Measurements of $\sin^2\theta_W^{eff}$ at Colliders
LEP/SLD, Tevatron, LHC, HL-LHC

Arie Bodek

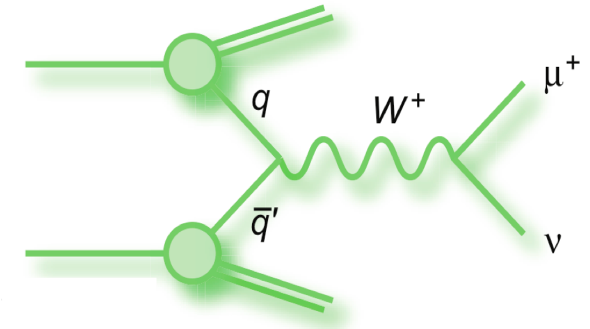
University of Rochester

1st COFI Workshop on Precision Electroweak
Old San Juan, Puerto Rico
https://indico.cern.ch/event/813143/
Thursday July 18, 2019 10:00 -11:00 AM

Thursday, July 18, 2019 9:00-10;00 AM

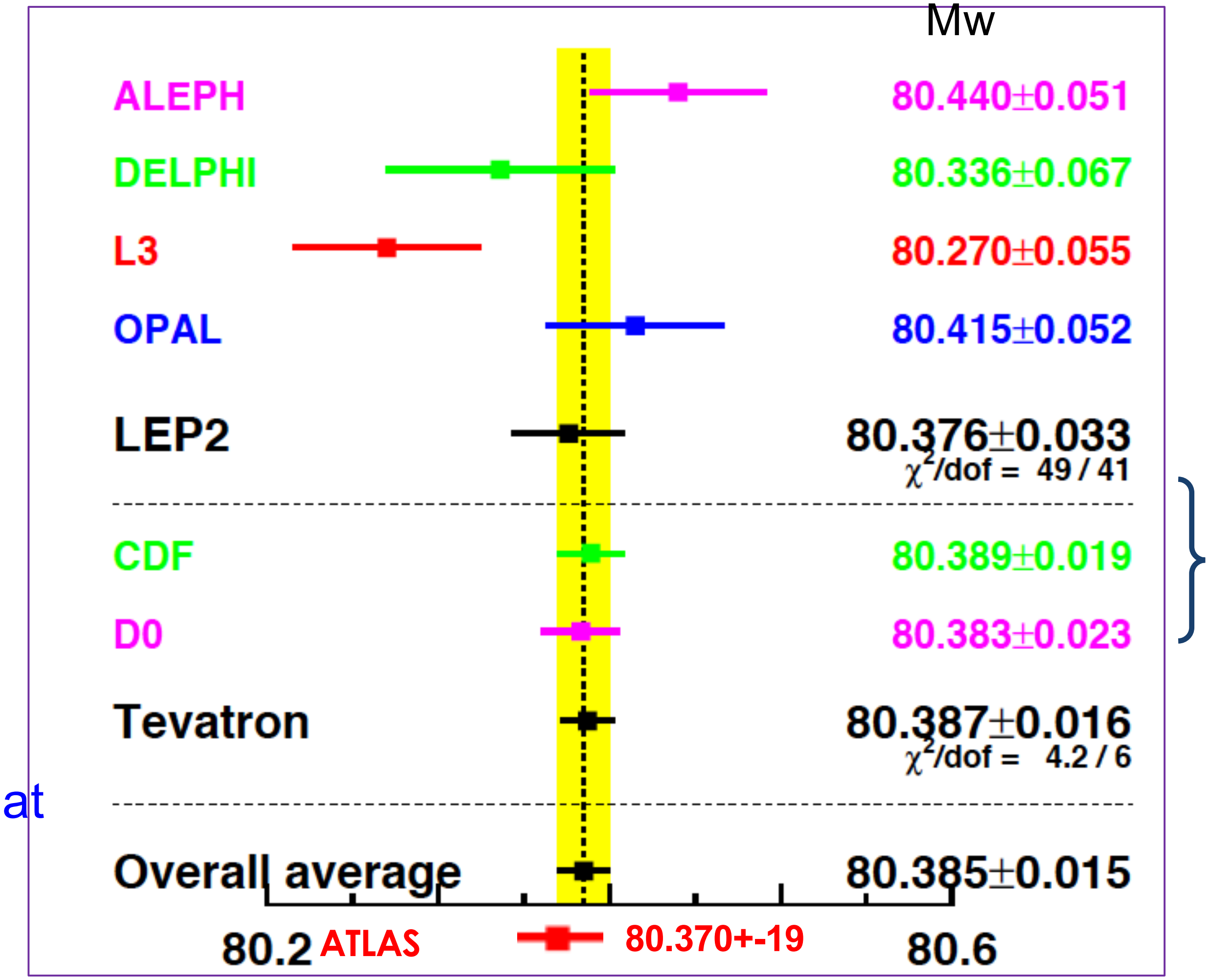
Currently direct Mw measurement's precision is 20 MeV

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



The most recent Measurements of Mw (CDF and Dzero 2.2 fb^{-1}), and ATLAS at 7 TeV have errors of **~20 MeV.**

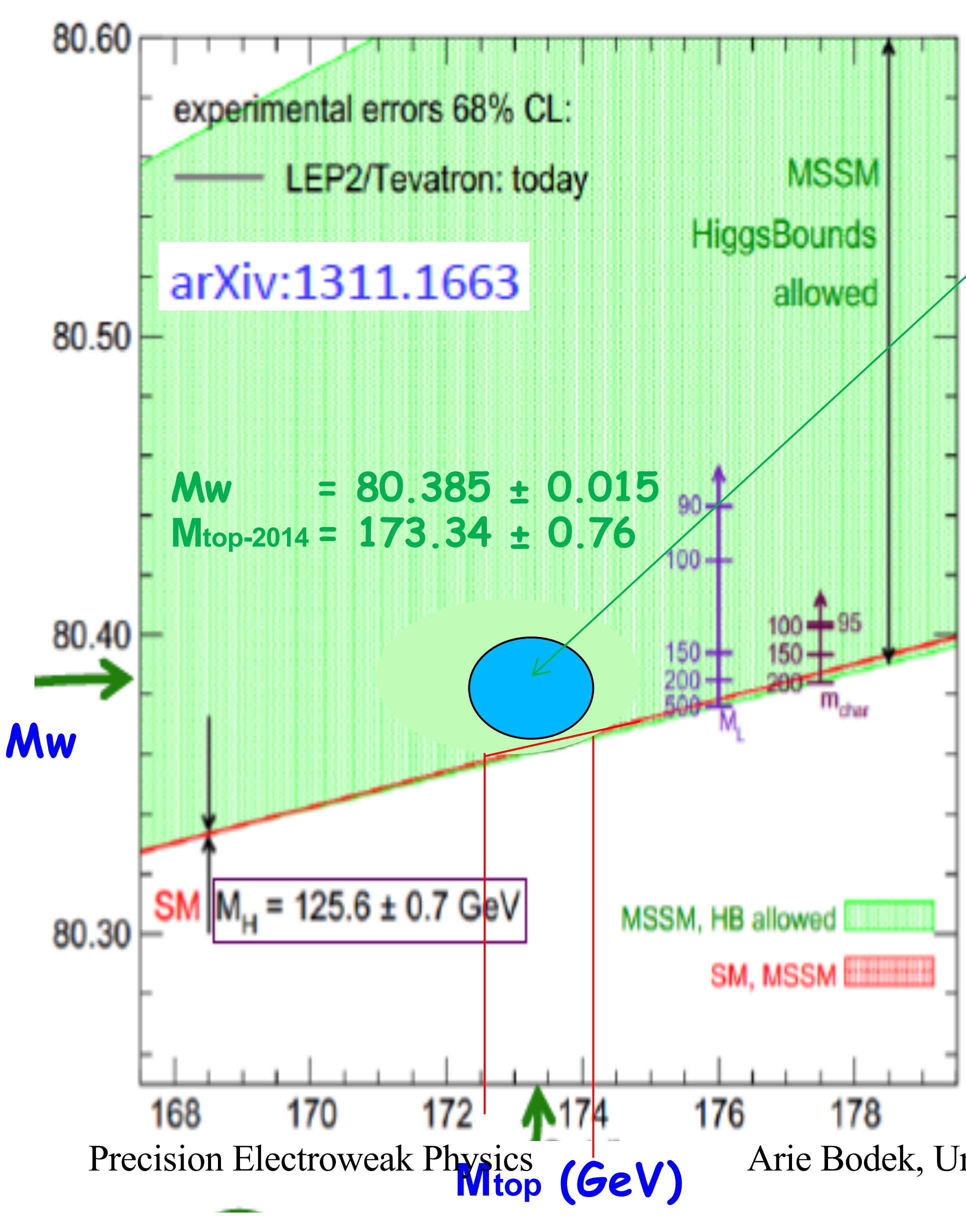
Tevatron Legacy sample 9.1 fb^{-1} analyses not yet completed. Aim at 10 MeV error ?



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

Testing the Standard Model

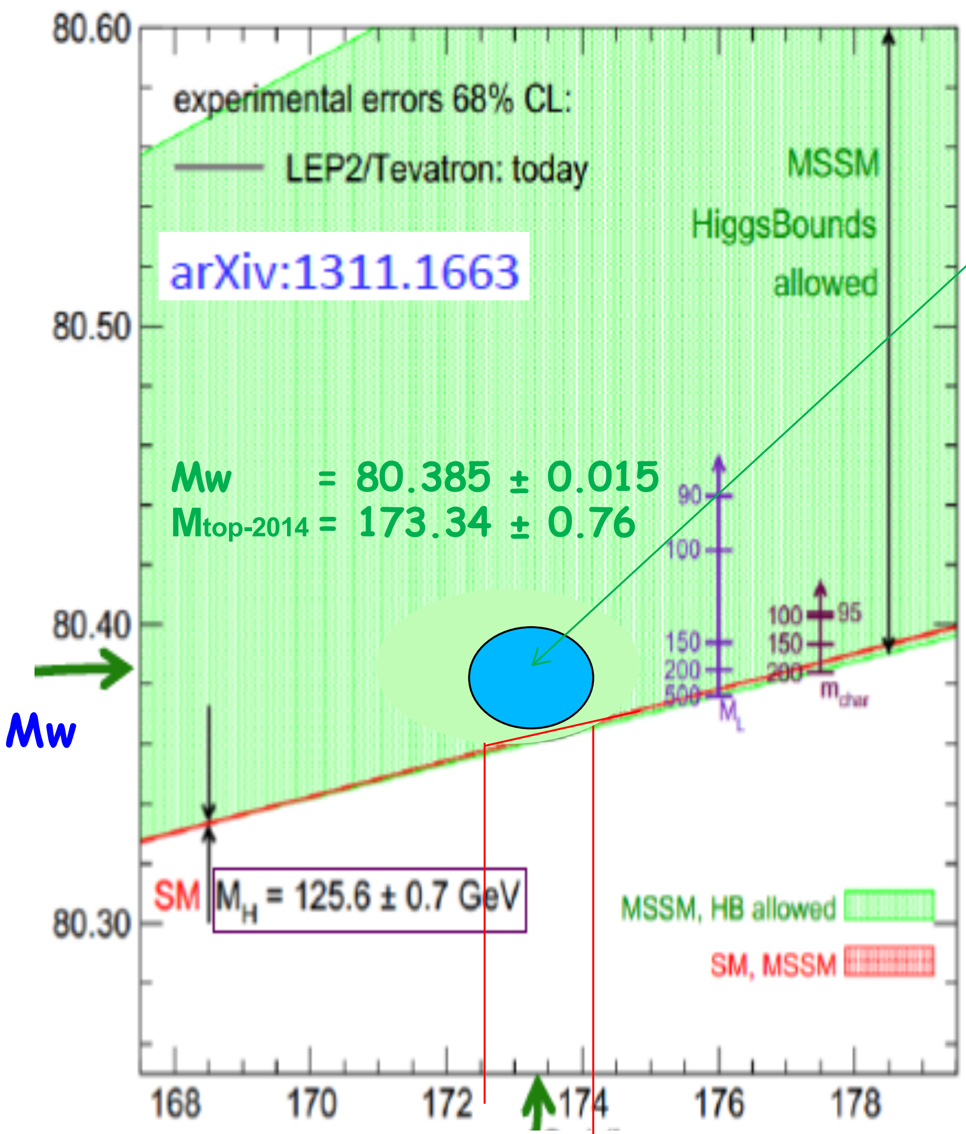
With a known Higgs mass, the SM is over-constrained. Measurement of Mw provides constraints on SM. Mw is consistent with supersymmetry



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

Testing the Standard Model

With a known Higgs mass, the SM is over-constrained. Measurement of Mw provides constraints on SM. Mw is consistent with supersymmetry



arXiv:1311.1663

M_W = 80.385 ± 0.015
$M_{top\text{-}2014}$ = 173.34 ± 0.76

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 ± 0.00016 in $\sin^2\theta_W^{eff}$ is equivalent to an indirect measurement of M_W to a precision of ± 8 MeV.

$$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\underbrace{\kappa_l(M_Z^2, \sin^2\theta_W)}_{\approx 1.037}]\sin^2\theta_W$$

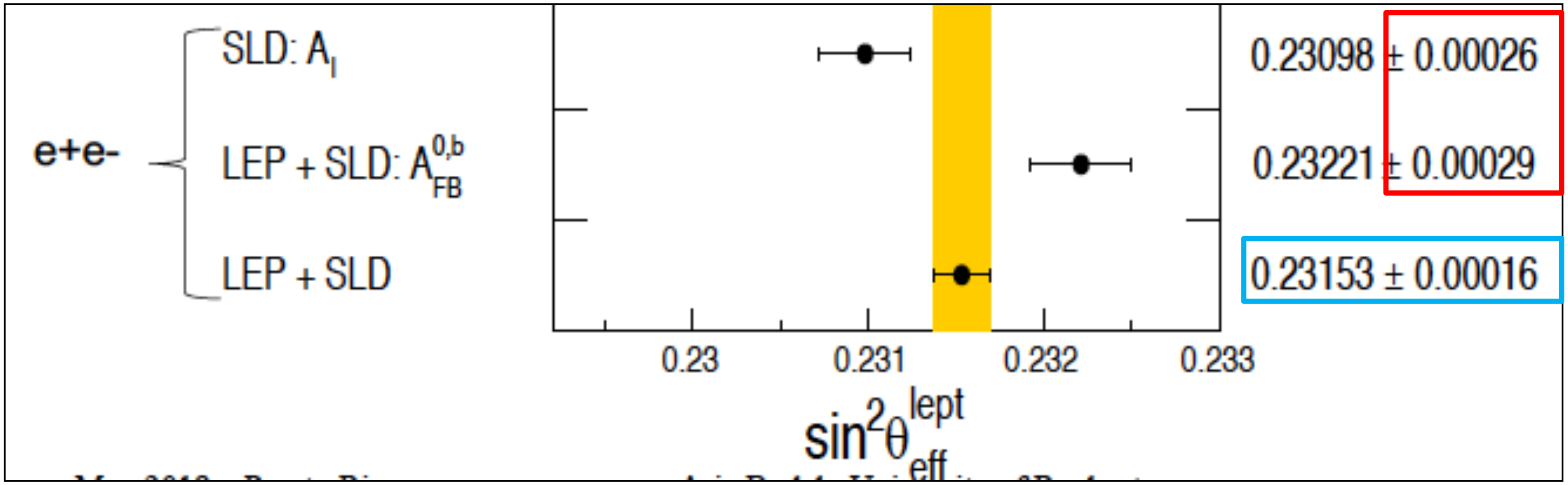
Aim at ± 0.00016 in $\sin^2\theta_W^{eff}$
M_W to ± 8 MeV.

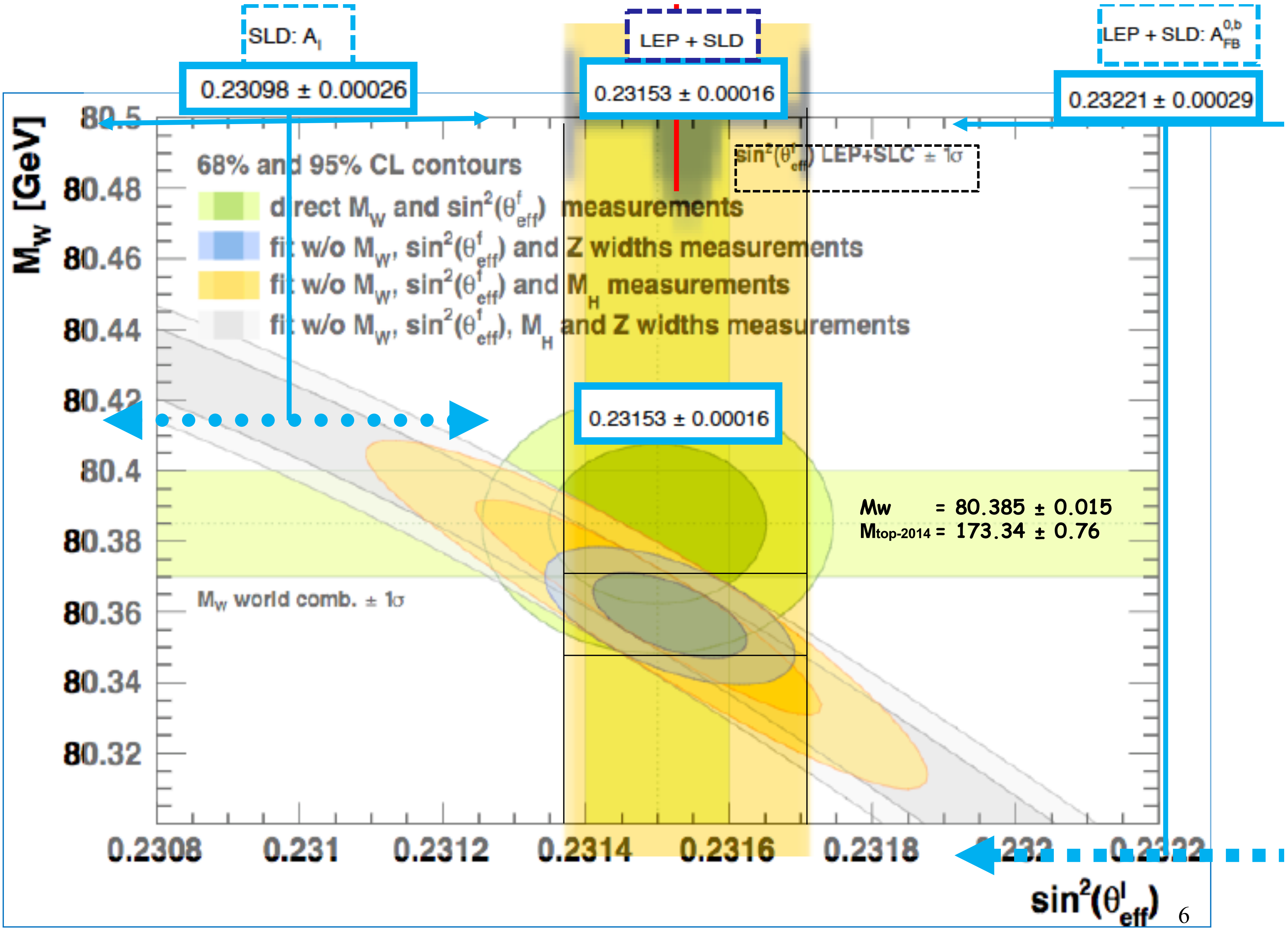
An error of ± 0.00016 in $\sin^2\theta_W$ is equivalent to an indirect measurement of M_W to a precision of ± 8 MeV (which is a factor of two better than the current uncertainty (± 15 MeV) in the world average of direct measurements of M_W

This level of precision is needed to probe for physics beyond the Standard Model. Currently Mw and $\sin^2\theta_W$ have similar errors.

