Precision measurements of electroweak parameters

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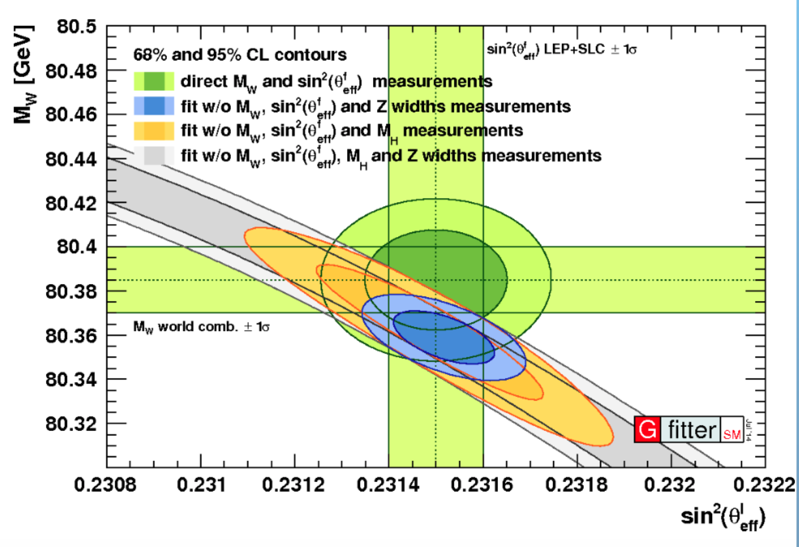
Introduction

- 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

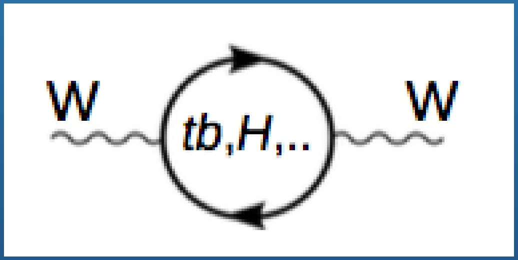
Standard Model Parameters

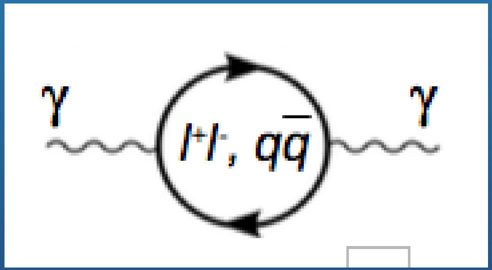
α_{em}, G_F, m_Z - these parameters are well measured ;

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





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

Incorporates higher-order + sensitive to top and Higgs masses + BSM

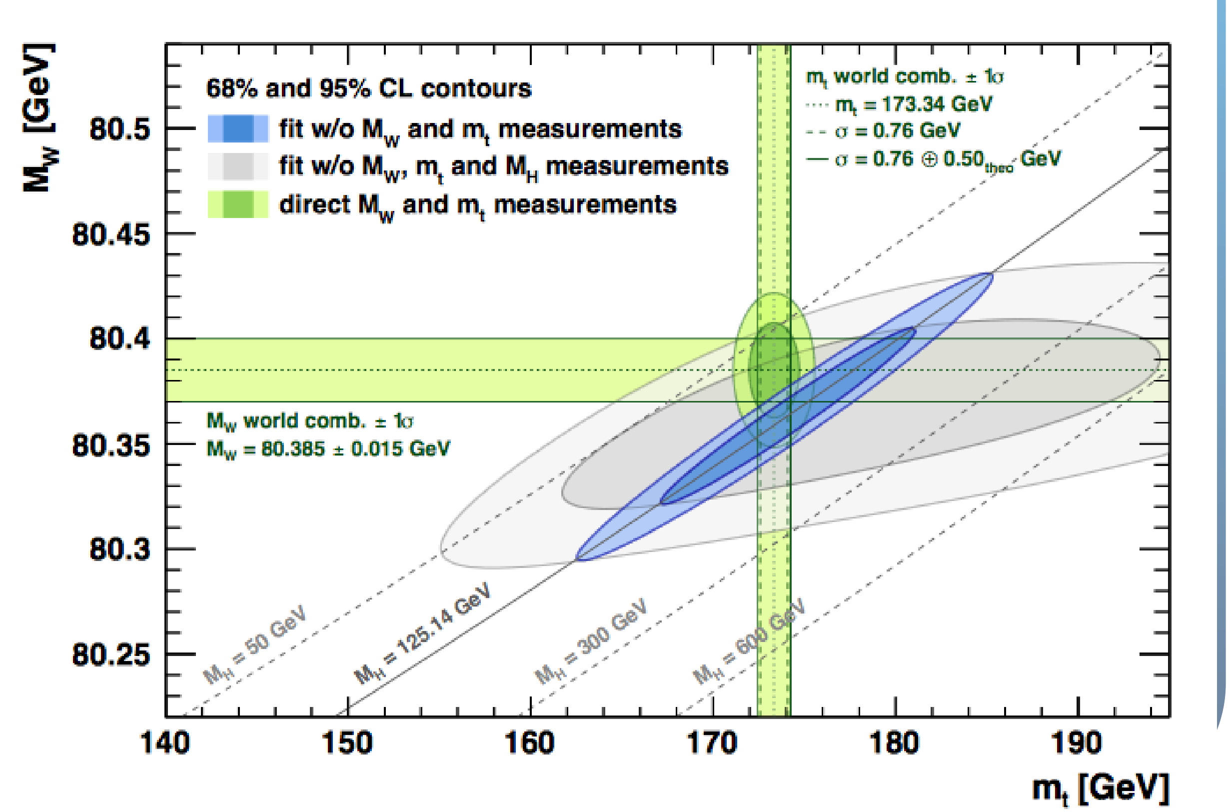
Direct measurements and global fit

	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	80.3618 ± 0.0080

arXiv:1608.01509

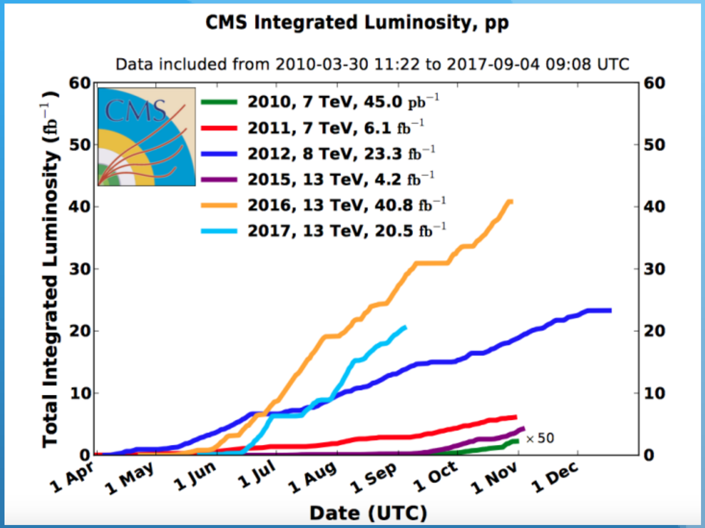
arXiv:1407.3792

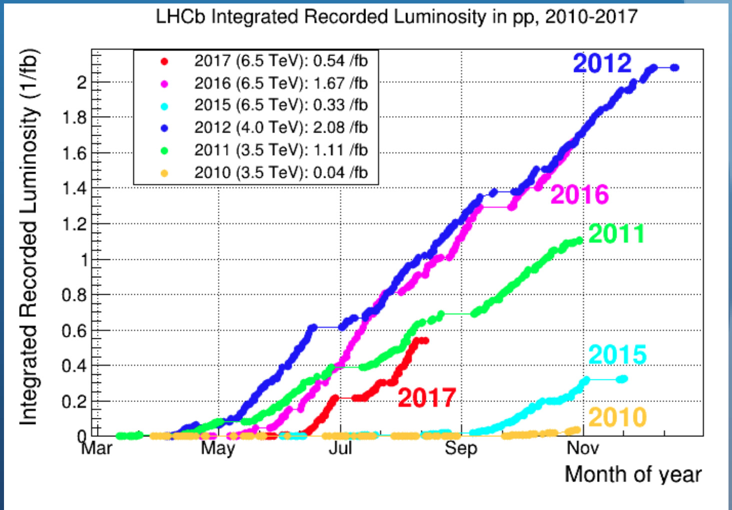
Gfitter



Measurements discussed in this talk

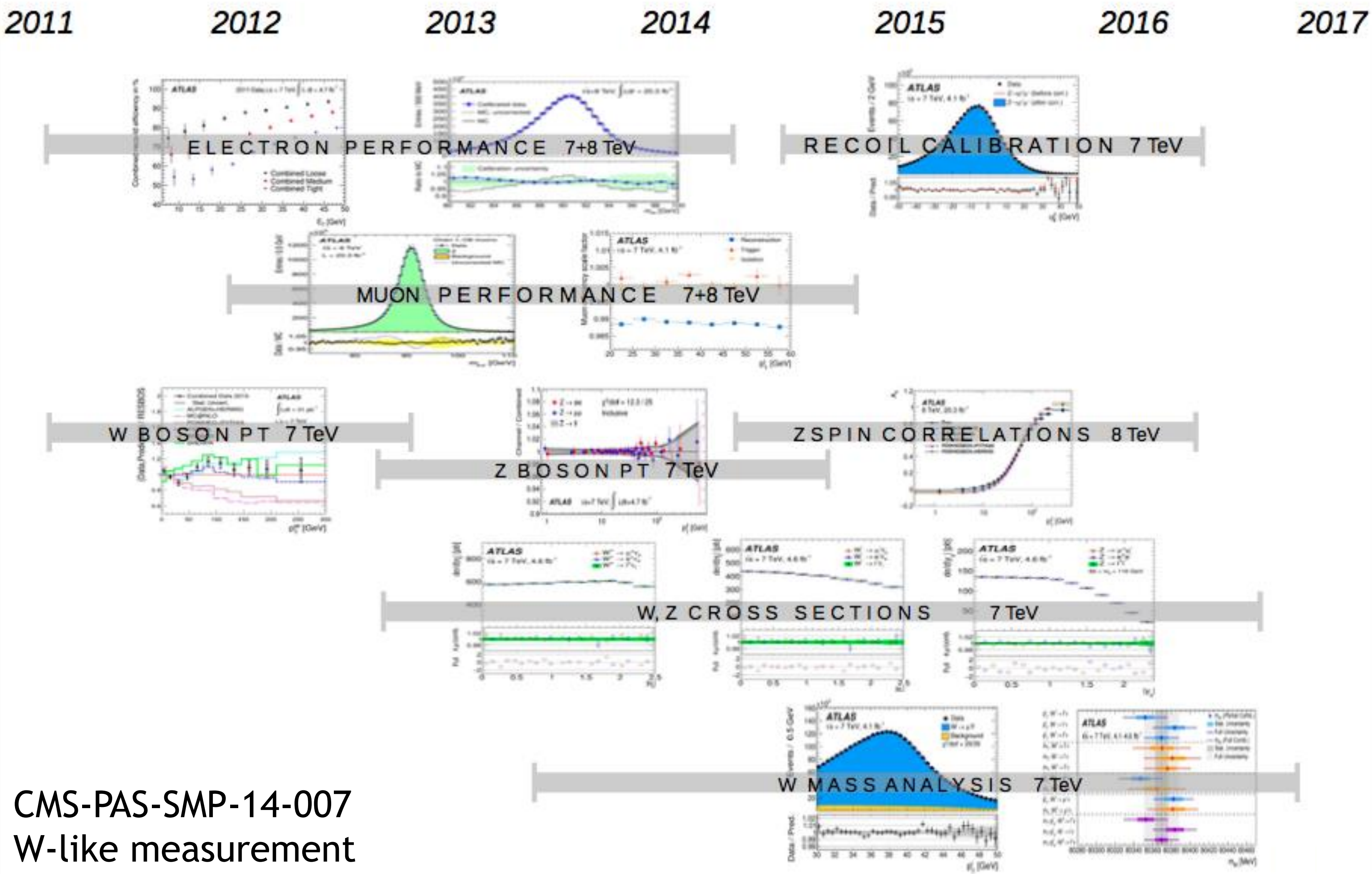
- W mass
  - ATLAS: arXiv:1701.07240
- Forward-Backward asymmetry A_{fb} and $\sin^2\theta_{eff}$
  - CMS: CMS-PAS-SMP-16-007
  - CMS: EPJC C76 (2016) 325
  - LHCb: JHEP 1511 (2015) 190
- Angular coefficients
  - ATLAS: JHEP 08 (2016) 159
  - CMS: PLB 750 (2015) 154
- Z/W + 2jets EWK
  - ATLAS: Zjj – CERN-EP-2017-115
  - CMS: Zjj – CMS-PAS-SMP-16-018
  - ATLAS: Wjj - arXiv:1703.04362
- Tau polarization
  - ATLAS: Z – ATLAS-CONF-2017-049





ATLAS W mass measurement

arXiv:1701.07240



CMS-PAS-SMP-14-007
W-like measurement

W production at LHC

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

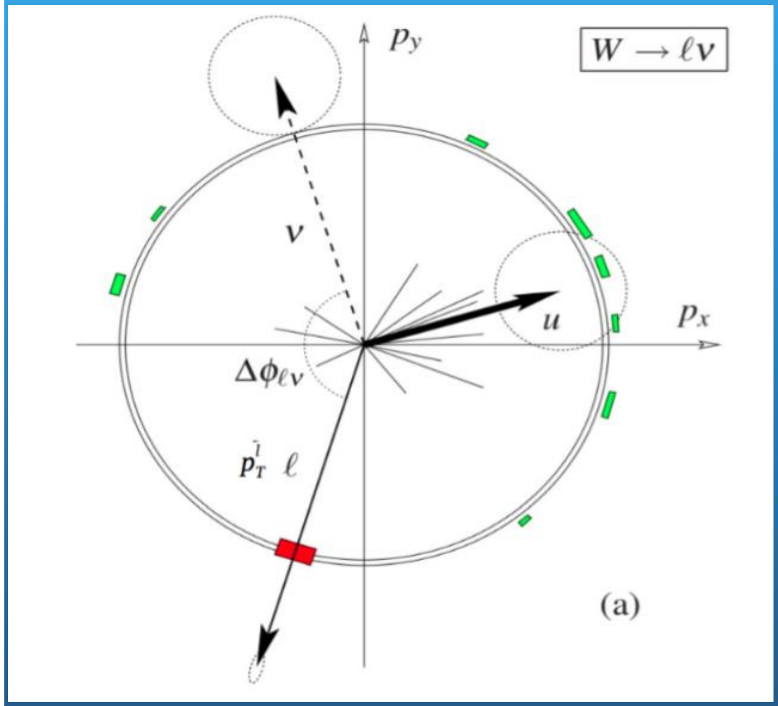
  80.367 ± 0.023 GeV

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

  80.387 ± 0.019 GeV

- In pp collisions at the LHC
  - Large signal (10^7) and calibration (10^6) samples
  - 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

Main experimental observables



Lepton kinematics:

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

Recoil to transverse plain

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

Transverse momentum of neutrino

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

W-boson transverse mass

$$m_T = \sqrt{2 p_T^\ell p_T^{miss} (1 - \cos \Delta\phi)}$$

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

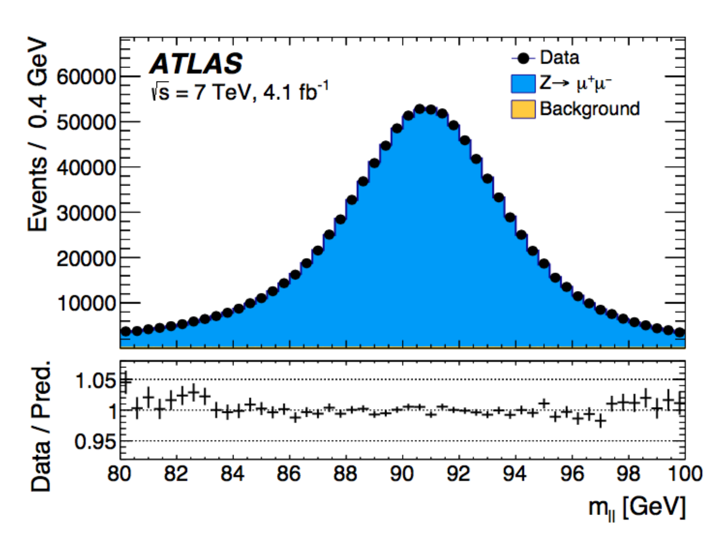
The mass of W boson is defined from the fit to:

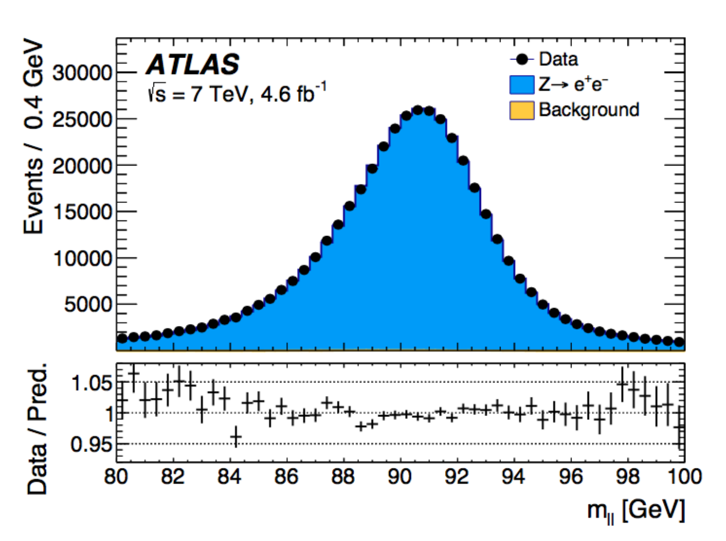
$$p_T^l, m_T$$

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



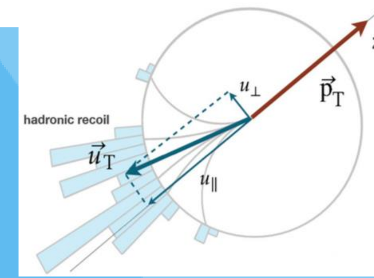


Systematics

$\|\eta_\ell\|$ 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

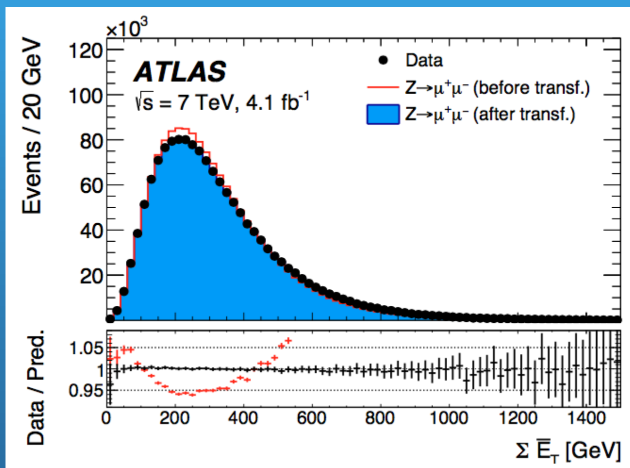
$\|\eta_\ell\|$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
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

