Precision measurements of electroweak parameters at the HL-LHC

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HL-LHC Workshop, CERN, October 30 – November 1, 2017

Introduction

- SM parameters - direct measurements and global fits
- Well measured

$$\alpha_{em}, G_F, m_Z$$

- Not subject of this talk

$$\alpha_S, m_t, m_H$$

- Discussed here

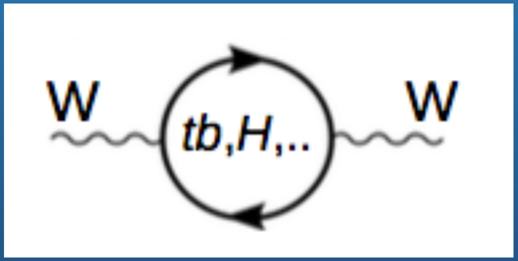
$$m_W, \Gamma_W, sin^2\theta_W$$

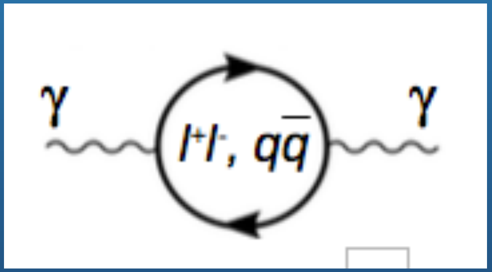
Standard Model Parameters

Some parameters are constrained

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$

but modified by high-order corrections

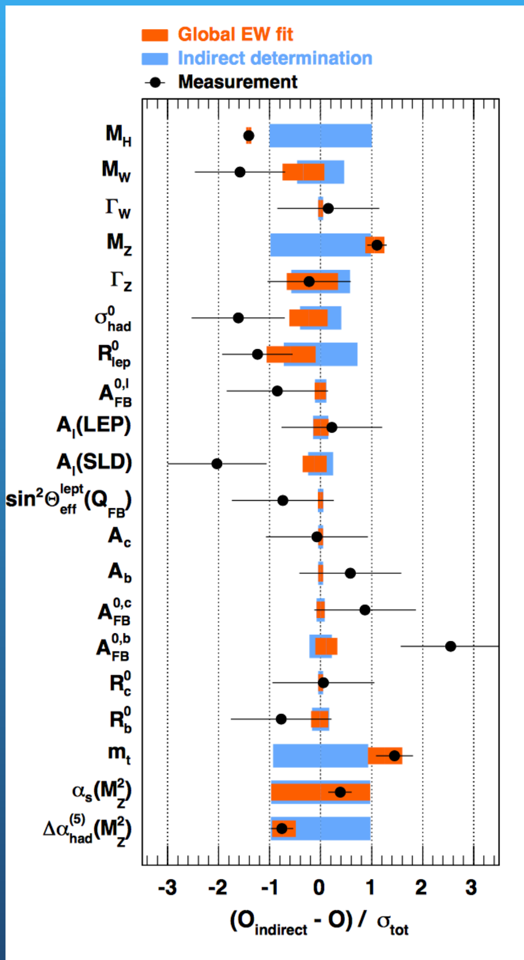




$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r}$$

Direct measurements and global fit

Gfitter arXiv:1407.3792



Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\bigtriangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\bigtriangledown)}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44
$\alpha_s(M^2_Z)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030

Similar results in HEPfit arXiv:1608.01509

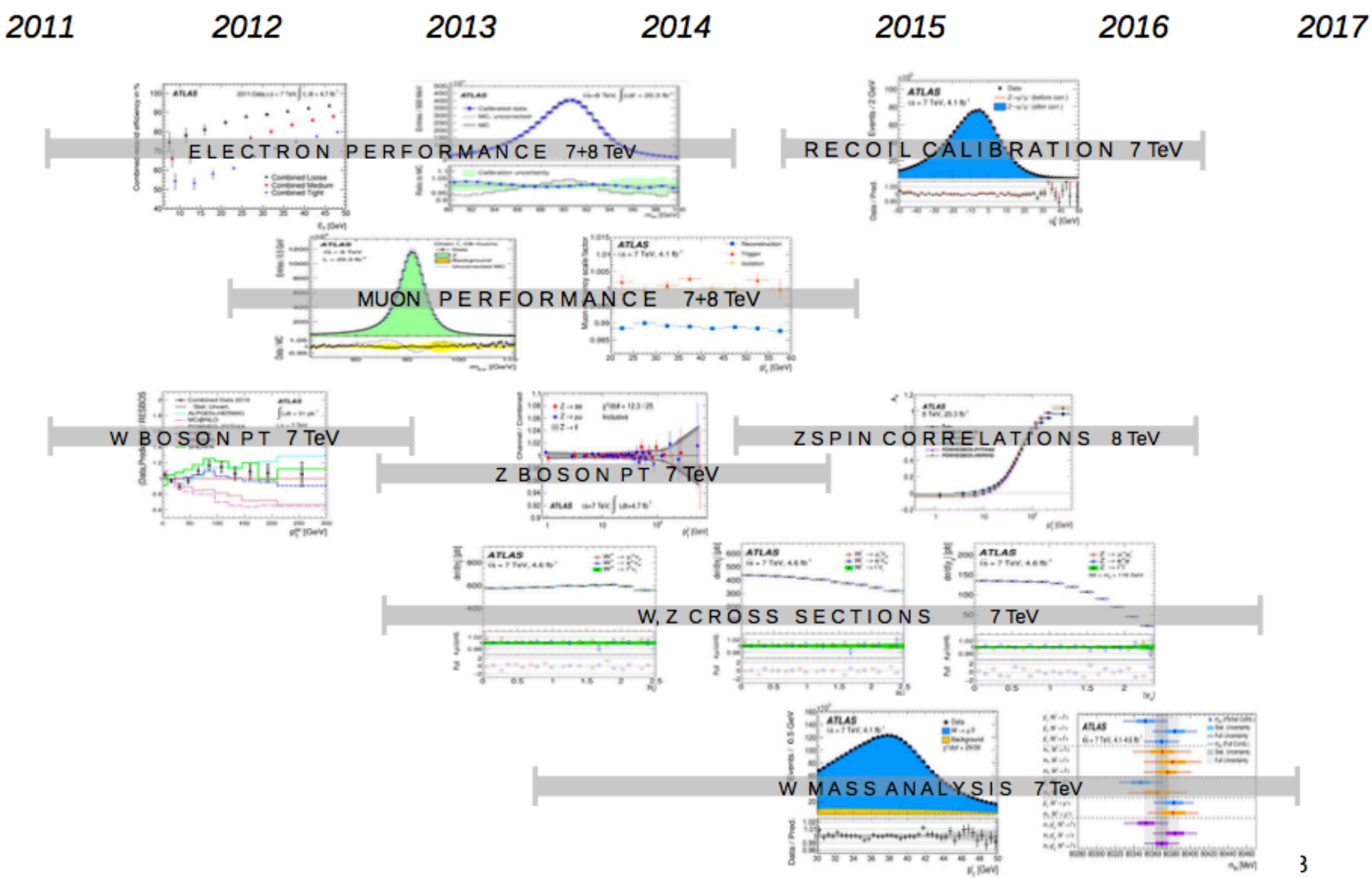
Measurements discussed in this talk

- W mass
  - ATLAS: arXiv:1701.07240
- W width
  - CMS: JHEP 10 (2011) 132
- Forward-Backward asymmetry A_{fb} and $\sin^2\theta_{eff}$
  - CMS: CMS-PAS-SMP-16-007
  - ATLAS: JHEP 1509 (2015) 49
  - LHCb:JHEP 1511 (2015) 190
  - CMS: CMP-PAS-FTR-17-001

and their possible future at the HL-LHC …

ATLAS W mass measurement

arXiv:1701.07240



W production at LHC

- D0 (Phys.Rev.Lett. 108 (2012) 151804

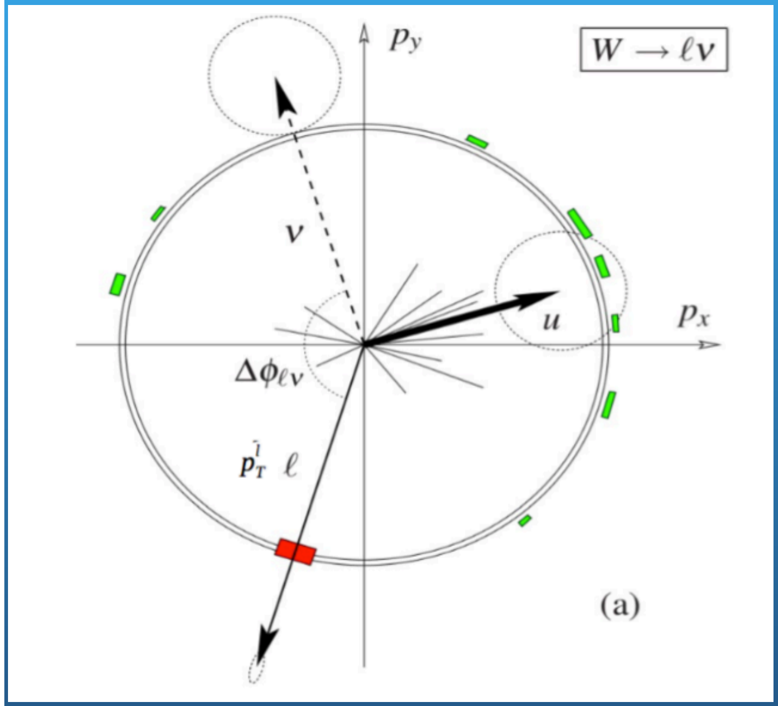
  80.367 ± 0.023 GeV

- CDF (Phys.Rev.Lett. 108 (2012) 151803

  80.387 ± 0.019 GeV

- In pp collisions at the LHC
  - Events are distributed between positive and negative helicity states – PDF uncertainty
  - HF contribution (25% of events) – W p_T
  - Z can be used for different calibrations and for checks, measurements can be performed in Z events and transformed to W
  - When going to HL-LHC – high PU up to 200 !

Main experimental observables



Lepton kinematics:

$$p_T^l, \eta_l, \phi_l, m_l$$

Recoil to transverse plain

$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$

Transverse momentum of neutrino

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$

W-boson transverse mass

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

Analysis strategy

$$p_T^l > 30GeV;$$
$$u_T < 30GeV;$$
$$p_T^{miss} > 30GeV;$$
$$m_T > 60GeV$$

$\lvert\eta_\ell\rvert$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\lvert\eta_\ell\rvert$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

p

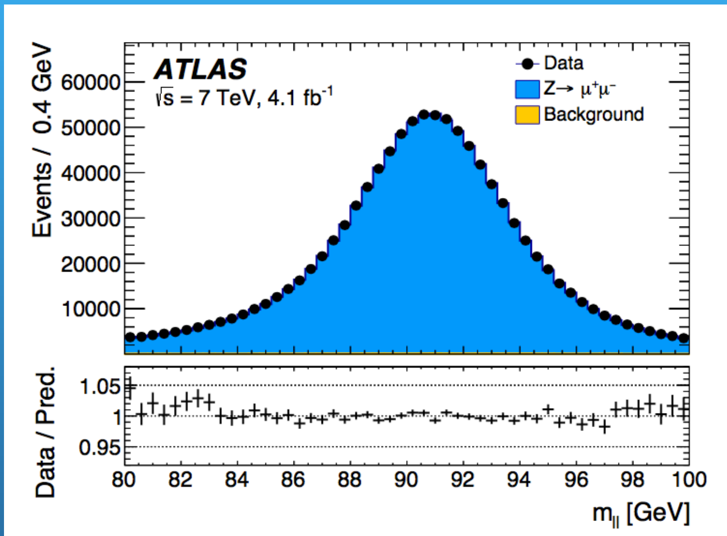
The mass of W boson is defined from the fit to:

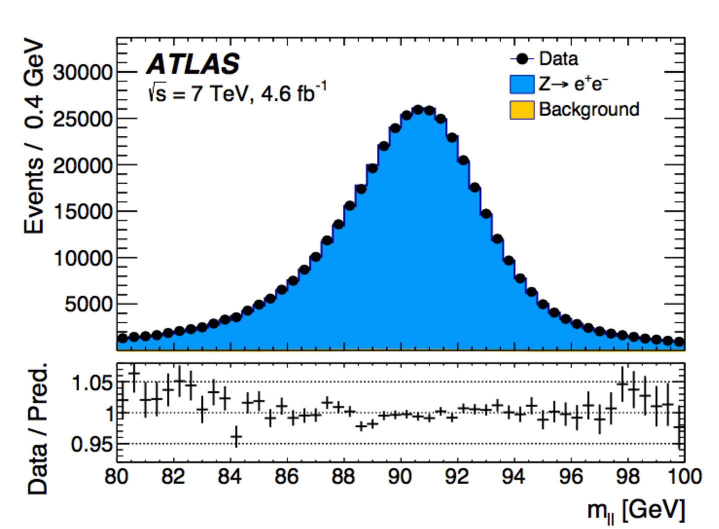
$$p_T^l, m_T$$

templates for signal+background for different W masses are compared to data using χ^2 – interpolation + minimization of χ^2 function.