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

LHC experiments can achieve this level of precision





SLD: A_l

0.23098 ± 0.00026

LEP + SLD

0.23153 ± 0.00016

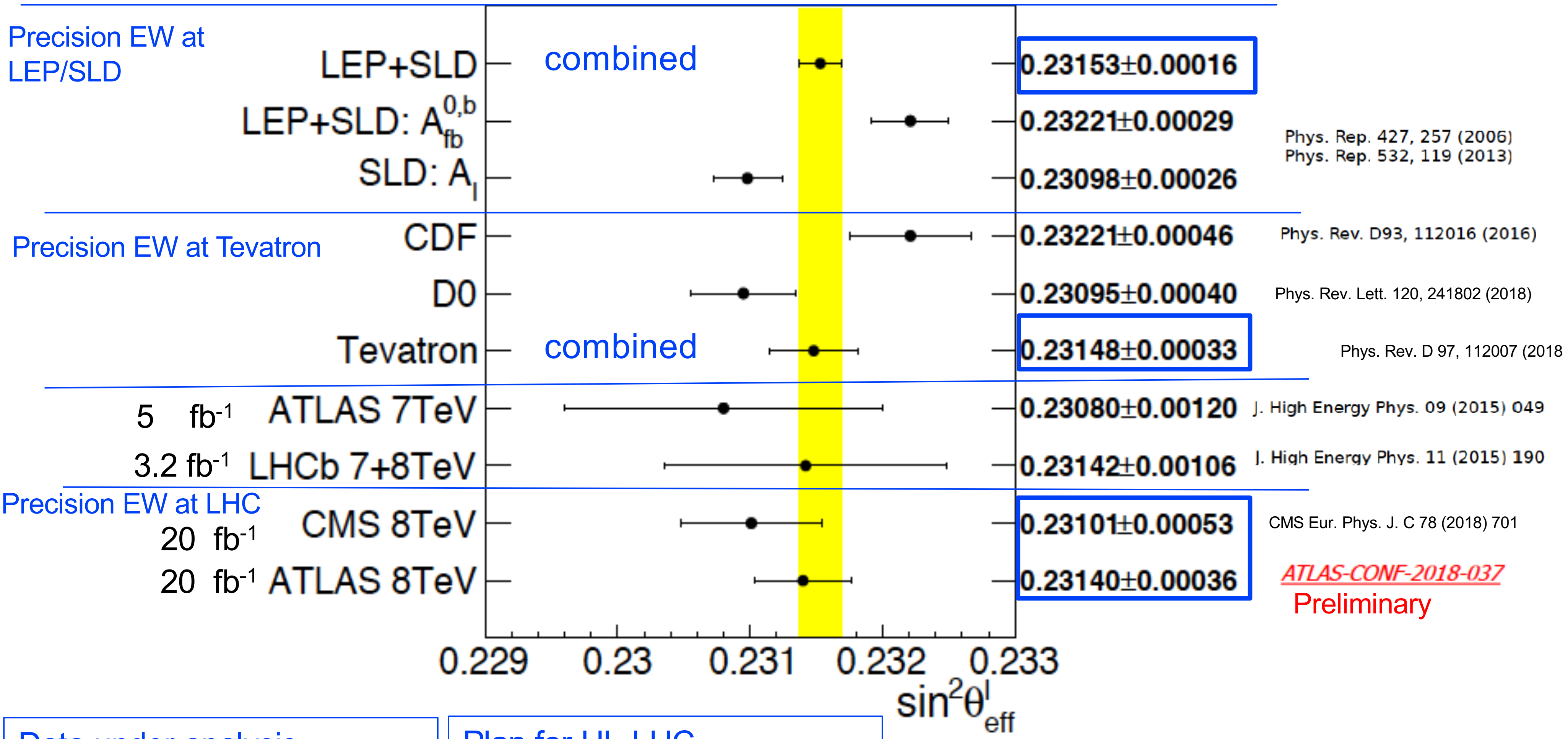
LEP + SLD: $A_{FB}^{0,b}$

0.23221 ± 0.00029

0.23153 ± 0.00016

M_W = 80.385 ± 0.015

$M_{top\text{-}2014}$ = 173.34 ± 0.76



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

Phys. Rev. D93, 112016 (2016)

Phys. Rev. Lett. 120, 241802 (2018)

Phys. Rev. D 97, 112007 (2018

J. High Energy Phys. 09 (2015) 049

J. High Energy Phys. 11 (2015) 190

CMS Eur. Phys. J. C 78 (2018) 701

ATLAS-CONF-2018-037
Preliminary

Data under analysis

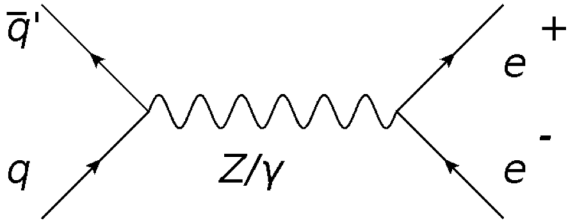
13 TeV	LHCb	5.4	fb^{-1}
13 TeV	ATLAS	140	fb^{-1}
13 TeV	CMS	140	fb^{-1}

Plan for HL-LHC

14 TeV	LHCb	300	fb^{-1}
14 TeV	ATLAS	3000	fb^{-1}
14 TeV	CMS	3000	fb^{-1}

Aim at ± 0.00016 in $\sin^2\theta_W^{eff}$ (SLD/ LEP combination)
Equivalent indirect M_W to ± 8 MeV

Dilepton production at Hadron Colliders



The axial and vector neutral currents interfere

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

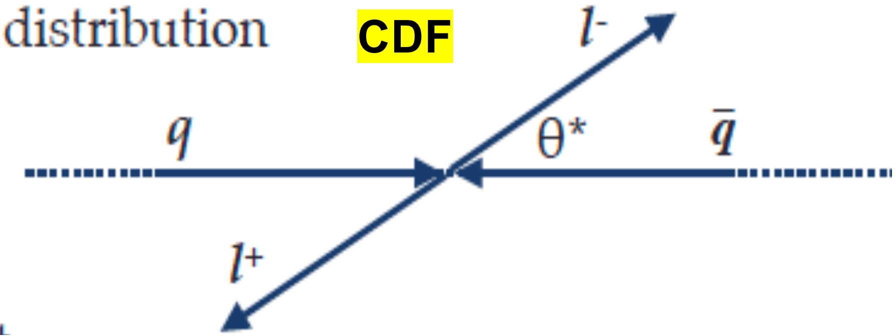
$\sin^2\theta_W = \sin^2\theta_W^{\text{on-shell}} = 1 - M_W^2 / M_Z^2$

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

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = \mathrm{Re}[\underbrace{\kappa_l(M_Z^2, \sin^2\theta_W)}_{\approx 1.037}]\sin^2\theta_W$$

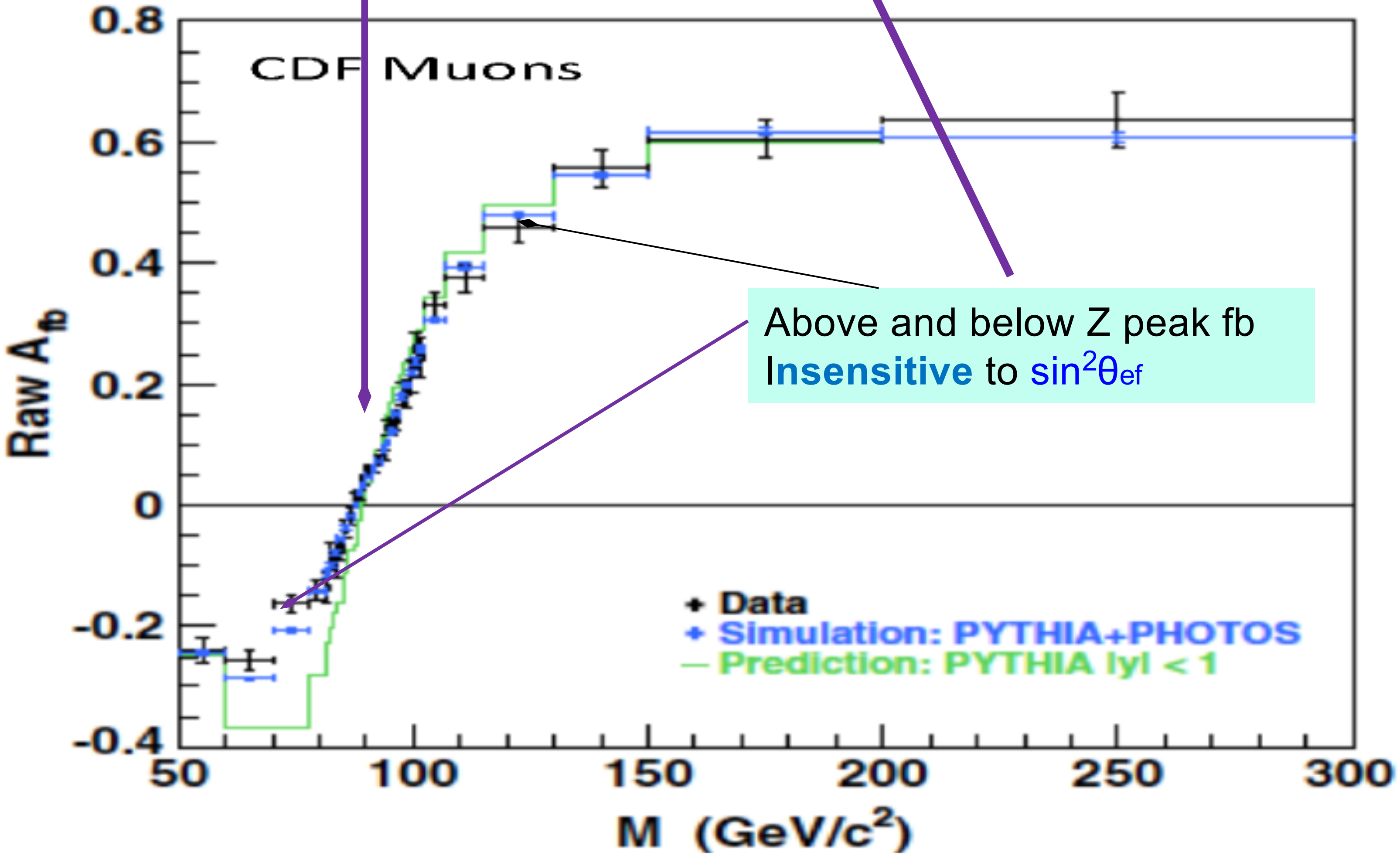
- Vector and axial couplings result in A_{FB} of $\cos\theta^*$ distribution
- A_{FB} near Z peak sensitive to leptonic $\sin^2\theta_{eff}$
- Mass dependence from Z/γ^* interference

CDF



Quark from proton direction, antiquark from antiproton direction

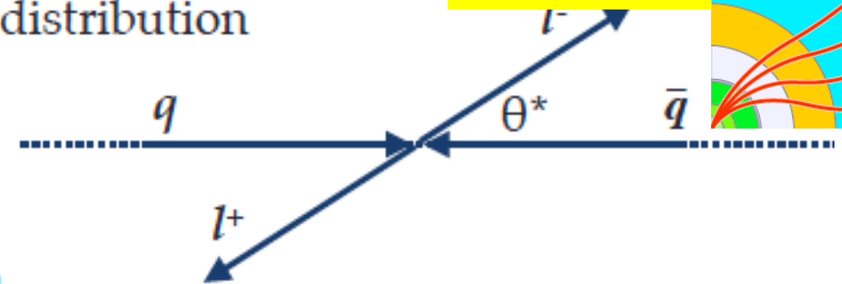
Sensitive to $\sin^2\theta_{ef}$
Z axial-vector interference



Above and below Z peak fb
Insensitive to $\sin^2\theta_{ef}$

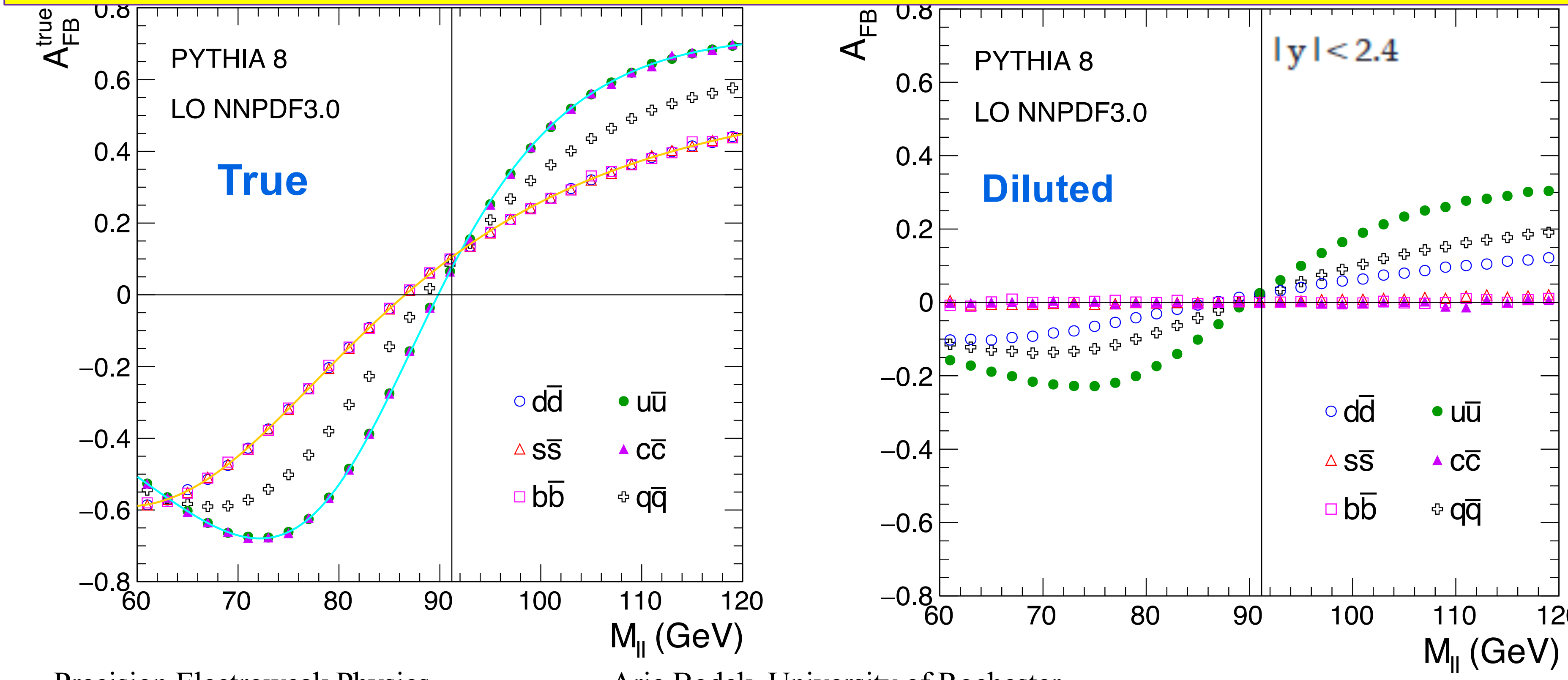
CMS

- 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:



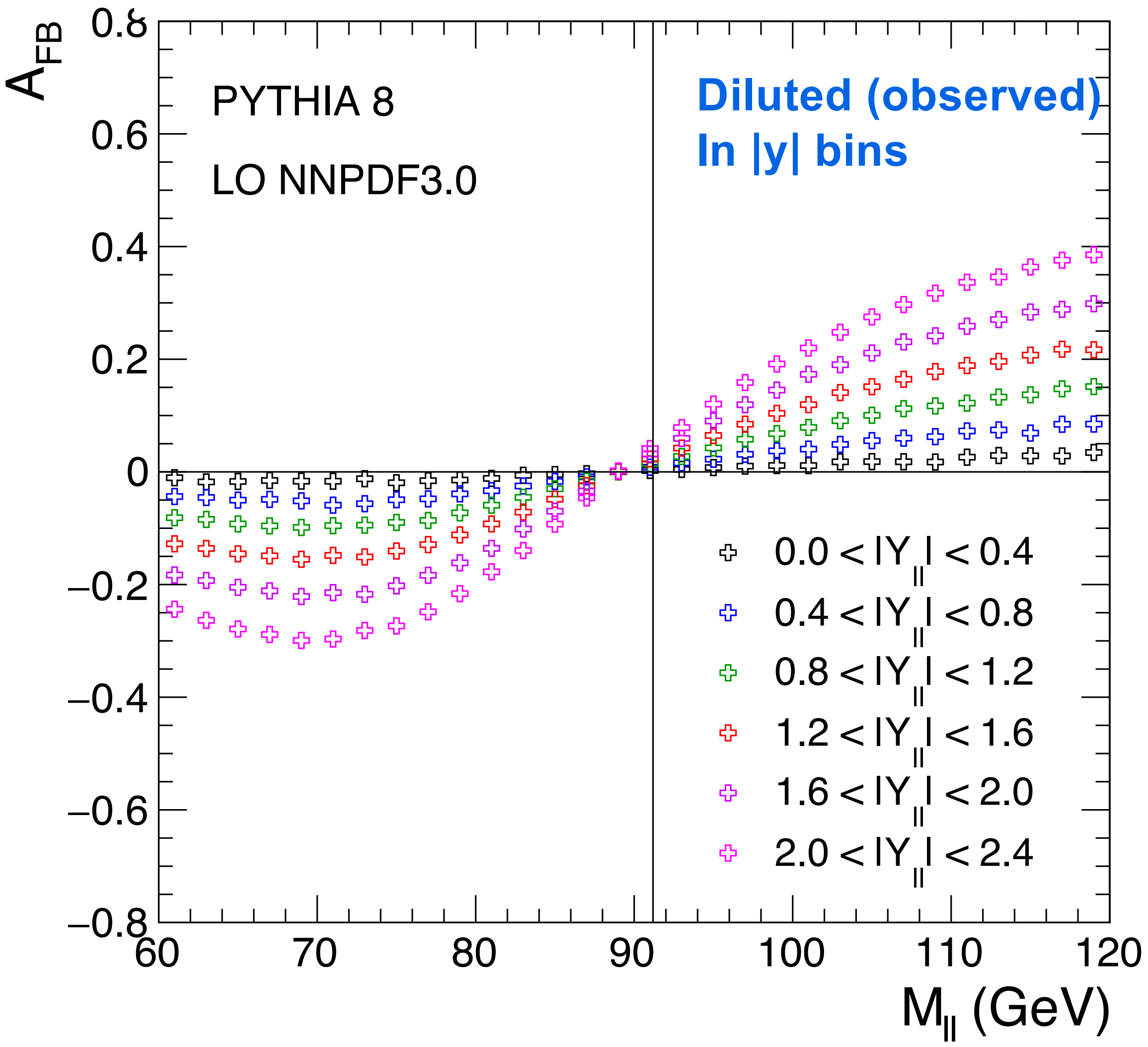
1. **Fraction of valence u vs. d**
2. **Dilution (y dependent) from high x antiquarks**

Quark direction chosen to be the direction of dilepton rapidity (not always true}



- 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

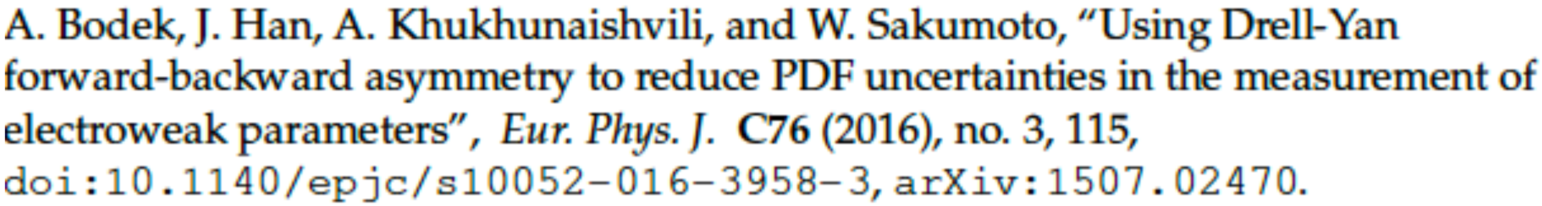


Dilution (y dependent). Therefore bin data in rapidity.

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 limited by PDFs

Precision measurements of standard model parameters at hadron colliders are possible because of a new technique to constrain PDFs (published in 2016)



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.`

At the Z peak, Afb yields a measurement of **$\sin^2\theta_{eff}$**

Above and below Z peak, axial coupling known. Does not depend on **$\sin^2\theta_{ef}$** .Therefore, measurements of Afb measure the dilution and provides constraints on PDF using the same Drell Yan sample (but above and below the Z peak)

At Tevatron: Reduced PDF error to $\Delta\sin^2\theta_{eff}$ from ±0.00023 to ±0.00017

Phys. Rev. D93, 112016 (2016)

At CMS: Reduced PDF error to $\Delta\sin^2\theta_{eff}$ from ±0.00054 to ±0.00030 at 8 TeV.

(It took 2 years to convince CMS of the validity of the technique) CMS Eur. Phys. J. C 78 (2018) 701

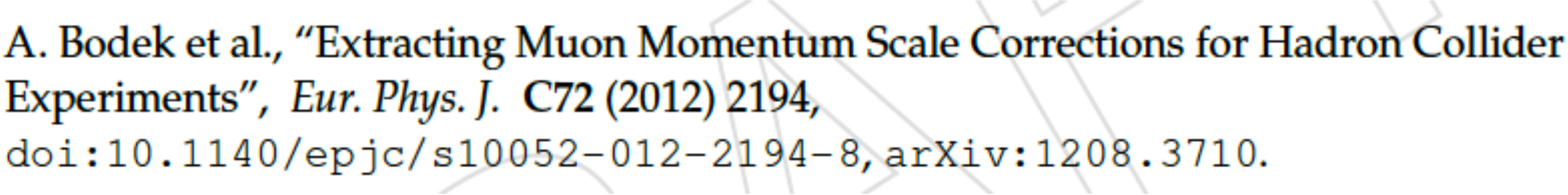
Constrains on PDF are *statistics limited only* by the precision of Afb.

(can be further reduced with more data e.g. 13 TeV)

The precision measurement at CMS and CDF used two additional new techniques:

1: Precise lepton momentum/energy scale (and modeling resolution)

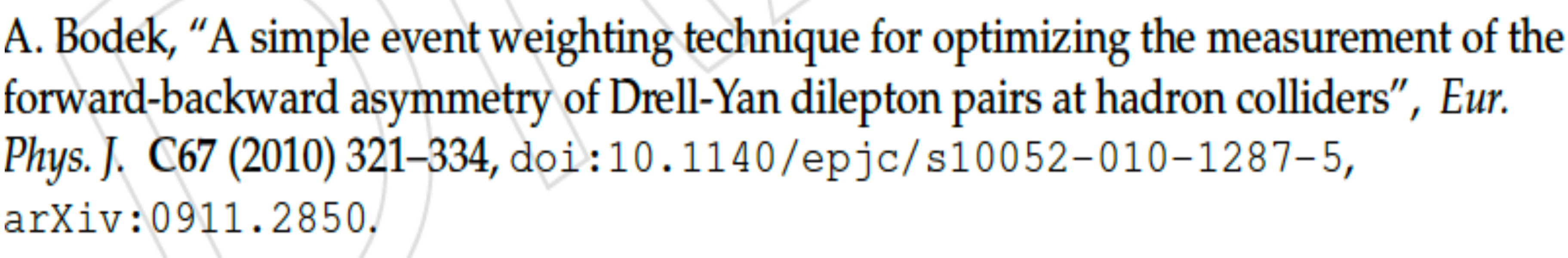
Reduces contribution at to $\Delta\sin^2\theta_{eff}$ to ±0.00008



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`.