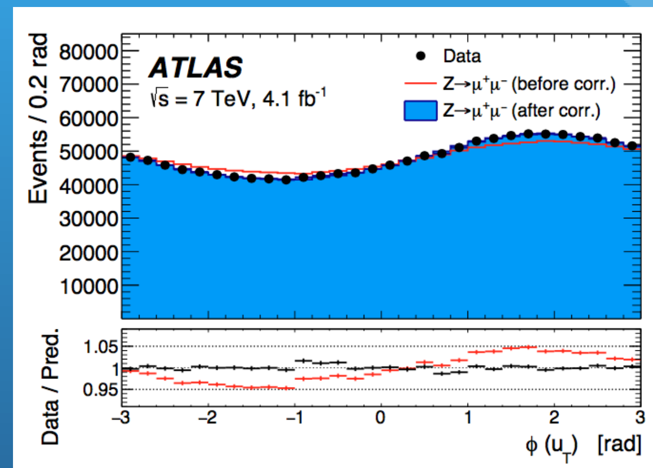
Recoil calibration



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

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

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

$\left[\frac{d\sigma(m)}{dm}\right]$ BW, EW corrections: QED FSR
(LO photon emission, NLO, Photos etc)

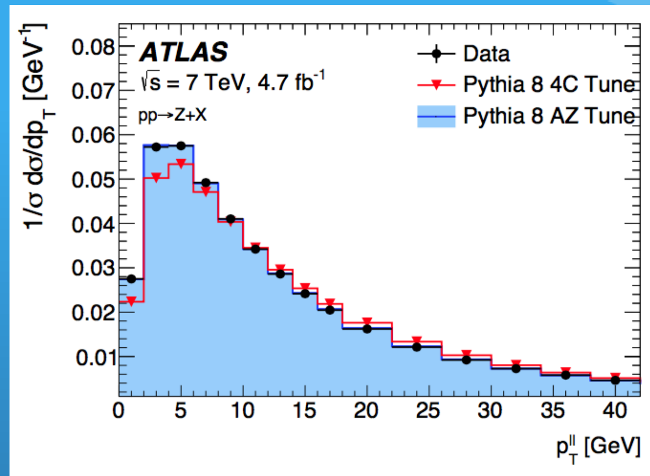
$\left[\frac{d\sigma(y)}{dy}\right]$ Fixed order optimized DYNNLO with CT10nnlo PDF

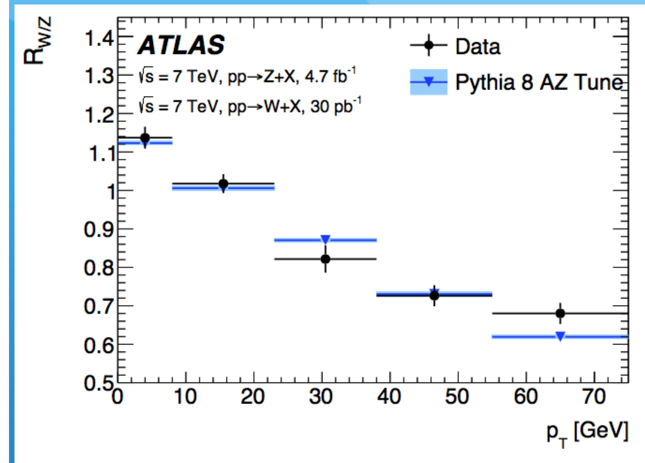
$\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$

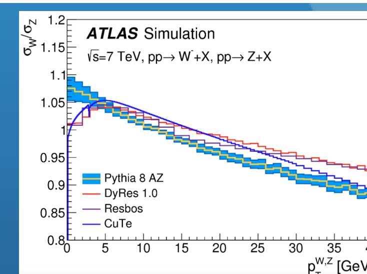
$\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]$ Low p_T, NP effects using Pythia 8 + AZ tune

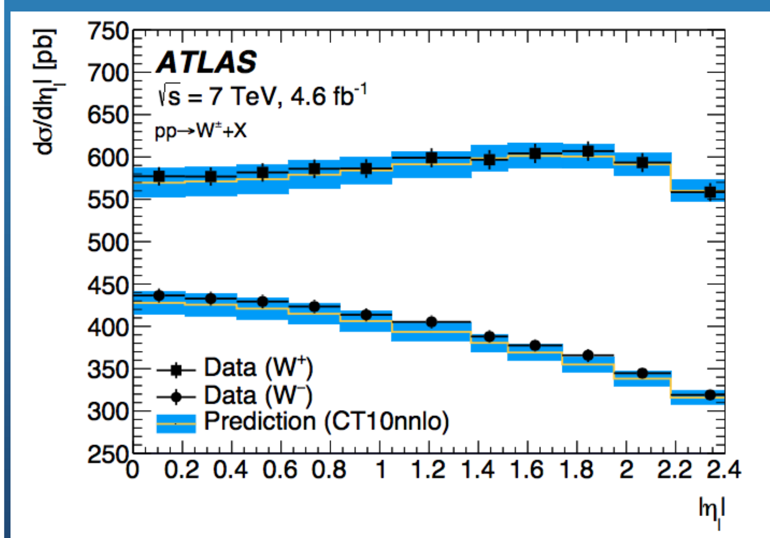
W/Z production and decay simulation

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





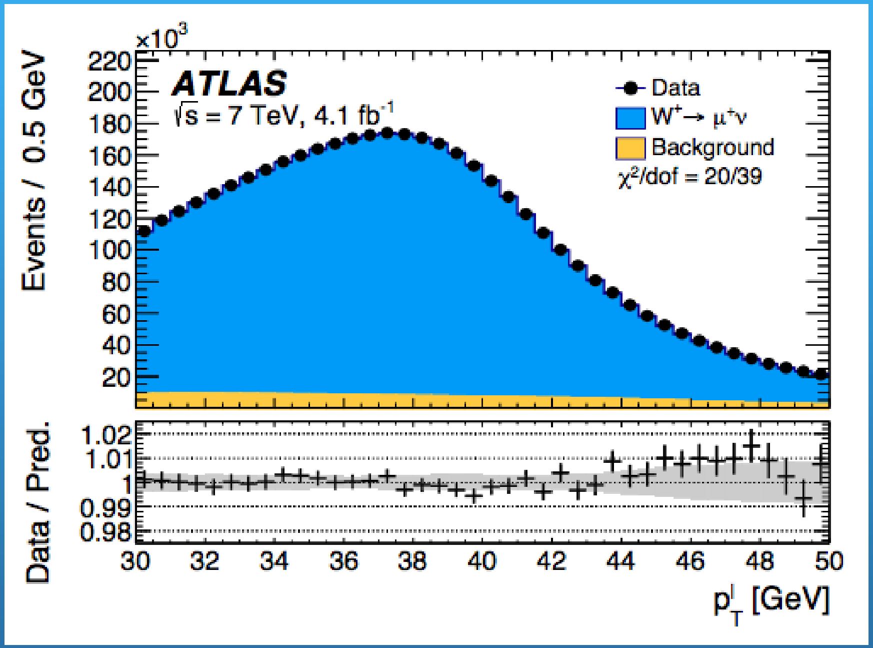


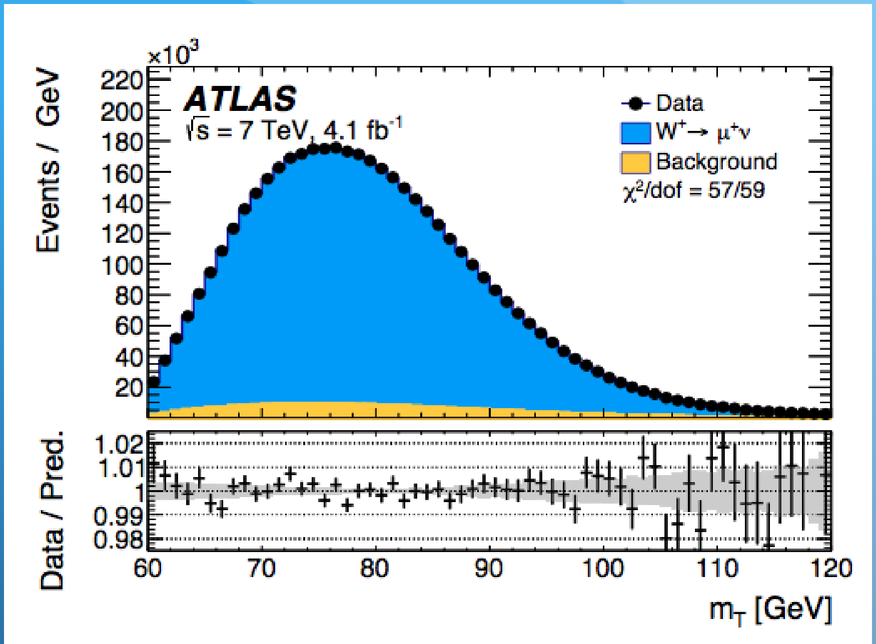


Major uncertainty is PDF,second largest - PS

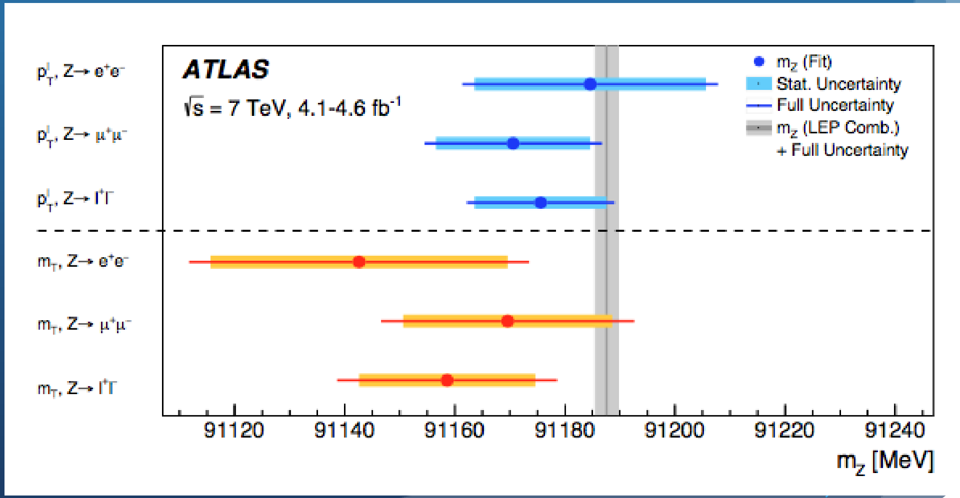
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

Fitted distributions, consistency test

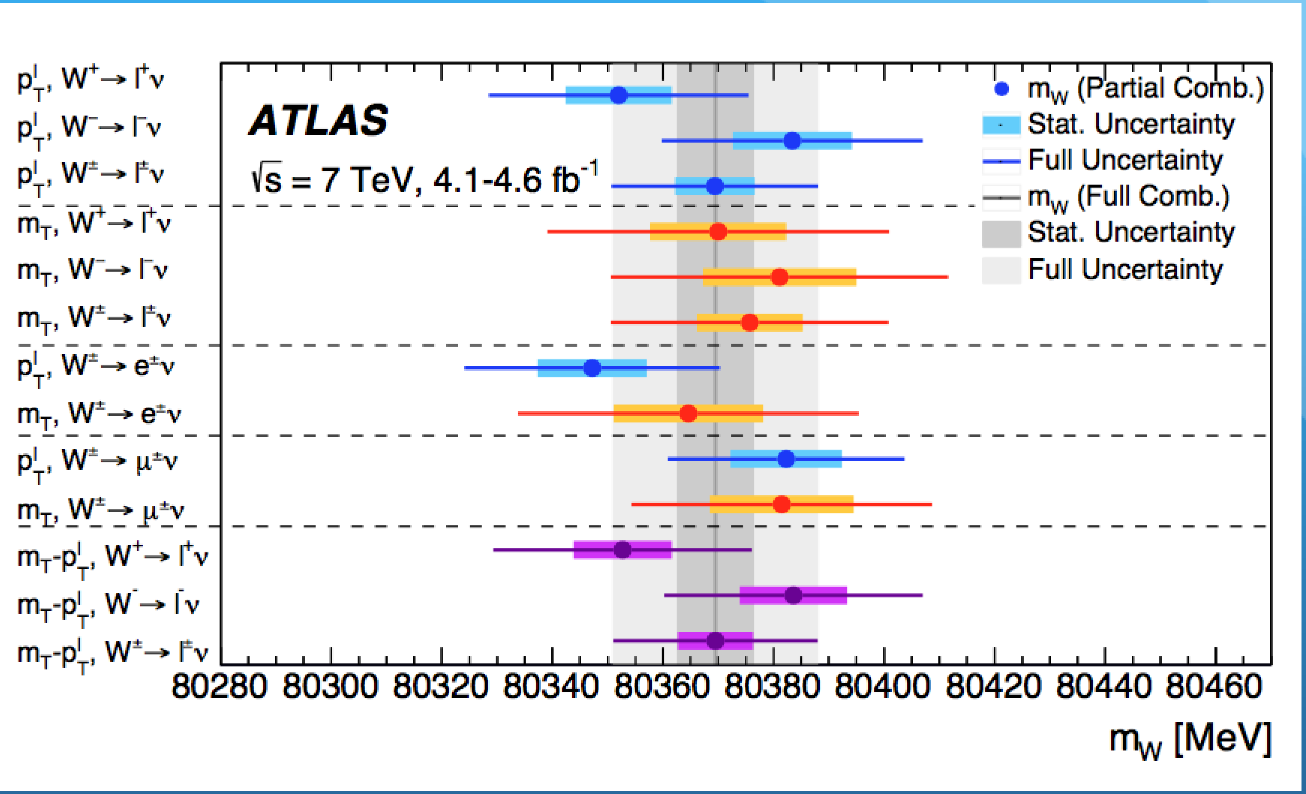




Consistency test on Z events shows expected performance of the mass measurement procedure



W mass measurement, diff. categories

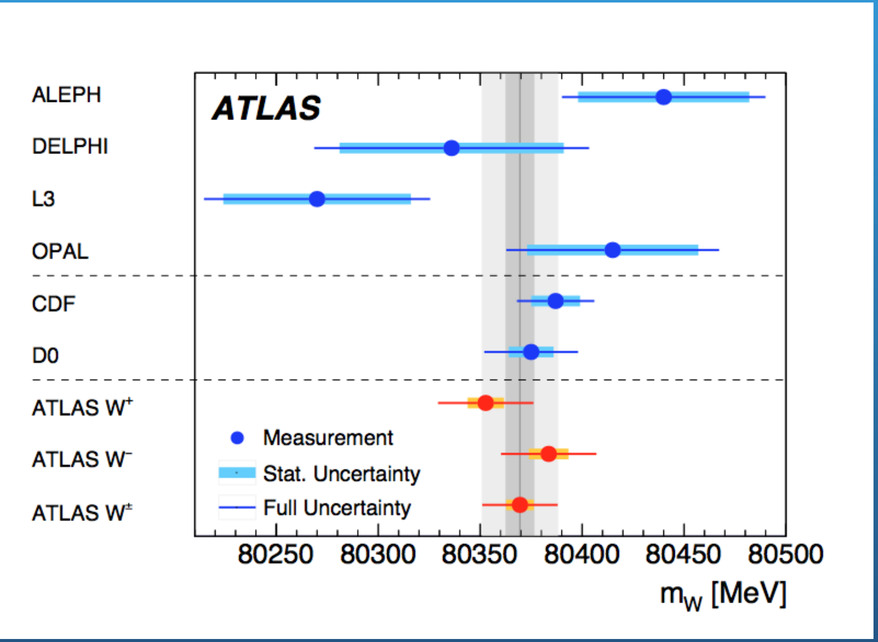


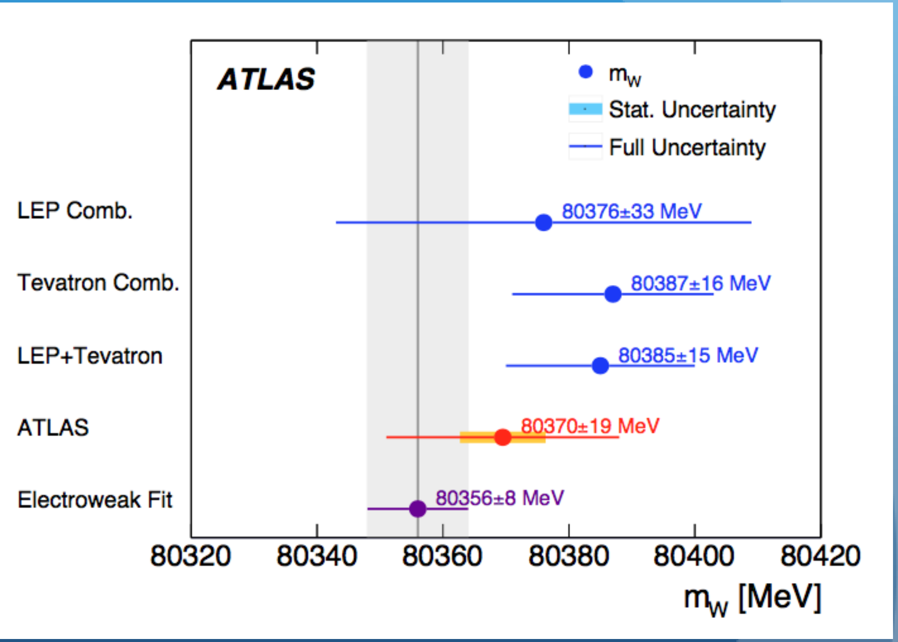
combined result

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

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

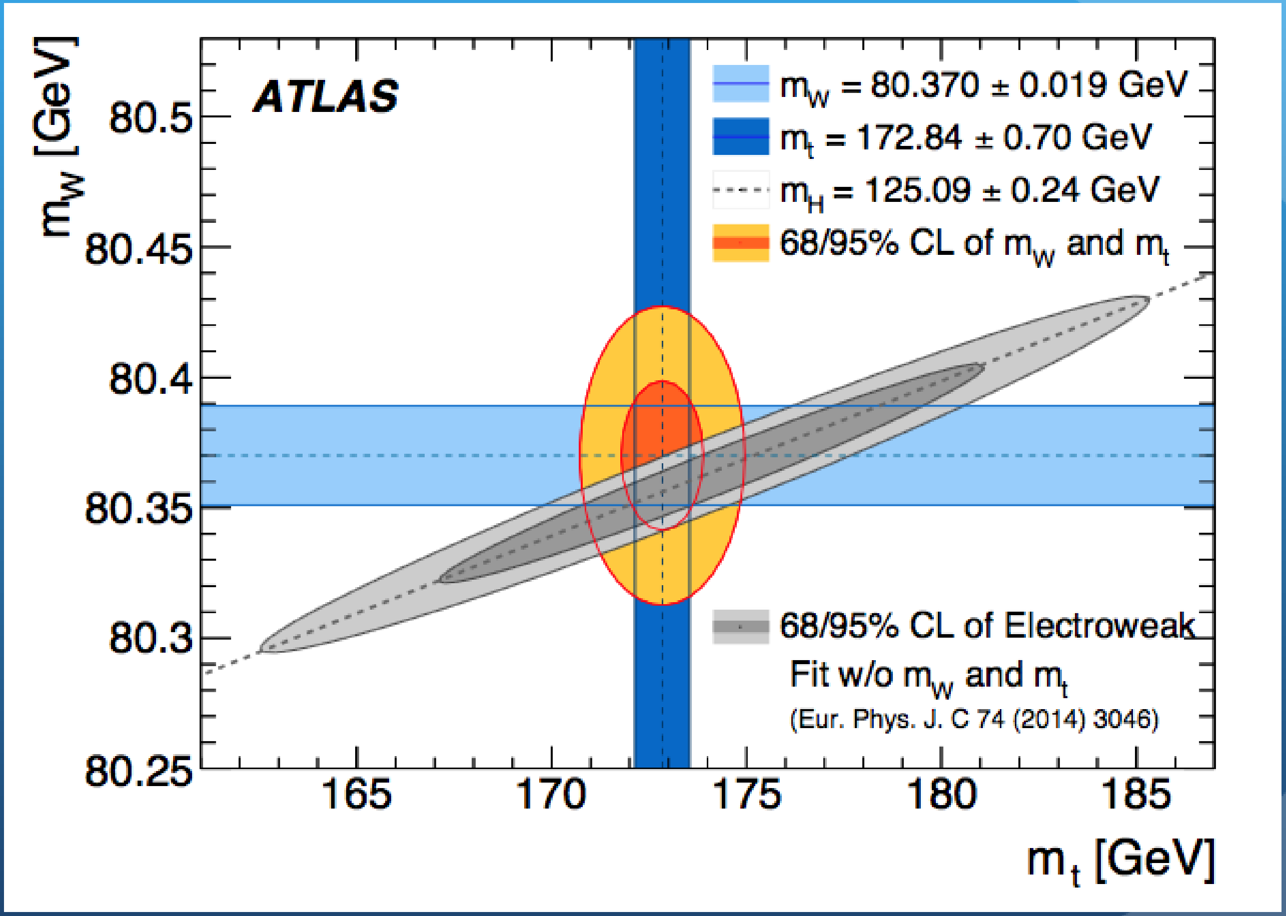
Comparison to other experiments





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

Compatibility in context of the global fit



Forward-Backward Asymmetry in Z's

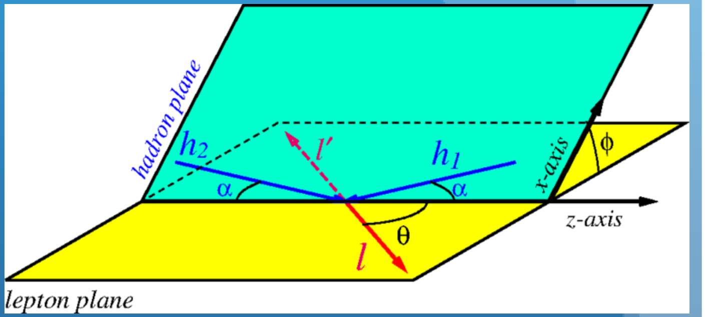
- Vector and axial-vector couplings in NC annihilation