Calibration of electrons and muons

Corr. of imperfect simulation/calibration of detector response.
Applied to simulation/muon sagitta bias + electron energy - to data



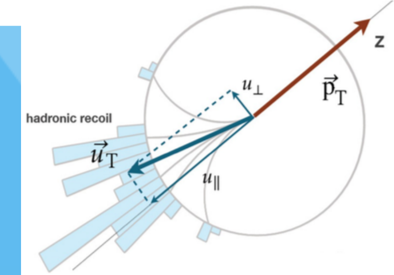


Systematics

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

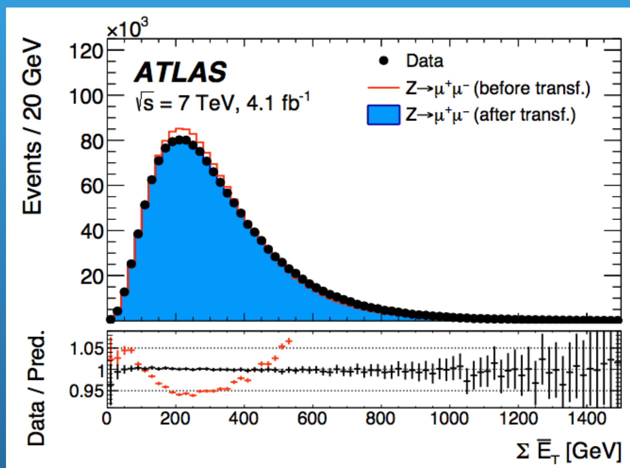
$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

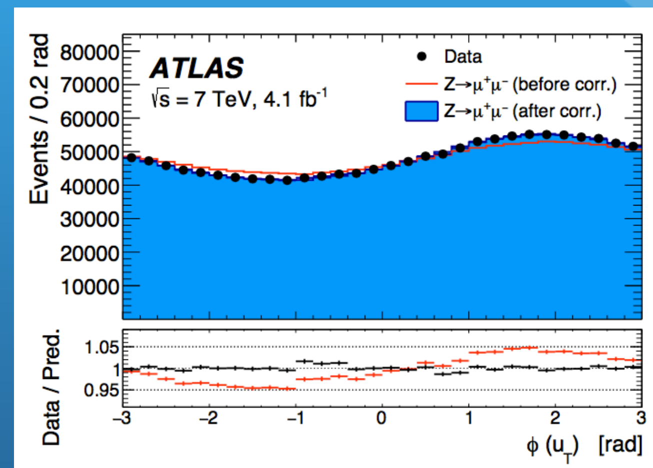
Recoil calibration



Event activity correction:
- Pile-up
- Transverse momentum

Residual correction:
- Beam effects
- Offset of IP





W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

W/Z production and decay simulation

Reweighted Powheg + Pythia 8 MC

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right],$$

$\left[\frac{d\sigma(m)}{dm}\right]$ BW, EW corrections: QED FSR

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

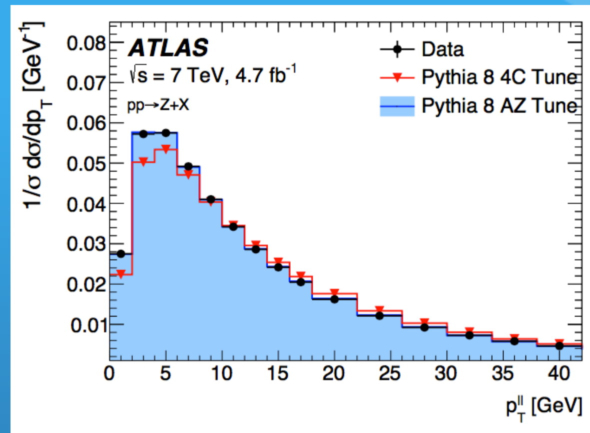
$\left[\frac{d\sigma(y)}{dy}\right]$ Fixed order DYNNLO with CT10nnlo PDF

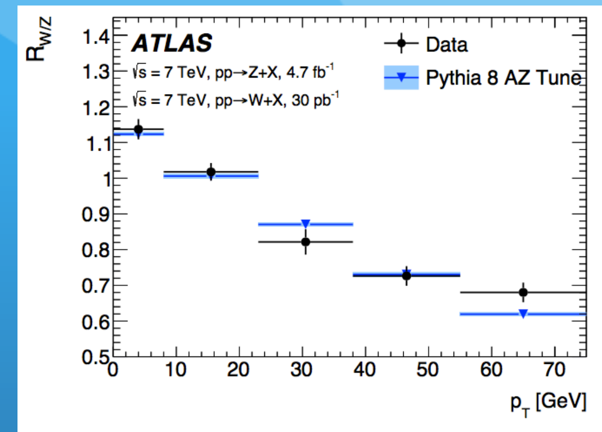
$$\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right],$$

$\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]$ Low p_T, NP effects using Pythia 8 + AZ tune

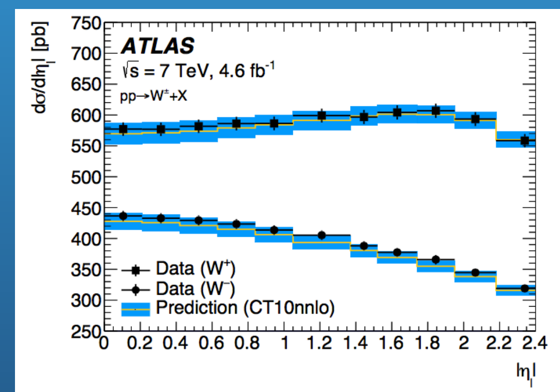
W/Z production and decay simulation

Validation of QCD parameters in Pythia 8 – AZ tune. Good description of p_T





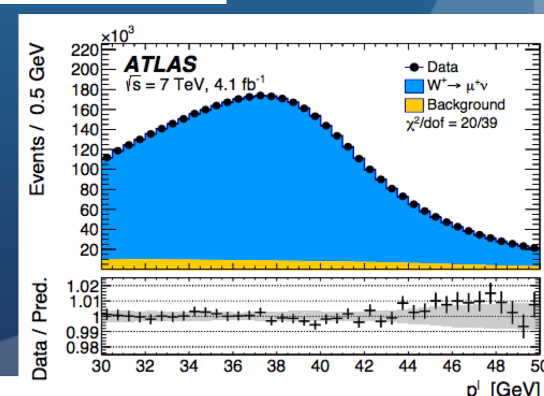
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9



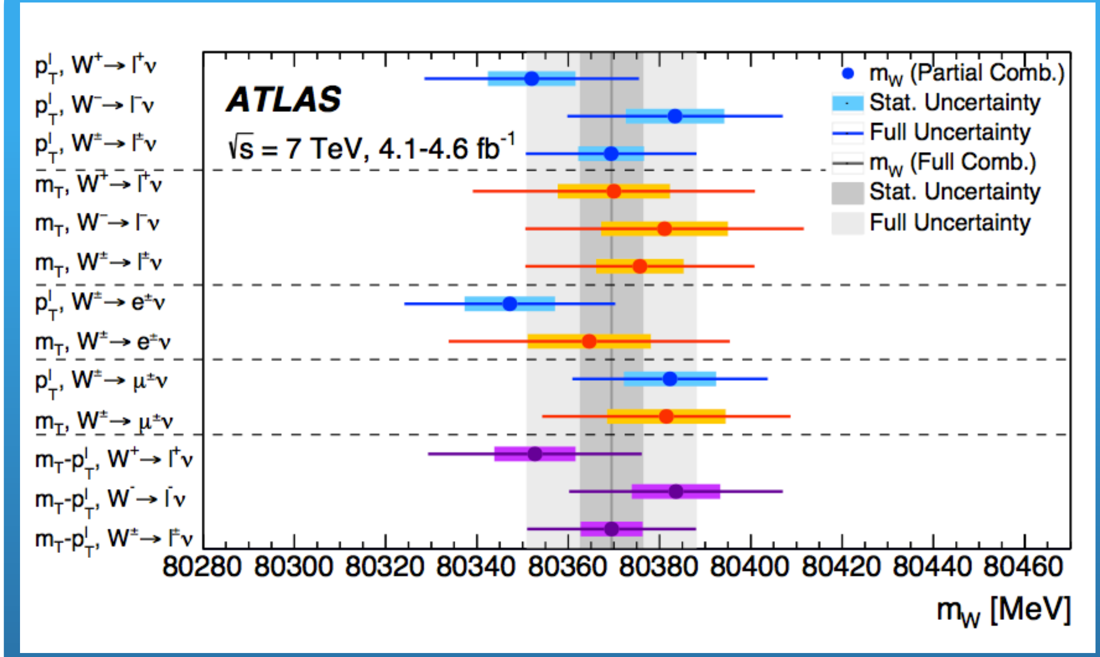
Major uncertainty is PDF, second largest - PS (see separated talks on PDF)

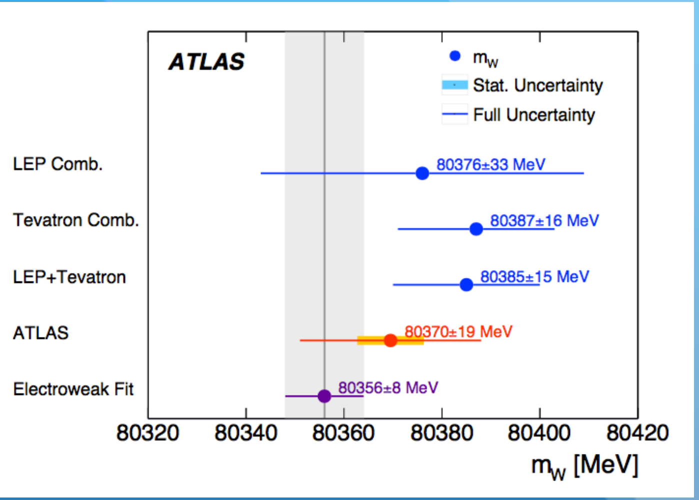
14:00 **PDFs, theory issues (inc. EW, ep/eA DIS option)**
Speaker: Dr. Lucian Harland-Lang (University of Oxford)

14:40 **Experimental Inputs to PDF fits**
Speaker: Amanda Sarkar (University of Oxford (GB))



W mass measurement, diff. categories





combined result

$$m_W = 80369.5 \pm 6.8\,\text{MeV(stat.)} \pm 10.6\,\text{MeV(exp. syst.)} \pm 13.6\,\text{MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

W mass perspectives at the HL-LHC

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Will be significantly reduced

Requires better muon and electron calibration

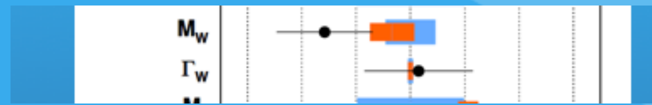
Better simulation of the W P_T, NNLL analytic resummation