Precise Lepton Energy/Momentum calibration at CDF and CMS (gets better with more luminosity)

CMS

Technique used for both $\mu^+\mu^-$ and e^+e^- for both data and MC.

Used in CDF and CMS for muons and electrons.

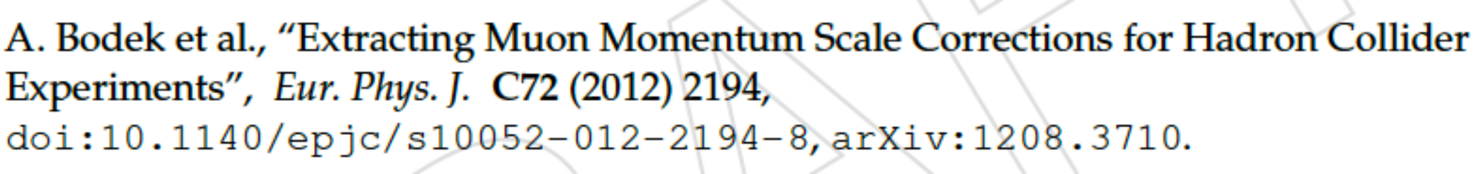
Step I : Remove the correlations between the scale for the two leptons by getting an initial calibration using Z events and requiring that the **mean $<1/P_T>$** of each lepton in bins of η, Φ and charge be correct.

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.

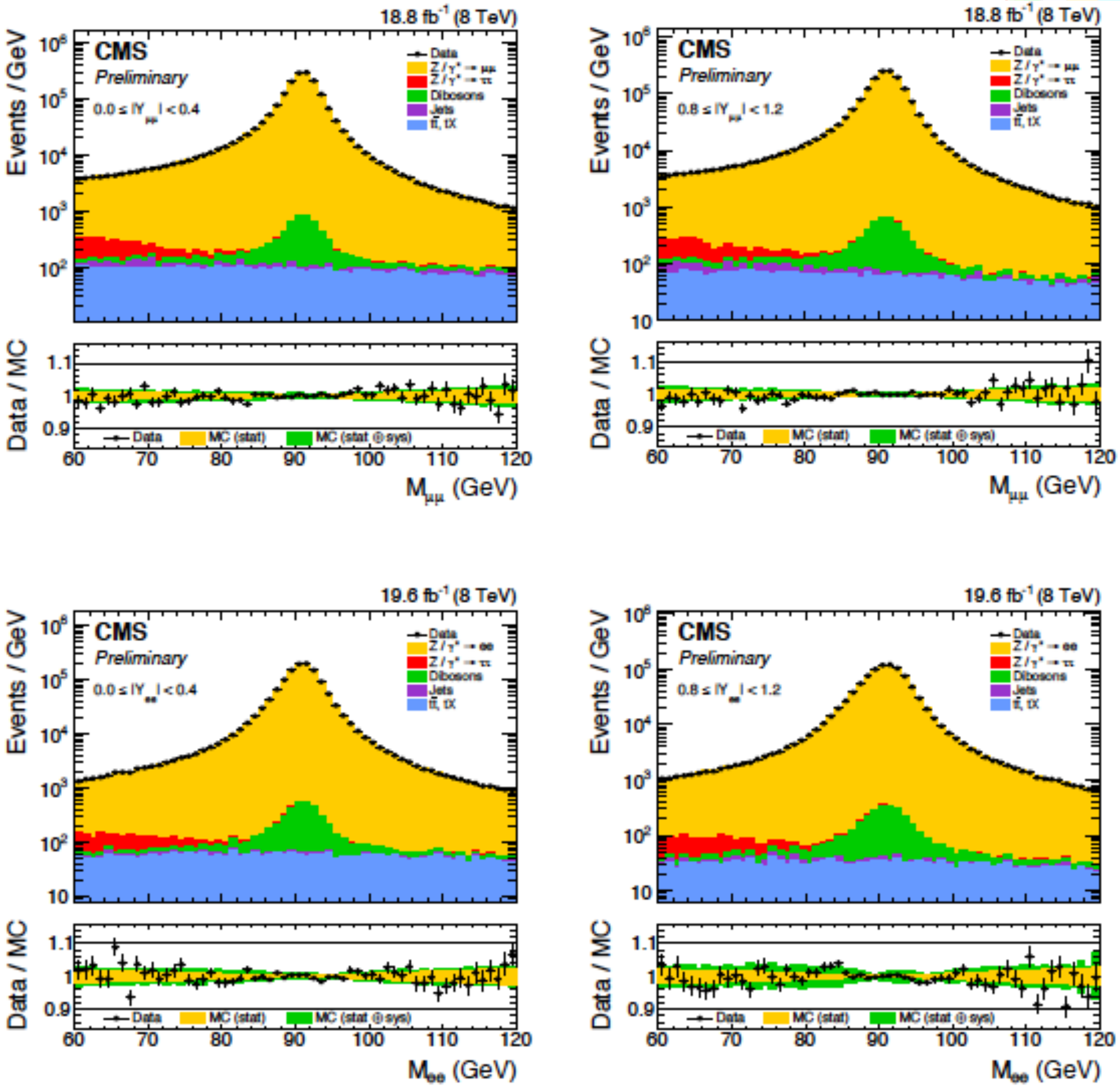
Mass distributions

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



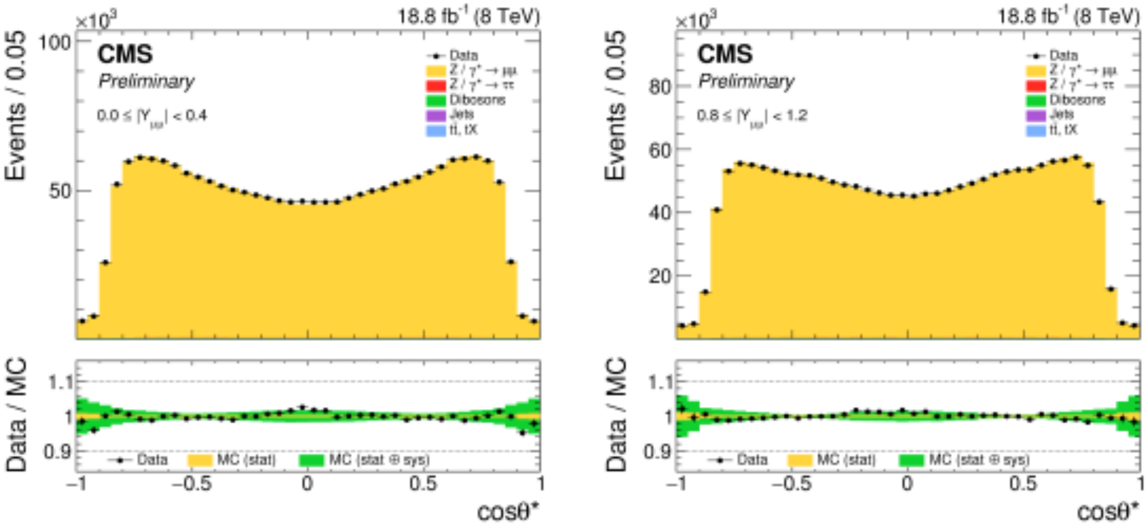
Cosθ distributions

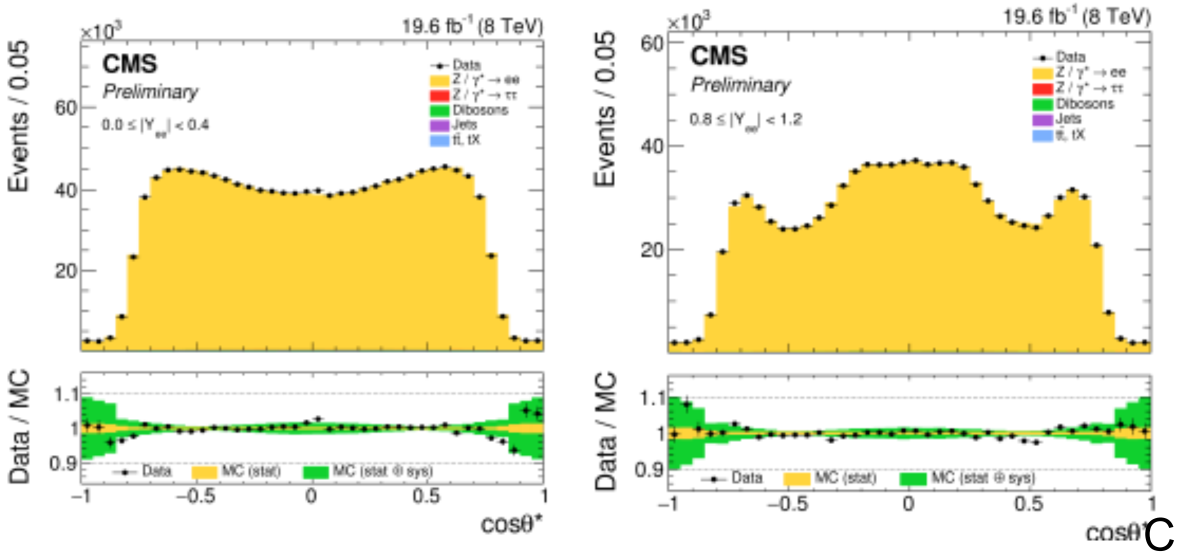
CMS

- 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

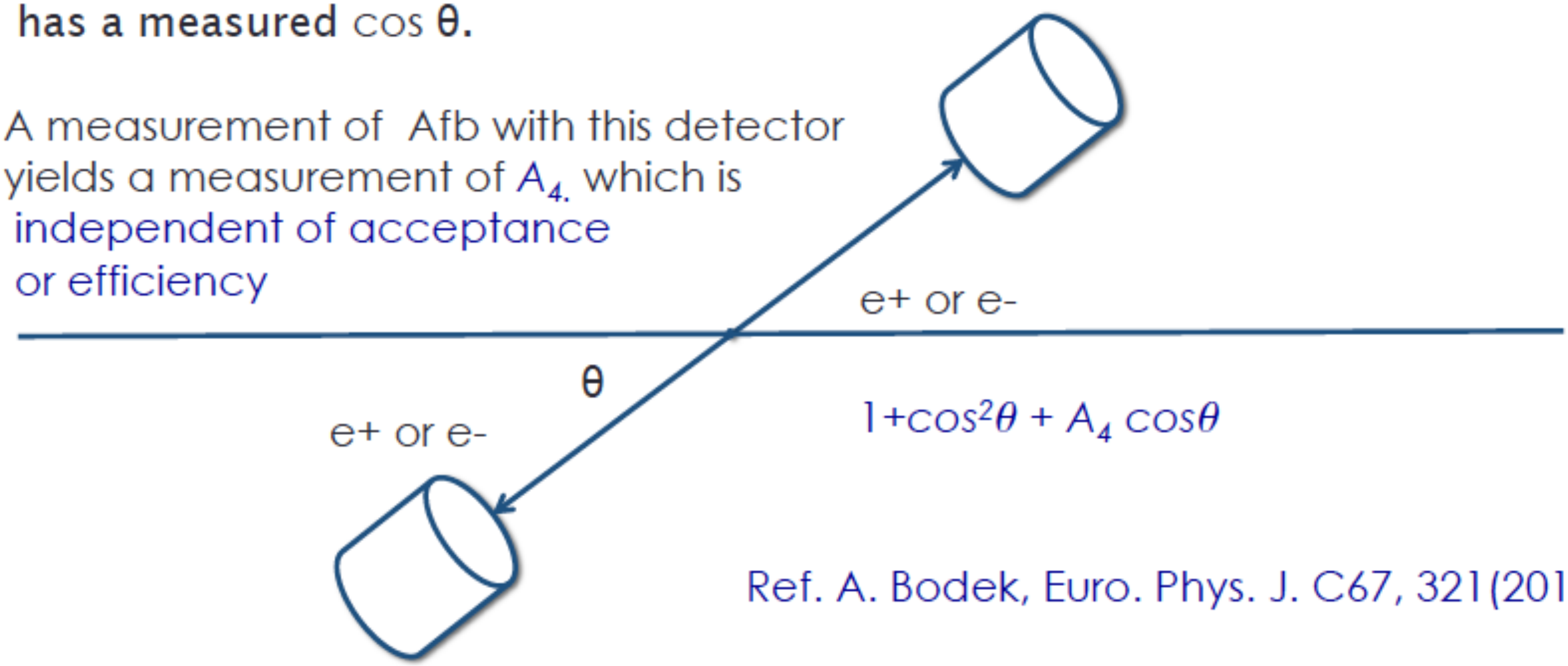
CMS Eur. Phys. J. C 78 (2018) 701

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



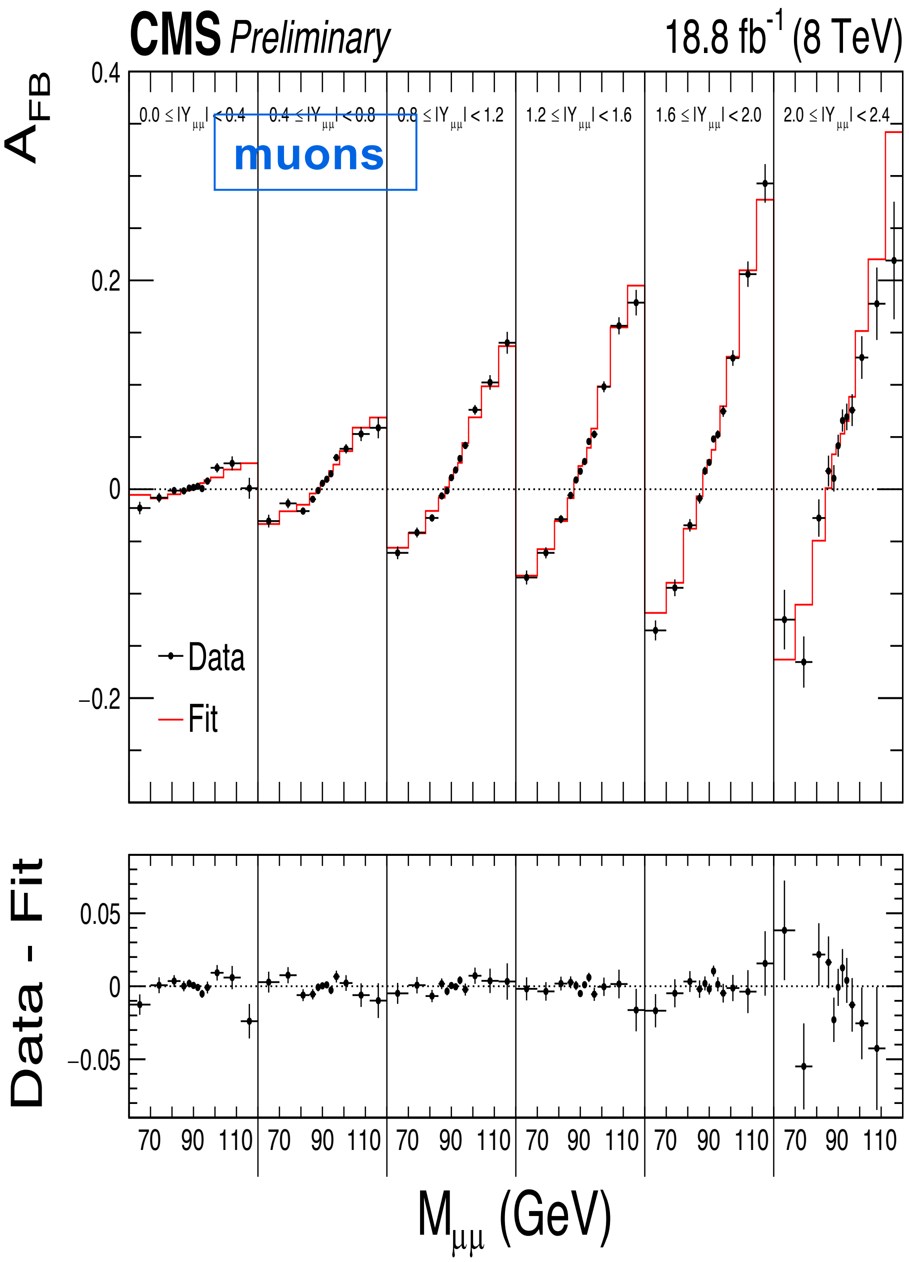
Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

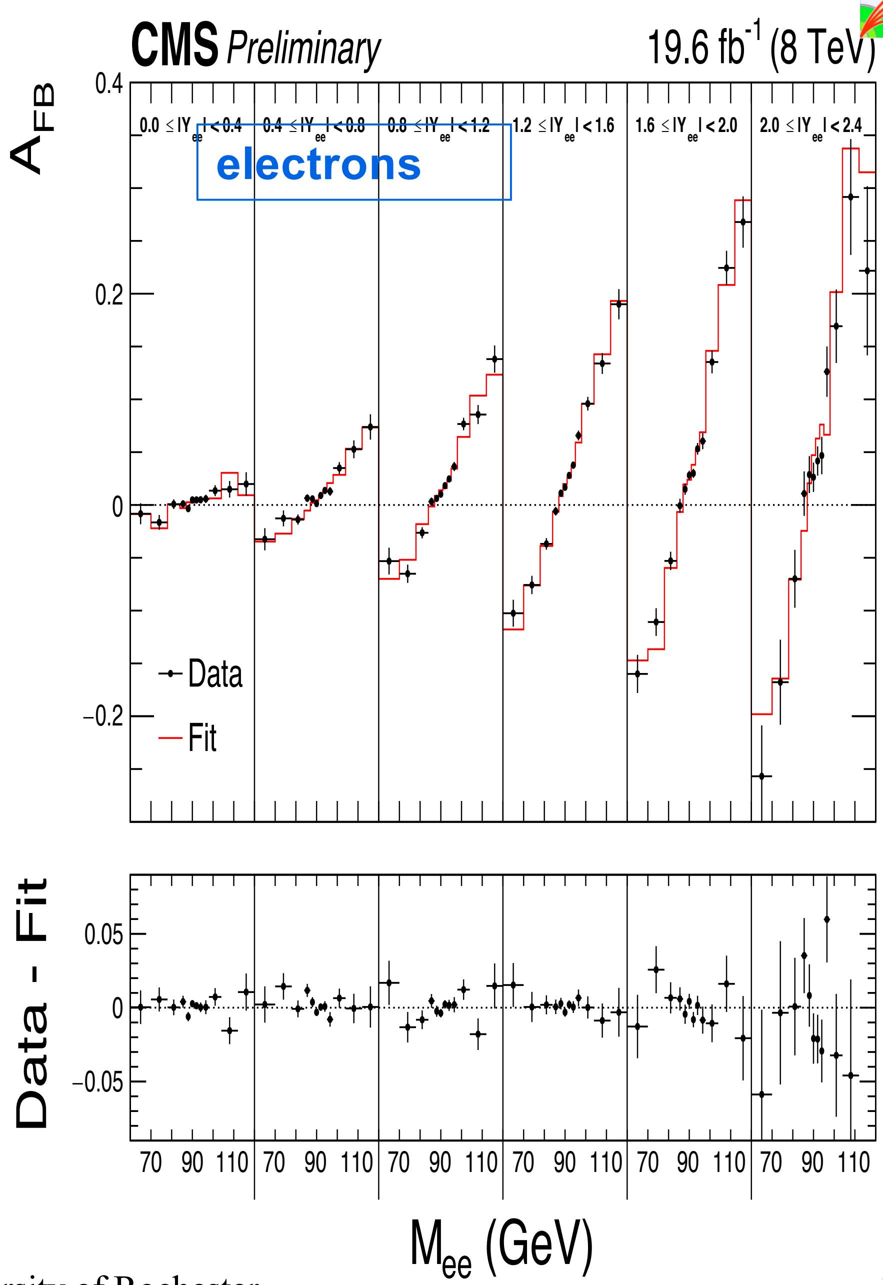
cos **θ=1 yields best** measurement of A_4. cos **θ=0 yields no measurement of** A_4