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

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

- Differential cross section

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



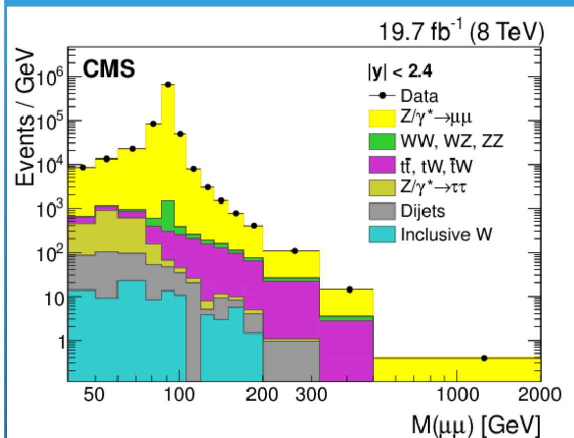
- Collins-Soper frame, the events are classified to forward and backward in CS to calculate the A_{FB}

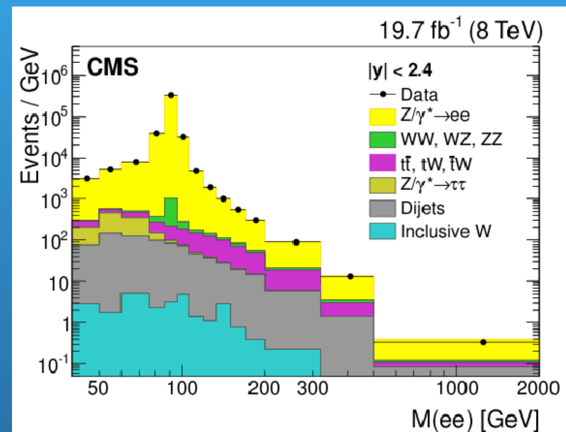
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

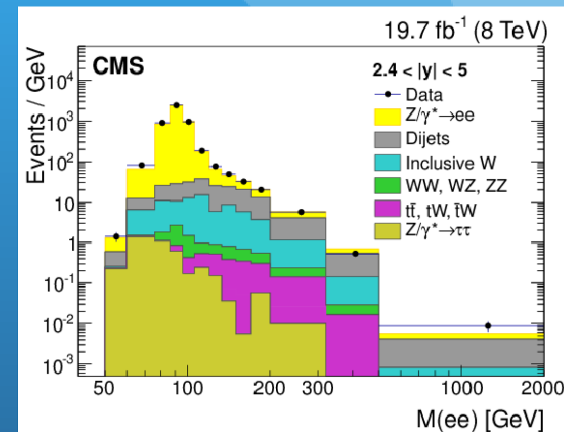
A_{FB} measurement with di-muon and di-election events

CMS: EPJC C76 (2016) 325

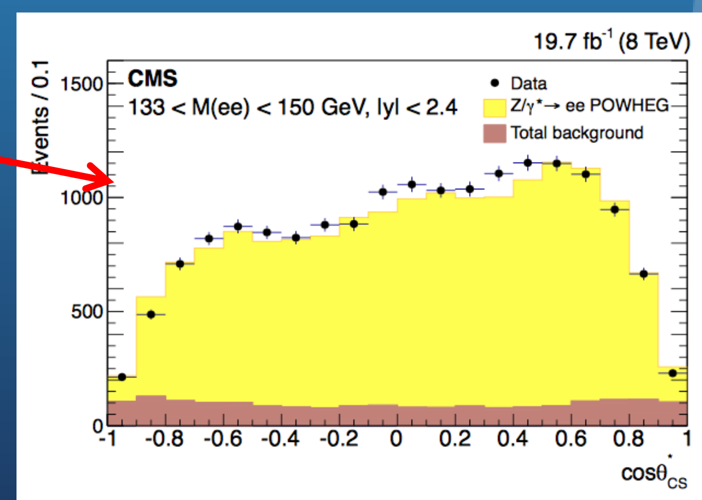
Muon/electron candidates with p_T>20 GeV, $|\eta|$<2.4 (for electrons up to 5!)





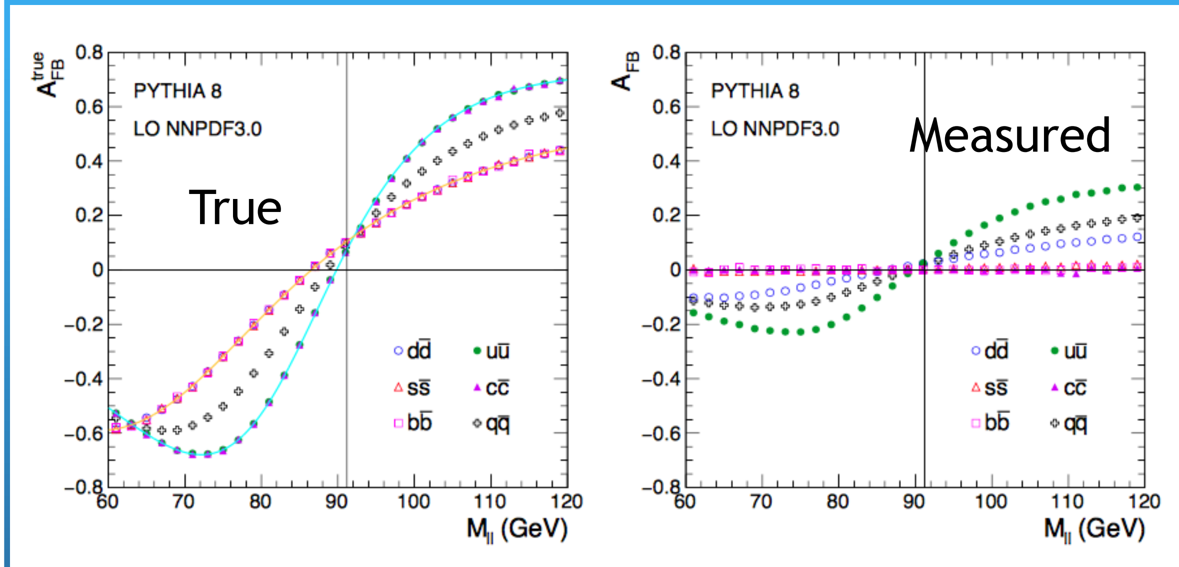


The measured $\cos\theta^*_{CS}$ distribution



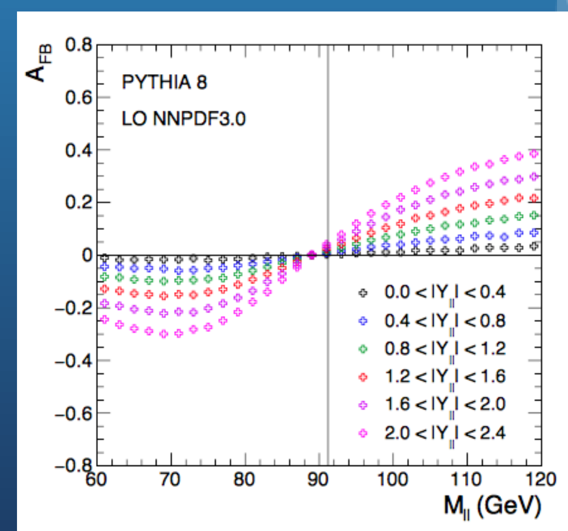
A_{FB} is measured as a function of dilepton mass in bins of pseudorapidity

Dilution of A_{FB}



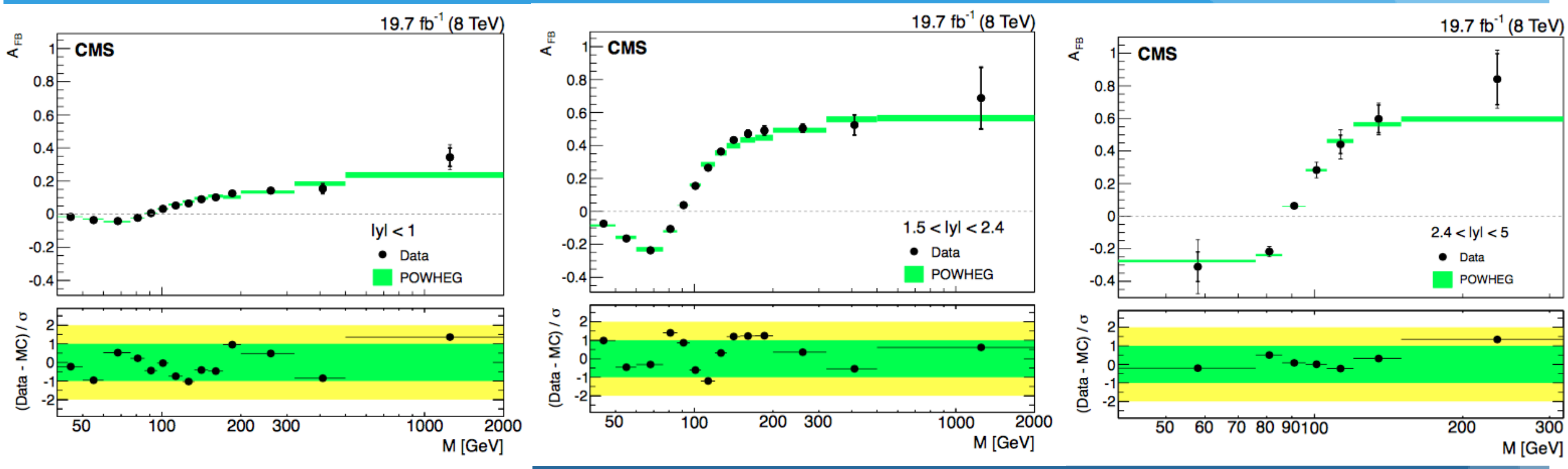
A_{FB} PDF dependence; near Z peak is sensitive to leptonic $\sin^2\theta_{eff}$

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



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 well describe the measured values

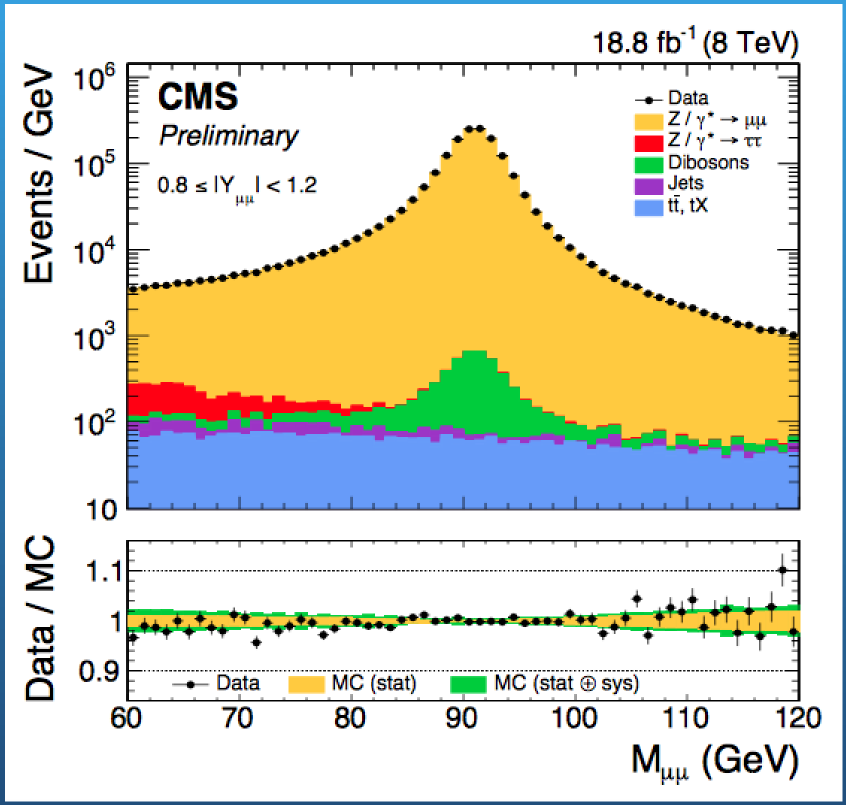
A.Savin, UW

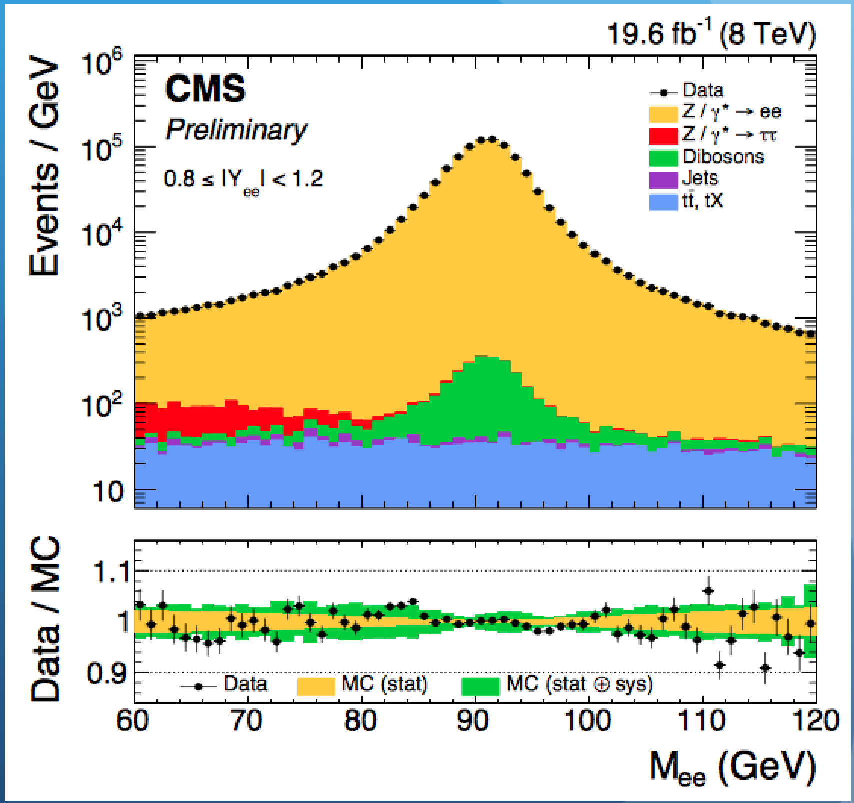
Effective mixing angle

CMS-PAS-SMP-16-007

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

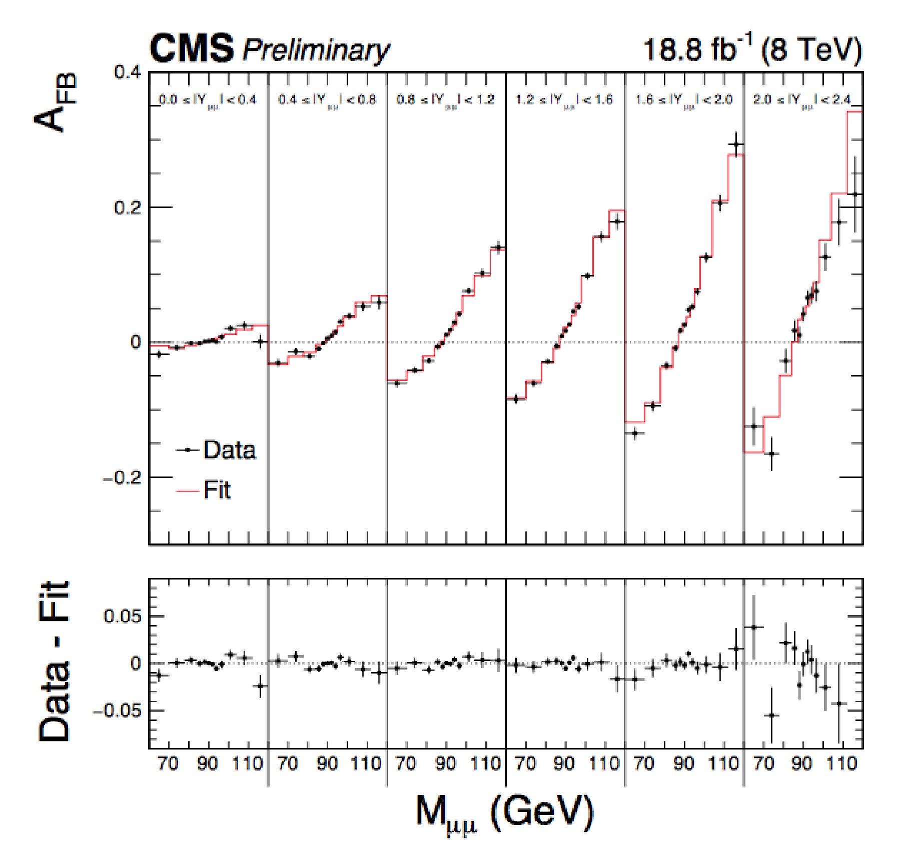
This measurement constraints the W mass !

