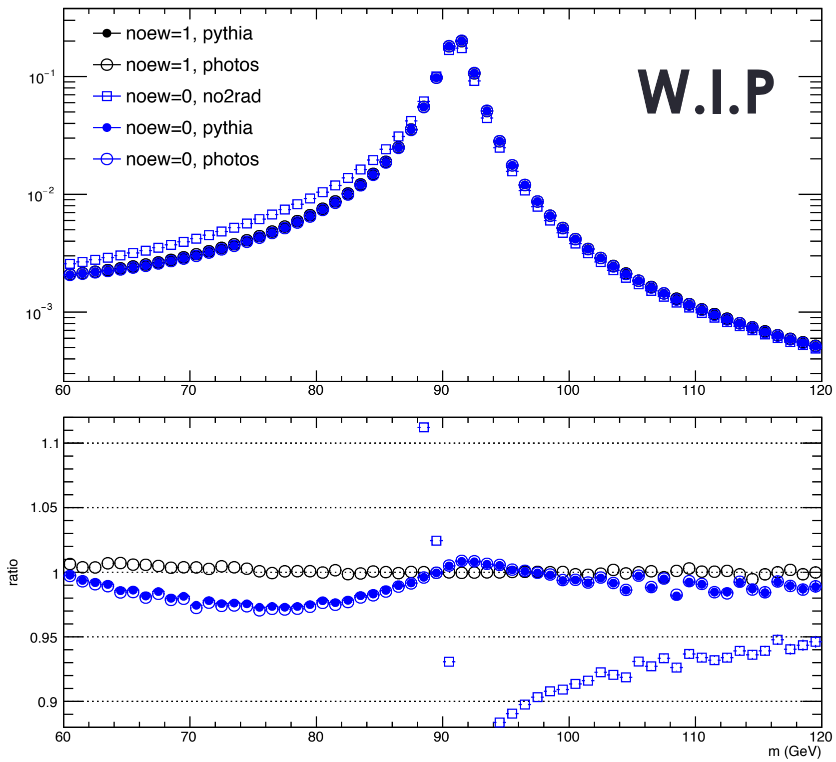
- at 13 TeV less valence quarks contribute (means less observable AFB in pp)
- > larger statistical and PDF errors (if we had same # of events)

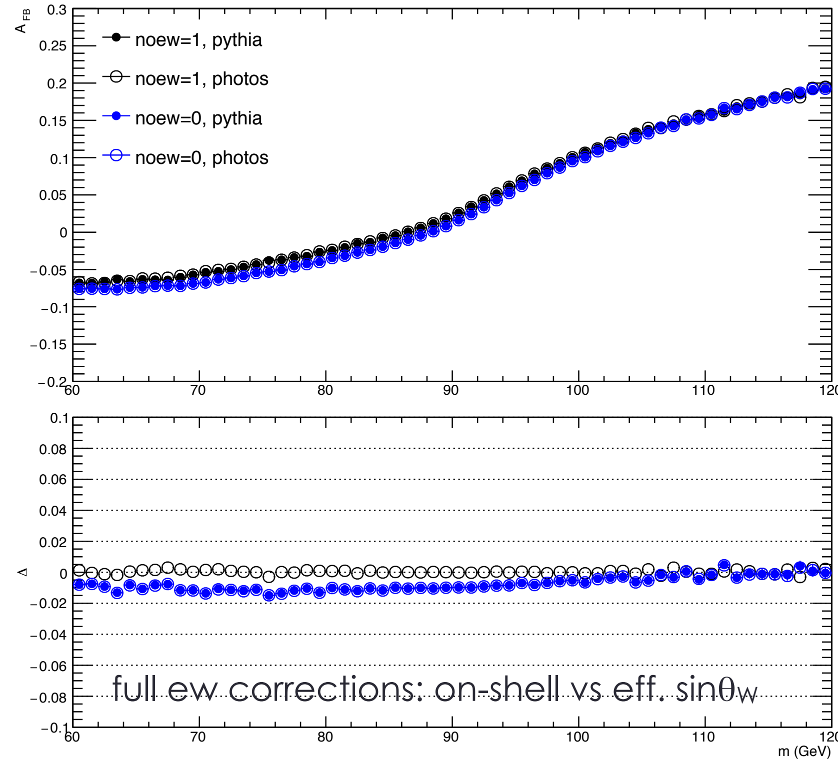


- But we will have a lot more data
- With Run2 data, statistical uncertainty will be about half, PDF errors also reduced
- With HL-LHC data, statistical uncertainty will be negligible, PDF errors can be constrained to improve current knowledge of sineff

POWHEG with EW corrections

- standalone powheg with “built-in” pythia/photos interface





- possibly I have some mis-configuration for matching (?)
- how can we disentangle electroweak effects from possible effects of imperfect matching?
- need $\sin^2\theta_{eff}$ EW input scheme to quantify the effect

Summary

- Presented results from $\sin^2\theta_{eff}^{l}$ measurement at 8 TeV
- Statistical uncertainties dominate
- PDF uncertainties constrained significantly using same AFB distributions
- Experimental uncertainties are small
- Modeling uncertainties, dominated by QCD scale variations, are small compared to current statistical errors
- Precision can be improved with more LHC data from run-2 and beyond