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

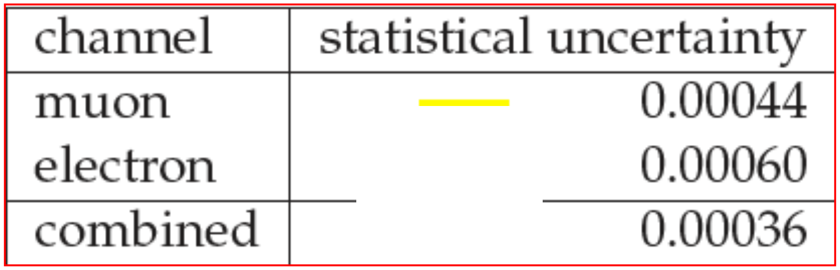




CMS Eur. Phys. J. C 78 (2018) 701

CMS Eur. Phys. J. C 78 (2018) 701

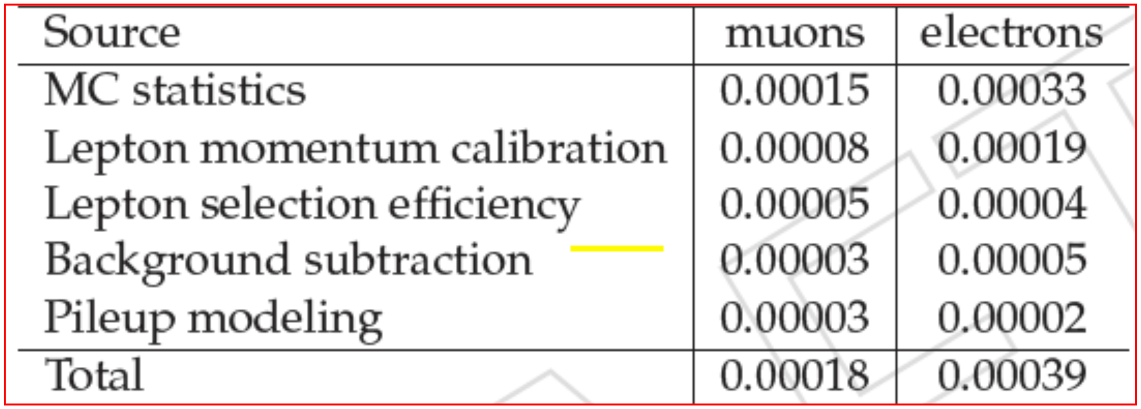
CMS



channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

Combined **± 0.00036 (stat)**

8 TeV 19 fb-1

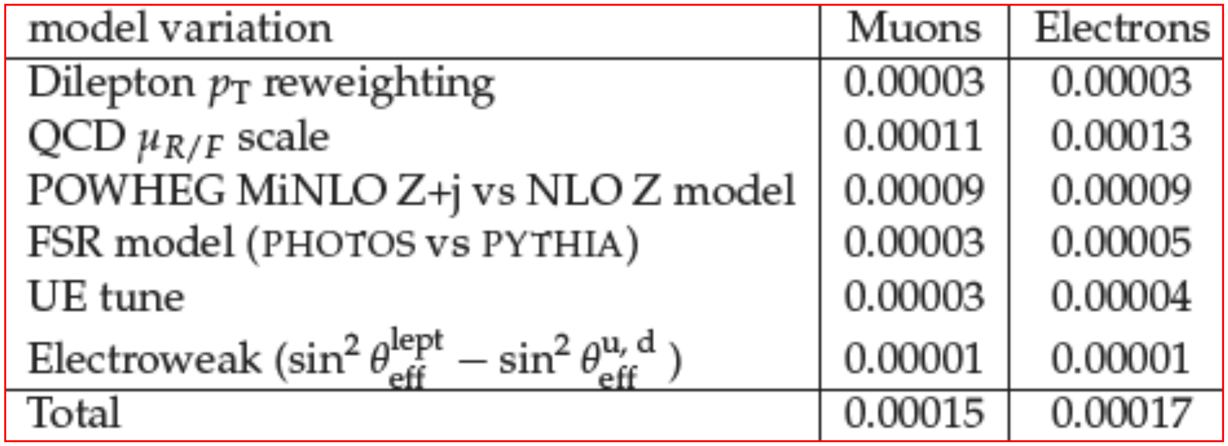


Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

Combined **± 0.00018 (syst)**

Dominated by MC statistics

Can be reduced with fast MC

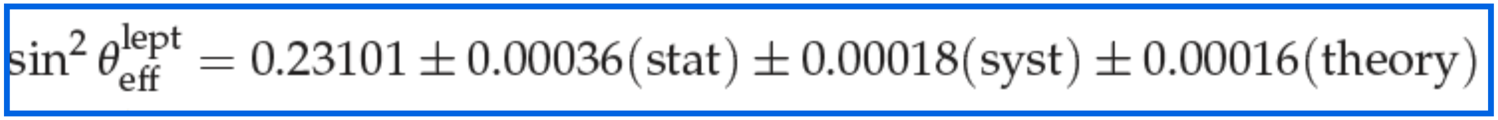


model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta^{\text{lept}}_{\text{eff}} - \sin^2\theta^{\text{u,d}}_{\text{eff}}$)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

Combined **± 0.00016 (theory)**

Dominated by higher order QCD

Can be reduced in the future.



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

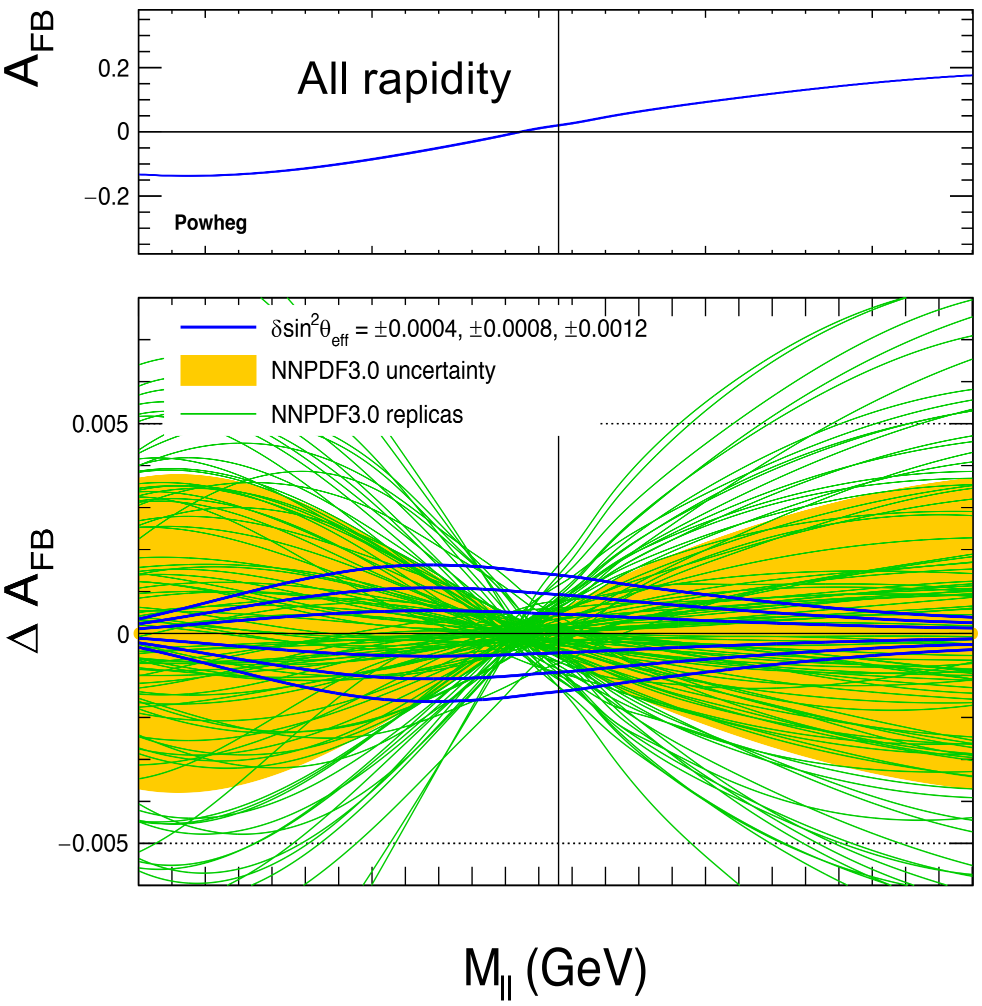
Next: PDF errors

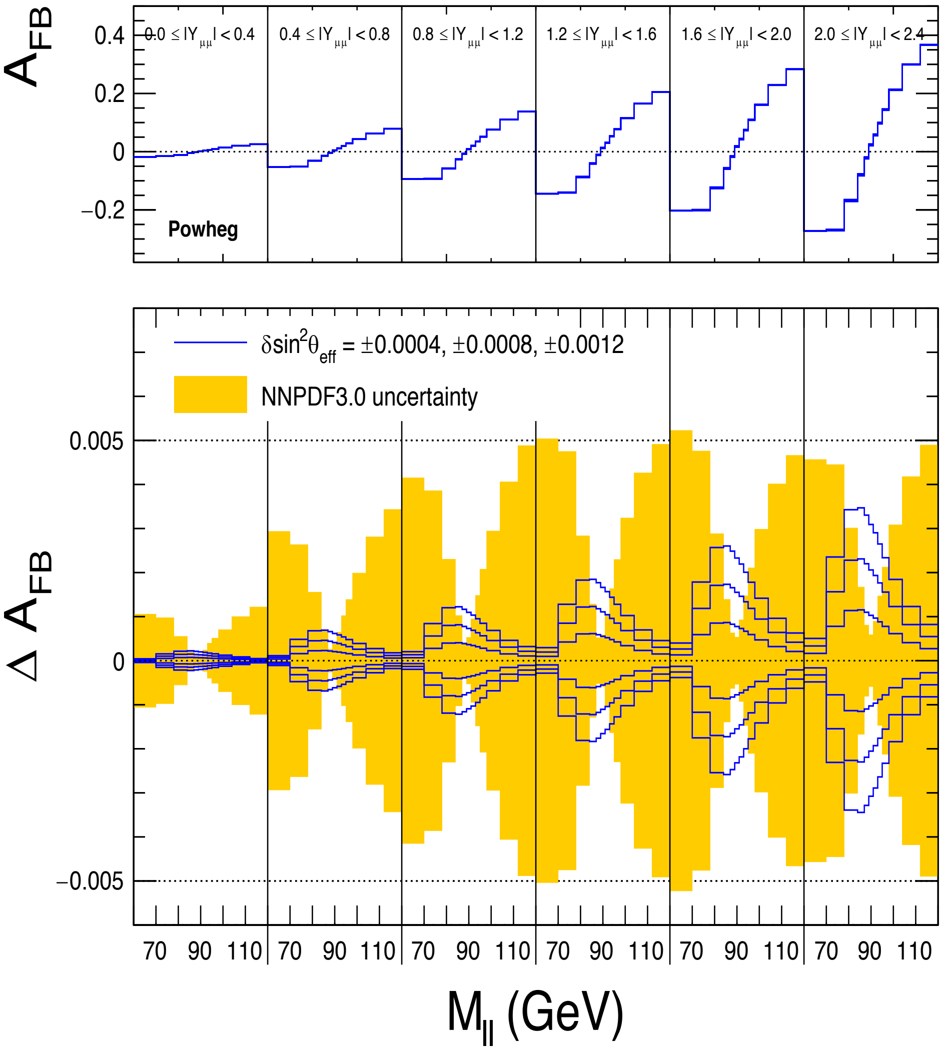
CMS

- 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 Bodek et al. EPJC 76, 115 (2016)

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





The new Technique can be implemented in both
Bayesian PDFs (done by CDF, CMS) or Hessian PDFs (done by CMS. ATLAS)
Both are equivalent.

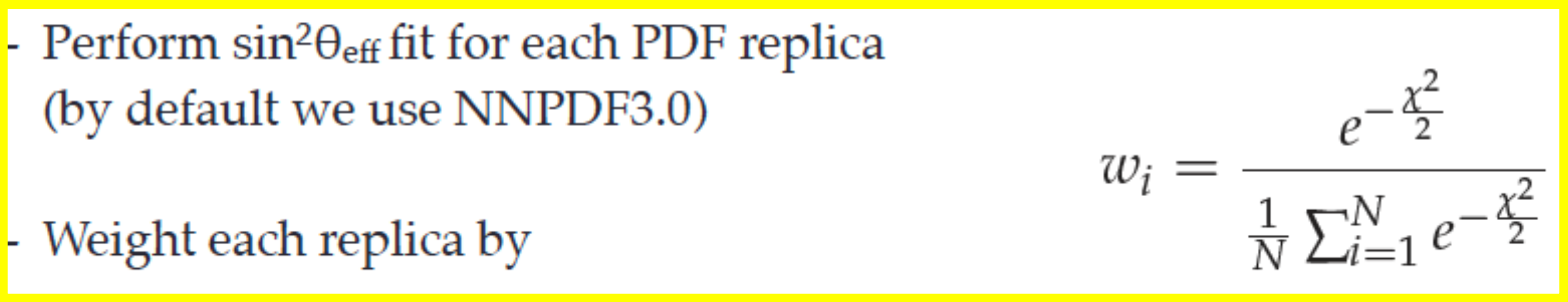
CMS

Bayesian PDFs use 100 to 1000 PDF replicas (which span the phase space of the PDF errors).

The standard technique is to take the mean of all replicas for best value, and the standard deviation for the PDF uncertainty.

The new technique constraining Bayesian PDFs

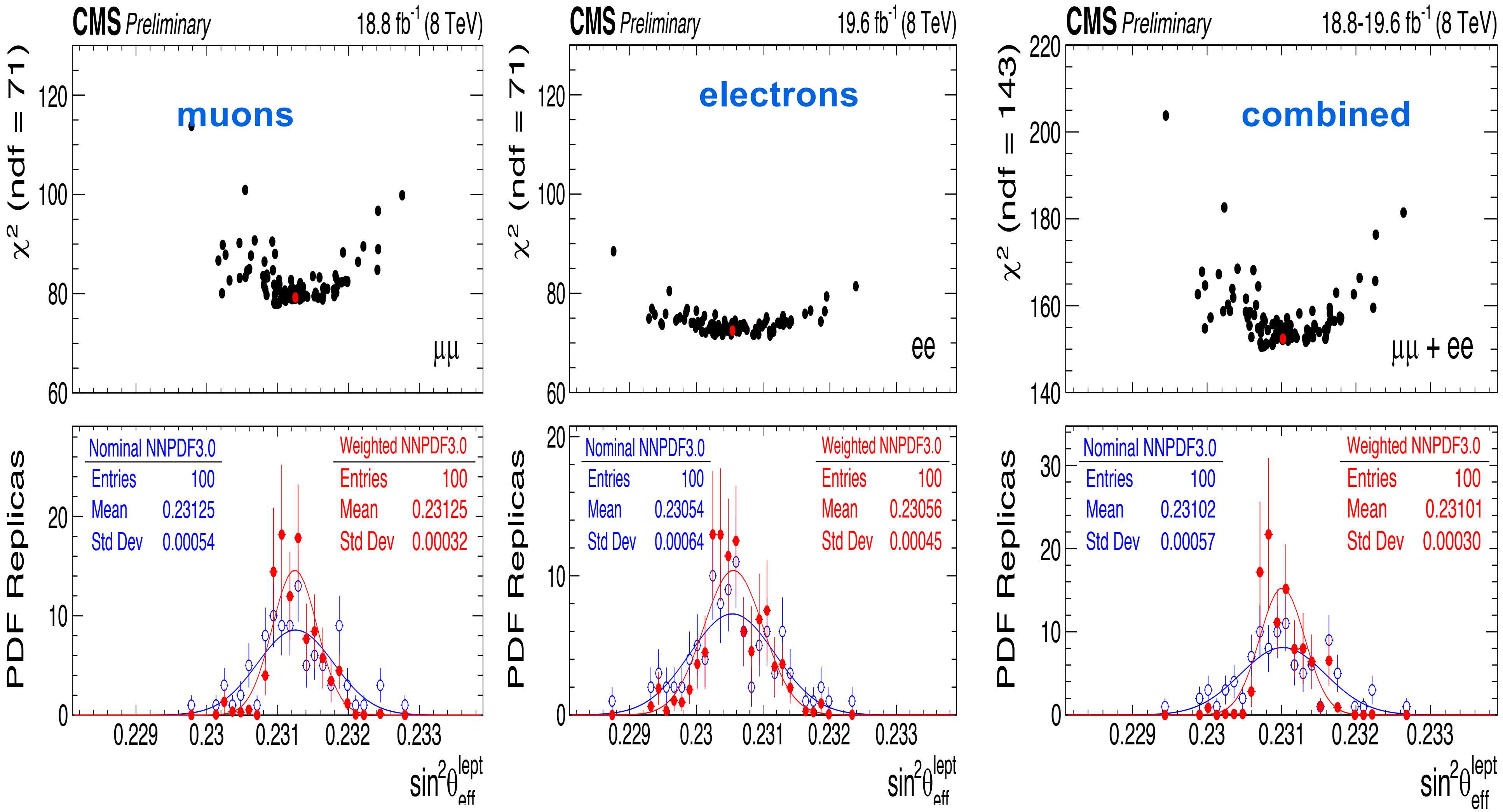
Bodek et al. EPJC 76, 115 (2016



- 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 their best fit **$\sin^2\theta_{\mathrm{eff}}$**



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	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

CMS Eur. Phys. J. C 78 (2018) 701

.

CMS

- Measured $\sin^2\theta_{\mathrm{eff}}$ 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

CMS Eur. Phys. J. C 78 (2018) 701

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

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

(26 MeV error in Mw indirect)

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

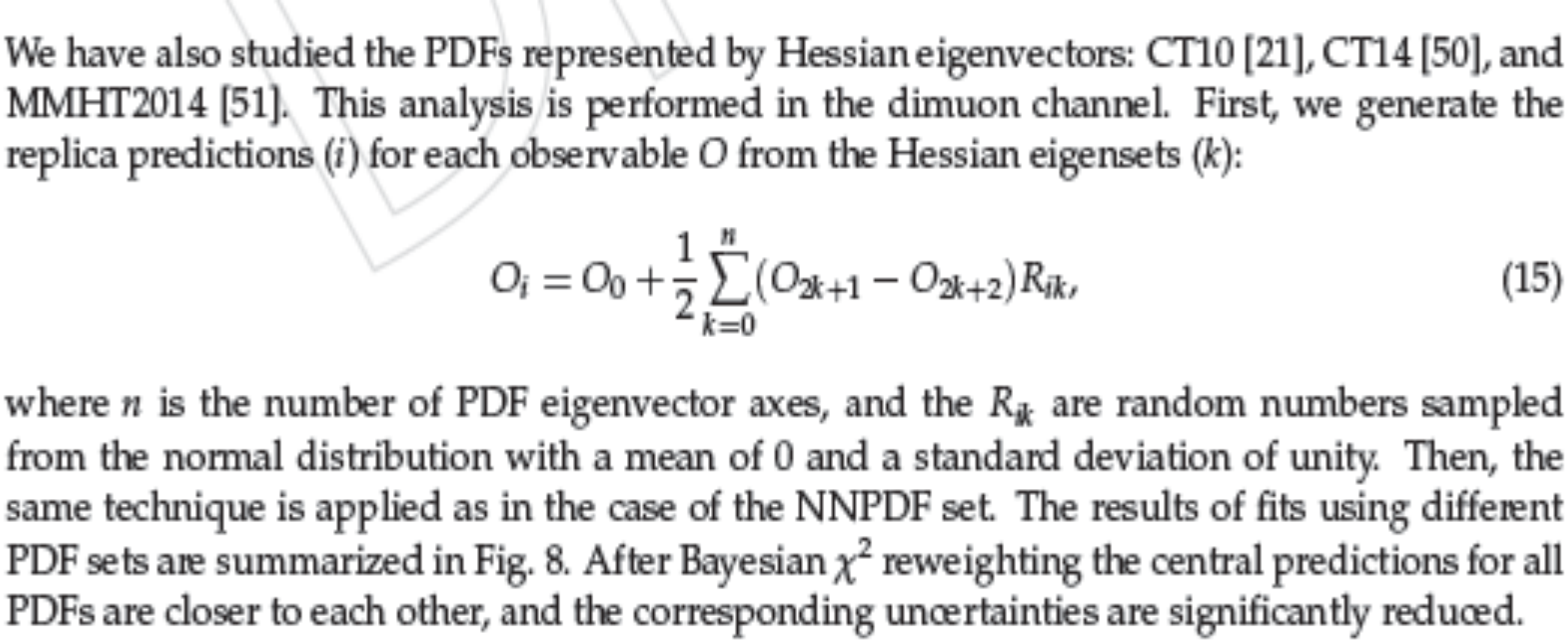
What about other PDF sets?

CMS Eur. Phys. J. C 78 (2018) 701

Hessian PDFs can also be converted to Replica PDFs. This allows us to test the Bayesian technique with any PDF set.