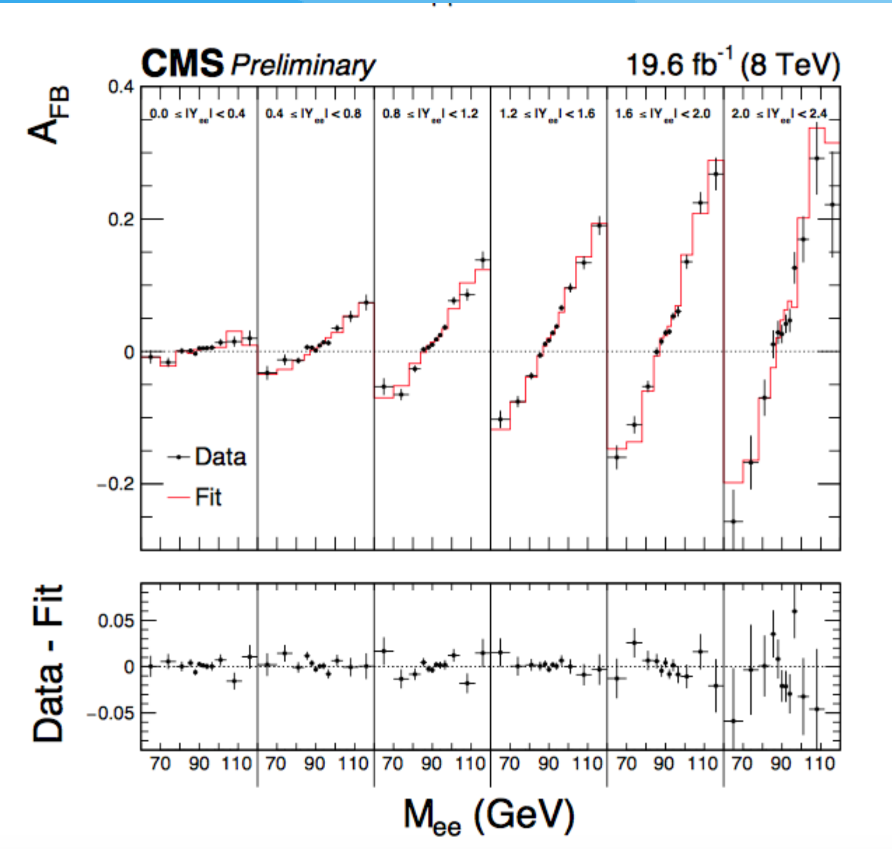




A_{FB} measurement near Z mass peak is used

Effective mixing angle measurement





Minimizing χ^2 between data and templates POWHEG+PYTHIA8

Uncertainties

channel	statistical uncertainty
muon	0.00044
electron	0.00060
combined	0.00036

Statistical

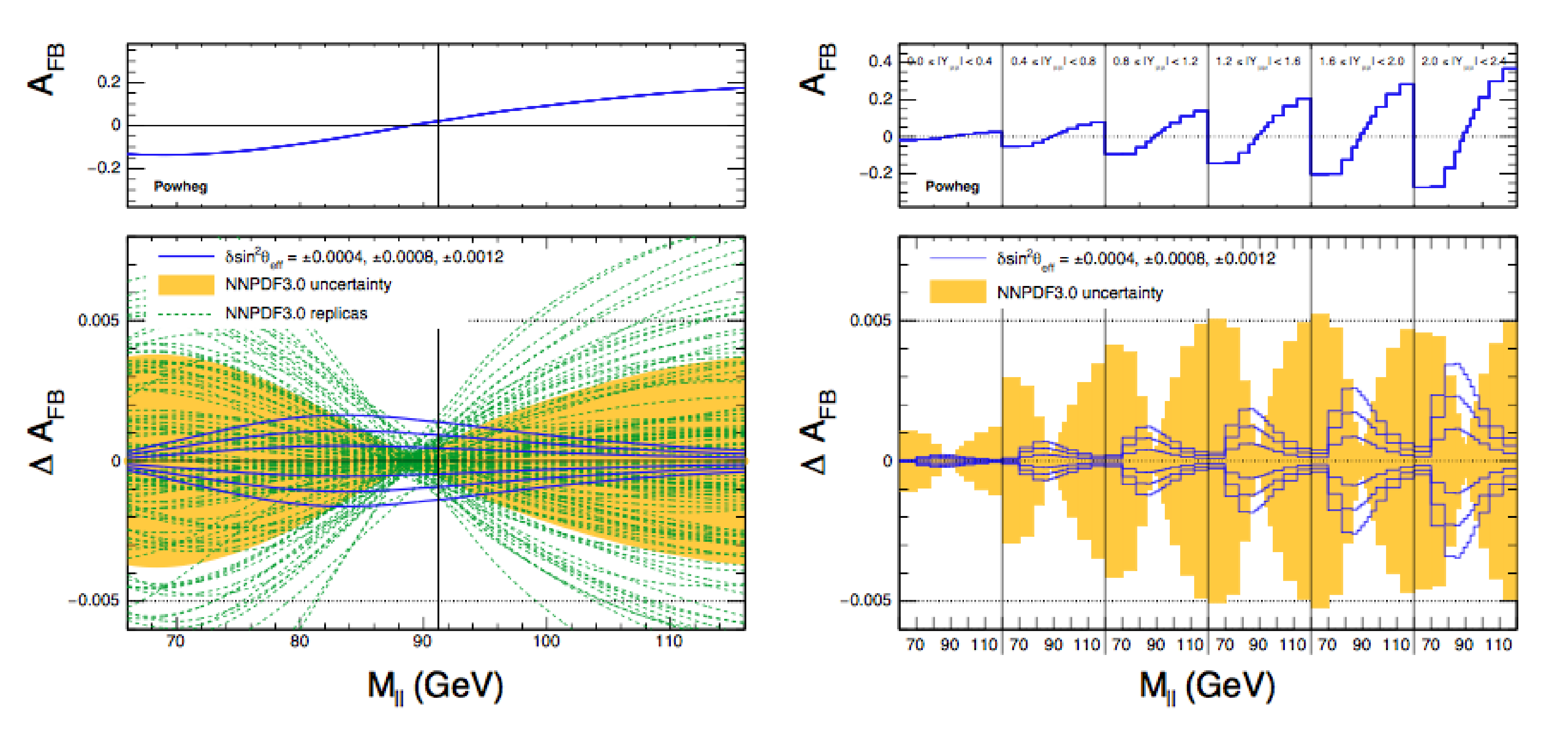
Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

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

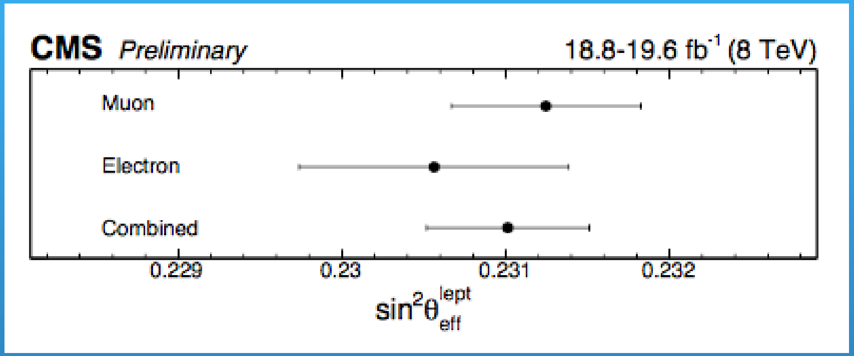
Theoretical systematics

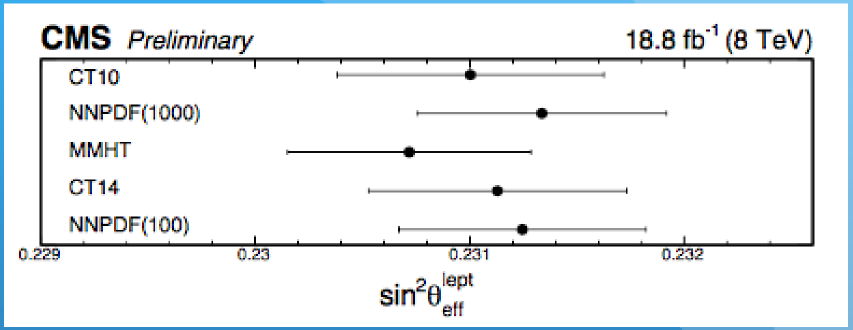
PDF uncertainty



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

Effective mixing angle results





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

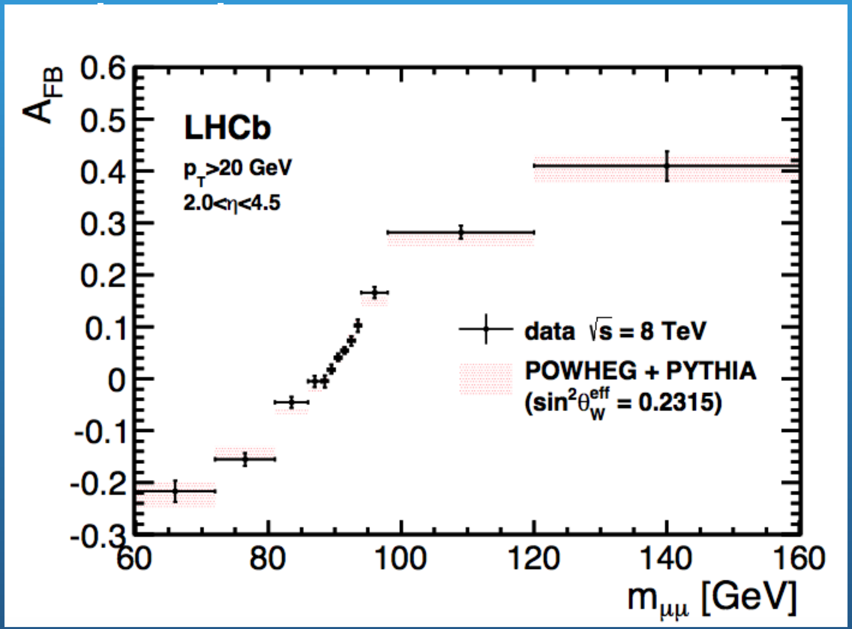
Statistical uncertainty still dominate, followed by PDF, that was reduced by reweighting by 50% . Experimental uncertainties are relatively small , theoretical are dominated by QCD/scales

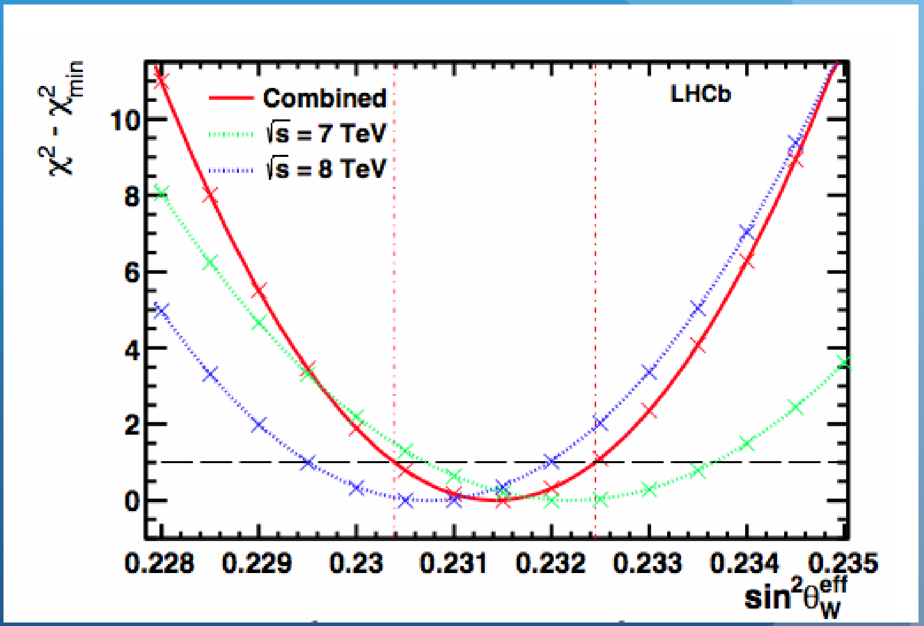
Effective mixing angle at LHCb

- 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

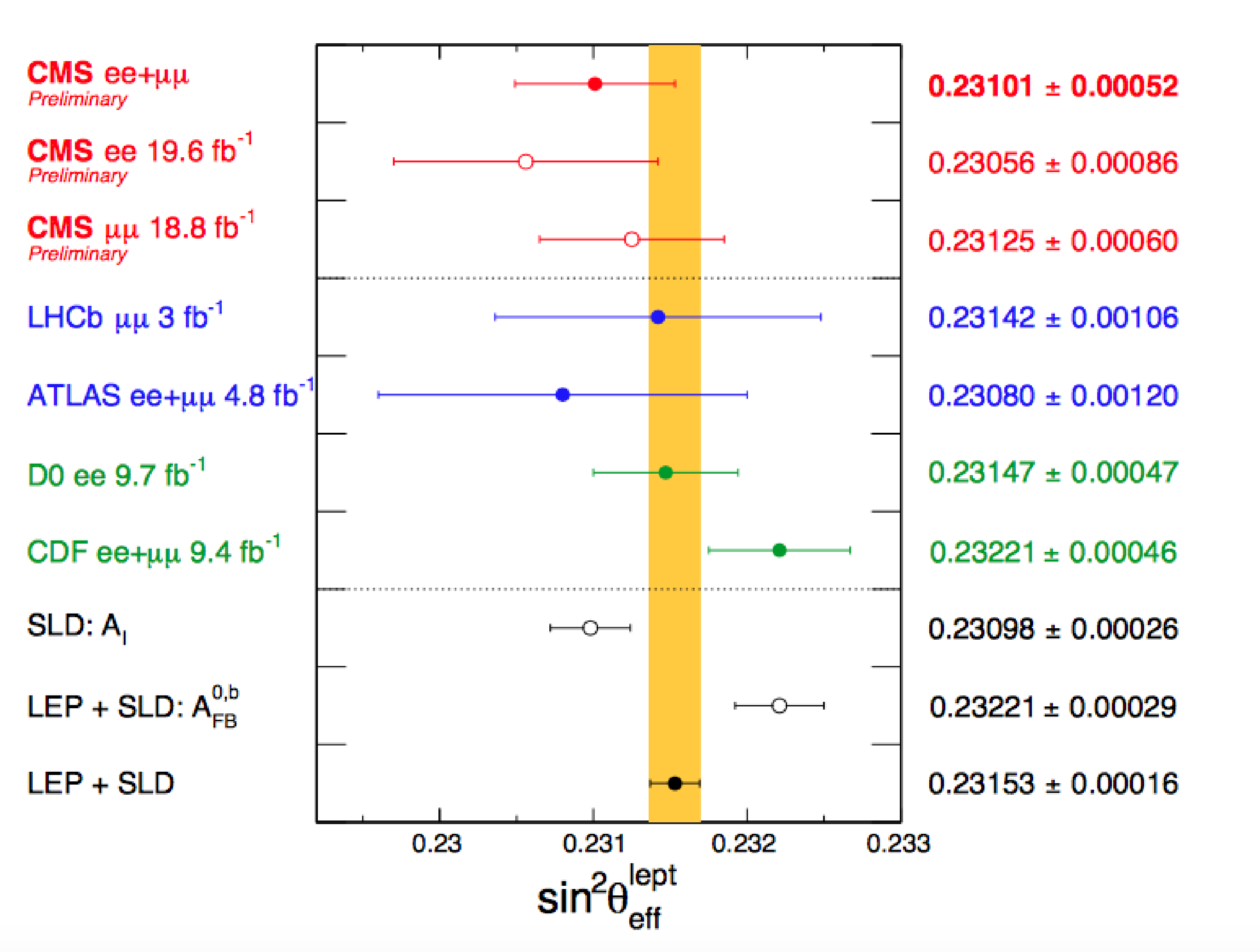




$$\sin^2\theta_W^{\rm eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$$

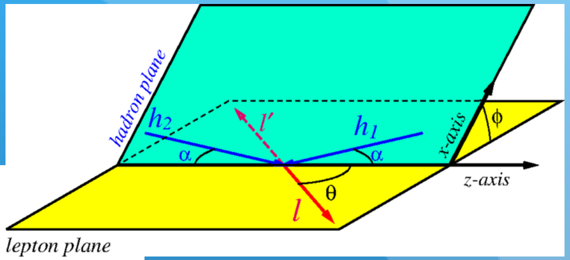
Uncertainties: stat (will improve with more data); theo (will improve with PDF) -> measurement most precise at LHC !

Effective mixing angle: experimental summary



Angular coefficients in Z events

The angles are defined in Collins-Soper frame. Differential cross section can be written as:



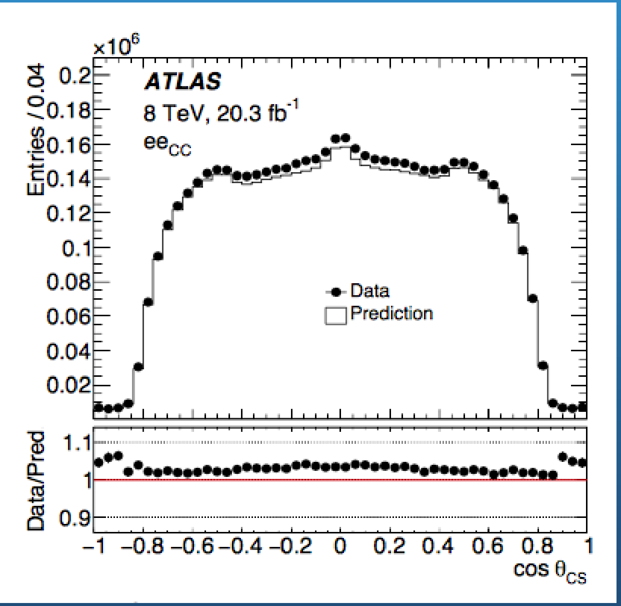
$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

A0-A3 become not 0 at NLO ;
A0-A2=0 Lam-Tung relation (valid at $O(\alpha_S)$) ;
A4 is only coefficient !=0 at LO ;
A5-A7 appear at NNLO .