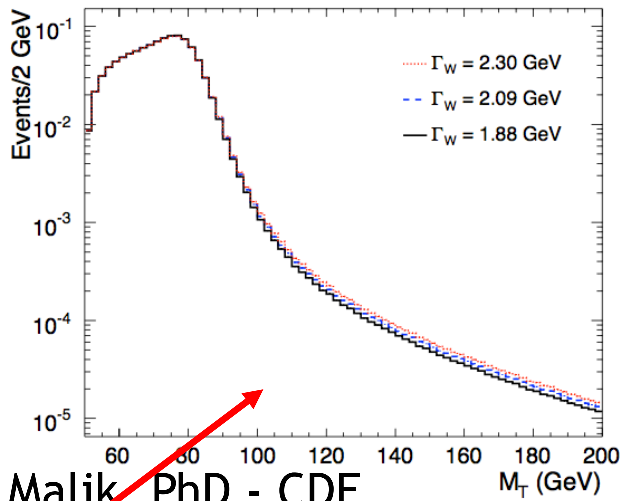
Including high-order corrections

Should be improved with new PDFs

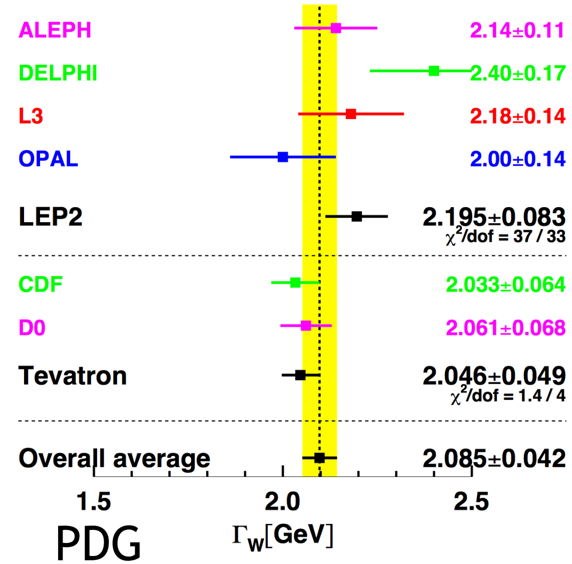
Improvements in PDF uncertainties, combination of ATLAS/CMS and LHCb

W width measurement





S.Malik, PhD - CDF



PDG

Direct and indirect measurement on the W width

$$R = \frac{\sigma(pp \to WX)}{\sigma(pp \to ZX)} \frac{\mathcal{B}(W \to \ell\nu)}{\mathcal{B}(Z \to \ell^+\ell^-)}.$$

$$\mathcal{B}(W \to \ell\nu) = 0.106 \pm 0.003$$

$$\mathcal{B}(W \to \ell\nu) = \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

$$\Gamma(W) = 2144 \pm 62 \ \text{MeV}$$

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Forward-Backward Asymmetry in Z's

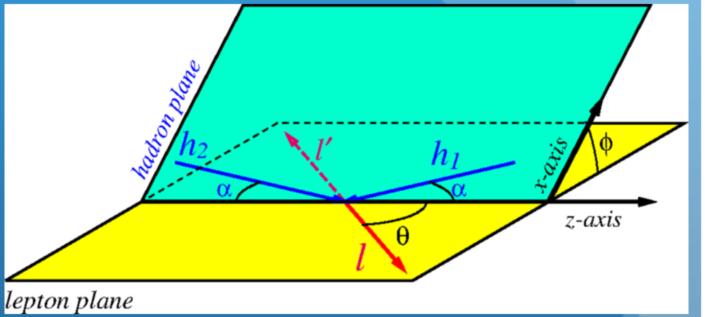
- Vector and axial-vector couplings in NC annihilation

$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$$

$$\bar{f}(g_V^f + g_A^f\gamma_5)f$$

- Differential cross section

$$\frac{d\sigma}{d(\cos\theta)} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$



- Collins-Soper frame, the events are classified to forward and backward in CS to calculate the A_{FB}

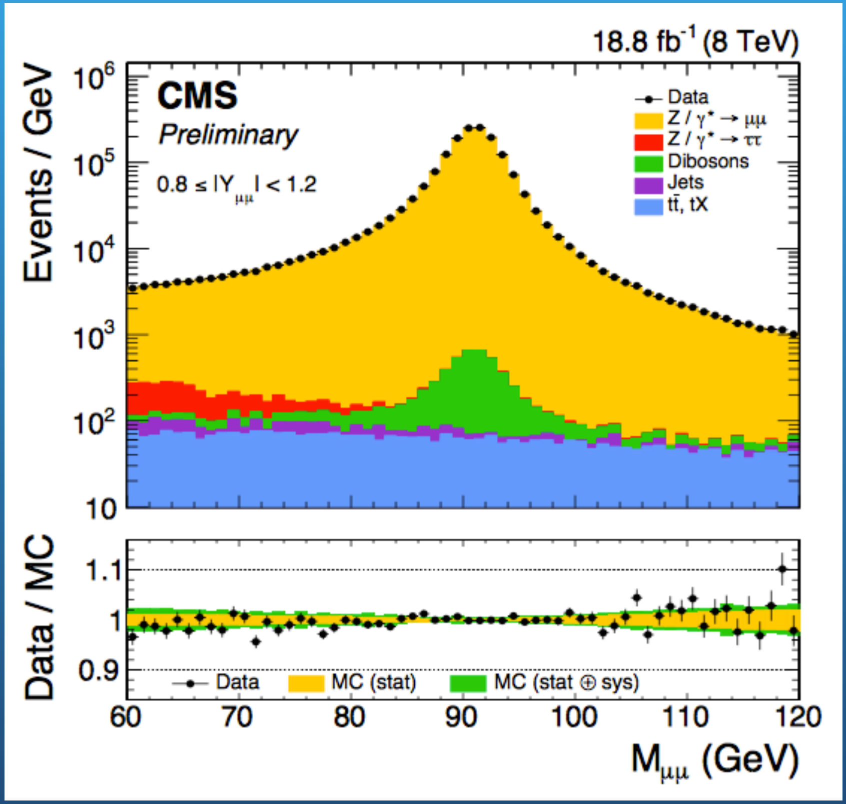
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

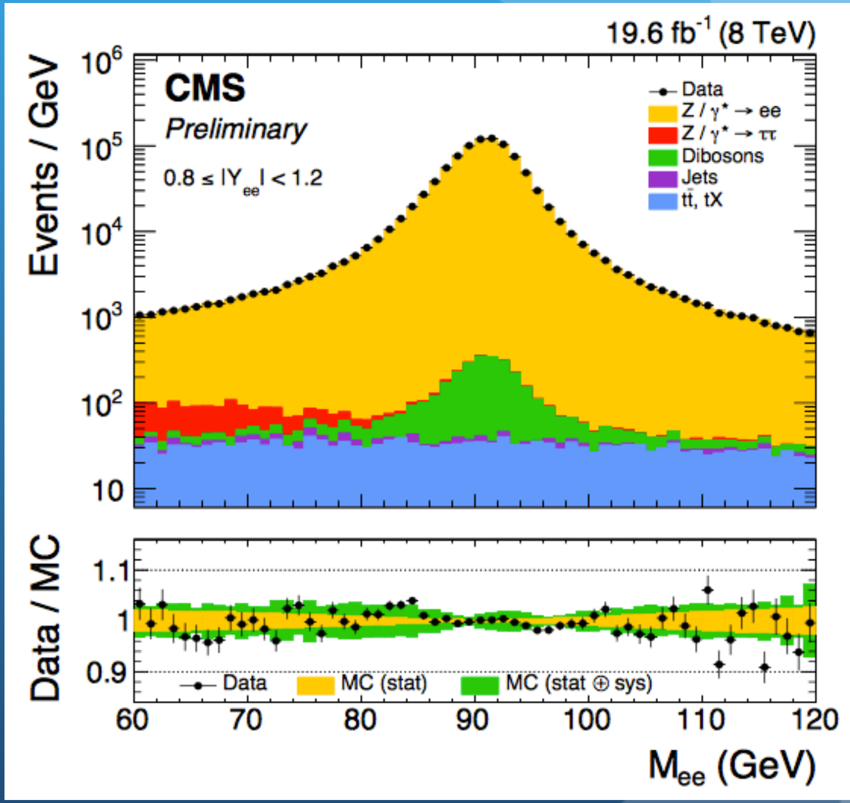
Effective mixing angle

CMS-PAS-SMP-16-007

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

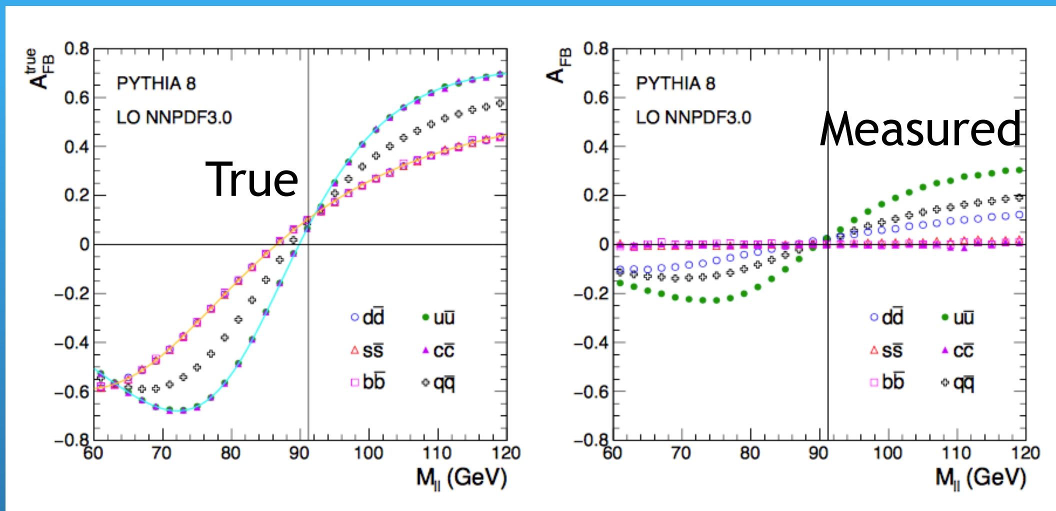
This measurement constraints the W mass !