Hessian PDFs have a set of error eigenvalue PDFS

Converting Hessian to Bayesian PDFs



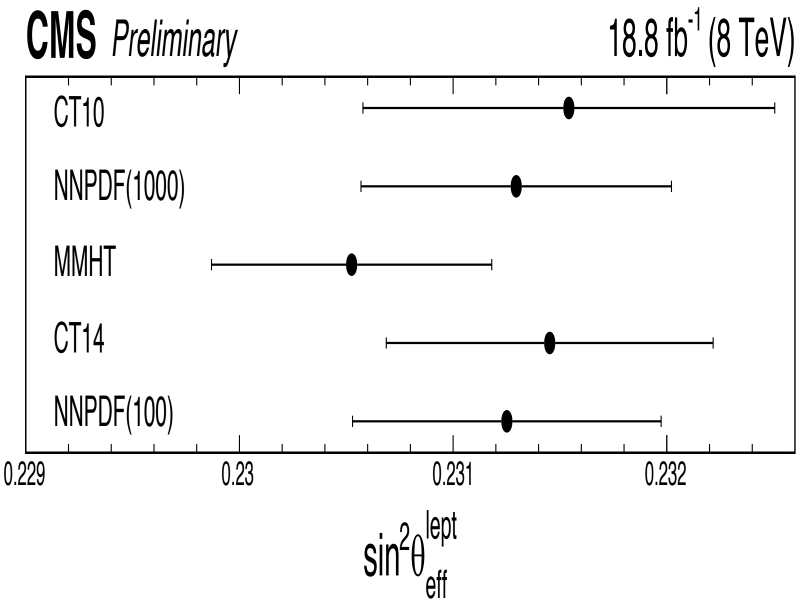
We have also studied the PDFs represented by Hessian eigenvectors: CT10 [21], CT14 [50], and MMHT2014 [51]. This analysis is performed in the dimuon channel. First, we generate the replica predictions (i) for each observable O from the Hessian eigensets (k):

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

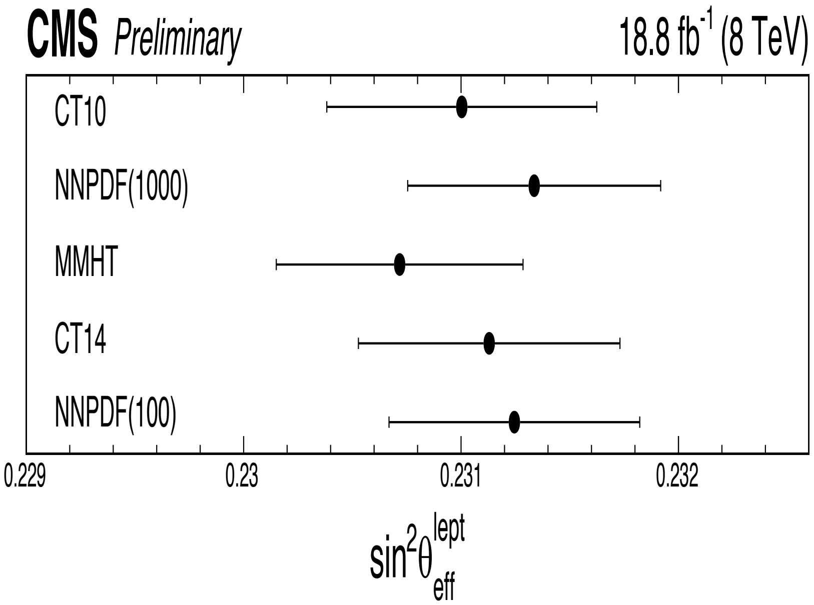
where n is the number of PDF eigenvector axes, and the R_{ik} are random numbers sampled from the normal distribution with a mean of 0 and a standard deviation of unity. Then, the same technique is applied as in the case of the NNPDF set. The results of fits using different PDF sets are summarized in 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.

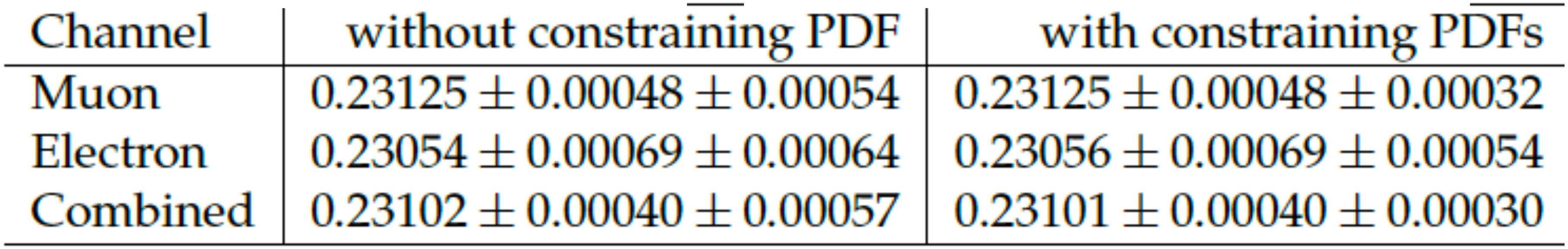
- CMS Eur. Phys. J. C 78 (2018) 701

CMS PDF nominal



CMS Bayesian PDF Weighted



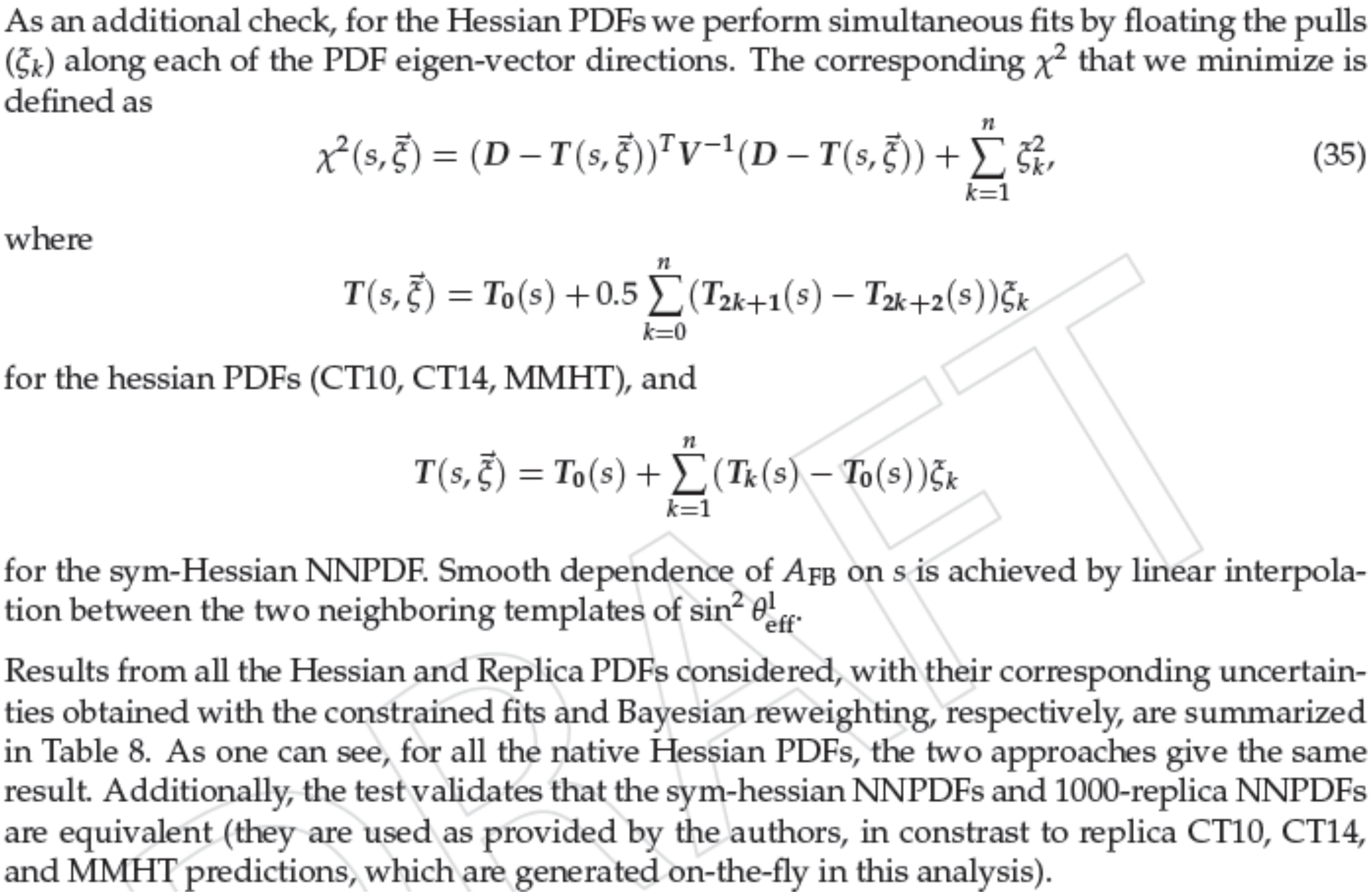


Channel	without constraining PDF	with constraining PDFs
Muon	$0.23125 \pm 0.00048 \pm 0.00054$	$0.23125 \pm 0.00048 \pm 0.00032$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$	$0.23056 \pm 0.00069 \pm 0.00054$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

Constraining Hessian PDFs Directly (equivalent) CMS Eur. Phys. J. C 78 (2018) 701

With Hessian constraints, we can only get the total (stat.+PDF) errors.

With Bayesian constraints we get Stat and PDF errors separately (and then add).



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

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

where

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

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

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

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

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).

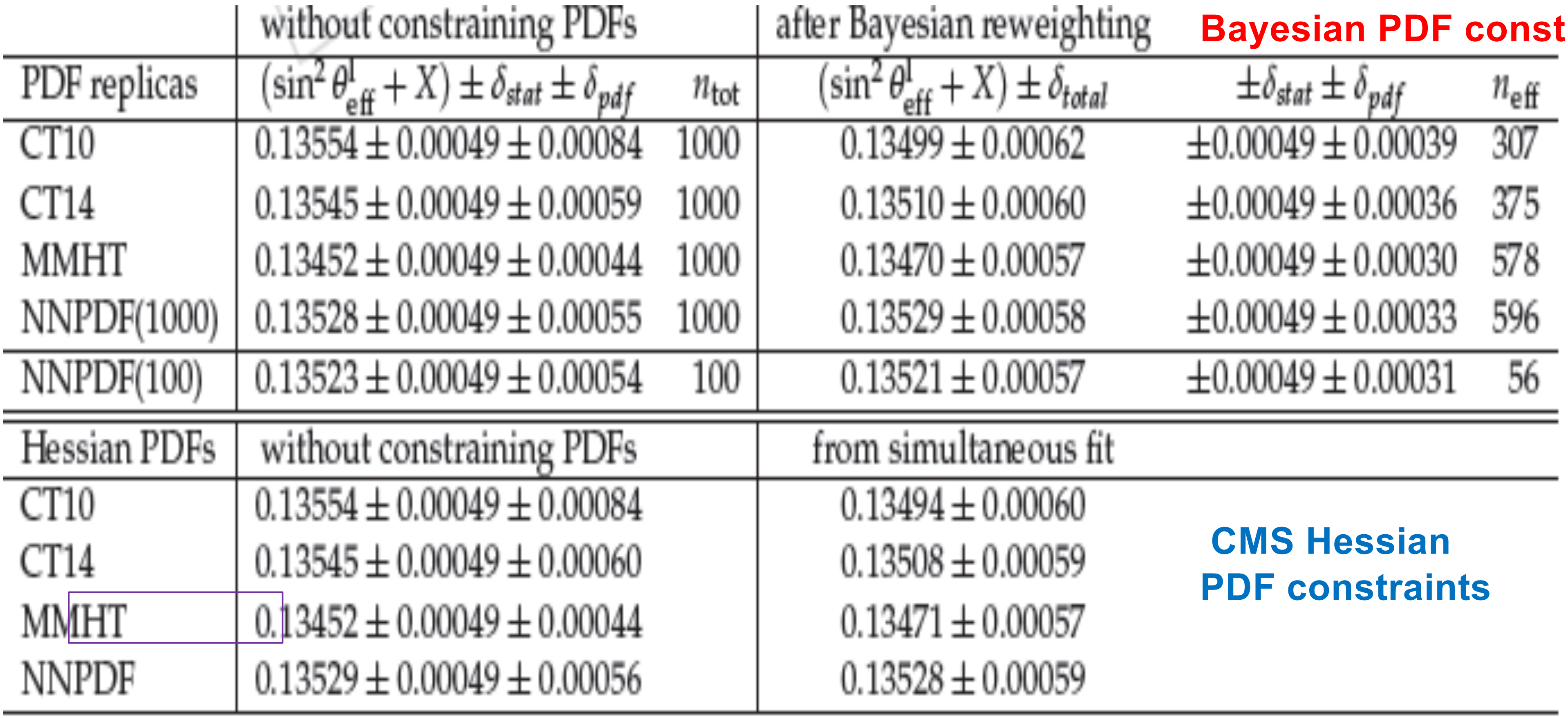
CMS Eur. Phys. J. C 78 (2018) 701

The PDF constraining technique works for both Hessian (eigenvectors) and Bayesian (Replica) PDFs. Same results are obtained from the two implementations

.

CMS Eur. Phys. J. C 78 (2018) 701

CMS
Bayesian PDF constraints



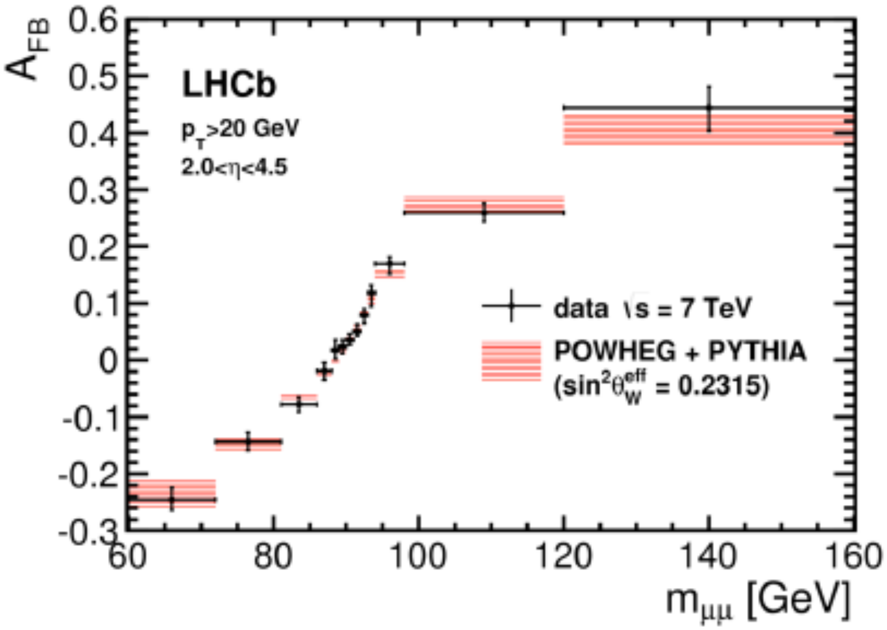
	without constraining PDFs		after Bayesian reweighting		
PDF replicas	$(\sin^2\theta^l_{eff}+X)\pm\delta_{stat}\pm\delta_{pdf}$	n_{tot}	$(\sin^2\theta^l_{eff}+X)\pm\delta_{total}$	$\pm\delta_{stat}\pm\delta_{pdf}$	n_{eff}
CT10	$0.13554\pm0.00049\pm0.00084$	1000	0.13499 ± 0.00062	$\pm0.00049\pm0.00039$	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		

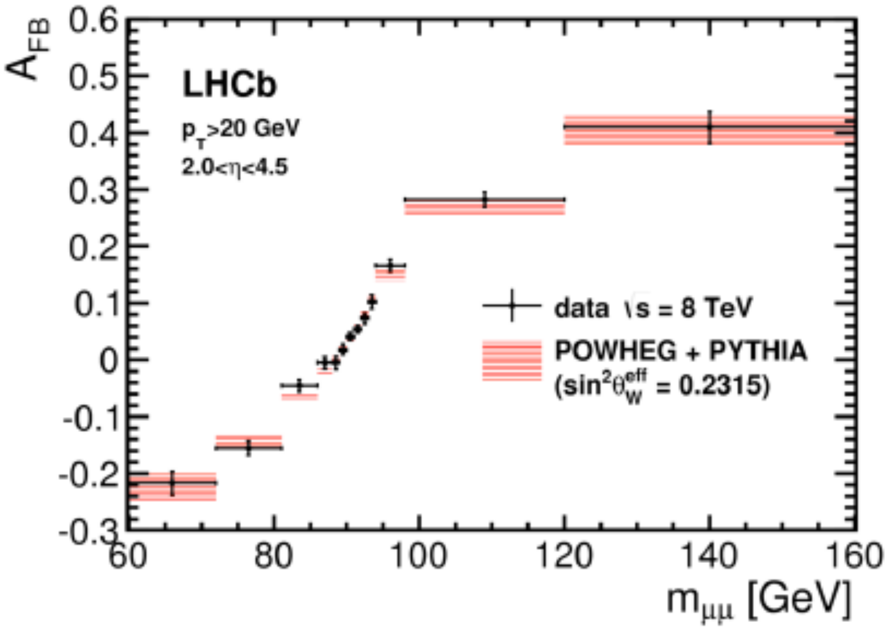
CMS Hessian
PDF constraints

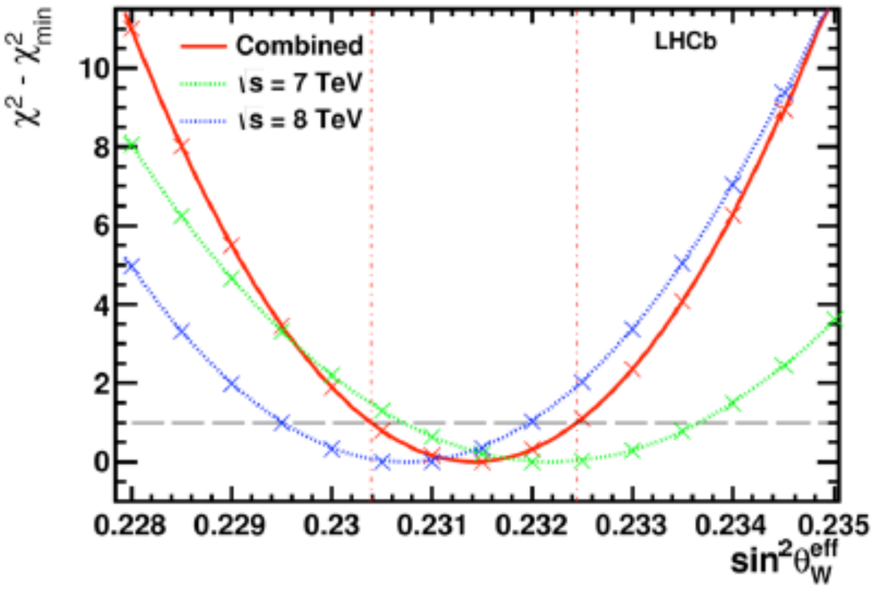
ATLAS uses Hessian PDFs constraints (they call it PDF profiling)

Weak mixing angle by LHCb

JHEP 1511(2015) 190







- Combined 7 and 8 TeV measurement

- Limited by statistical uncertainties

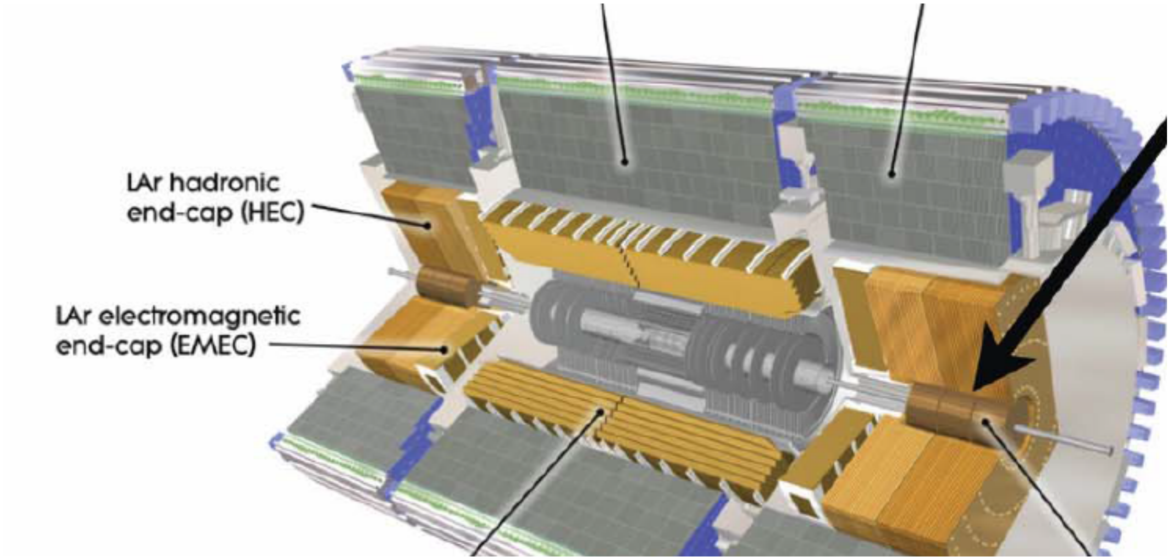
J. High Energy Phys. 11 (2015) 190

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

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

LHCb uses unconstrained PDF errors

LHCb paper was published before PDF constraints paper [Bodek et al. EPJ C76(2106) 115]



ATLAS forward electron detector (used for 8 TeV Preliminary results) and also for 13 TeV analysis