Angular coefficients in Z events

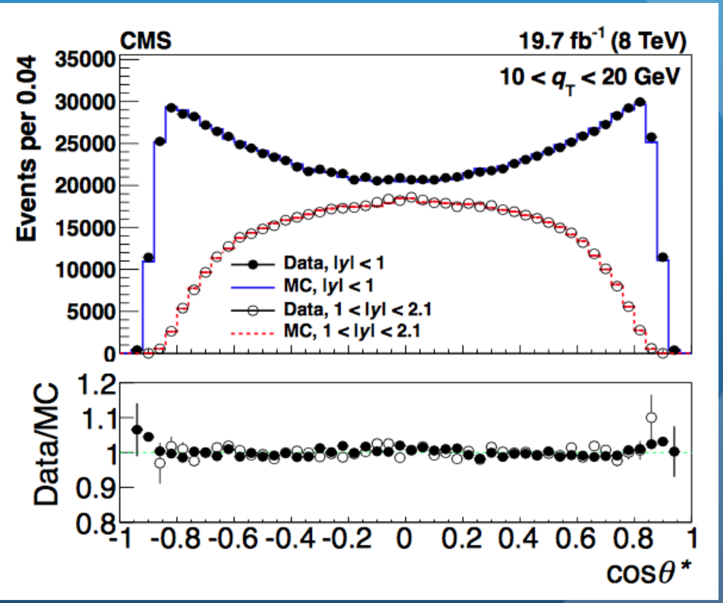
ATLAS: JHEP 08 (2016) 159

8 TeV, 20.3 fb^{-1}
muons and electrons
mass 80-100 GeV;
leptons p_T > 25 GeV
extended $|\eta|>2.5$ electrons



CMS: PLB 750 (2015) 154

8 TeV, 19.7 fb^{-1}
muons
mass 80-100 GeV;
leptons p_T > 25(10) GeV
$|\eta|<2.5$ (2.1)

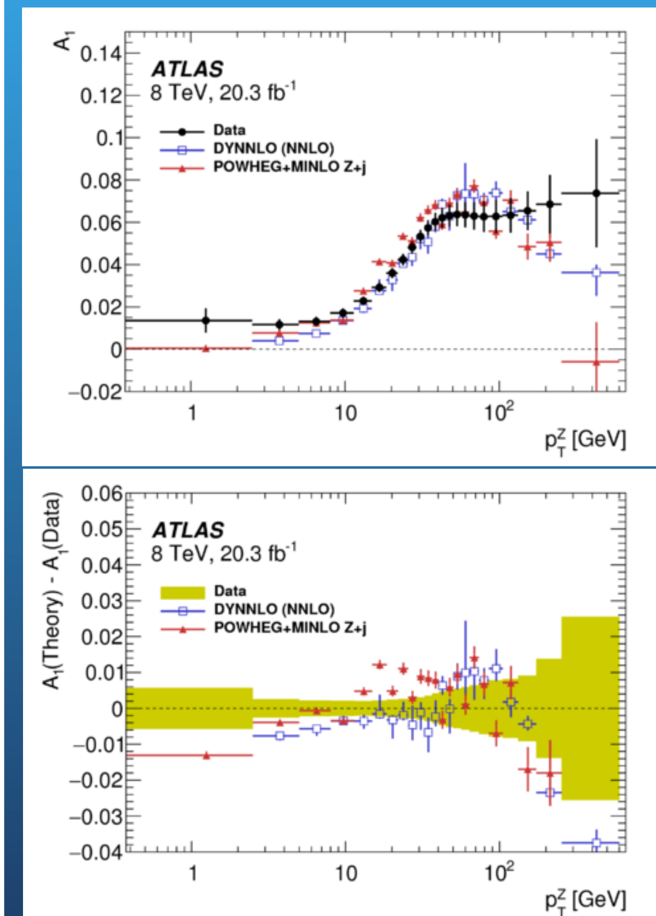


Template fit to extract the coefficients

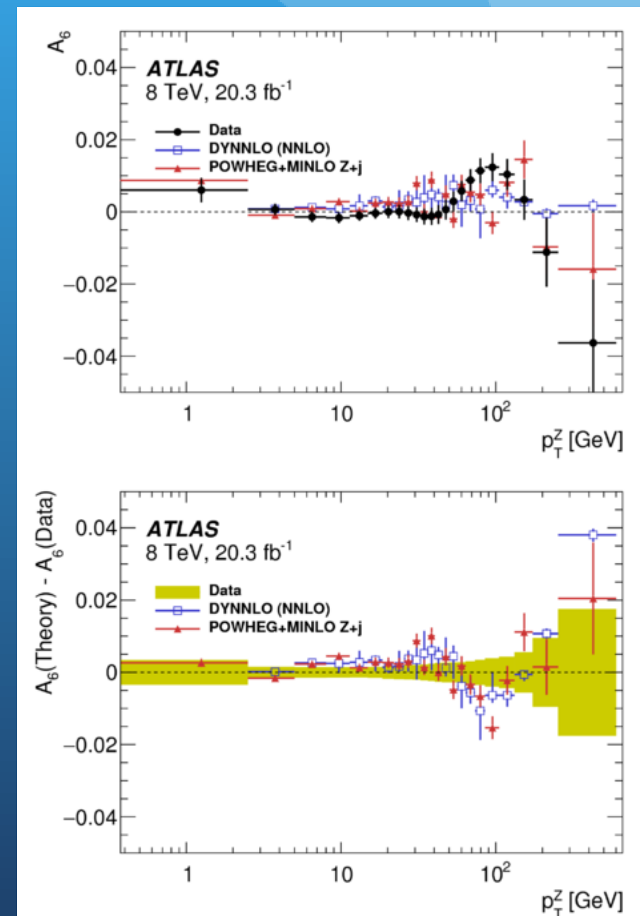
Angular coefficients in Z events

ATLAS: JHEP 08 (2016) 159

NNLO describes the data well within uncertainties



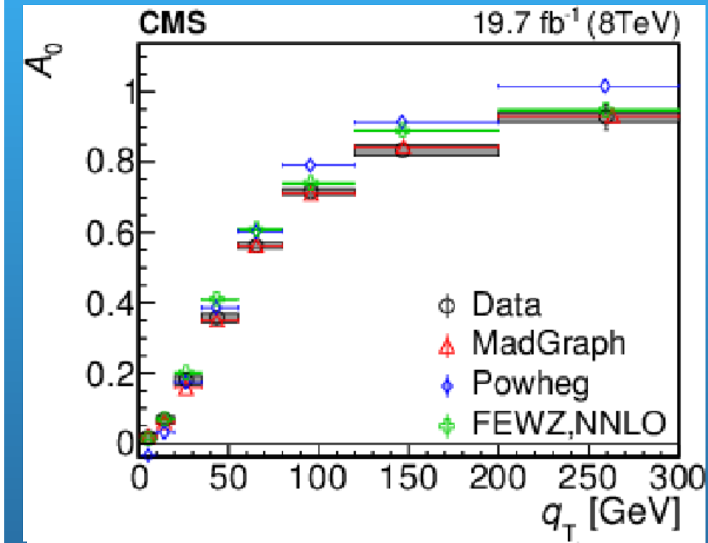
A_5-A_7 deviate from 0 in agreement with MC, at higher values of p^Z_T some deviations observed, still within uncertainties



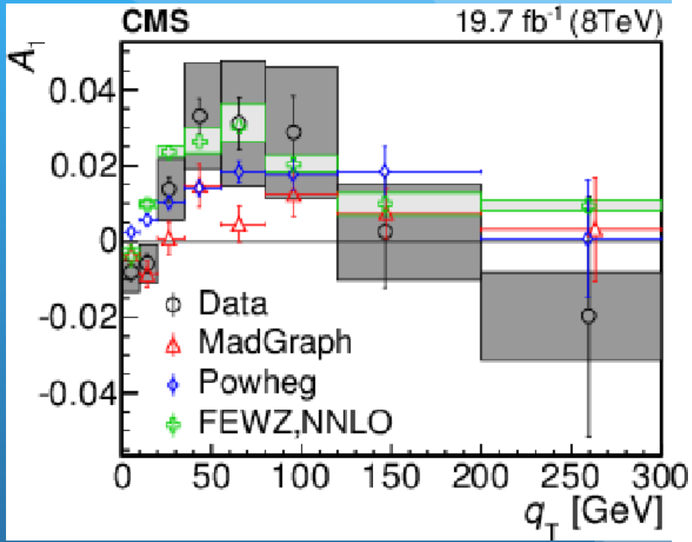
Angular coefficients in Z events

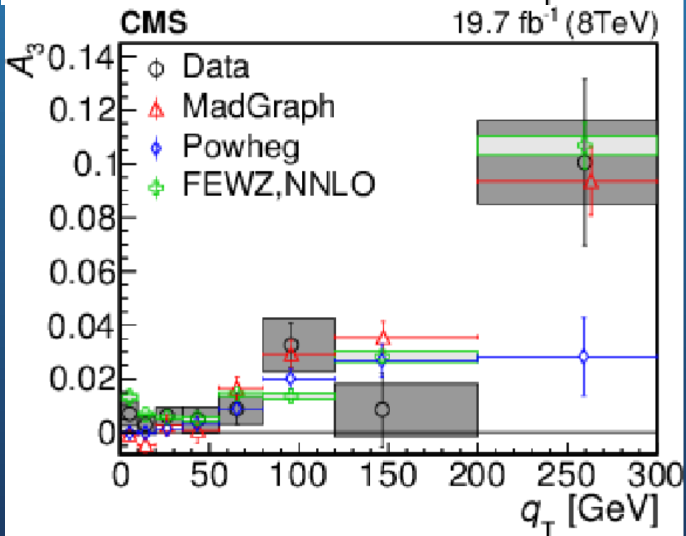
CMS: PLB 750 (2015) 154

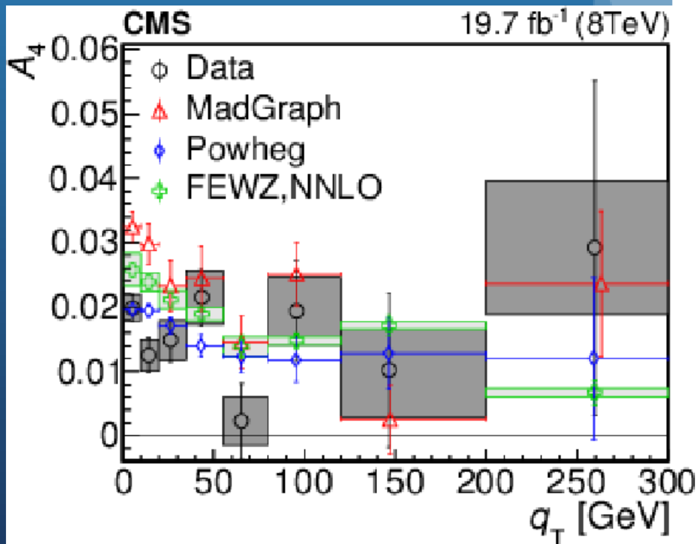
FEWZ(NNLO) and POWHEG(NLO) in general describe the data



MadGraph (LO) +up to 4 jets describes the data except A4 -> uses $\sin^2\theta_W$ without radiative corrections

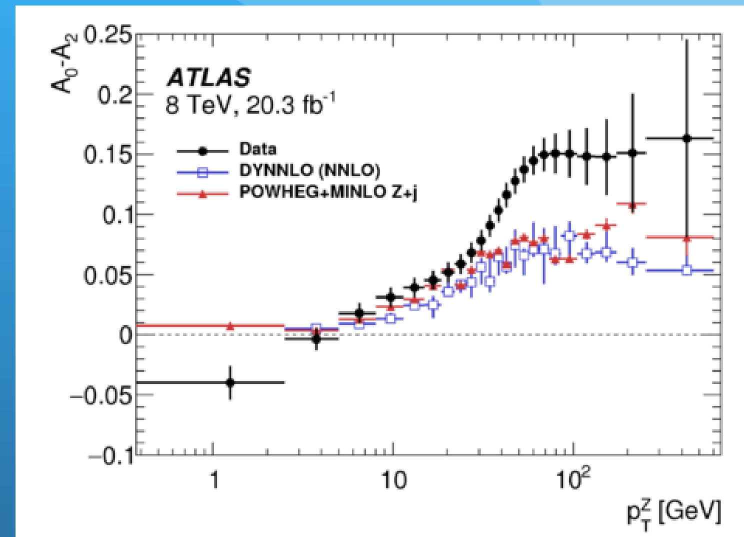






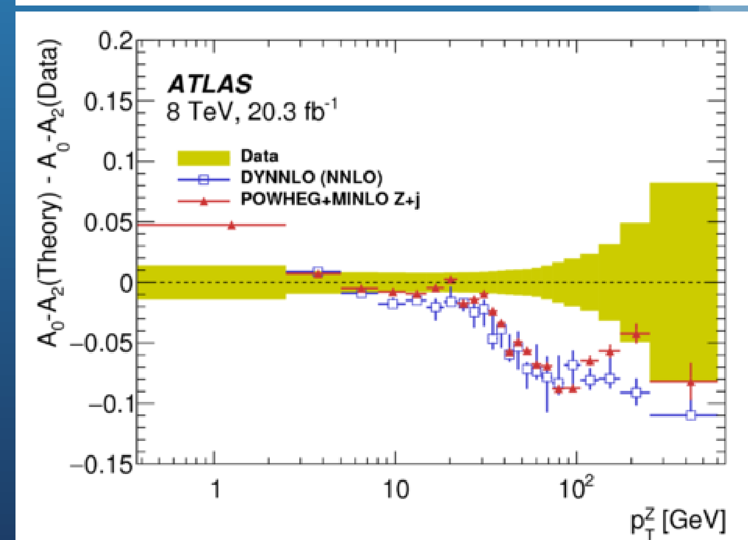
Checking Lam-Tung relation (A_0-A_2=0)

ATLAS: JHEP 08 (2016) 159

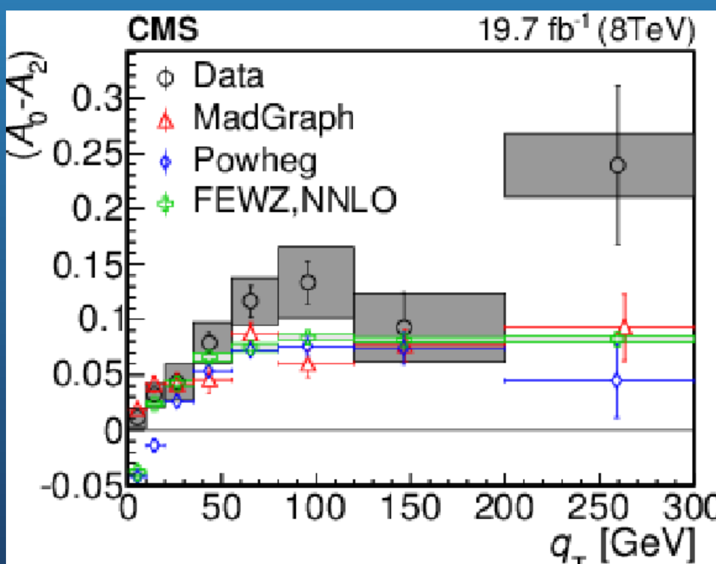


Violating (as anticipated) Lam-Tung relation

At high p^Z_T the models do not describe data



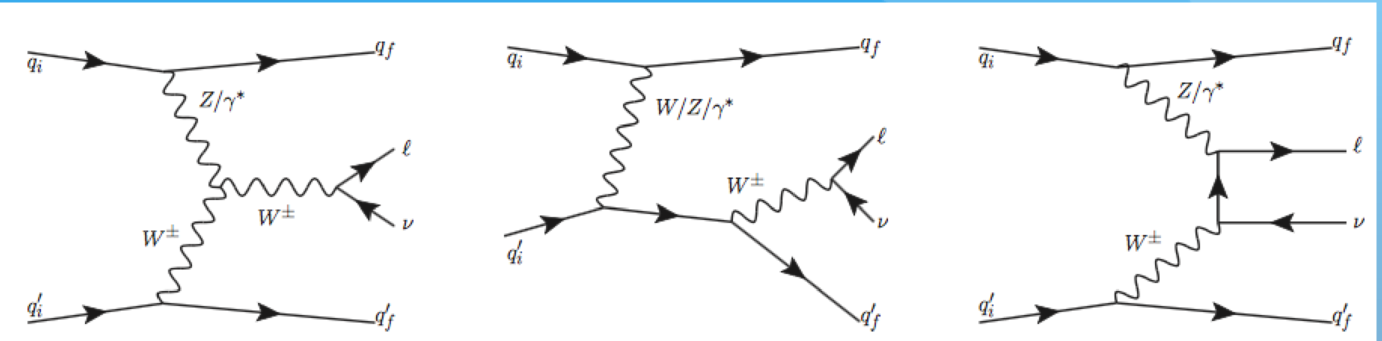
CMS: PLB 750 (2015) 154



EW production of W/Z with two jets

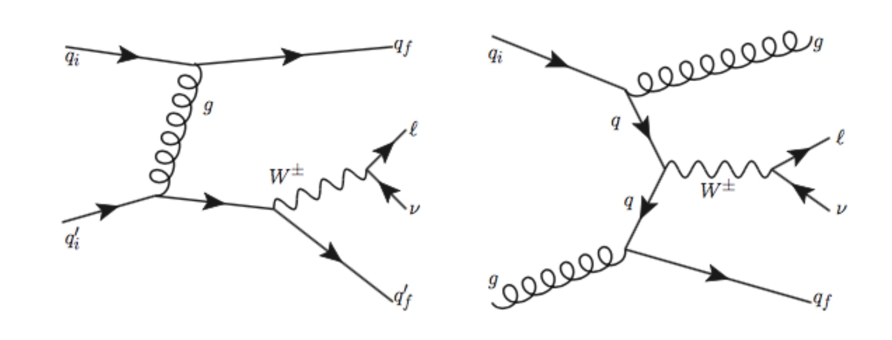
VBF W bremsstrahlung non-resonant

Signal



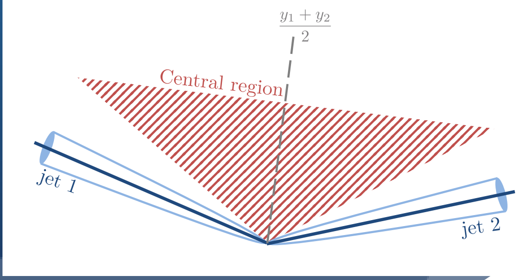
(a) Vector boson fusion (b) W bremsstrahlung (c) Non-resonant

Background



Interferes with EW

Topology: central electron/muon (Z:2 electrons/muons) + 2 jets



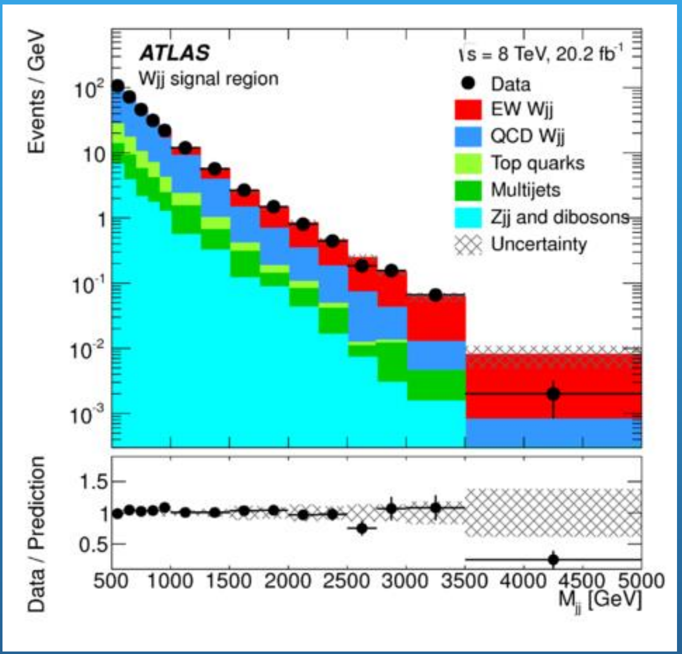
EW production W+2jets at 8 TeV

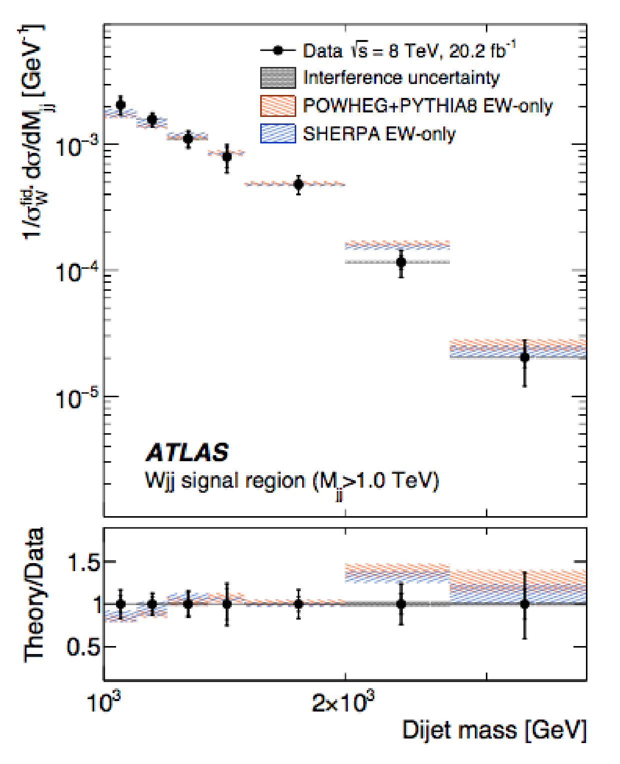
- Di-muons in region 60-160 GeV;
- 7 TeV + 8 TeV