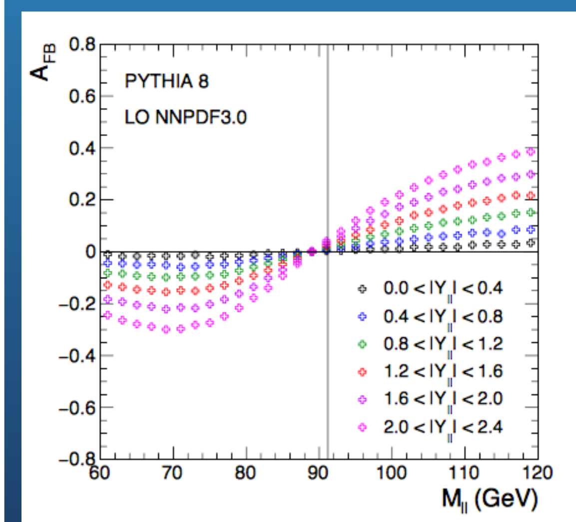


A_{FB} is measurement near Z mass peak is used

Dilution of A_{FB}

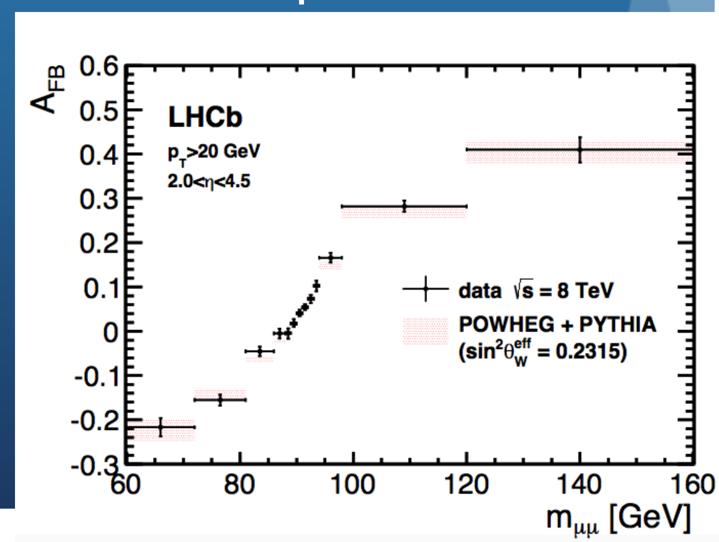


A_{FB} PDF dependence; near Z peak is sensitive to leptonic $\sin^2\theta_{eff}$

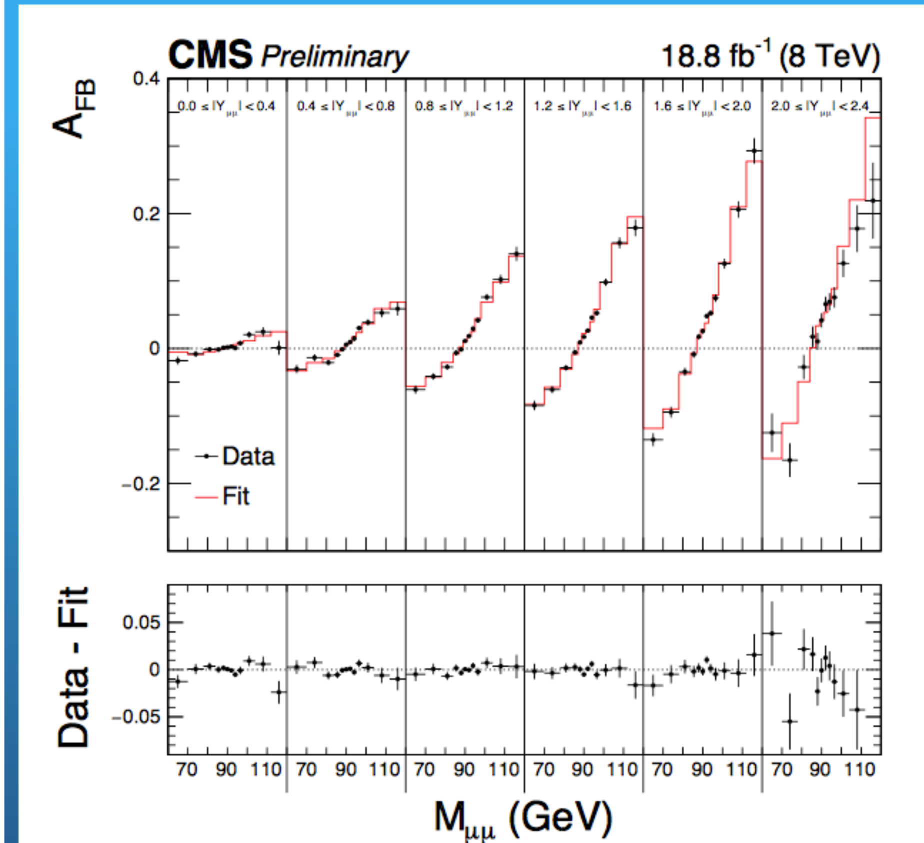


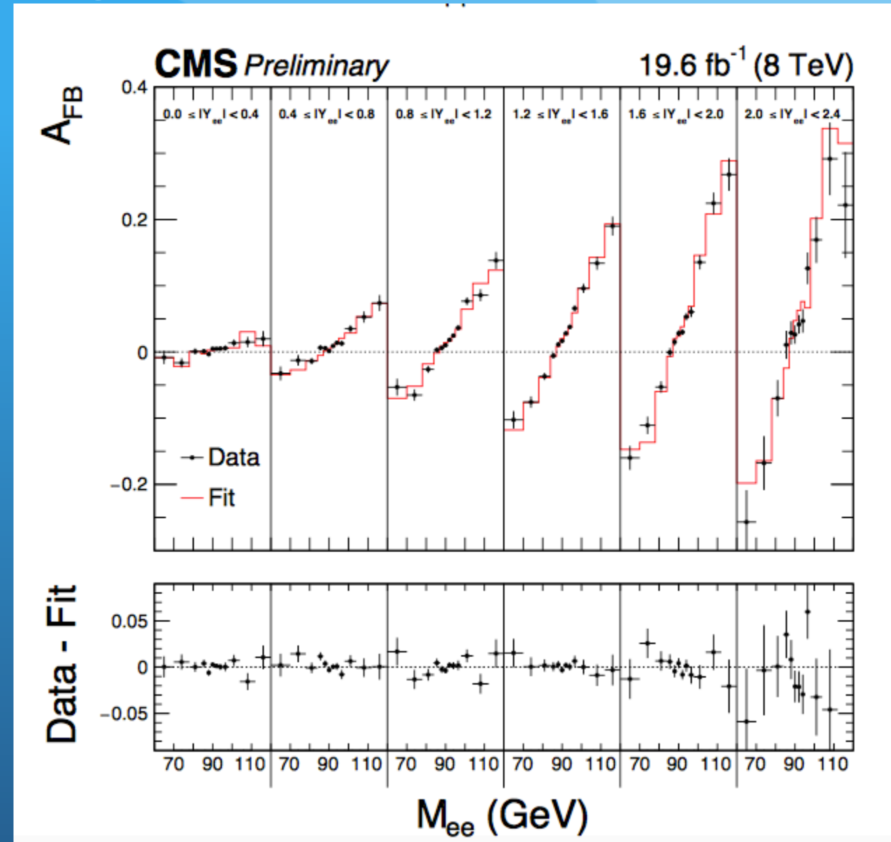
Since ambiguity of the quark direction - is more significant at low |y|, the dilution of A_{FB} is also larger there -> the measurement is done in bins of |y|

LHCb high rapidity - less dilution between parton and proton levels



Effective mixing angle measurement





Minimizing χ^2 between data and templates POWHEG+PYTHIA8.

CMS reweighting with $\cos\Theta$, ATLAS – central-central, central – forward etc categories

Uncertainties

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

Statistical

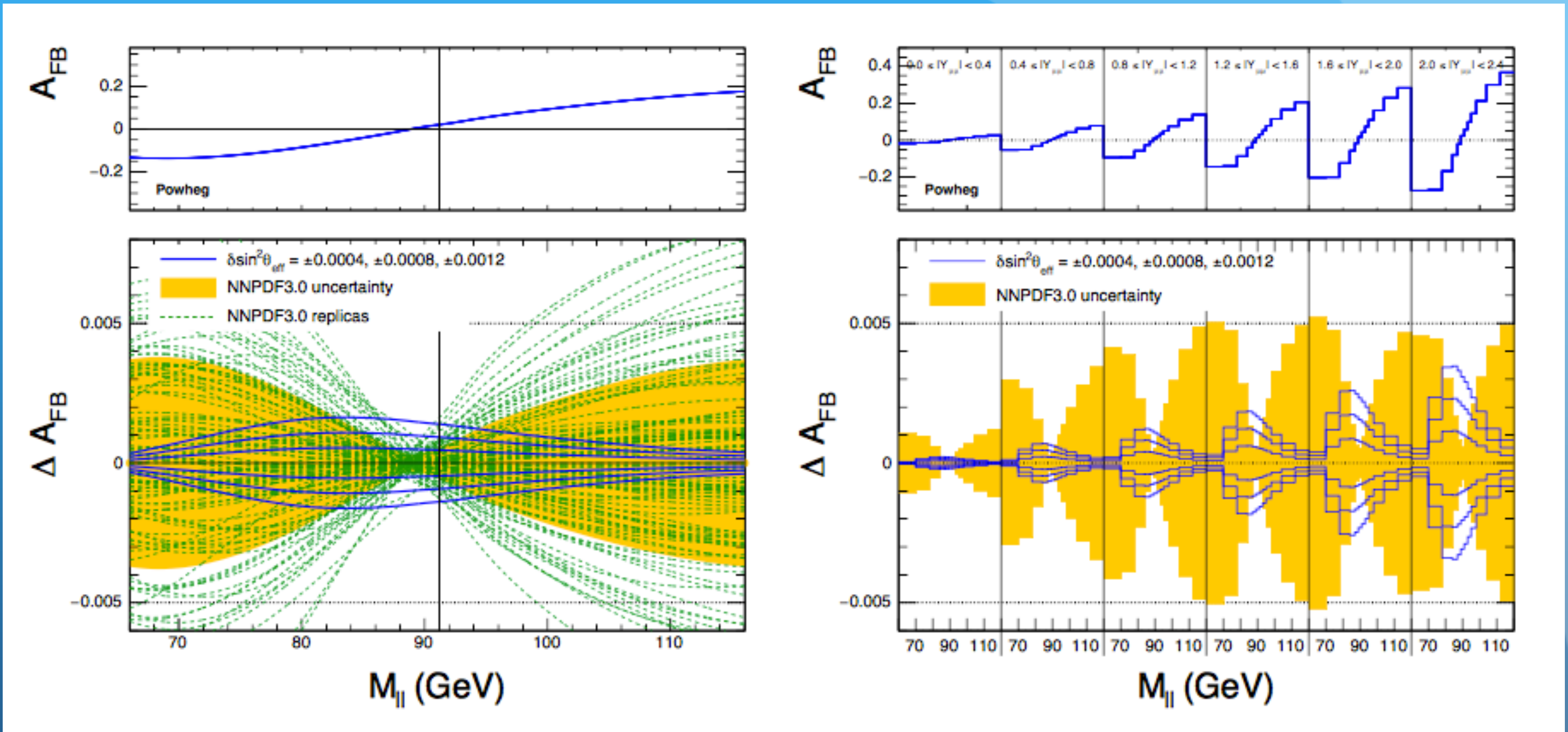
Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