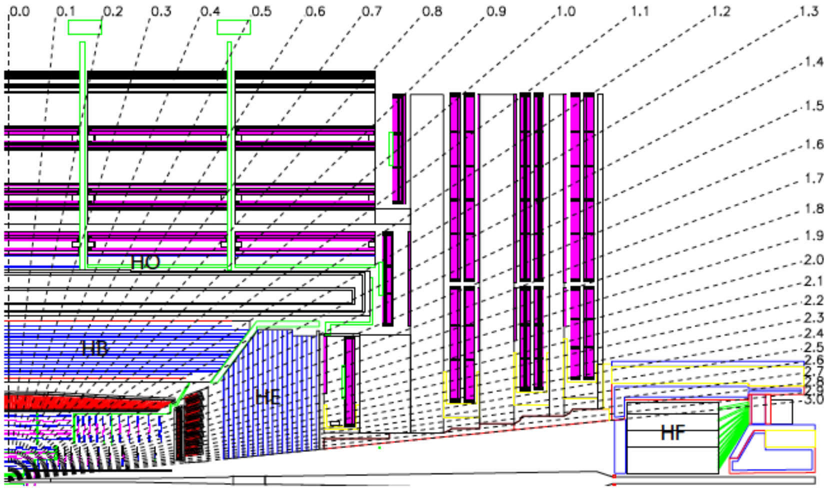
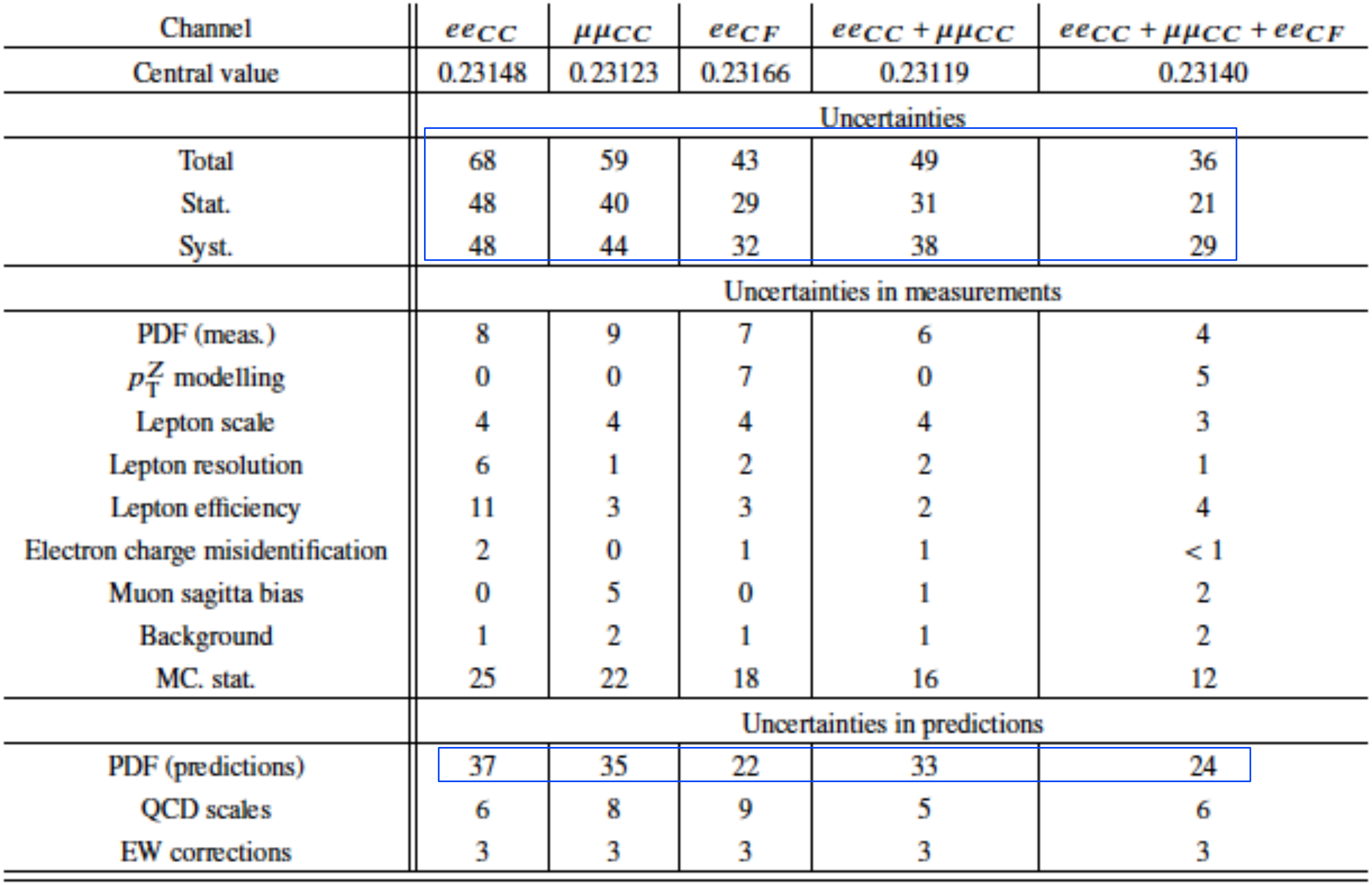


Figure 1: An elevation view of the CMS detector showing the HCAL subsystems (HB, HE, HO, and HF). Lines of constant pseudo-rapidity are shown as the dashed lines in the figure.

CMS HF* forward electron detector (upgraded for 13 TeV) now being used in 13 TeV analysis.

.



Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_{T}^{Z} modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

ATLAS preliminary 8 TeV (with PDF constraints)

CMS (8 TeV eeCC+ CC$\mu\mu$): $\sin^2\theta_W^{eff}$ = 0.23101 +- 0.00052 (with PDF constraints)
Preliminary ATLAS (8 TeV eeCC+ CC$\mu\mu$): $\sin^2\theta_W^{eff}$ = 0.23119 +- 0.00049 (with PDF constraints)*

* Using Bodek et al. EPJC 76, 115 (2016) Method)

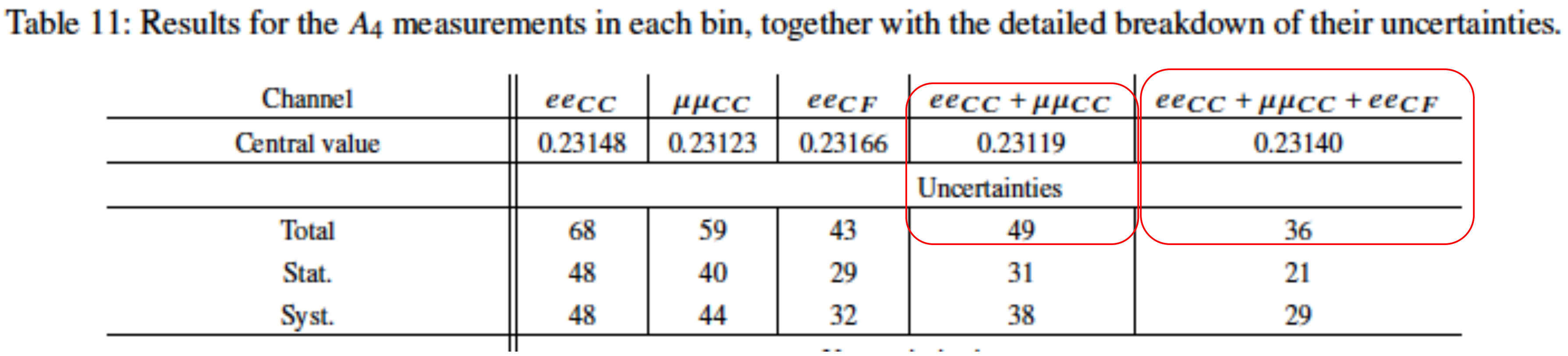


Table 11: Results for the A_4 measurements in each bin, together with the detailed breakdown of their uncertainties.

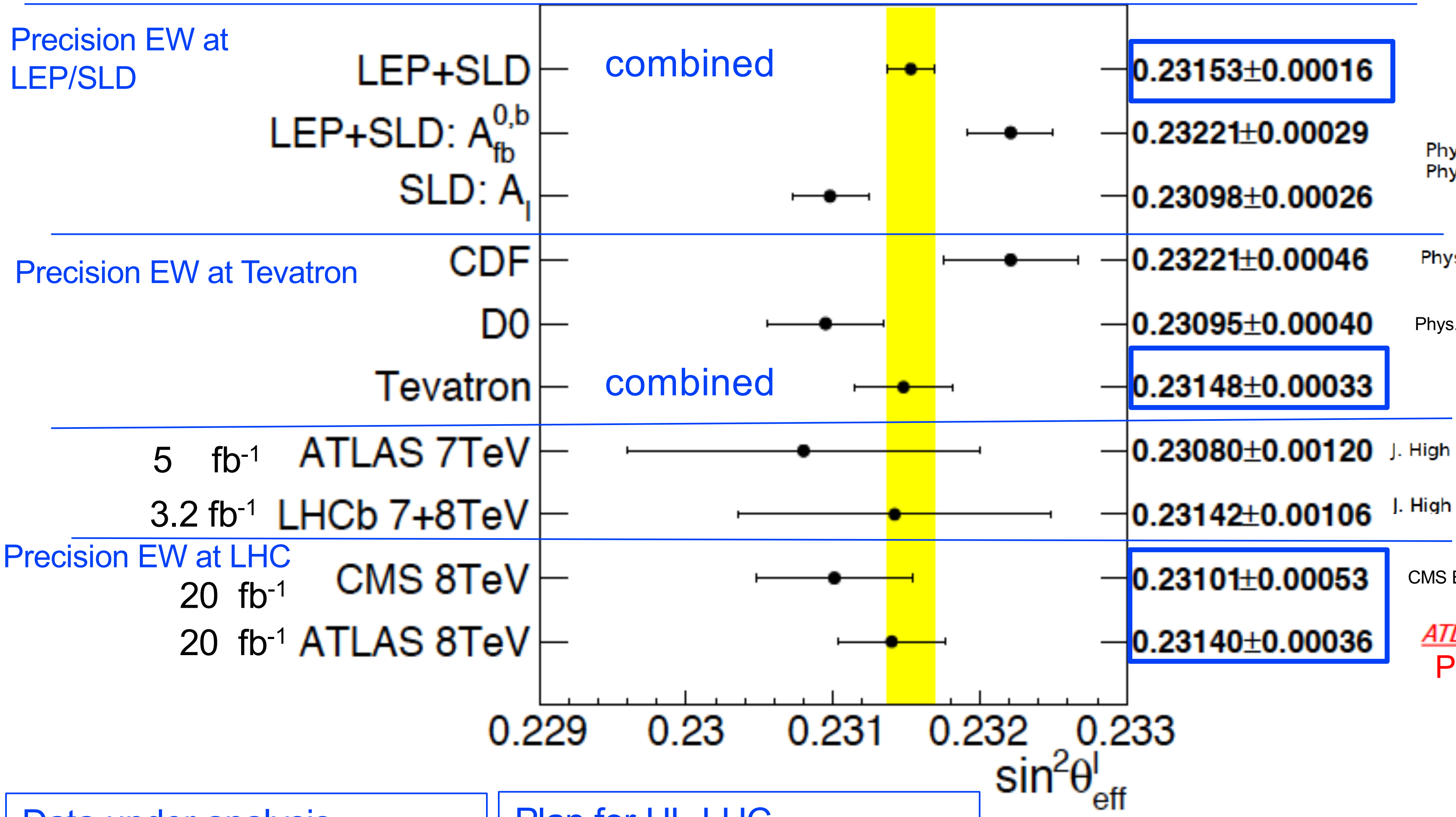
Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
				Uncertainties	
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29

ATLAS also Including forward detector

ATLAS-CONF-2018-037

$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23140 \pm 0.00021(\mathrm{stat.}) \pm 0.00024(\mathrm{PDF}) \pm 0.00016(\mathrm{syst.})$ (0.00036 tot)

ATLAS 8 TeV $\sin^2\theta_W^{eff}$ = 0.23140 +- 0.00036 (with PDF constraints)



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

Phys. Rev. D93, 112016 (2016)

Phys. Rev. Lett. 120, 241802 (2018)

Phys. Rev. D 97, 112007 (2018

J. High Energy Phys. 09 (2015) 049

J. High Energy Phys. 11 (2015) 190

CMS Eur. Phys. J. C 78 (2018) 701

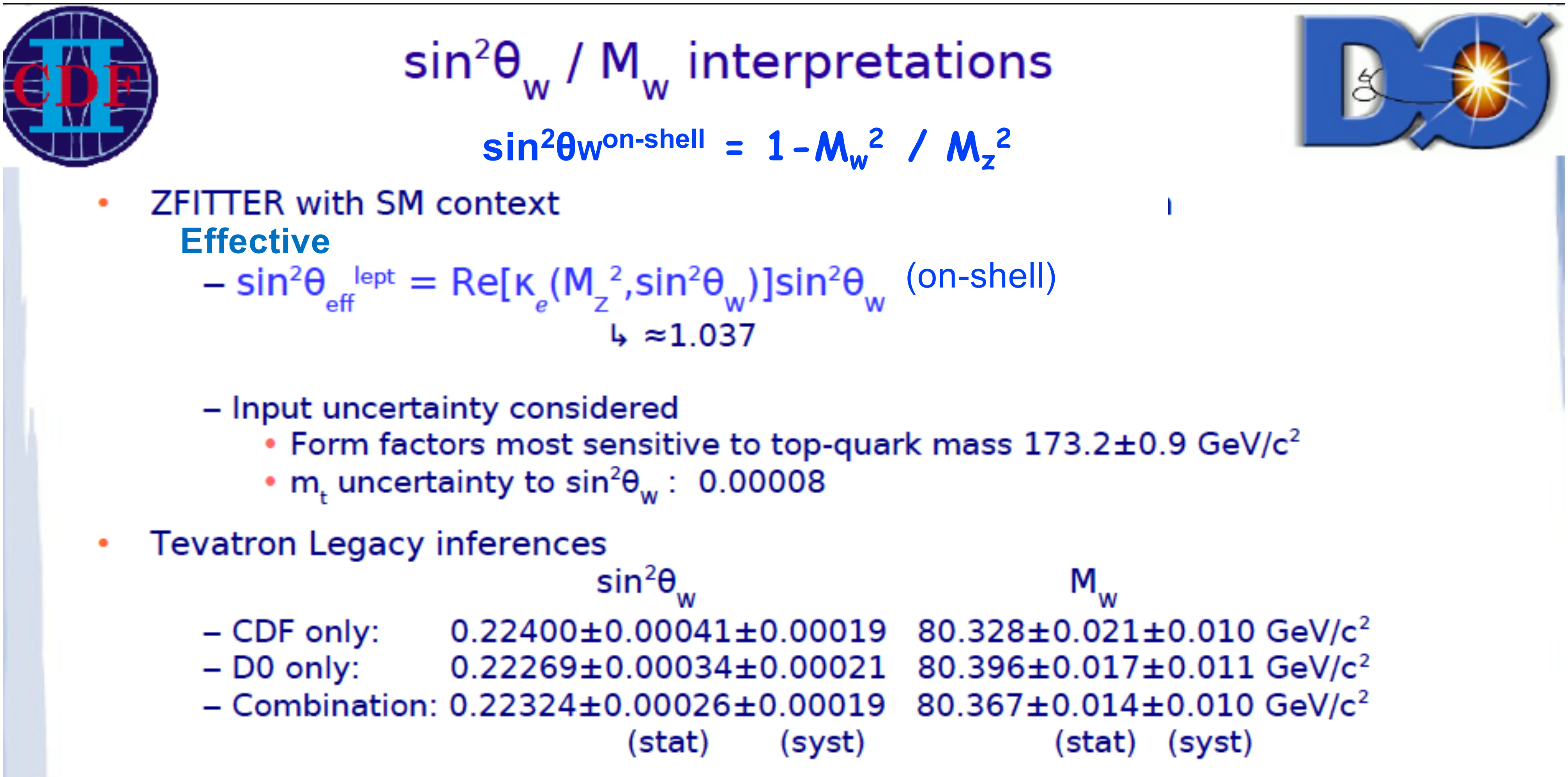
ATLAS-CONF-2018-037
Preliminary

Data under analysis			
13 TeV	LHCb	5.4	fb^{-1}
13 TeV	ATLAS	140	fb^{-1}
13 TeV	CMS	140	fb^{-1}

Plan for HL-LHC			
14 TeV	LHCb	300	fb^{-1}
14 TeV	ATLAS	3000	fb^{-1}
14 TeV	CMS	3000	fb^{-1}

Aim at ± 0.00016 in $\sin^2\theta_w^{eff}$ (SLD/ LEP combination)
Equivalent indirect M_W to ± 8 MeV

Tevatron Analysis



$\sin^2\theta_W$ / M_W interpretations

$\sin^2\theta_W^{\text{on-shell}} = 1 - M_W^2 / M_Z^2$

- ZFITTER with SM context

  Effective

  - $\sin^2\theta_{\text{eff}}^{\text{lept}} = \text{Re}[\kappa_e(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$ (on-shell)

    $\kappa_e \approx 1.037$

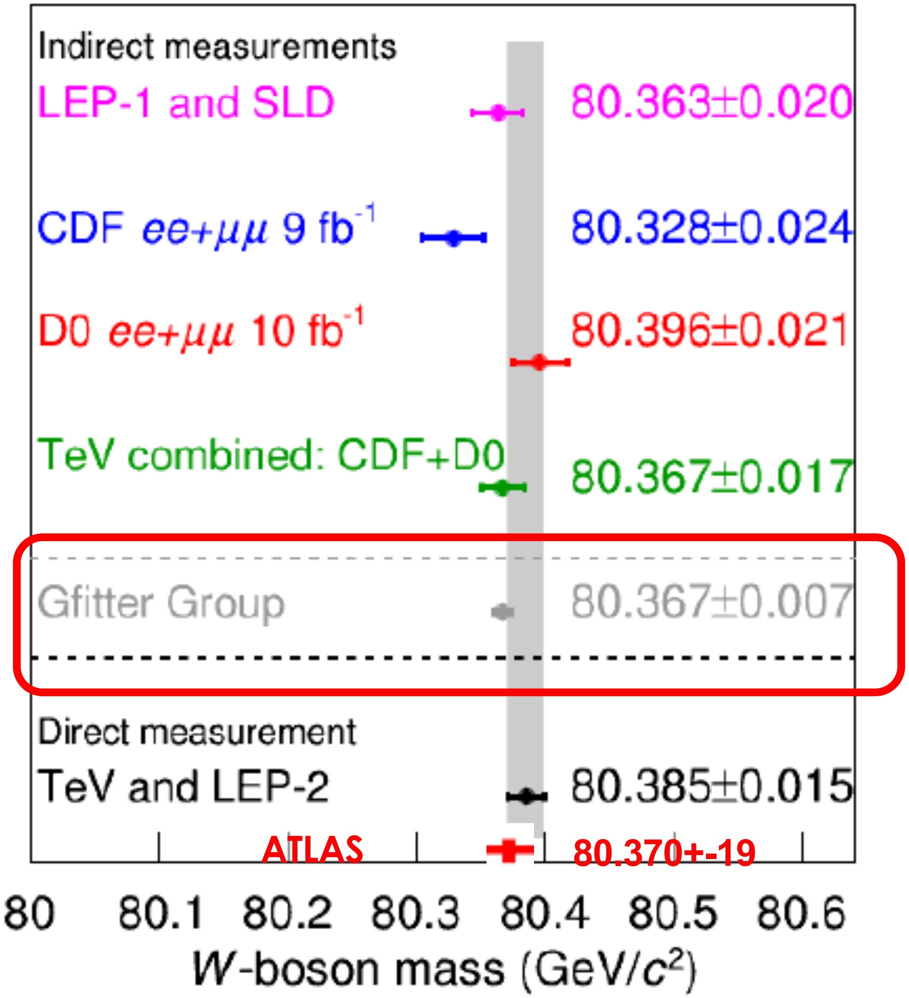
  - Input uncertainty considered
    - Form factors most sensitive to top-quark mass 173.2±0.9 GeV/c^2
    - m_t uncertainty to $\sin^2\theta_W$: 0.00008
- Tevatron Legacy inferences

	$\sin^2\theta_W$	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)

On-shell

Indirect measurement of Mw within standard model (W. Sakumoto U. of Rochester)

$$\sin^2\theta_W^{\text{on-shell}} = 1 - M_W^2 / M_Z^2$$



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)