ATLAS: arXiv:1703.04362

Selection requirements

Lepton $p_{\mathrm{T}} > 25$ GeV
Lepton $|\eta| < 2.5$
$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
$m_{\mathrm{T}} > 40$ GeV
$p_{\mathrm{T}}^{j_1} > 80$ GeV
$p_{\mathrm{T}}^{j_2} > 60$ GeV
Jet $|y| < 4.4$
$M_{jj} > 500$ GeV
$\Delta y(j_1, j_2) > 2$
$\Delta R(j, \ell) > 0.3$





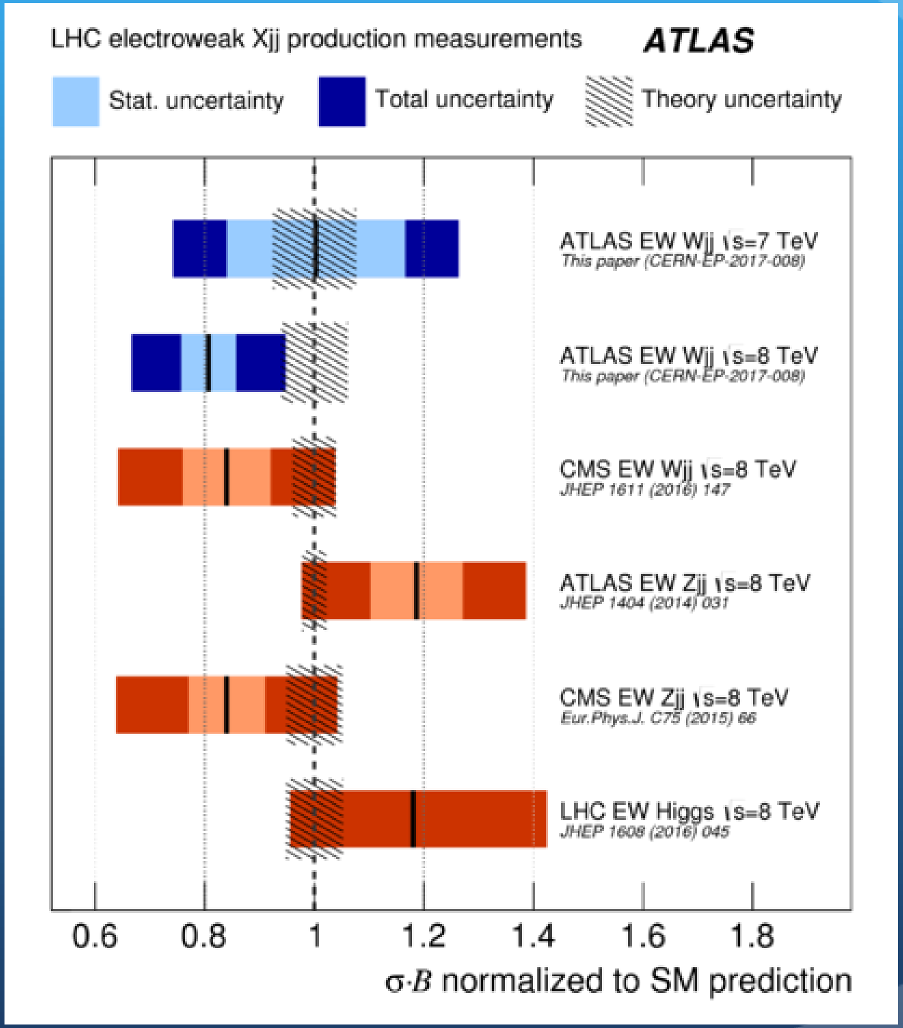
$$\sigma^{\mathrm{fid}}_{\mathrm{EW}\ W(\to\ell\nu)jj}\,(7\ \mathrm{TeV}) = 144 \pm 23\,(\mathrm{stat}) \pm 23\,(\mathrm{exp}) \pm 13\,(\mathrm{th})\ \mathrm{fb},$$

$$\sigma^{\mathrm{fid}}_{\mathrm{EW}\ W(\to\ell\nu)jj}\,(8\ \mathrm{TeV}) = 159 \pm 10\,(\mathrm{stat}) \pm 17\,(\mathrm{exp}) \pm 20\,(\mathrm{th})\ \mathrm{fb},$$

144 ± 11 (198 ± 12) fb

Measured cross sections agree well with SM predictions

LHC EW X+2jets measurements 7 and 8 TeV

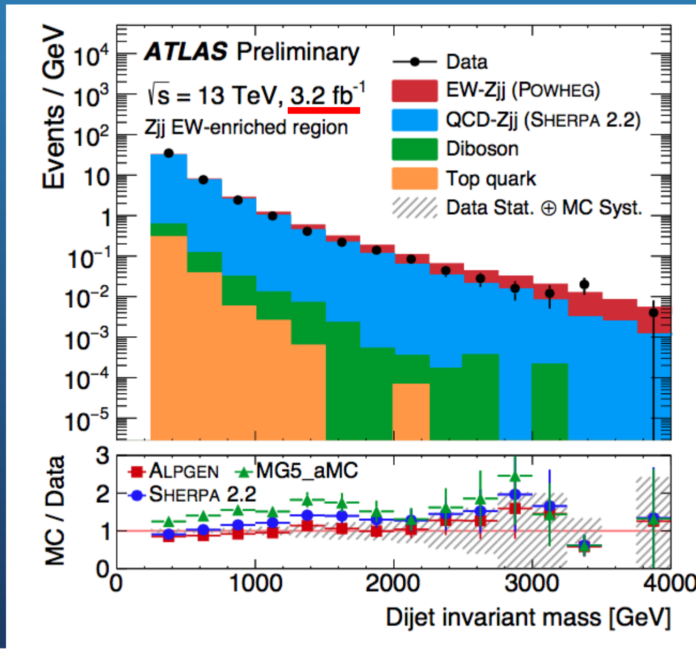


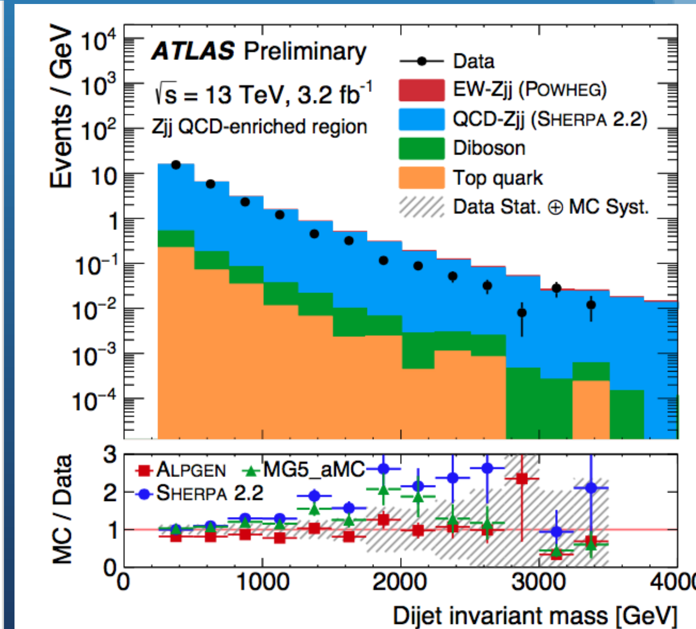
EW production Z + 2 jets at 13 TeV

ATLAS:
Zjj – CERN-EP-2017-115

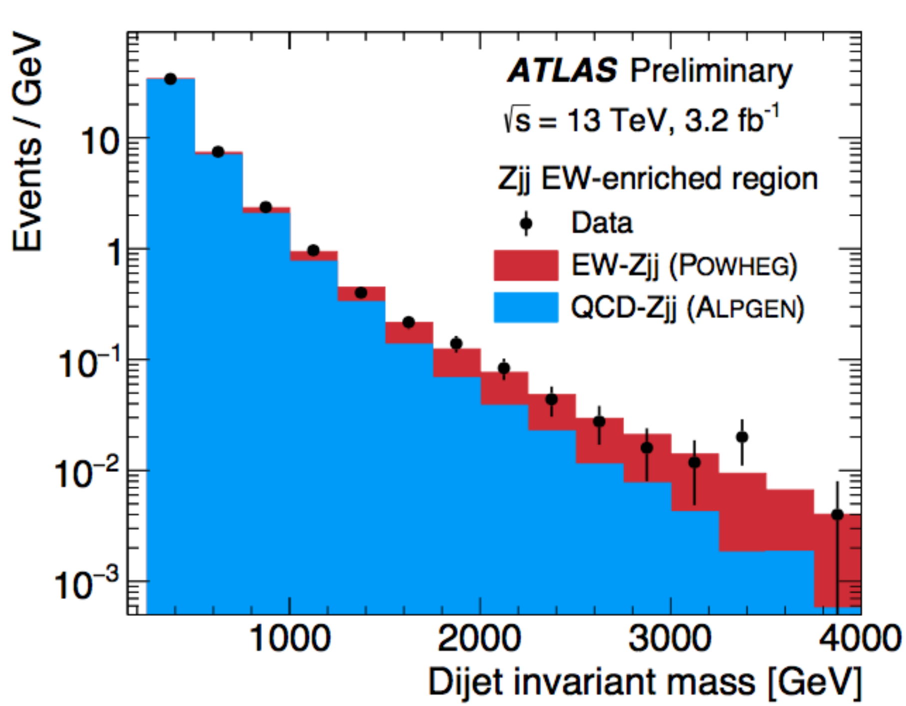
- Electrons/muons
- QCD corrected

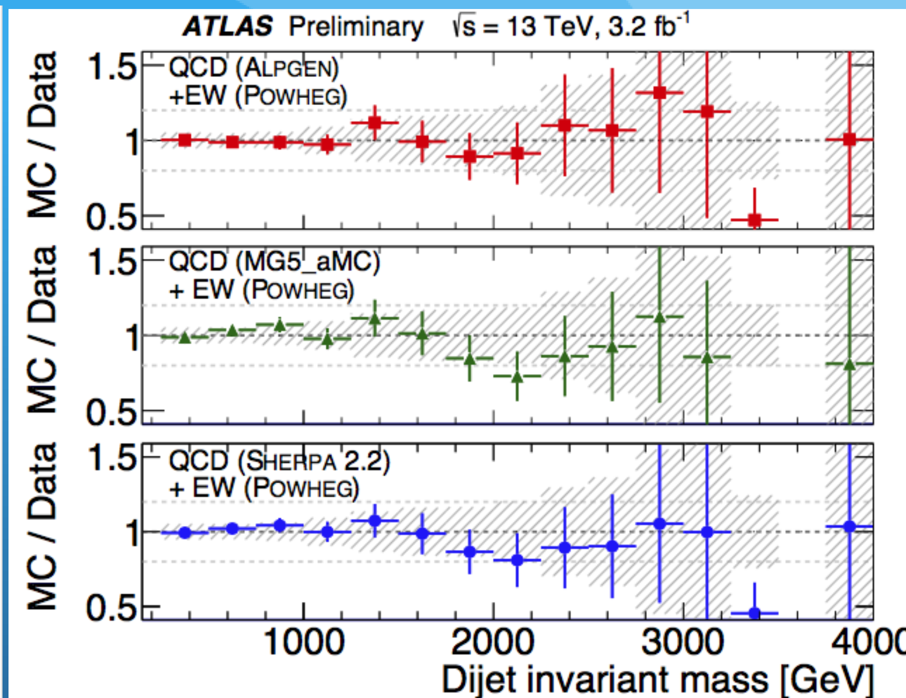
Object	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Di-lepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_T^{j_1} > 55$ GeV		$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV		
Di-jet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N^{\text{interval}}_{\text{jet } (p_T > 25 \text{ GeV})} = 0$		$N^{\text{interval}}_{\text{jet } (p_T > 25 \text{ GeV})} \geq 1$
Zjj system	—			$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance},3} < 0.15$





EW production Z + 2 jets at 13 TeV





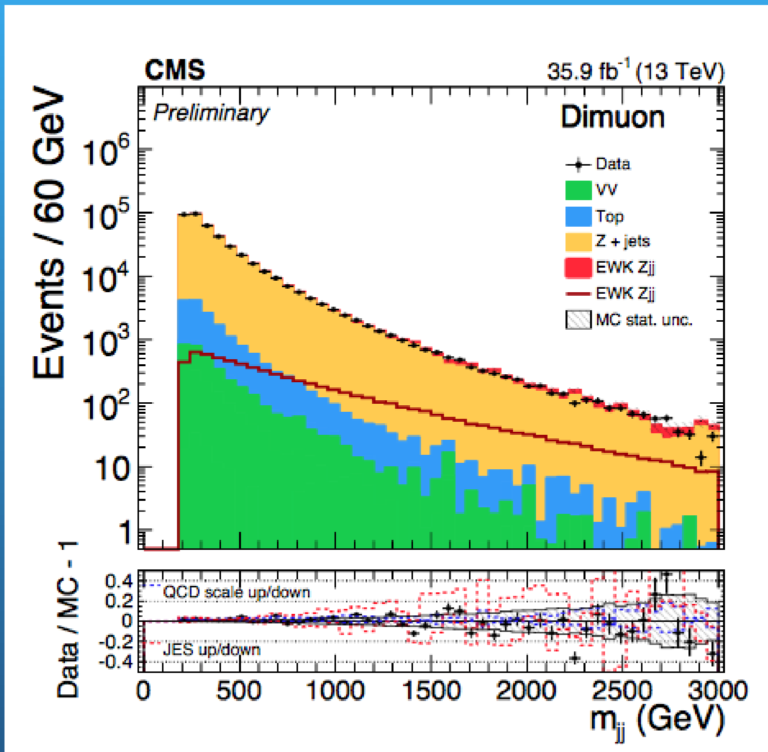
Fiducial region	EW-Zjj cross-sections [fb]	
	Measured	POWHEG+PYTHIA
EW-enriched, m_{jj} > 250 GeV	119 ± 16 ± 20 ± 2	125.2 ±3.4
EW-enriched, m_{jj} > 1 TeV	34.2 ± 5.8 ± 5.5 ± 0.7	38.5 ±1.5

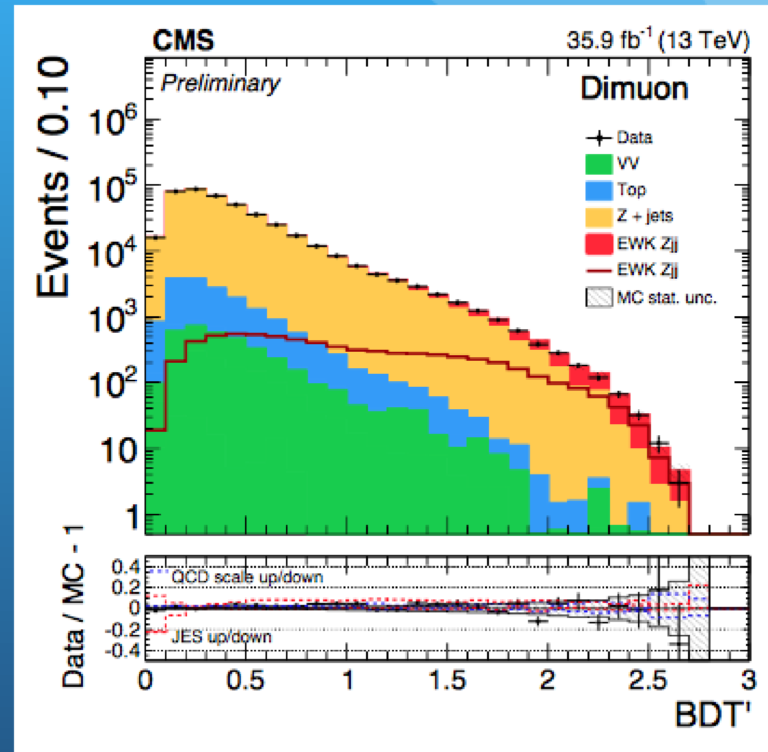
- In agreement with the SM predictions

EW production Z + 2 jets at 13 TeV

- Electrons and muons

CMS: CMS-PAS-SMP-16-018





$$\sigma(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 552 \pm 19\,(\mathrm{stat}) \pm 55\,(\mathrm{syst})\ \mathrm{fb} = 552 \pm 58\,(\mathrm{total})\ \mathrm{fb}$$

For m_{ll}>50 GeV, p^{j}_{T}>25 GeV, $|\eta^{j}|$<5, m_{jj}>120 GeV, ΔR_{jj}>0.5

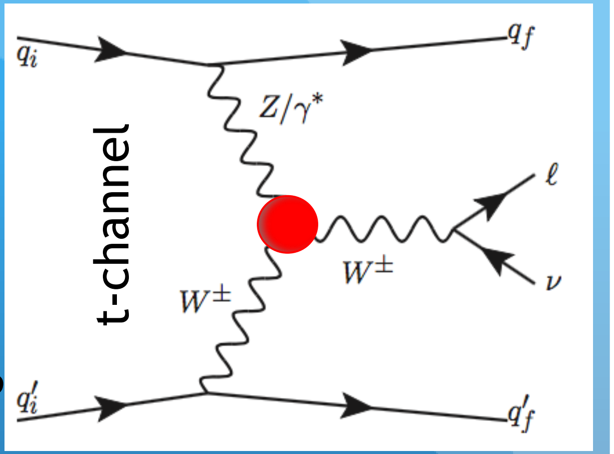
Theoretical value at LO: 543 ±28 fb

Measurement of aTGC with Wjj events

The measurement is sensitive to WWV coupling, eff. Lagrangian operators up to mass-dimension six

$$i\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV}\left\{\left[g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu}\right]\right.$$ CP

$$\left. - \left[\frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} + \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\right]\right\},$$ nCP



SM values $g_1^V = 1, \kappa_V = 1, \lambda_V = 0, \tilde{\kappa}_V = 0$, and $\tilde{\lambda}_V = 0$

$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma, \quad \lambda_\gamma = \lambda_Z \equiv \lambda_V, \quad g_1^\gamma = 1, \quad \tilde{\kappa}_\gamma = -\cot^2\theta_W \tilde{\kappa}_Z, \quad \text{and} \quad \tilde{\lambda}_\gamma = \tilde{\lambda}_Z \equiv \tilde{\lambda}_V$$

Presence of anomalous couplings -> cross section increase, to preserve unitarity form-factor with Λ=4 TeV

$$\alpha(q^2) = \frac{\alpha}{(1 + q^2/\Lambda^2)^2}$$

EFT

$$\mathcal{L}_{\text{EFT}} = \sum_i \frac{c_i}{\Lambda^2} O_i$$

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}(g_1^Z - 1),$$

$$\frac{c_B}{\Lambda^2} = \frac{2}{\tan^2\theta_W m_Z^2}(g_1^Z - 1) - \frac{2}{\sin^2\theta_W m_Z^2}(\kappa_Z - 1),$$

$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_V,$$

$$\frac{c_{\tilde{W}}}{\Lambda^2} = -\frac{2}{\tan^2\theta_W m_W^2}\tilde{\kappa}_Z,$$