Experimental systematics

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

Theoretical systematics

PDF uncertainty

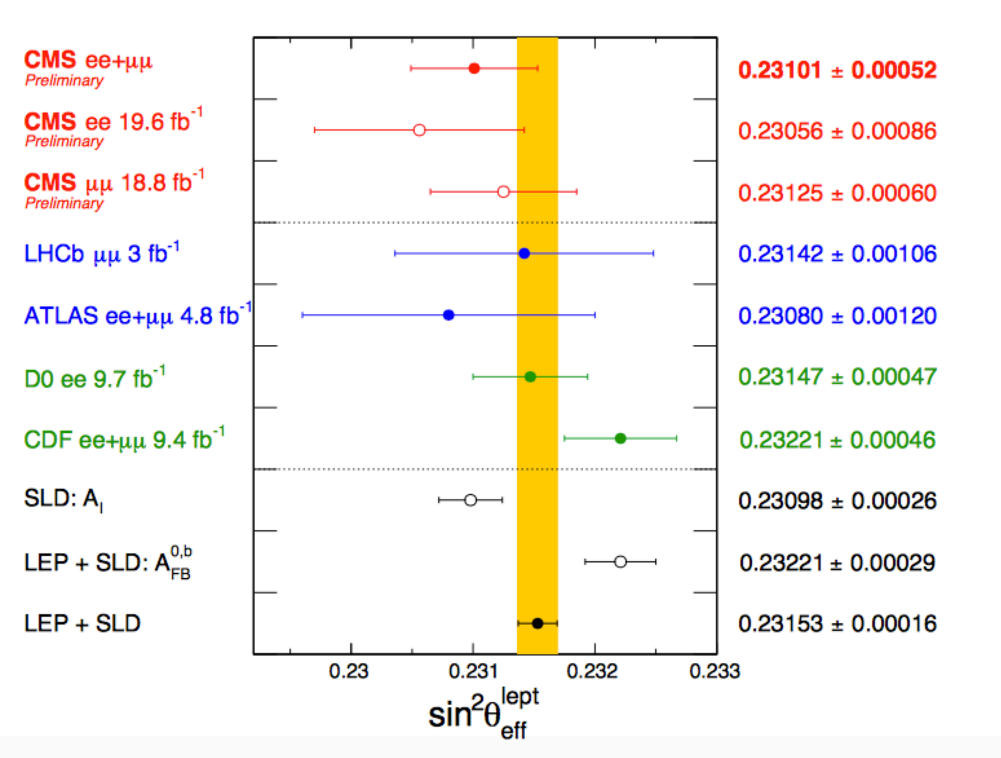


Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

Experimental summary

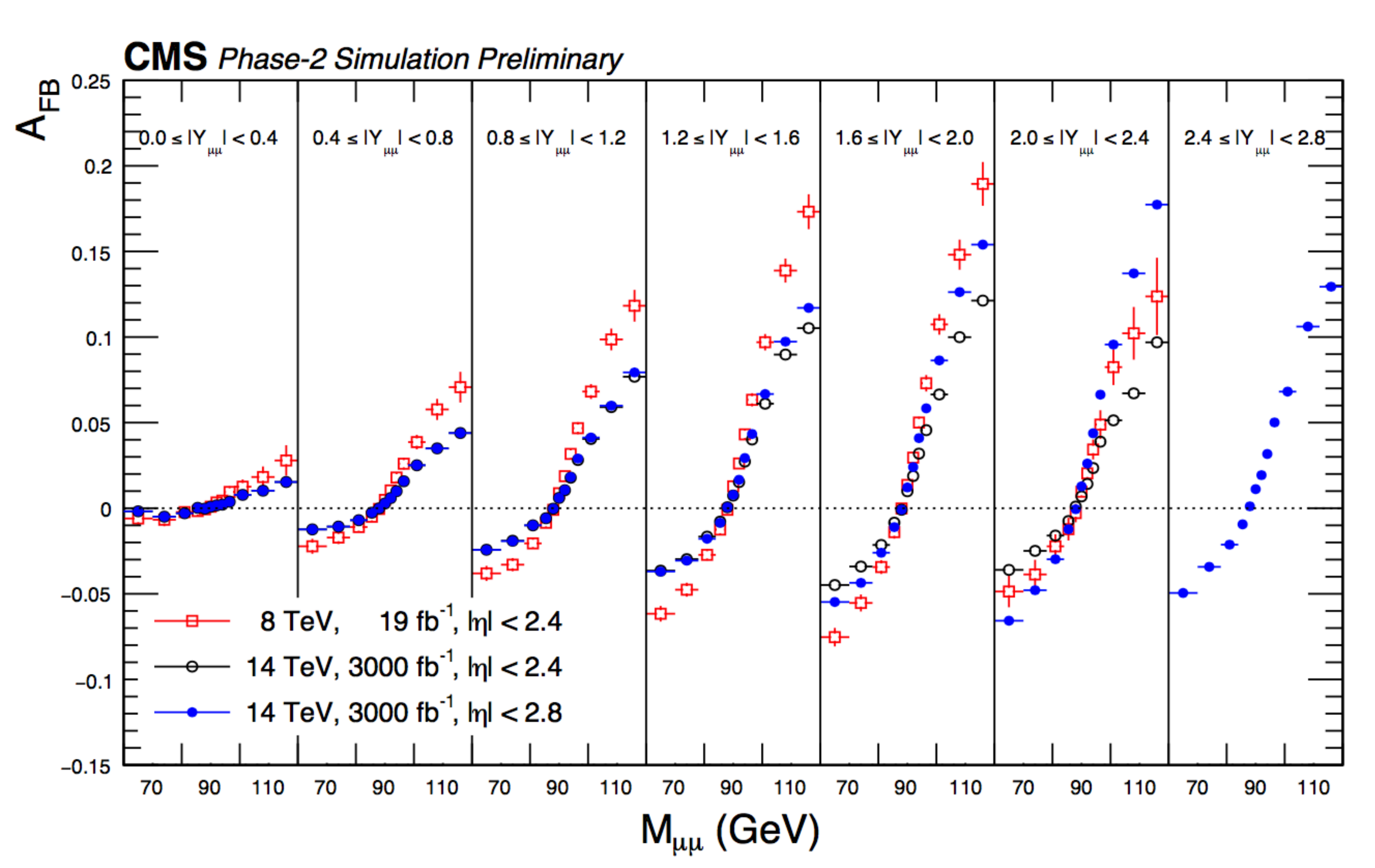
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

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



Statistical uncertainty still dominate, followed by PDF, that was reduced by reweighting by 50% .
Experimental uncertainties are relatively small , theoretical are dominated by QCD/scales

Effective mixing angle at HL-LHC

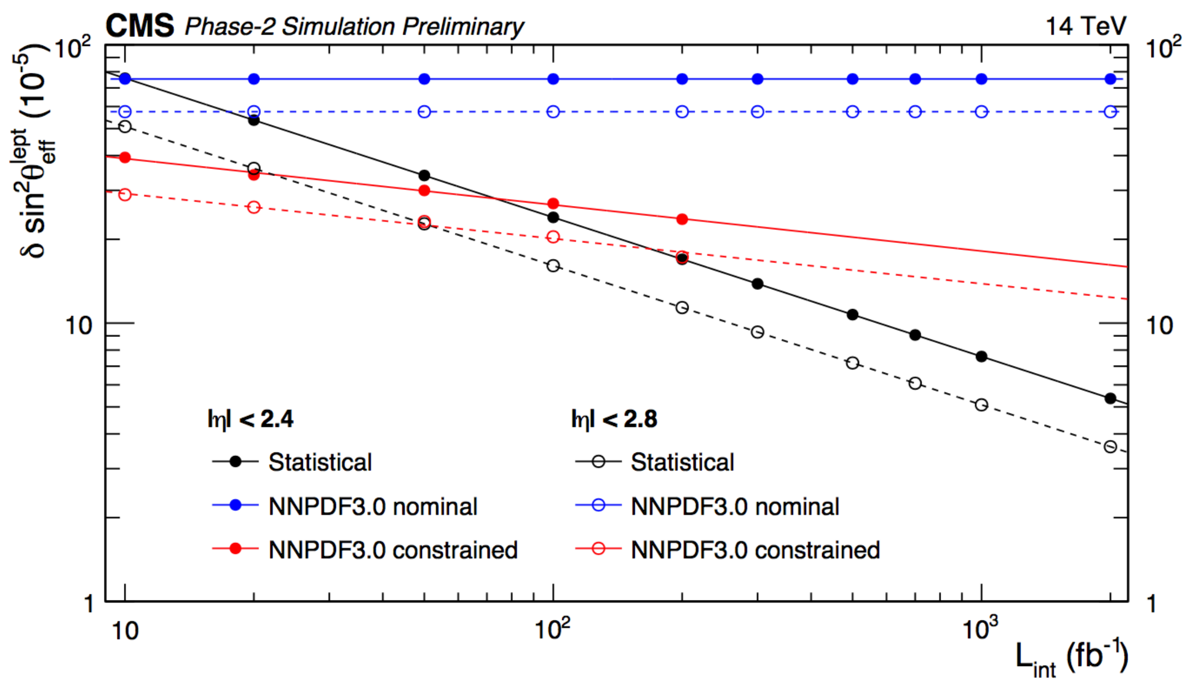


CMS: CMP-PAS-FTR-17-001

Effective mixing angle at HL-LHC

CMS: CMP-PAS-FTR-17-001

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



Conclusions

- HL-LHC should allow for extremely precise measurements of the SM parameters
- The measurement should profit from extending of the pseudorapidity coverage of the experiments
- More work is needed to make a reasonable estimate of the possible measurements uncertainties

Backup

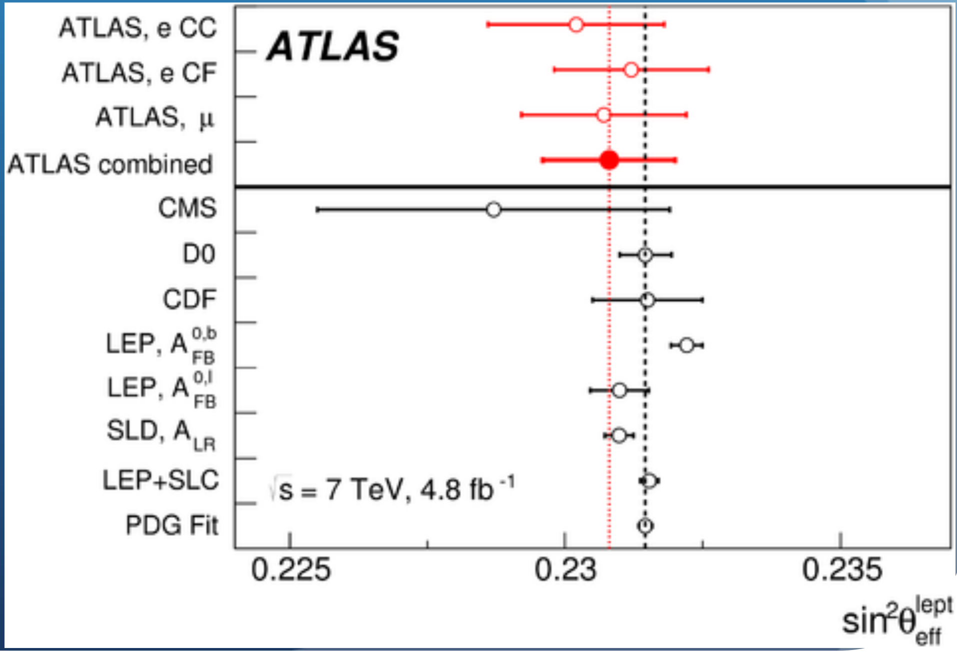
Effective mixing angle

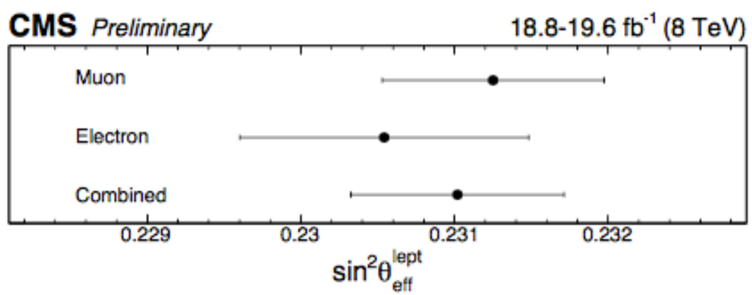
ATLAS: JHEP 1509 (2015) 49

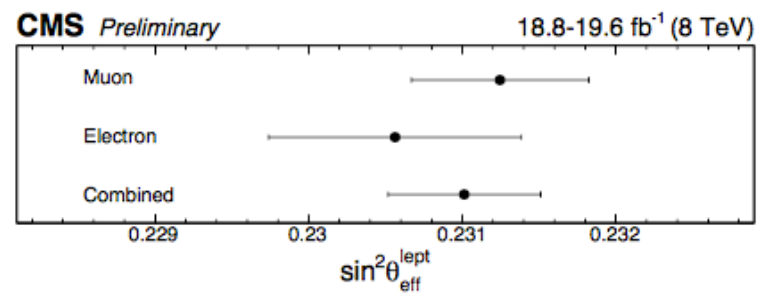
- A_{FB} vs mass for different $\sin\theta_{eff}$ in region 70-250 GeV;
- Only 7 TeV with 4.8 fb^{-1}

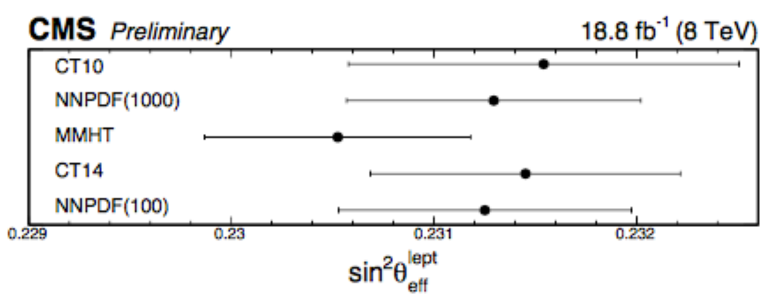
	$\sin^2\theta_{eff}^{lept}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.})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