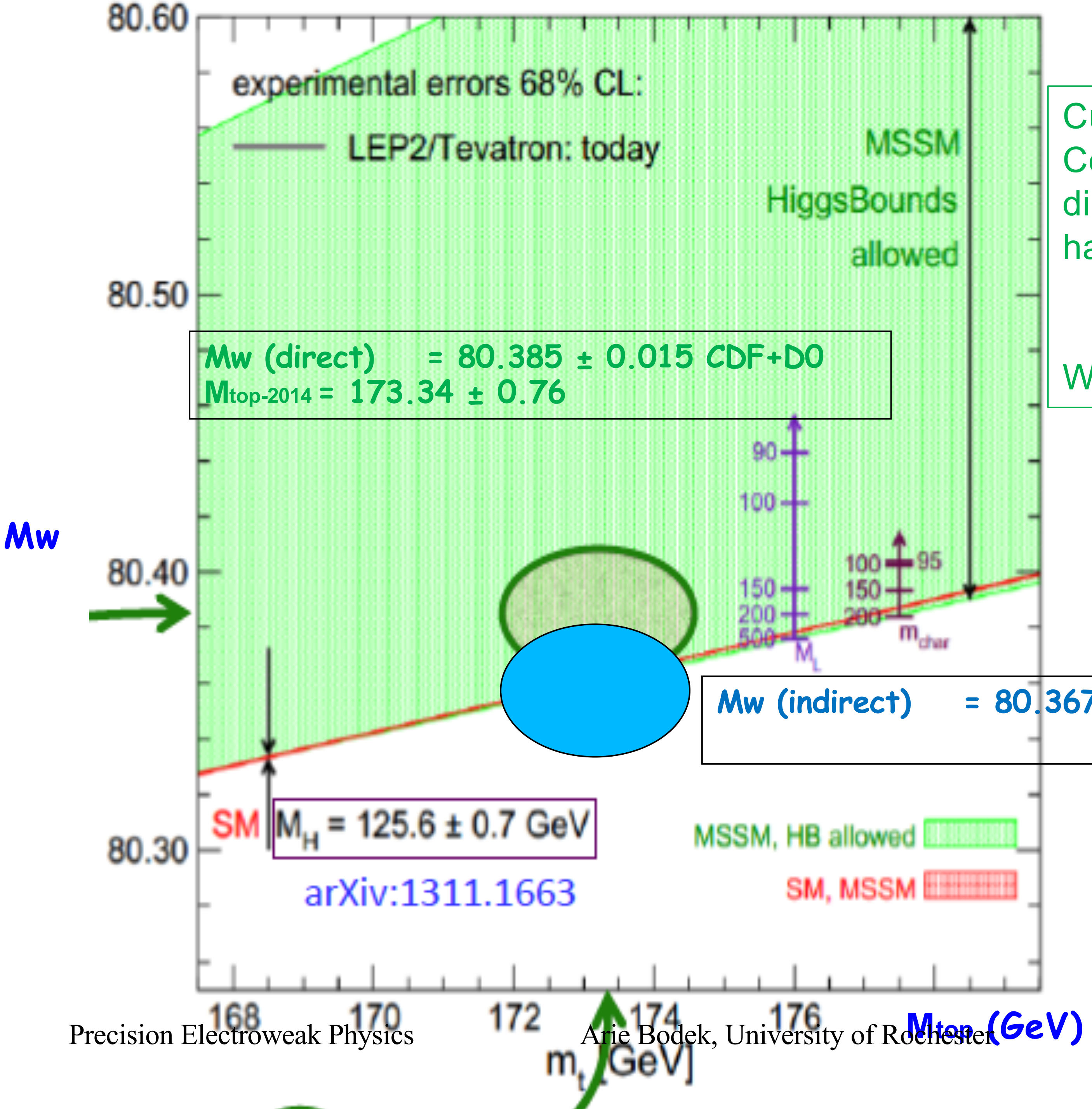
Includes M_H value

Phys. Rev. D 97, 112007 (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



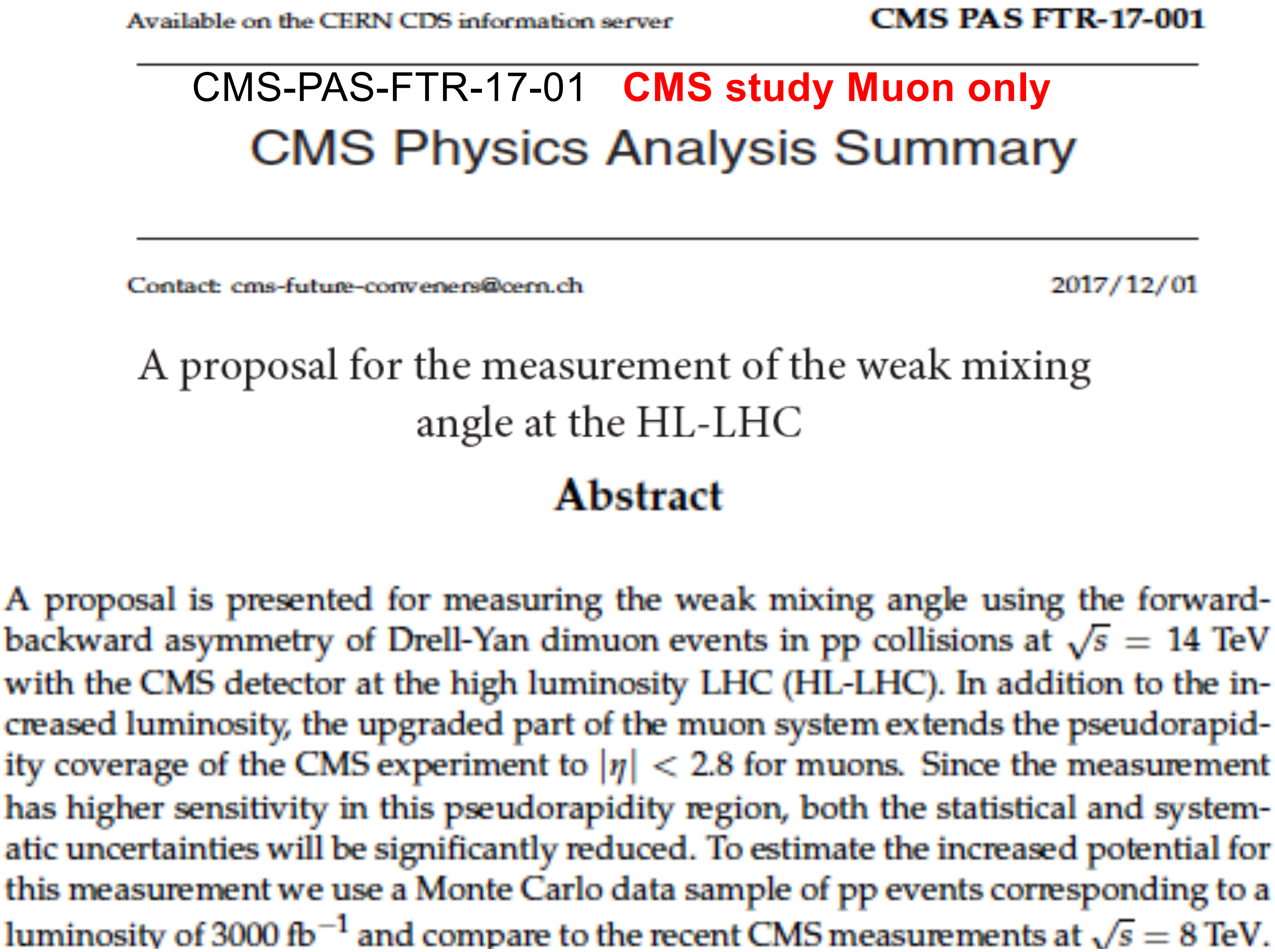
Mw (direct) = 80.385 ± 0.015 CDF+D0

Mtop-2014 = 173.34 ± 0.76

Mw (indirect) = 80.367 ± 0.017 CDF+D0

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

We can do better at the LH



Available on the CERN CDS information server

CMS PAS FTR-17-001

CMS-PAS-FTR-17-01 **CMS study Muon only**

CMS Physics Analysis Summary

Contact: cms-future-conveners@cern.ch

2017/12/01

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

Abstract

A proposal is presented for measuring the weak mixing angle using the forward-backward asymmetry of Drell-Yan dimuon events in pp collisions at $\sqrt{s} = 14$ TeV with the CMS detector at the high luminosity LHC (HL-LHC). In addition to the increased luminosity, the upgraded part of the muon system extends the pseudorapidity coverage of the CMS experiment to $|\eta| < 2.8$ for muons. Since the measurement has higher sensitivity in this pseudorapidity region, both the statistical and systematic uncertainties will be significantly reduced. To estimate the increased potential for this measurement we use a Monte Carlo data sample of pp events corresponding to a luminosity of 3000 fb^{-1} and compare to the recent CMS measurements at $\sqrt{s} = 8$ TeV.

CMS (muons and electrons)

2012	**2015-2018**	**HL-LHC (tracker upgrade from η <2.5 to η <2.8)**	
8 TeV	**13 TeV**	**14 TeV**	
20 fb^{-1}	**140 fb^{-1}**	**3000 fb^{-1}**	→ 0.00003 Stat, 0.00012 PDF

CMS-PAS-FTR-17-01 **CMS study Muon only**

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

Table 1: Setup for MC study for $\sin^2\theta^{\ell}_{\mathrm{eff}}$ 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	- 3000

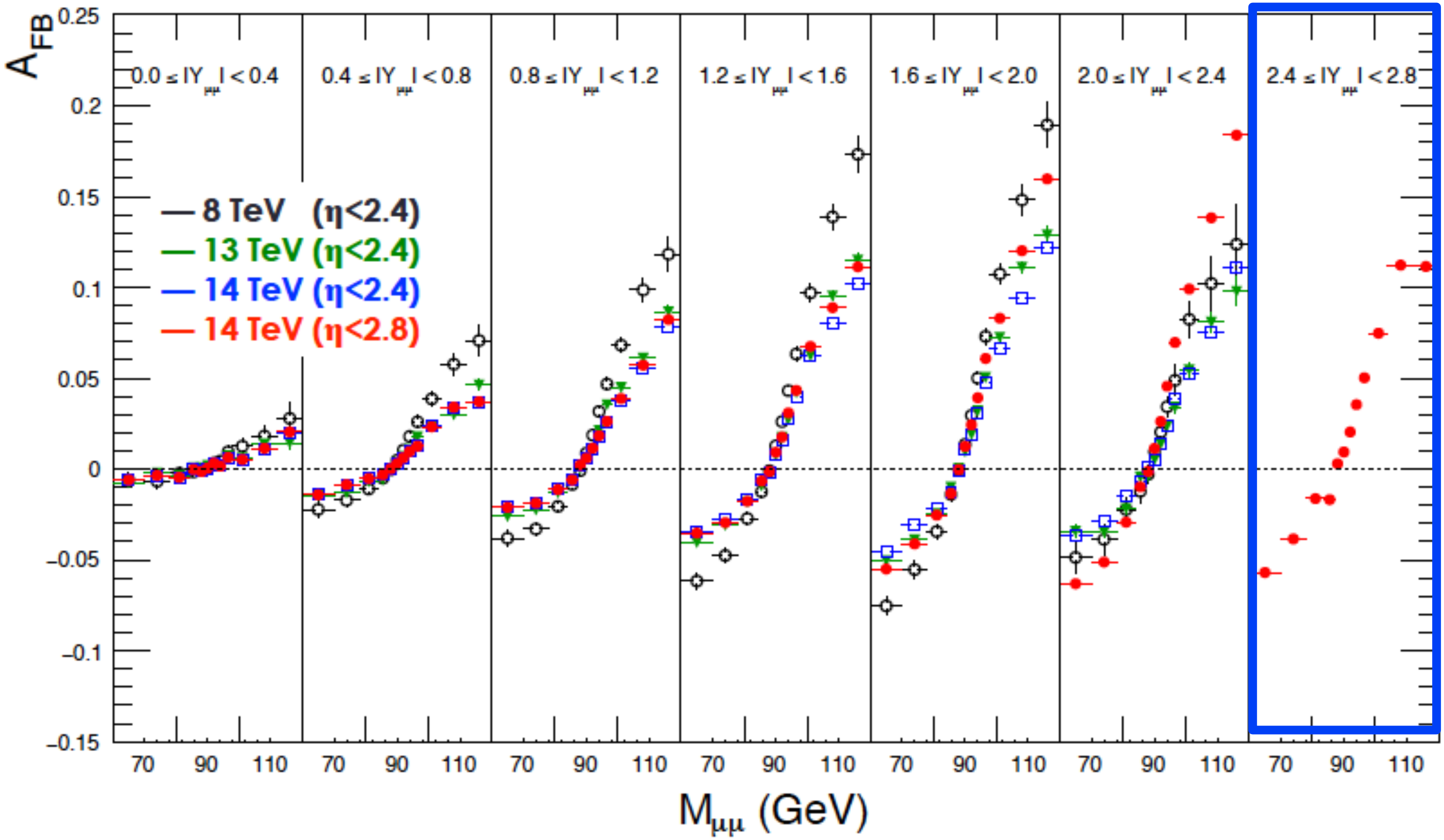
- Generator-level study (no efficiency loss or resolution smearing)
- Lepton acceptance cuts: $p_T^{0\,(1)} > 25\ (15)$ GeV
- $|\eta| < 2.4$ (2.8) (Upgrade tracking to 2.8)
- Uncertainties are scaled from effective to target integrated luminosity
- Fits are performed to A_{FB} in bins of mass and rapidity:

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

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

CMS-PAS-FTR-17-01 **CMS study Muon only**

Important Tracking upgrade

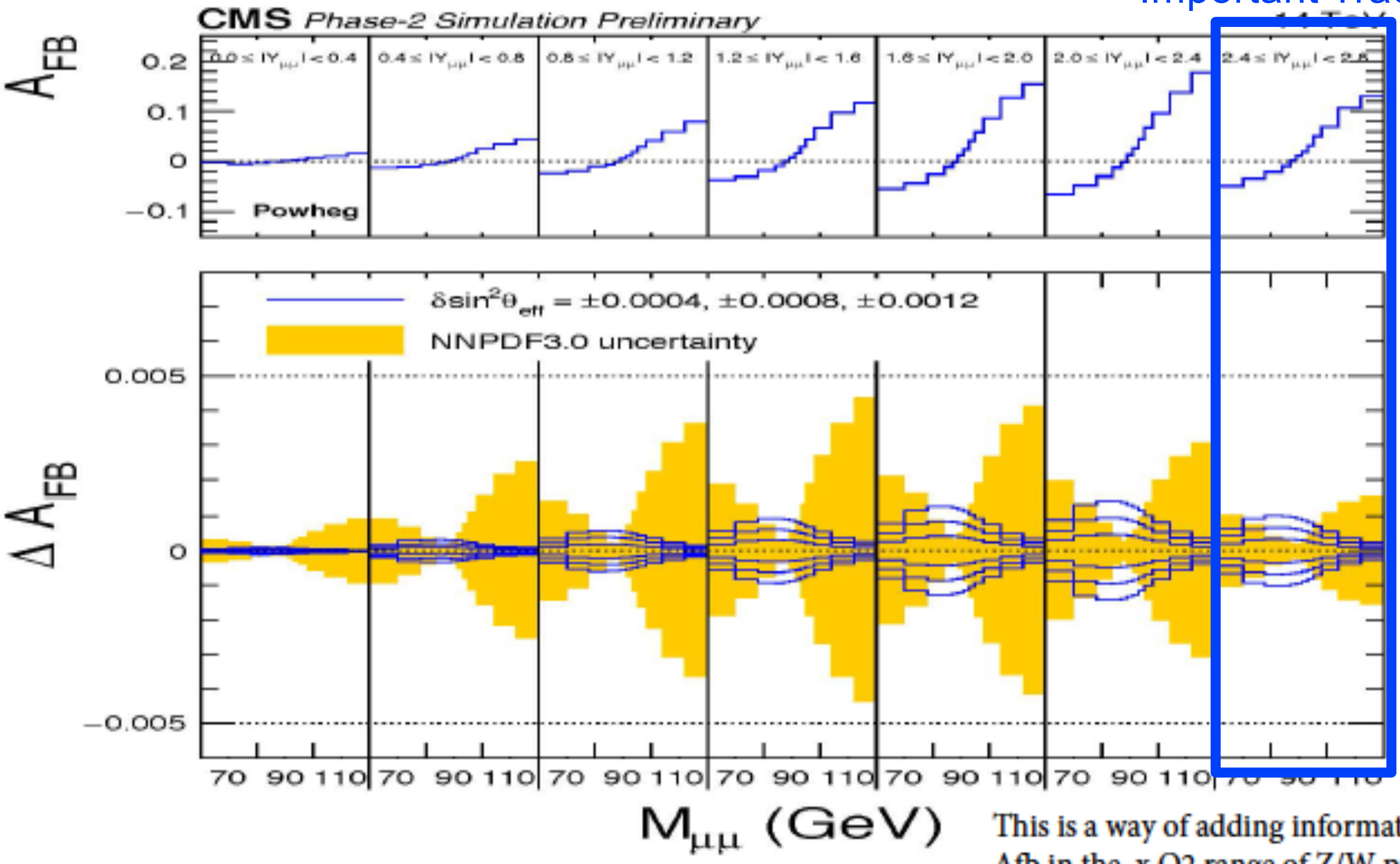


- larger dilution for higher sqrt(s) due to less contribution from valence quarks at lower x
- extending η coverage to 2.8 significantly reduces both stat. and pdf errors (next slide)

CMS-PAS-FTR-17-01 **CMS study Muon only**

- 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)