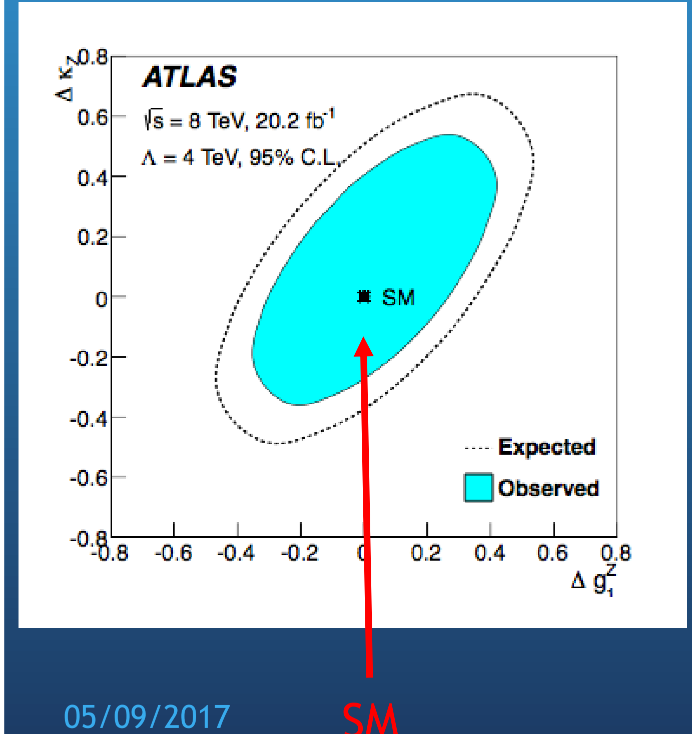
$$\frac{c_{\tilde{W}WW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\tilde{\lambda}_V,$$

Measurement of aTGC with Wjj events

ATLAS: arXiv:1703.04362

Region with
M_{jj} > 1 TeV and
p_T(lead.jet) > 600 GeV
SHERPA for aTGC +
k=NLO/LO at SM

	Λ = 4 TeV		$\Lambda = \infty$	
	Expected	Observed	Expected	Observed
Δg_1^Z	[−0.39, 0.35]	[−0.32, 0.28]	[−0.16, 0.15]	[−0.13, 0.12]
$\Delta\kappa_Z$	[−0.38, 0.51]	[−0.29, 0.42]	[−0.19, 0.19]	[−0.15, 0.16]
λ_V	[−0.16, 0.12]	[−0.13, 0.090]	[−0.064, 0.054]	[−0.053, 0.042]
$\tilde{\kappa}_Z$	[−1.7, 1.8]	[−1.4, 1.4]	[−0.70, 0.70]	[−0.56, 0.56]
$\tilde{\lambda}_V$	[−0.13, 0.15]	[−0.10, 0.12]	[−0.058, 0.057]	[−0.047, 0.046]



Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$\frac{c_W}{\Lambda^2}$	[−39, 37]	[−33, 30]
$\frac{c_B}{\Lambda^2}$	[−200, 190]	[−170, 160]
$\frac{c_{WWW}}{\Lambda^2}$	[−16, 13]	[−13, 9]
$\frac{c_{\tilde{W}}}{\Lambda^2}$	[−720, 720]	[−580, 580]
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	[−14, 14]	[−11, 11]

Measurement of Tau polarisation

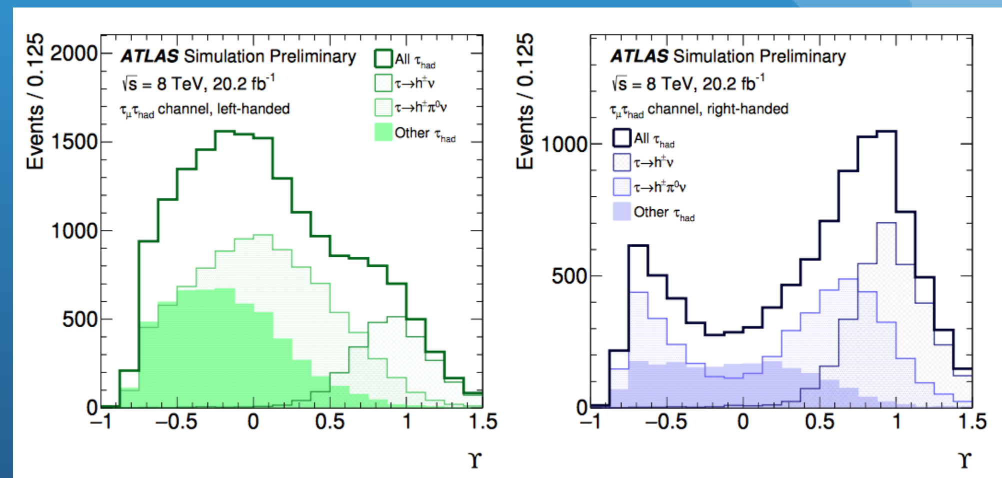
ATLAS: arXiv:1703.04362

- Z/γ^* decaying to $\tau\tau$, where one tau lepton decays hadronically (is used to measure polarization) and another one leptonically (electron/muon)
- Polarization – negative/positive helicity

$$P_\tau = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

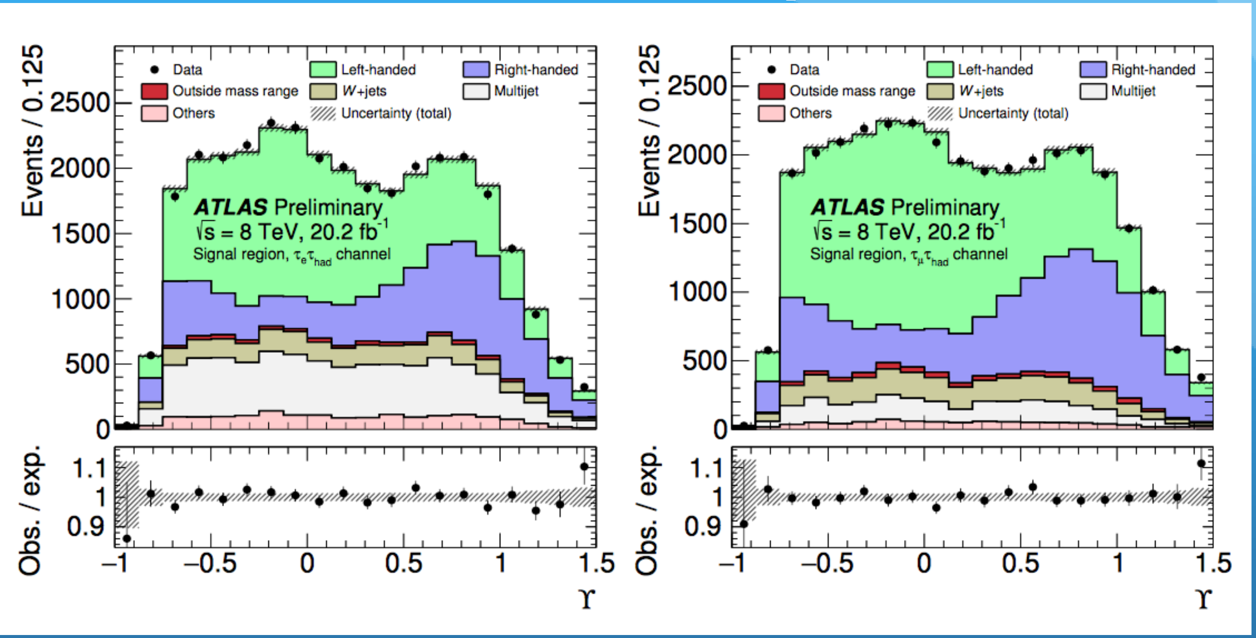
- Experimental observable

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{h^0}}{E_T^{\tau^\pm}} = 2\frac{p_T^{\text{track}}}{E_T^{\tau^\pm}} - 1,$$



One τ_{lep} decay	One single prong τ_{had} decay
$p_{T,\text{lepton}} > 26$ GeV	$p_{T,\tau_{\text{had-vis}}} > 20$ GeV
$\lvert\eta_e\rvert < 2.47$ and not $1.37 < \lvert\eta_e\rvert < 1.52$ or $\lvert\eta_\mu\rvert < 2.5$	$\lvert\eta_{\tau_{\text{had-vis}}}\rvert < 2.47$
$m_T < 30$ GeV	40 GeV$< m_{\text{vis}} < 85$ GeV

Measurement of Tau polarisation



Channel	P_τ in mass range	P_τ in fiducial region
$\tau_e - \tau_{\text{had}}$	-0.195 ± 0.024 (stat) $^{+0.048}_{-0.050}$ (syst)	-0.331 ± 0.026 (stat) $^{+0.049}_{-0.052}$ (syst)
$\tau_\mu - \tau_{\text{had}}$	-0.129 ± 0.020 (stat) $^{+0.045}_{-0.046}$ (syst)	-0.259 ± 0.021 (stat) $^{+0.046}_{-0.046}$ (syst)
Combination	-0.141 ± 0.015 (stat) $^{+0.041}_{-0.041}$ (syst)	-0.268 ± 0.016 (stat) $^{+0.040}_{-0.041}$ (syst)

Agrees well with the
LEP combination - 0.1439 ± 0.0043
theoretical prediction – 0.1517 ± 0.0019

Conclusions

- This talk presents only some of the EW measurements. Precise measurements require more time and we are now finishing with 8 TeV data
- We are expecting measurements at 13 TeV with more statistics, but in many cases we are already restricted by systematics, understanding of uncertainties is extremely important
- Looking forward to see more new results soon !

Backup

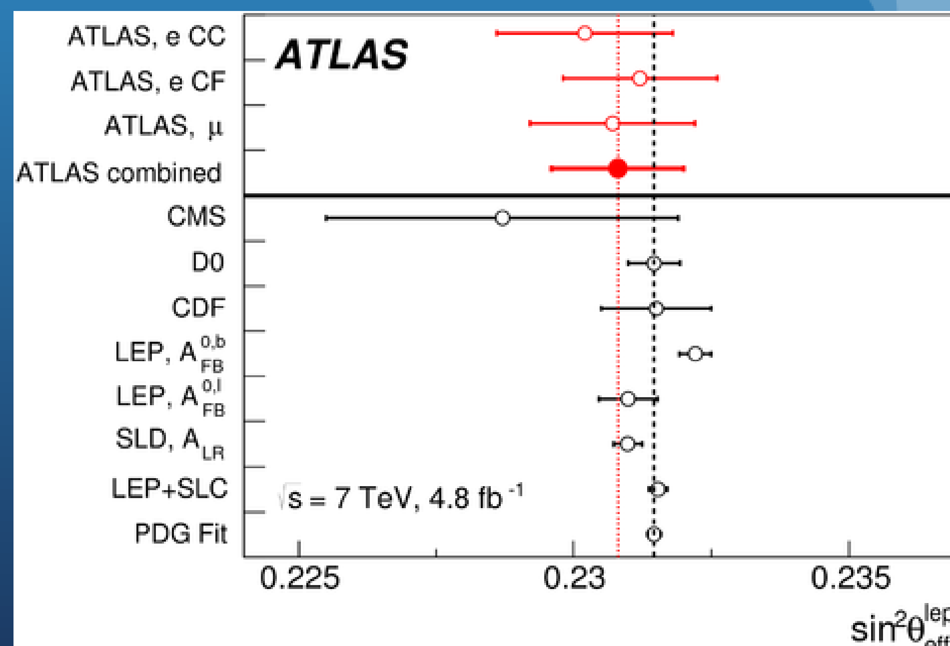
Effective mixing angle

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}

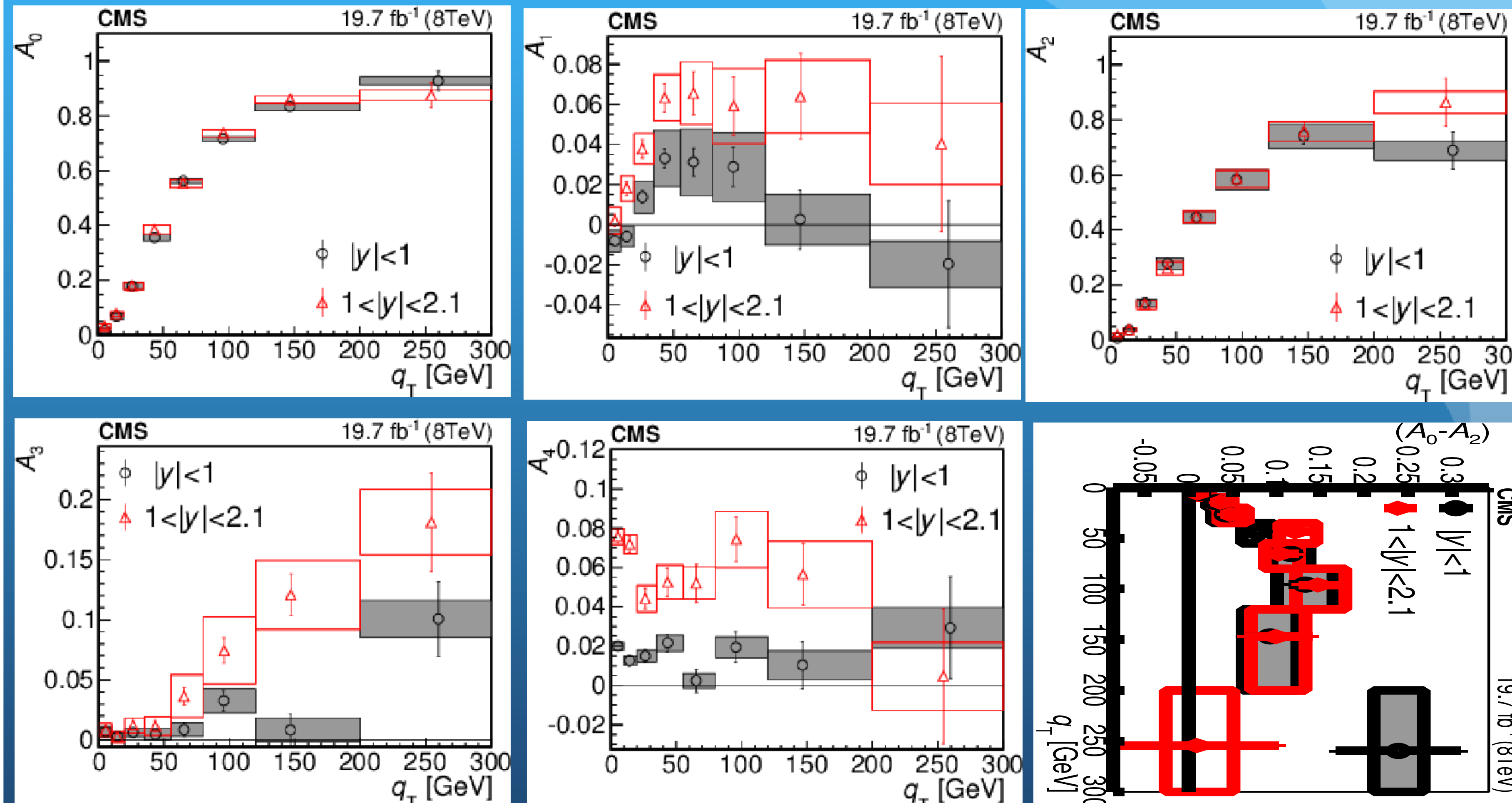
	$\sin^2\theta_{\text{eff}}^{\text{lept}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.})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



Angular coefficients at different |η|

CMS: PLB 750 (2015) 154



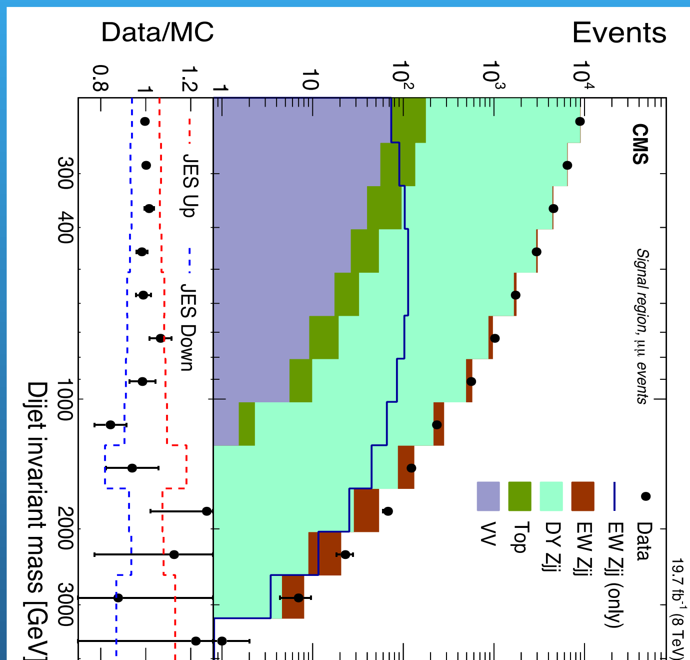
Major uncertainties: statistical, efficiencies

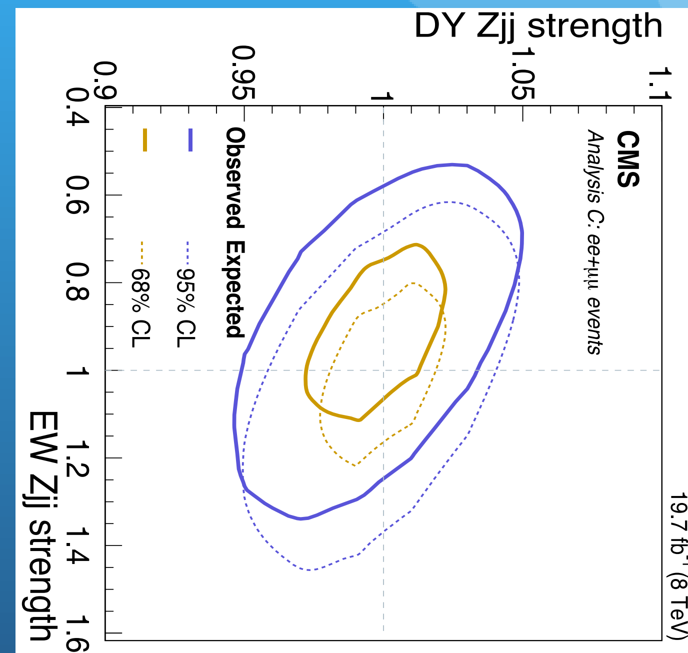
low p_T – scale/resolution/templates

EW production Z + 2 jets at 8 TeV

- Electrons(muons): p_T>25 GeV, $|\eta|$<2.5(2.4), $|M_Z$-$M_{ll}|$<15 GeV
- Jets with P_T > 50 (30) GeV