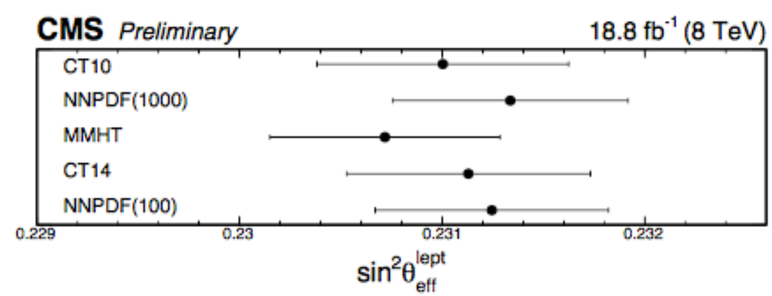
Compared to other experiments and PDG. LEP+SLC are the most precise




CMS Preliminary
18.8-19.6 fb-1 (8 TeV)
Muon
Electron
Combined
0.229
0.23
0.231
0.232
sin2θeff lept


CMS Preliminary
18.8-19.6 fb-1 (8 TeV)
Muon
Electron
Combined
0.229
0.23
0.231
0.232
sin2θeff lept


CMS Preliminary
18.8 fb-1 (8 TeV)
CT10
NNPDF(1000)
MMHT
CT14
NNPDF(100)
0.229
0.23
0.231
0.232
sin2θeff lept


CMS Preliminary
18.8 fb-1 (8 TeV)
CT10
NNPDF(1000)
MMHT
CT14
NNPDF(100)
0.229
0.23
0.231
0.232
sin2θeff lept

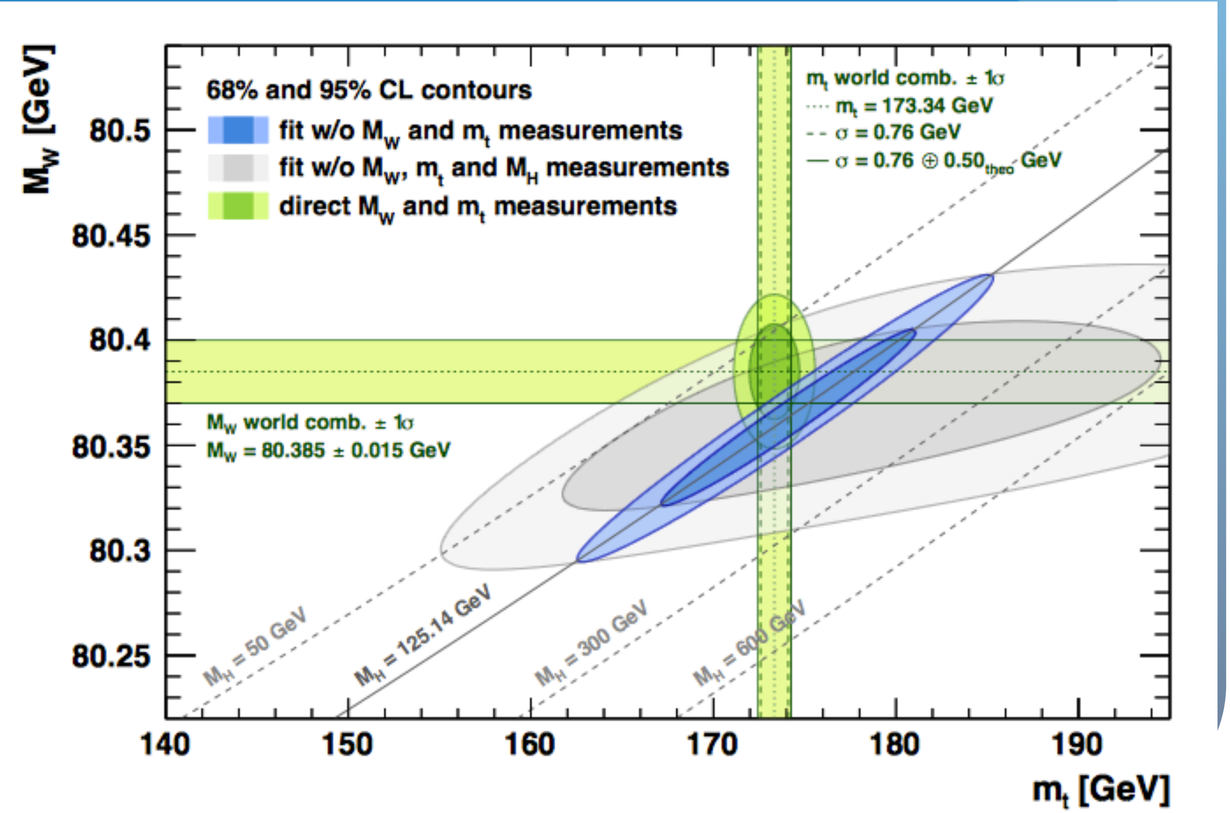
Direct measurements and global fit

	Measurement	HEPfit result
m_H ,GeV	125.09 ± 0.24	102.8 ± 26.3
m_t ,GeV	173.34 ± 0.76	176.6 ± 2.5
m_W ,GeV	80.385 ± 0.015	80.3604 ± 0.0066

arXiv:1608.01509

arXiv:1407.3792

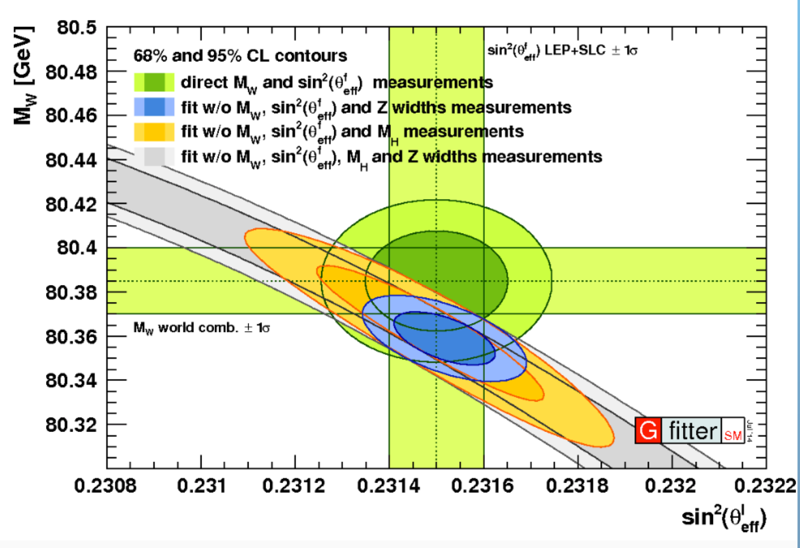
Gfitter



Introduction

- EW motivation at LHC:
  - Cross sections, better understanding of SM predictions
  - Backgrounds for searches
  - **SM parameters**

$$\alpha_{em}, G_F, m_W, m_Z, \sin^2\theta_W, m_H$$

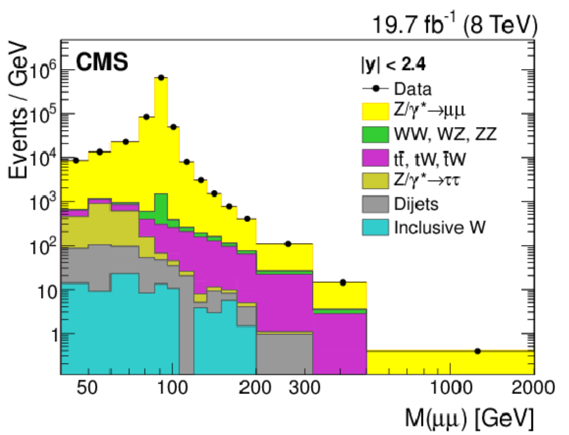


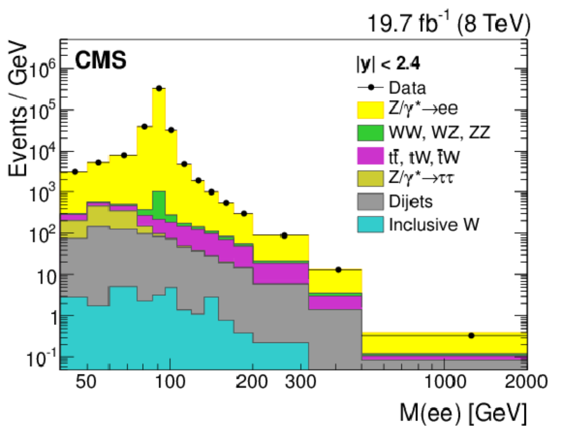
- Provide critical tests of SM (NNLO QCD and NLO EW predictions are available)
- Require precise understanding of different sources of experimental uncertainties, both experimental and theoretical

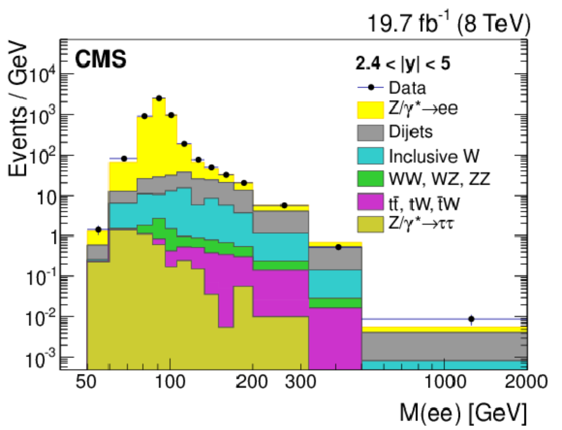
A_{FB} measurement with di-muon and di-electron events

CMS: EPJC C76 (2016) 325

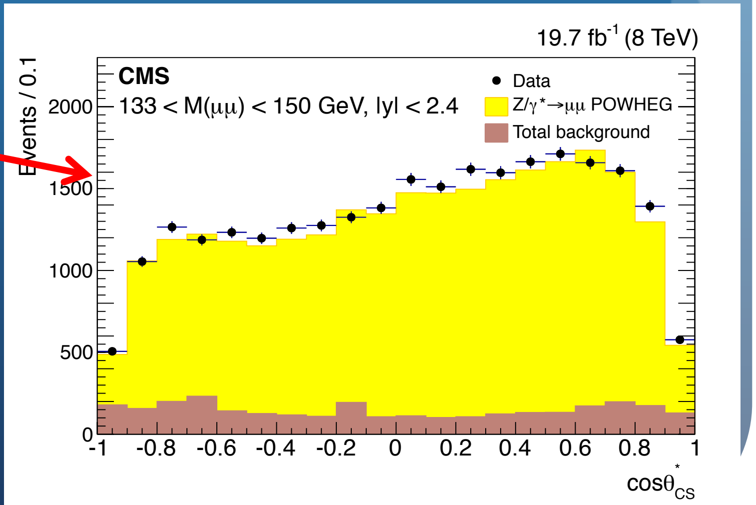
Muon/electron candidates with p_T>20 GeV, |η|<2.4 (for electrons up to 5!)