Important Tracking upgrade

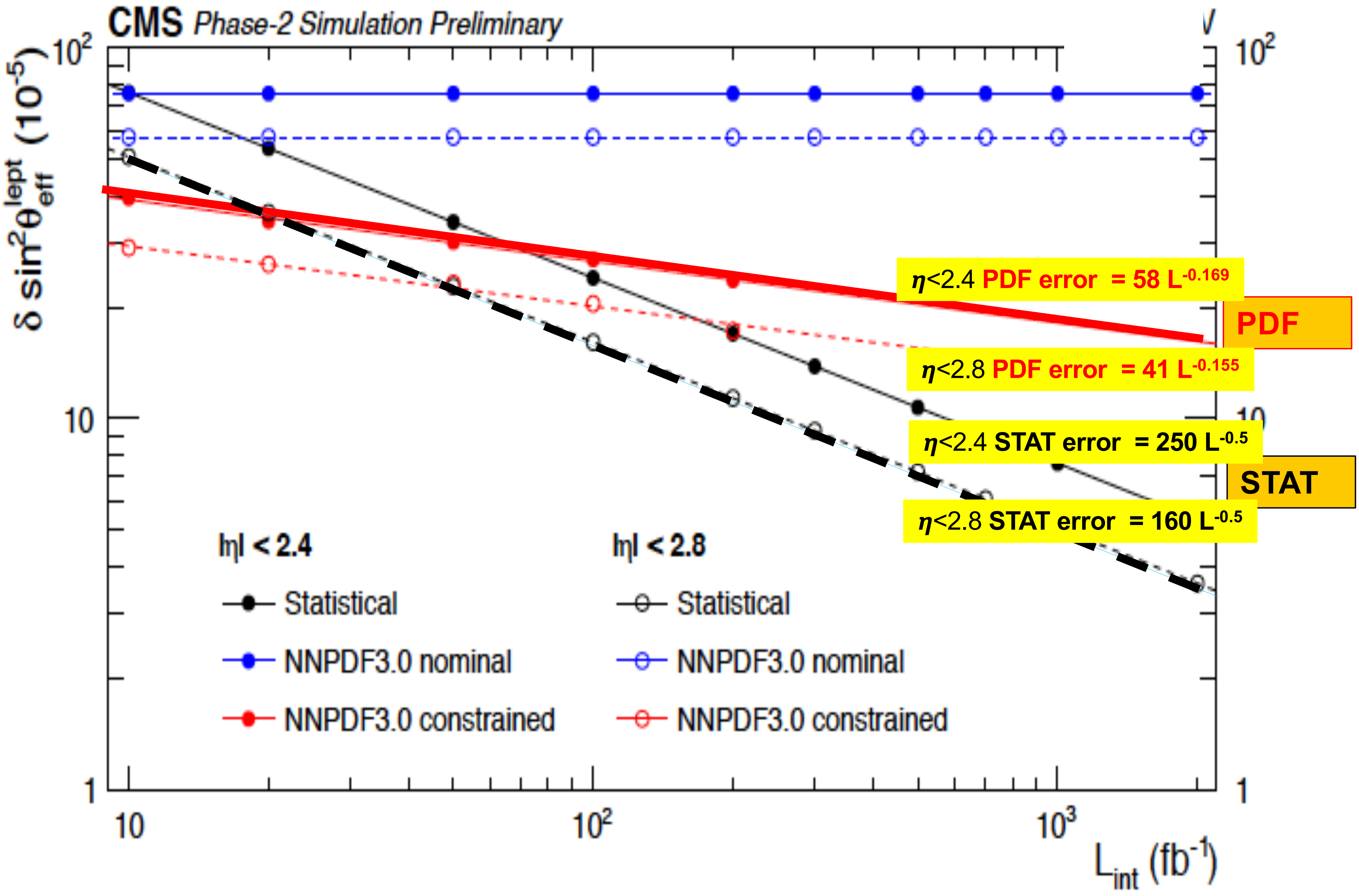


This is a way of adding information from Afb in the x,Q2 range of Z/W produciton

- 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 CMS

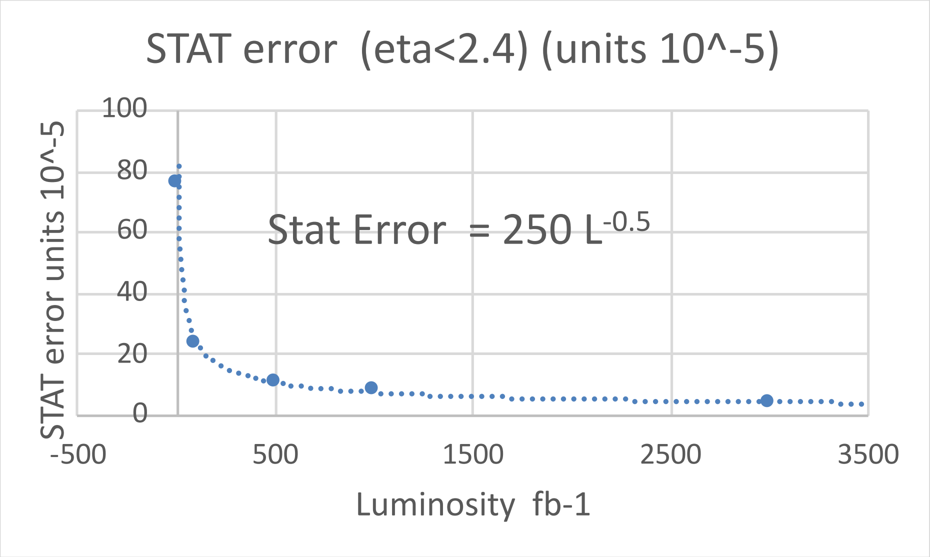


η<2.4 **PDF error = 58 $L^{-0.169}$**

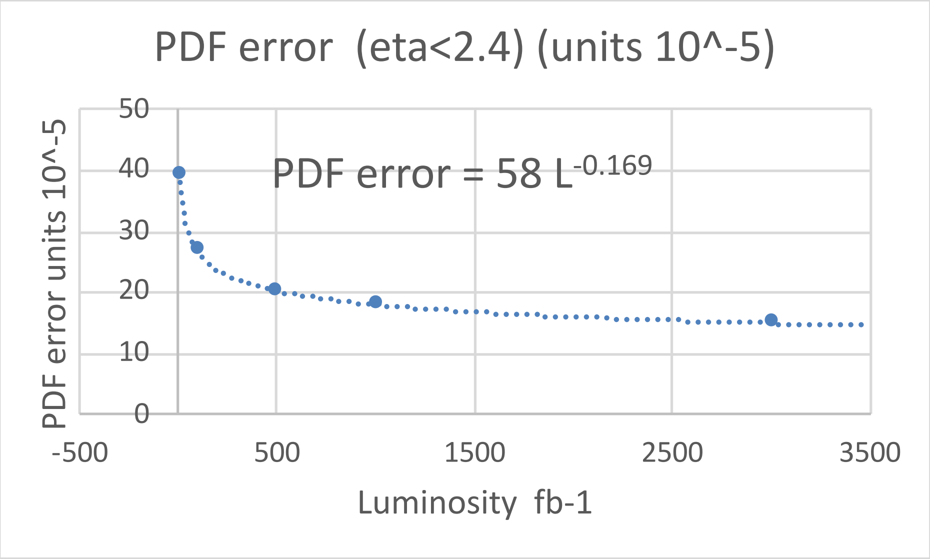
η<2.8 **PDF error = 41 $L^{-0.155}$**

η<2.4 **STAT error = 250 $L^{-0.5}$**

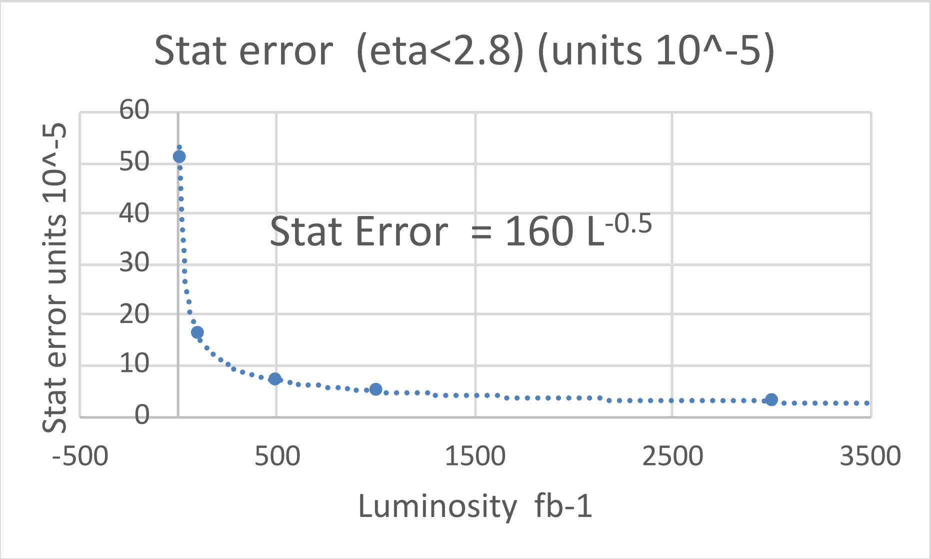
η<2.8 **STAT error = 160 $L^{-0.5}$**

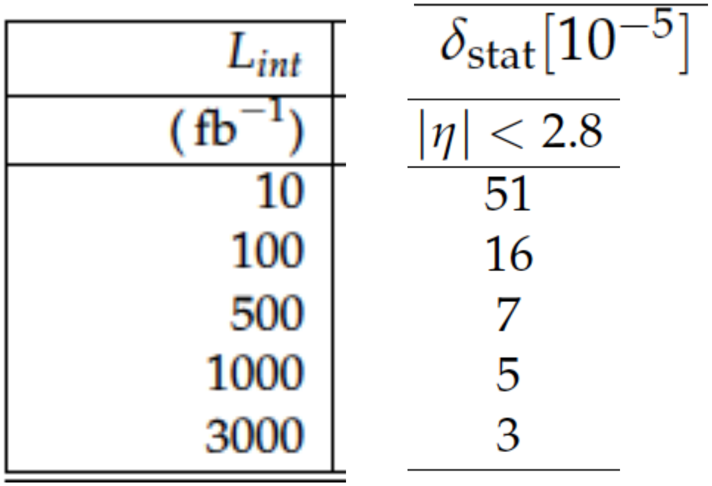


L_{int} (fb^{-1})	$\delta_{\text{stat}}[10^{-5}]$ $\lvert\eta\rvert < 2.4$
10	76
100	24
500	11
1000	8
3000	4

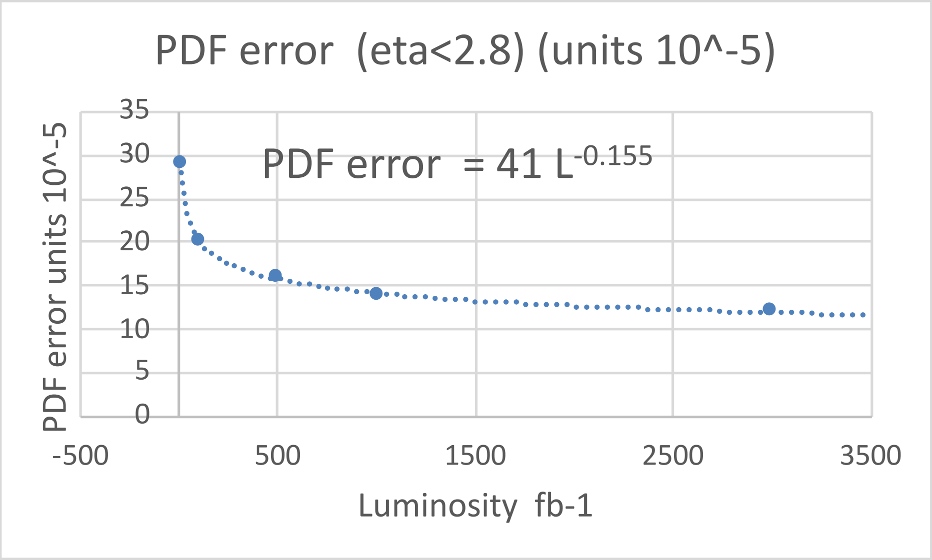


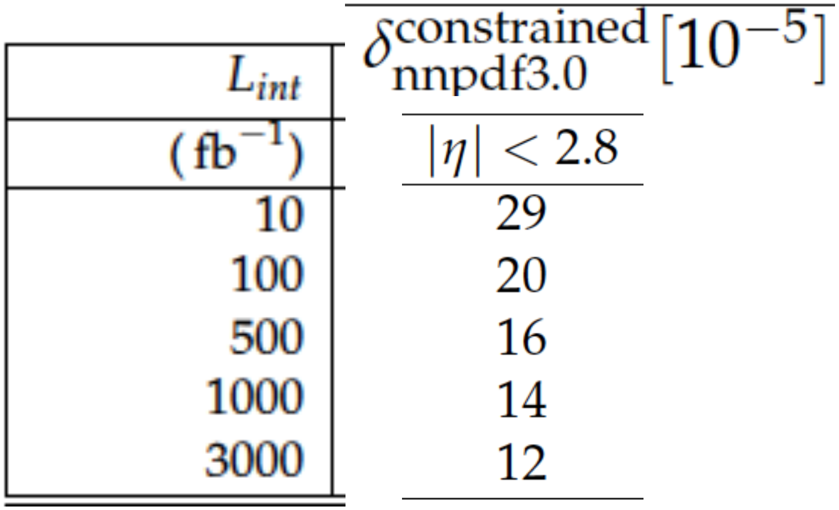
L_{int} (fb^{-1})	$\delta^{\text{constrained}}_{\text{nnpdf3.0}}[10^{-5}]$ $\lvert\eta\rvert < 2.4$
10	39
100	27
500	20
1000	18
3000	15



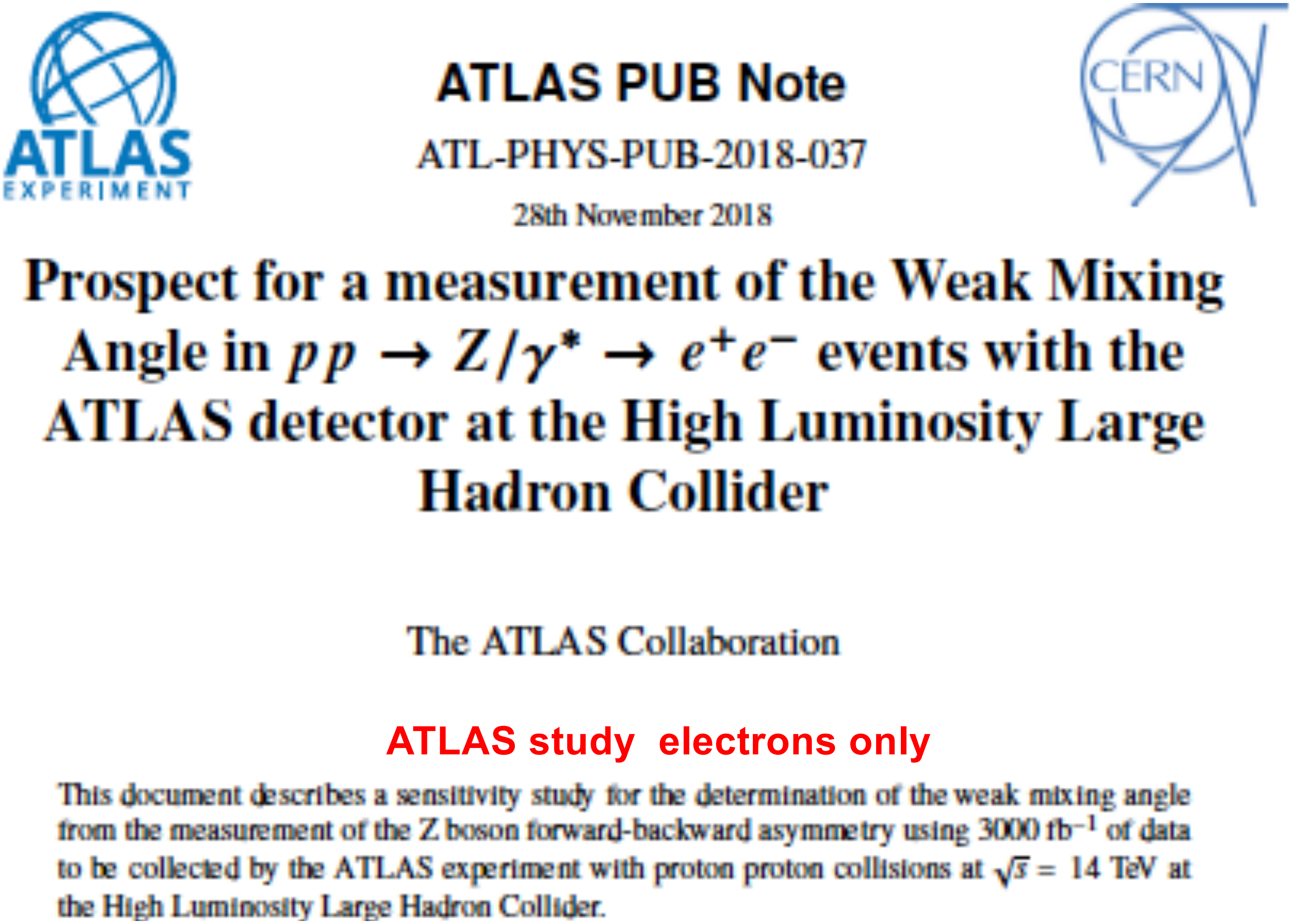


L_{int}	$\delta_{\mathrm{stat}}[10^{-5}]$
(fb^{-1})	$\vert\eta\vert < 2.8$
10	51
100	16
500	7
1000	5
3000	3





L_{int}	$\delta^{\mathrm{constrained}}_{\mathrm{nnpdf3.0}}[10^{-5}]$
(fb^{-1})	$\vert\eta\vert < 2.8$
10	29
100	20
500	16
1000	14
3000	12



ATLAS PUB Note

ATL-PHYS-PUB-2018-037

28th November 2018

Prospect for a measurement of the Weak Mixing Angle in $pp \to Z/\gamma^* \to e^+e^-$ events with the ATLAS detector at the High Luminosity Large Hadron Collider

The ATLAS Collaboration

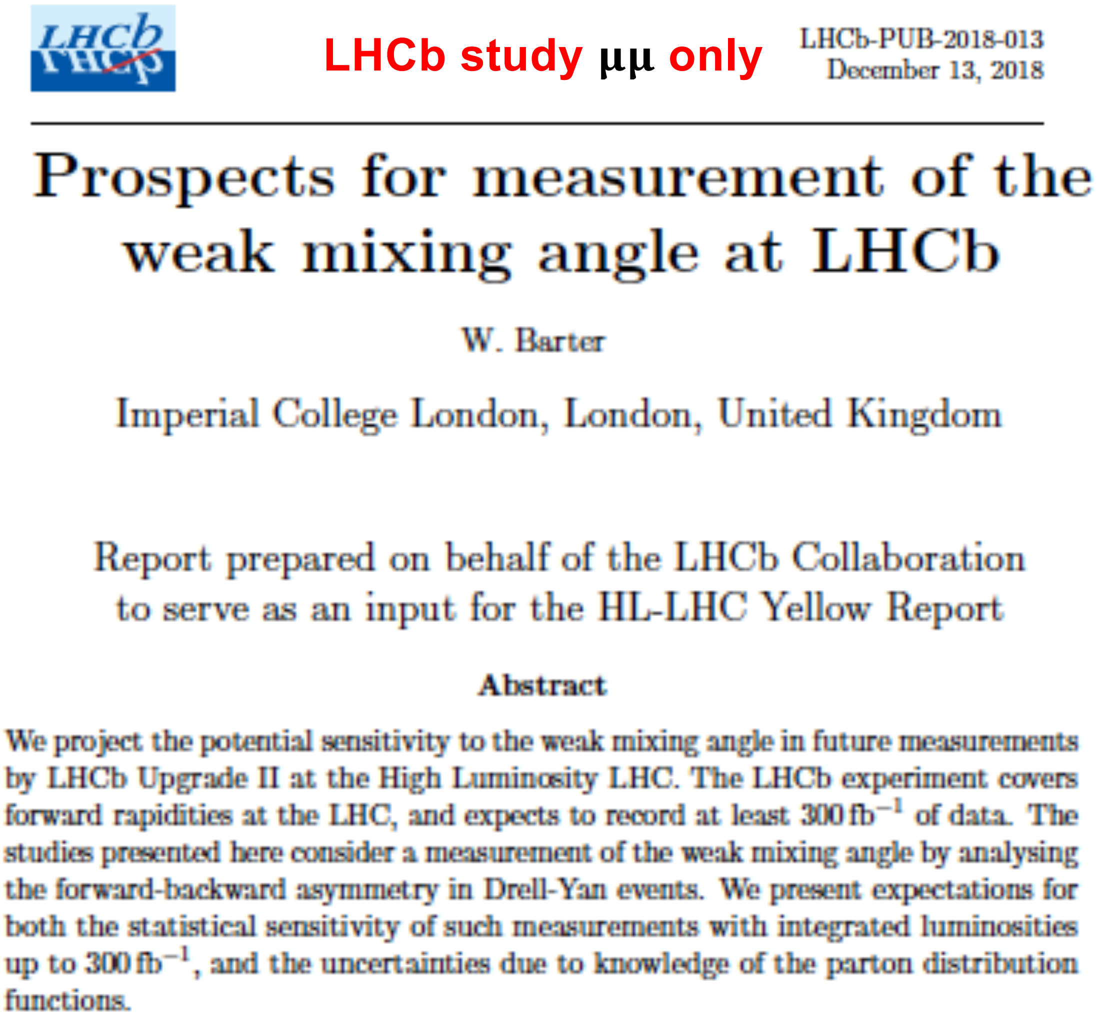
ATLAS study electrons only

This document describes a sensitivity study for the determination of the weak mixing angle from the measurement of the Z boson forward-backward asymmetry using 3000 fb^{-1} of data to be collected by the ATLAS experiment with proton proton collisions at $\sqrt{s} = 14$ TeV at the High Luminosity Large Hadron Collider.

ATLAS (muons and electrons)

2012	2015-2018	HL-LHC	(tracker upgrade from $\eta < 2.4$ to $\eta < 4.0$)
8 TeV	13 TeV	14 TeV	
20 fb^{-1}	140 fb^{-1}	3000 fb^{-1}	→ 0.00004 stat 0.00016 PDF

LHCb study μμ only



LHCb-PUB-2018-013
December 13, 2018

Prospects for measurement of the weak mixing angle at LHCb

W. Barter

Imperial College London, London, United Kingdom

Report prepared on behalf of the LHCb Collaboration
to serve as an input for the HL-LHC Yellow Report

Abstract

We project the potential sensitivity to the weak mixing angle in future measurements by LHCb Upgrade II at the High Luminosity LHC. The LHCb experiment covers forward rapidities at the LHC, and expects to record at least 300 fb^{-1} of data. The studies presented here consider a measurement of the weak mixing angle by analysing the forward-backward asymmetry in Drell-Yan events. We present expectations for both the statistical sensitivity of such measurements with integrated luminosities up to 300 fb^{-1}, and the uncertainties due to knowledge of the parton distribution functions.

LHCb Requires upgrade to enable running with a factor of 50 in luminosity at HL-LHC

2011-2012	2015-2018	HL-LHC	
7 & 8 TeV	13 TeV	14 TeV	
3.1 fb^{-1}	4.5 fb^{-1}	300 fb^{-1}	→0.00005 Stat, 0.00010 PDF

Compare to combined LEP+SLD error of 16x10^{-5} (equivalent to 8 MeV error on Mw)

Energy	**8 TeV**	**13 TeV (*my estimate*)**	***14 TeV HL-LHC expected***
			------*CMS PAS FTR17-001*---
	$\mu\mu$+ee	$\mu\mu$+ee+eHF	$\mu\mu$ /$\mu\mu$ +ee+eHF
CMS	$\eta<2.4$	$\eta<2.8$	$\eta<2.8$
L fb-1	**20**	**140**	**3000/2000**
Stat	**40x10^{-5}**	**11x10^{-5}**	**3x10^{-5} error in $\sin^2\theta_{eff}$**
PDF.	**30x10^{-5}** constrained	**18x10^{-5}** constrained	**12x10^{-5} error in $\sin^2\theta_{eff}$** constrained
			------*ATL-PHY-PUB-2018-037*---
	ee+ $\mu\mu$+ eCF	ee+$\mu\mu$+eCF	ee+eCF/ ee $\mu\mu$+eCF
ATLAS	$\eta<2.8$	$\eta<2.8$	$\eta<4.0$
L fb-1	**20**	**140**	**3000/2000**
Stat	**21x10^{-5}**	**11x10^{-5}**	**4x10^{-5} error in $\sin^2\theta_{eff}$**
PDF.	**24x10^{-5}** constrained	**18x10^{-5}** constrained	**16x10^{-5} error in $\sin^2\theta_{eff}$** constrained
			------*LHCb-PUB-2018-013*-----
	$\mu\mu$	$\mu\mu$	$\mu\mu$
LHCb	$2<\eta<5$	$2<\eta<5$	$2<\eta<5$
L fb-1	**3**	**5.4**	**300**
Stat	**73x10^{-5}**	**37x10^{-5}**	**5x10^{-5} error in $\sin^2\theta_{eff}$**
PDF.	**56x10^{-5}** (unconstrained)	**19x10^{-5}** constrained	**10x10^{-5} error in $\sin^2\theta_{eff}$** constrained

****conclude: with HL-LHC sample, each experiment will match LEP+SLD error***

Current LHC plan – 13 TeV

Each experiment will provide Born level unfolded Afb spectra for different mass bins.

This will allow for a combined analysis for **$\sin^2\theta_{eff}$** and better PDF constraints.

My unofficial estimates for 13 TeV :

CMS	**Stat**	**11x10^{-5}**	**ATLAS**	**Stat**	**11x10^{-5}**	**LHCb**	**Stat**	**37x10^{-5}**
CMS	**PDF**	**18x10^{-5}**	**ATLAS**	**PDF**	**18x10^{-5}**	**LHCb**	**PDF**	**19x10^{-5}**

Which imply that the combined STAT error from the 13 TeV sample will be 8x10^{-5}

And the combined PDF error at 13 TeV is would be about 15x10^{-5}

Therefore, the error from the combined three 13 TeV samples would be similar to the precision of LEP+SLD combination

Aim at ± 0.00016 in $\sin^2\theta_W^{eff}$ (SLD/ LEP combination)
Equivalent indirect M_W to ± 8 MeV

Conclusion

- The combination of unfolded Afb data from the three LHC experiments at 13 TeV could achieve PDF errors in $\sin^2\theta_w^{eff}$ at the level of the SLD/ LEP combination.

- Run II 14 TeV measurements in each experiment could achieve PDF errors in $\sin^2\theta_w^{eff}$ which are smaller than the error in the SLD/ LEP combination.

- The expected precision in upcoming the measurements of $\sin^2\theta_w^{eff}$ and Mw at the LHC can provide similar constraints on physics beyond the standard model.

- Unfolded Afb data provide a new channel for constraining PDFs.