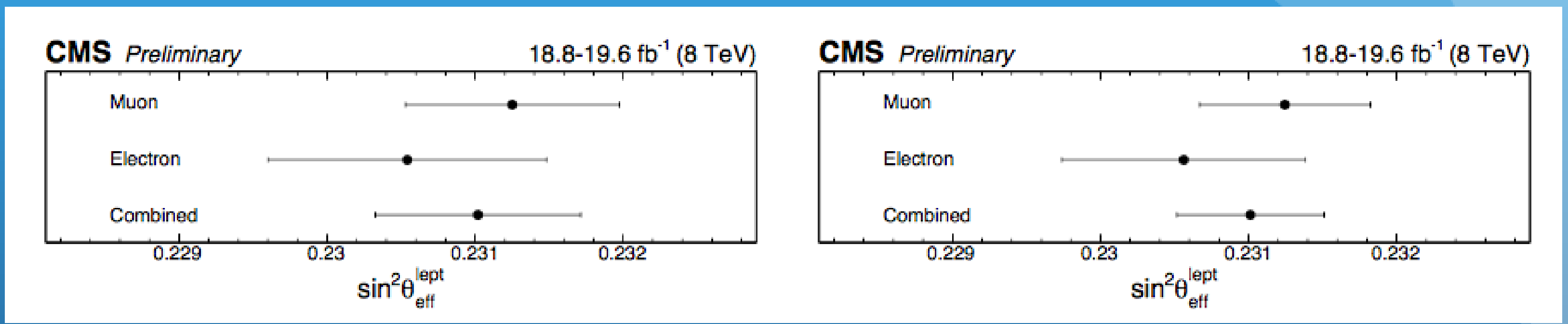
CMS: EPJC 75 (2015) 66

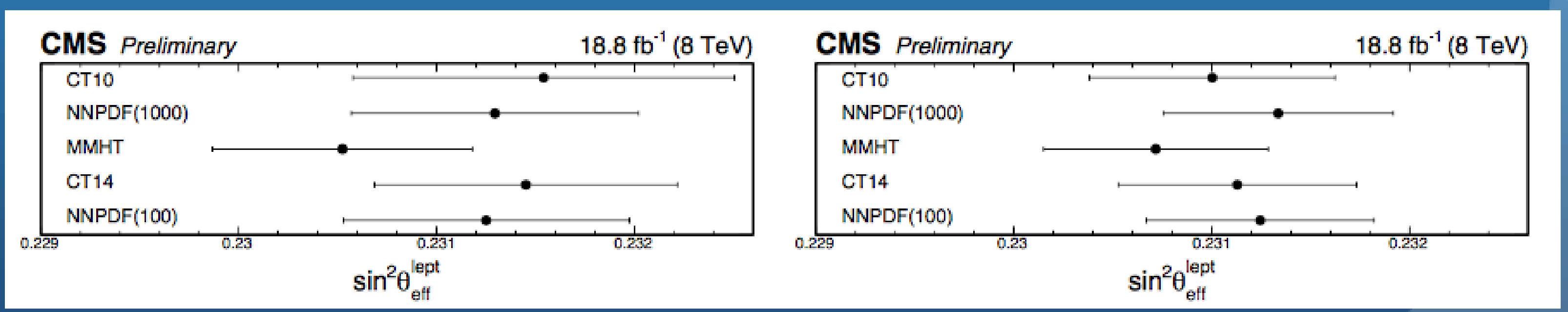




$$\sigma(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 174 \pm 15\,(\mathrm{stat}) \pm 40\,(\mathrm{syst})\ \mathrm{fb} = 174 \pm 42\,(\mathrm{total})\ \mathrm{fb}$$

For m_{ll}>50 GeV, p^j_T>25 GeV, $|\eta^j|$<5, m_{jj}>120 GeV, ΔR_{jj}>0.5
Theoretical value at LO: 208 ±18 fb

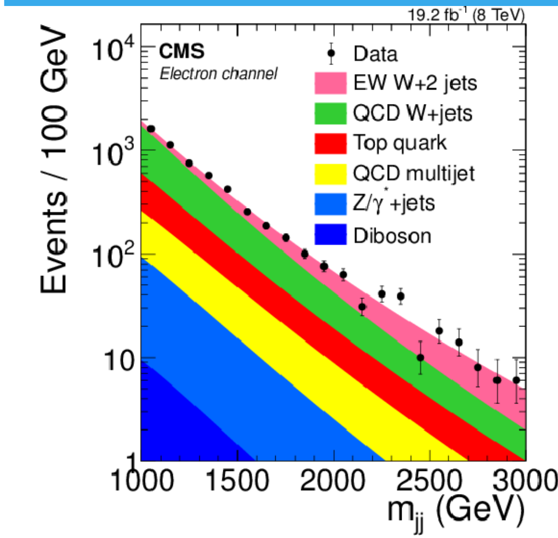

CMS Preliminary
18.8-19.6 fb-1 (8 TeV)
Muon
Electron
Combined
0.229
0.23
0.231
0.232
sin2θeff lept
CMS Preliminary
18.8-19.6 fb-1 (8 TeV)
Muon
Electron
Combined
0.229
0.23
0.231
0.232
sin2θeff lept


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

EW production W + 2jets at 8 TeV

- Electrons(muons): p_T>30(25) GeV, |η|<2.5(2.4)
- Jets with P_T > 60 (50) GeV, |η|<4.7 ; E_T^{MISS} > 30(25) GeV

CMS: JHEP11 (2016) 147



Fiducial XS for

P^j_T > 60(50) GeV,

$|\eta^j|$<4.7, m_{jj}>1000 GeV

0.42

±0.04(stat)±0.09(sys)

±0.01(lumi) pb

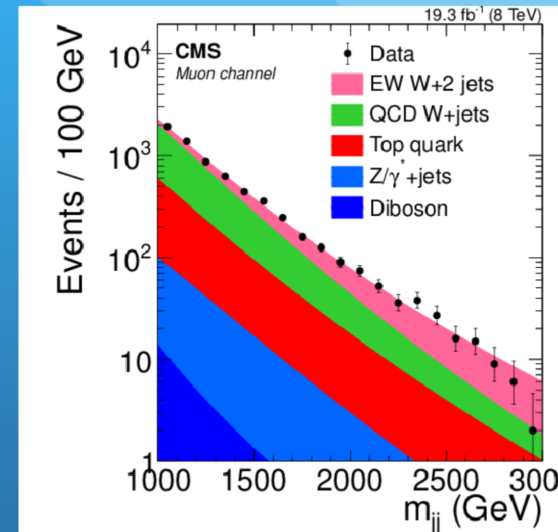
can be compared with

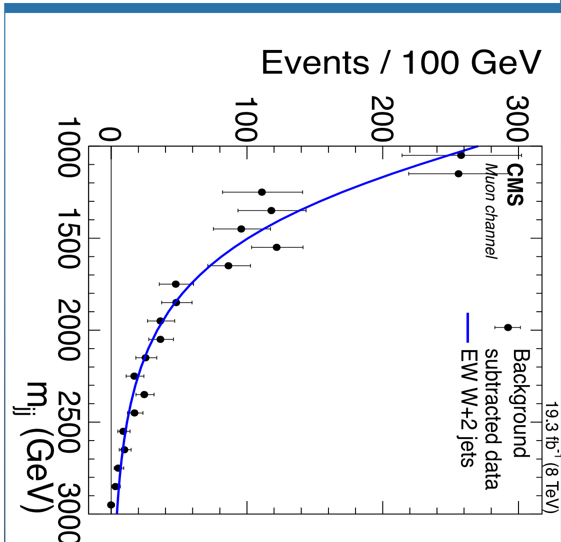
MadGraph5-aMC@NLO2.1

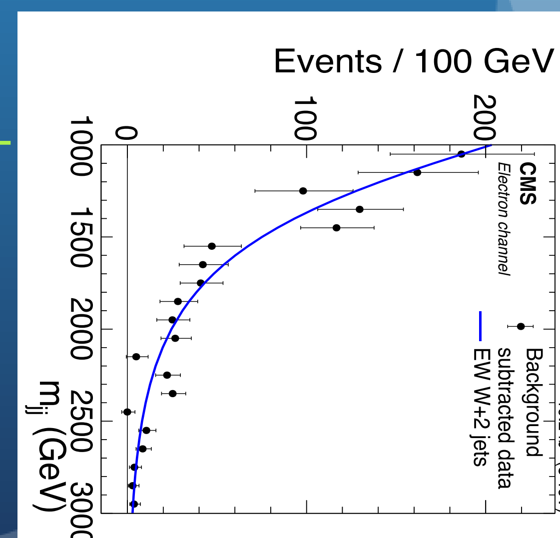
+ PYTHIA 6.4

0.50

±0.02(scale)±0.02(PDF)

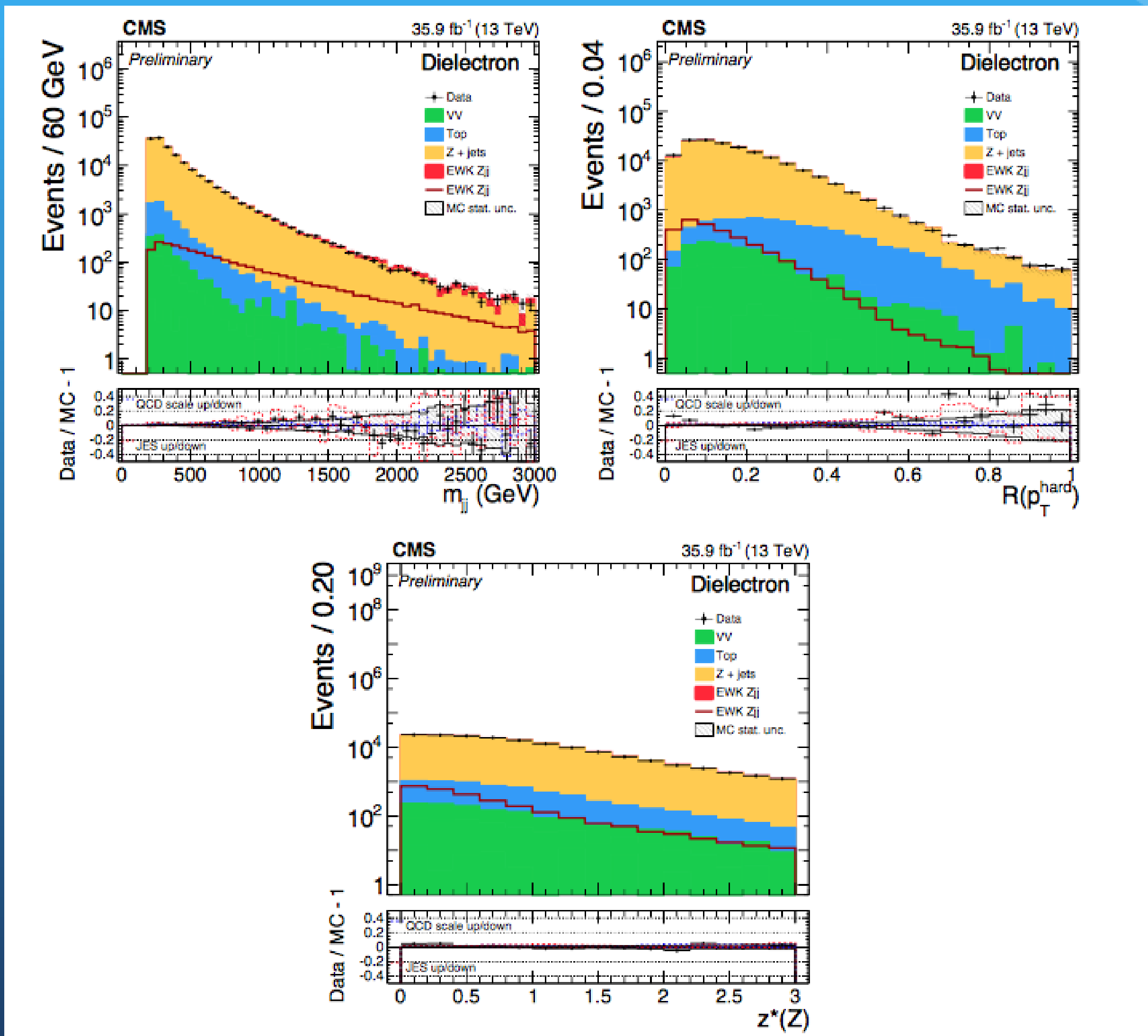






Region	Event selection changes compared to signal region
same sign region	inverted opposite charge sign requirement
opposite sign multijet control region	inverted lepton isolation requirement
same sign multijet control region	inverted lepton isolation and opposite charge sign requirements
opposite sign W+jets control region	$\sum \Delta\phi \geq 3.5$, $m_{\mathrm{T}} > 70$ GeV (instead of $\sum \Delta\phi < 3.5$, $m_{\mathrm{T}} < 30$ GeV)
same sign W+jets control region	$\sum \Delta\phi \geq 3.5$, $m_{\mathrm{T}} > 70$ GeV (instead of $\sum \Delta\phi < 3.5$, $m_{\mathrm{T}} < 30$ GeV), inverted opposite charge sign requirement

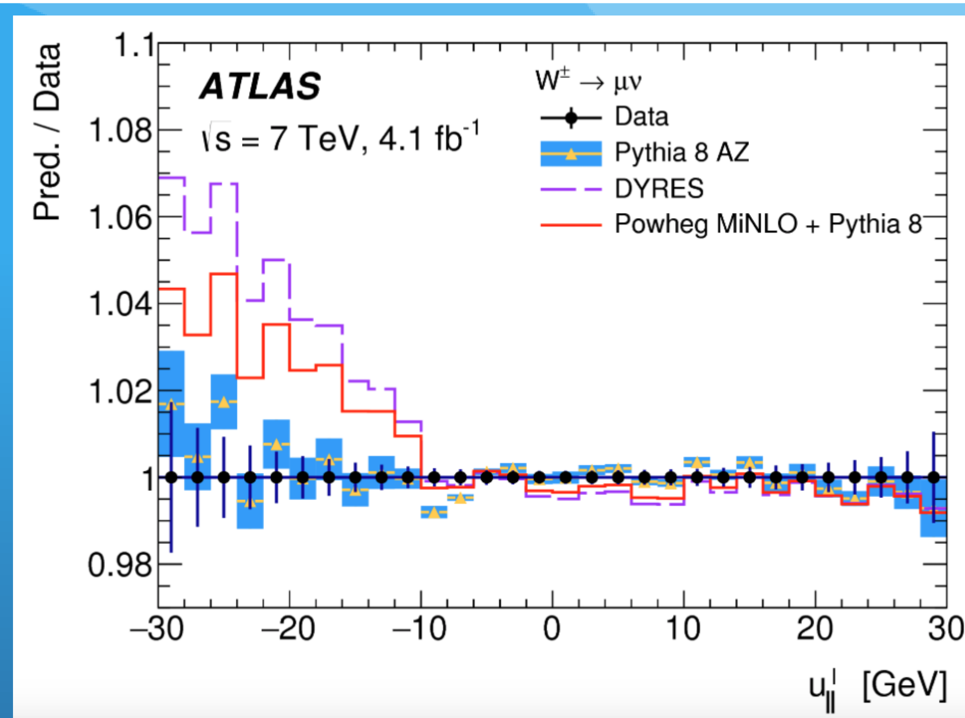
$$R\left(p_{\mathrm{T}}^{\mathrm{hard}}\right) = \frac{\left|\vec{p}_{\mathrm{Tj_1}} + \vec{p}_{\mathrm{Tj_2}} + \vec{p}_{\mathrm{TZ}}\right|}{\left|\vec{p}_{\mathrm{Tj_1}}\right| + \left|\vec{p}_{\mathrm{Tj_2}}\right| + \left|\vec{p}_{\mathrm{TZ}}\right|} = \frac{\left|\vec{p}_{\mathrm{T}}^{\mathrm{hard}}\right|}{\left|\vec{p}_{\mathrm{Tj_1}}\right| + \left|\vec{p}_{\mathrm{Tj_2}}\right| + \left|\vec{p}_{\mathrm{TZ}}\right|},$$

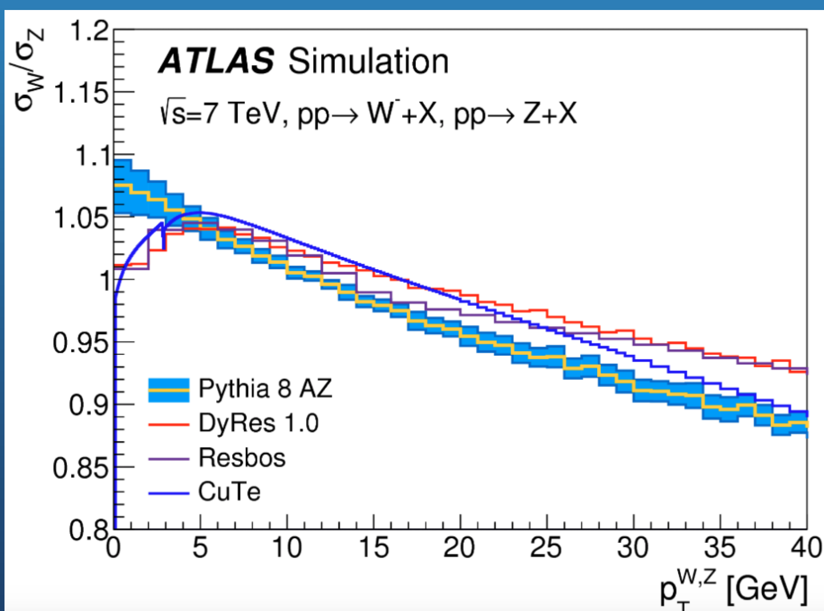


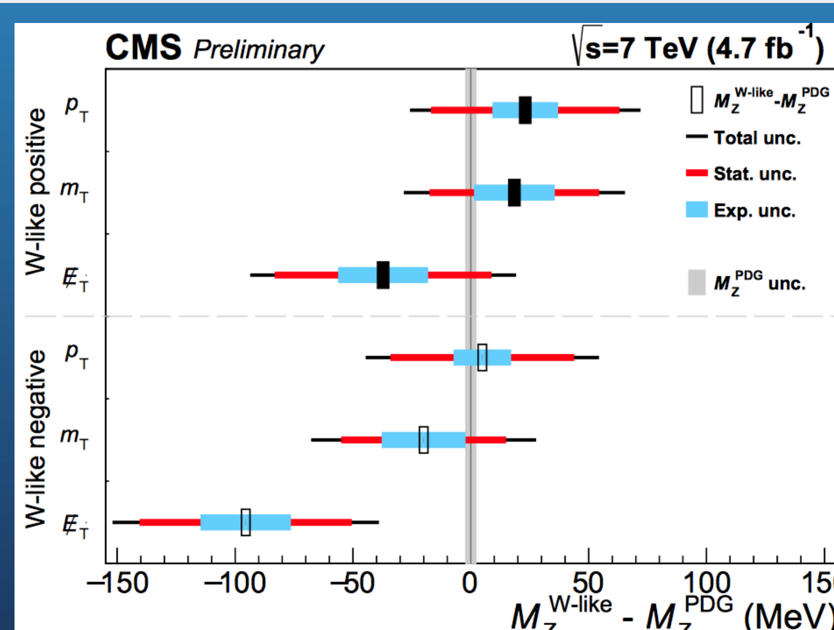
$$y^{*} = y_{\mathrm{Z}} - \frac{1}{2}\left(y_{\mathrm{j_1}} + y_{\mathrm{j_2}}\right),$$

$$z^{*} = \frac{y^{*}}{\Delta y_{\mathrm{jj}}}.$$

W ATLAS


ATLAS
√s = 7 TeV, 4.1 fb-1
W± → μν
Data
Pythia 8 AZ
DYRES
Powheg MiNLO + Pythia 8
Pred. / Data
u‖ℓ [GeV]


ATLAS Simulation
√s=7 TeV, pp→ W+X, pp→ Z+X
Pythia 8 AZ
DyRes 1.0
Resbos
CuTe
σW/σZ
pTW,Z [GeV]


CMS Preliminary
√s=7 TeV (4.7 fb-1)
MZW-like-MZPDG
Total unc.
Stat. unc.
Exp. unc.
MZPDG unc.
W-like positive
W-like negative
pT
mT
MZW-like - MZPDG (MeV)