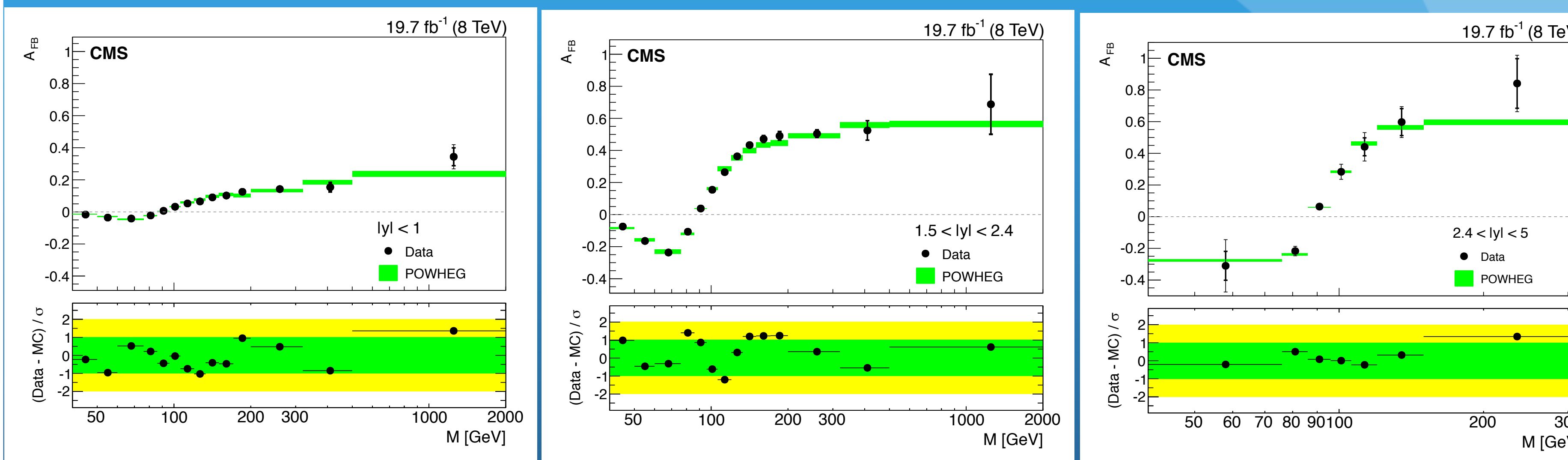
The measured $\cos\theta^*_{CS}$ distribution



A_{FB} is measured as a function of dilepton mass in bins of pseudorapidity

A_{FB} measurement with di-muon and di-election events

CMS: EPJC C76 (2016) 325



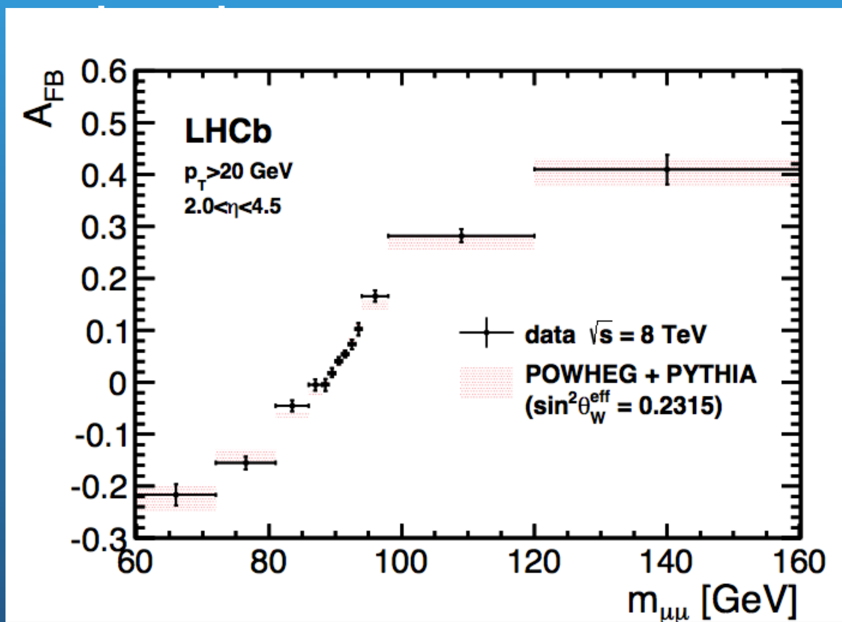
- Wrt 7 TeV CMS A_{FB} measurement is extended to high |y| - closer to parton-level asymmetry ;
- Predictions describe well the measured values

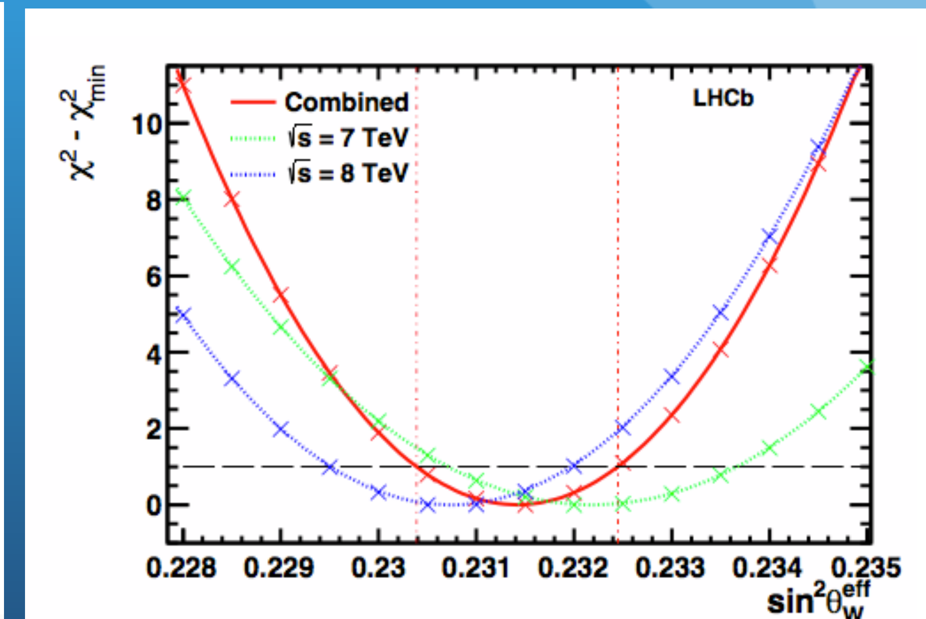
Effective mixing angle at LHCb

- Di-muons in region 60-160 GeV;
- 7 TeV (1 fb^{-1}) + 8 TeV (2 fb^{-1})

LHCb: JHEP 1511 (2015) 190

high rapidity - less dilution between parton and proton

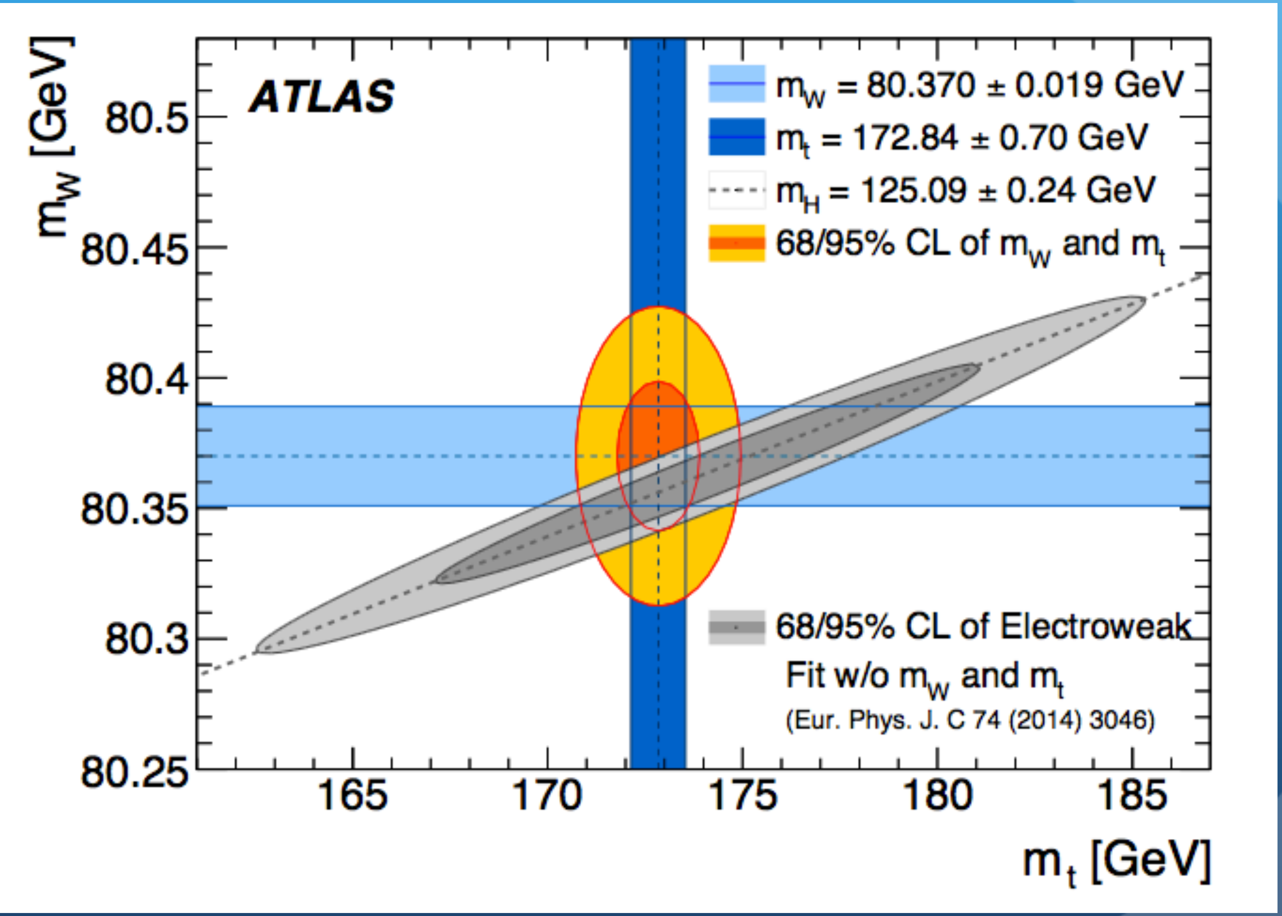




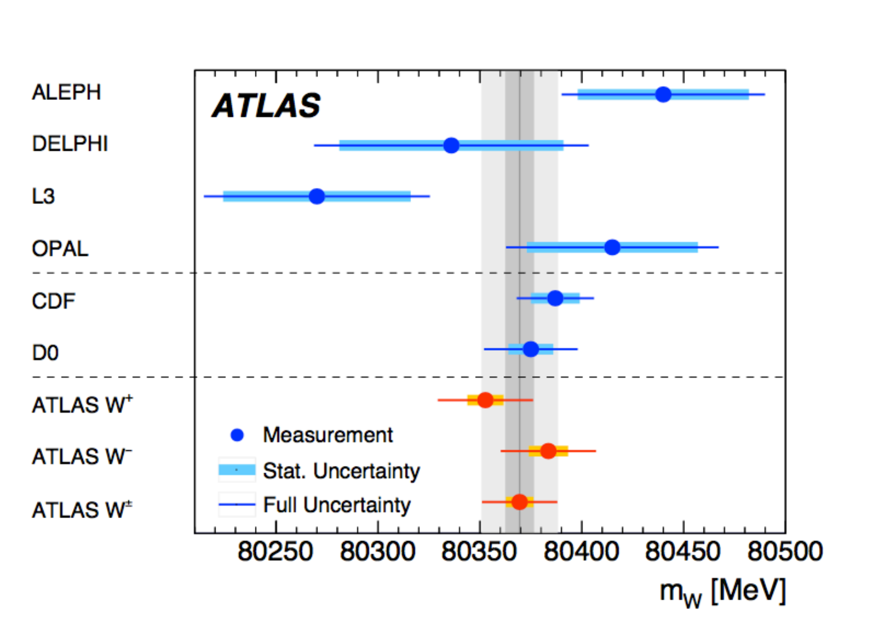
$$\sin^2\theta_W^{\rm eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$$

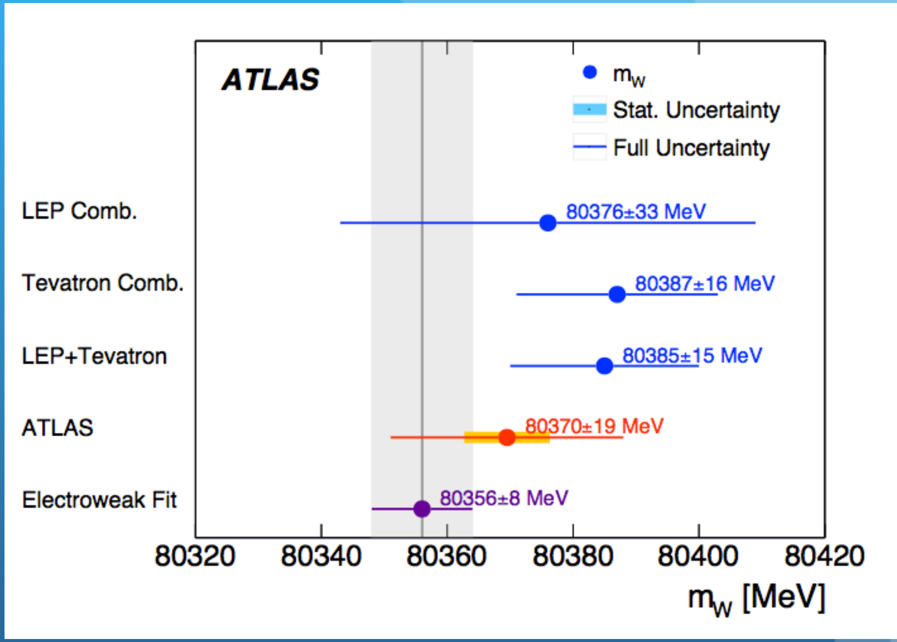
Uncertainties: stat (will improve with more data); theo (will improve with PDF) -> measurement most precise at LHC !

Compatibility in context of the global fit



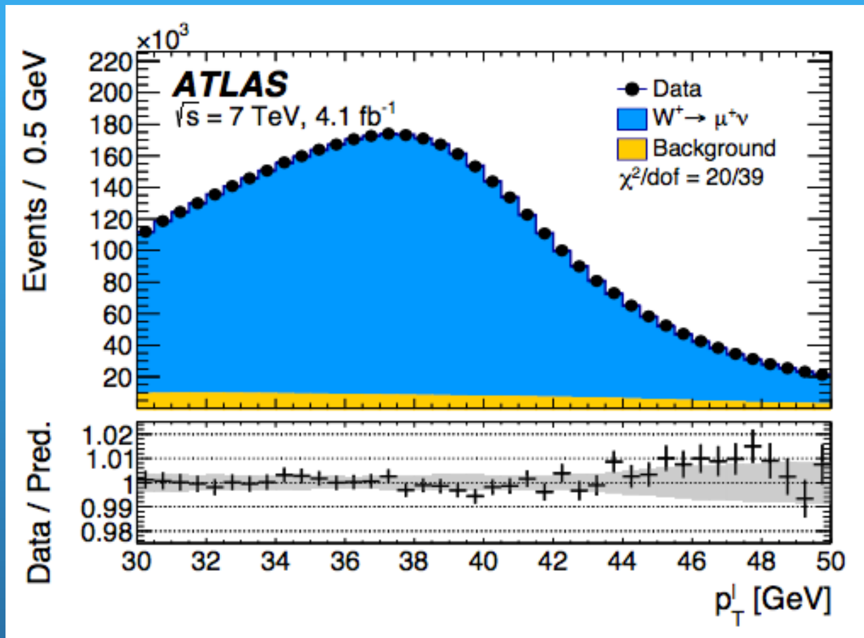
Comparison to other experiments

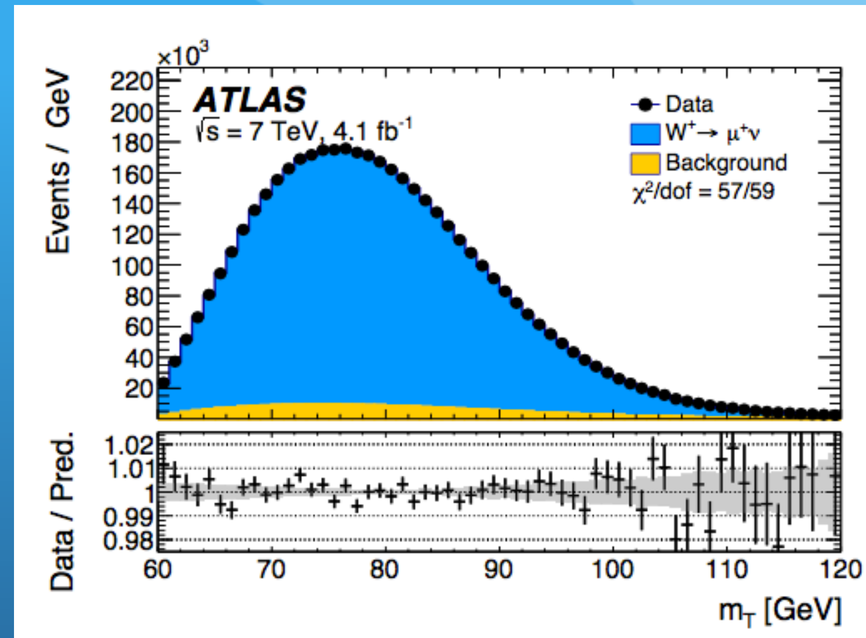




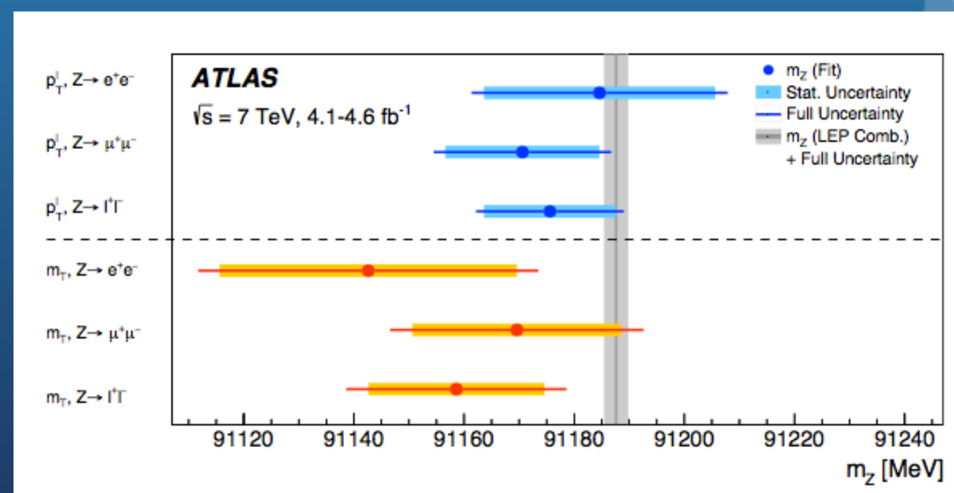
The result is compatible with the current world average and similar in precision to the currently leading measurements

Fitted distributions, consistency test

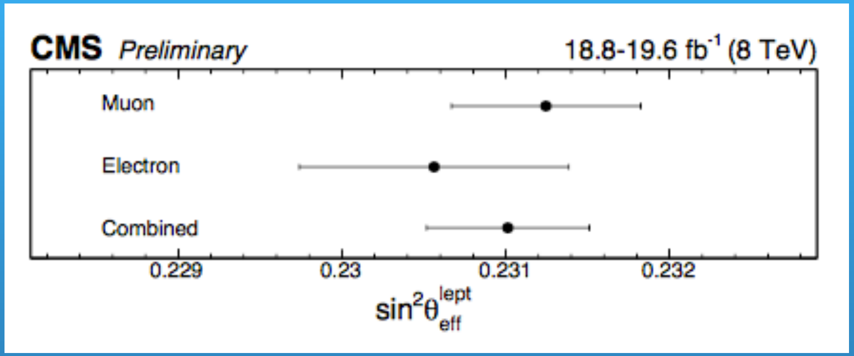


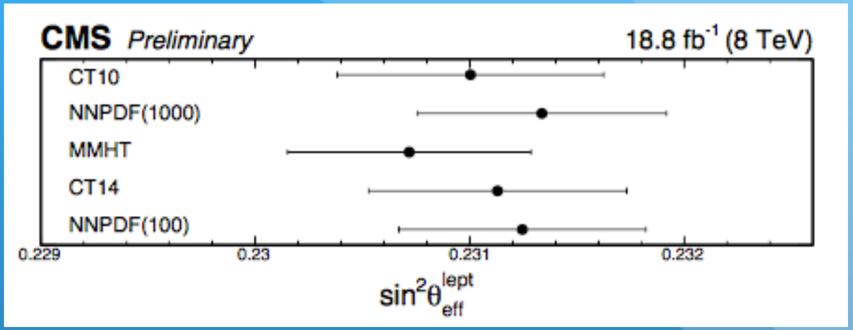


Consistency test on Z events shows expected performance of the mass measurement procedure



Effective mixing angle results

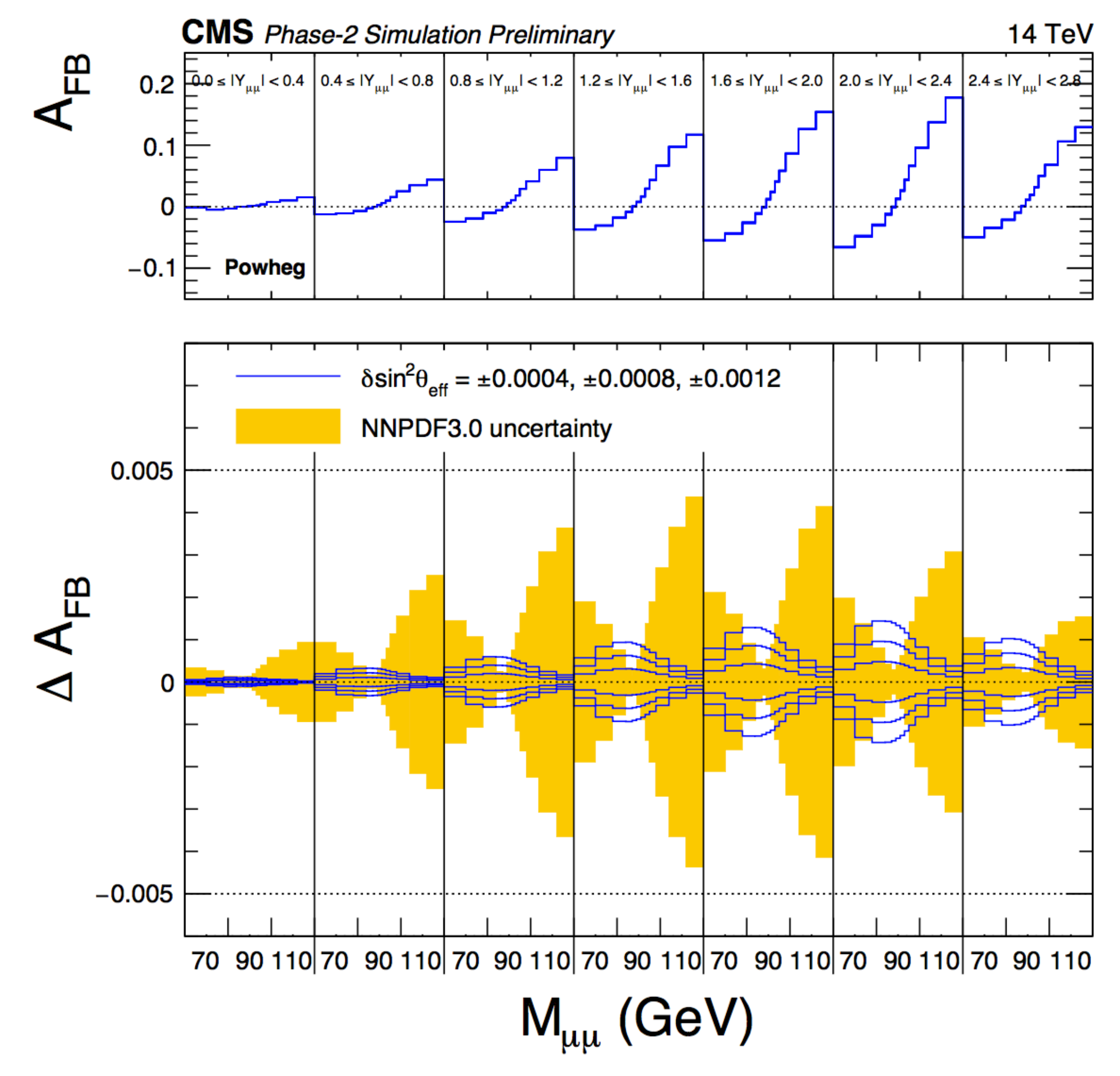




$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$
$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00052.$$

Statistical uncertainty still dominate, followed by PDF, that was reduced by reweighting by 50% . Experimental uncertainties are relatively small , theoretical are dominated by QCD/scales

Effective mixing angle at HL-LHC



CMS: CMP-PAS-FTR-17-001