W Mass Measurement at LHC

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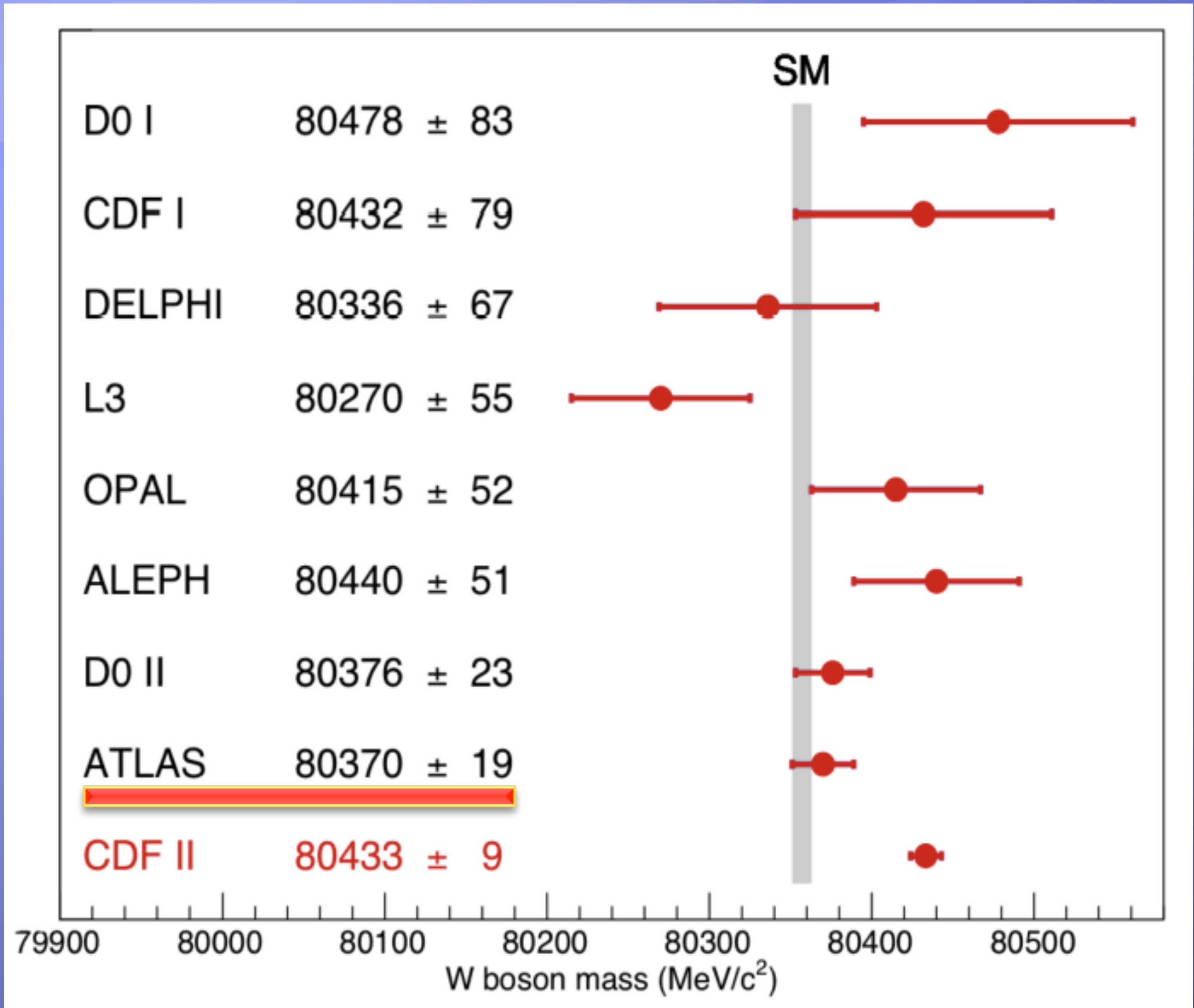
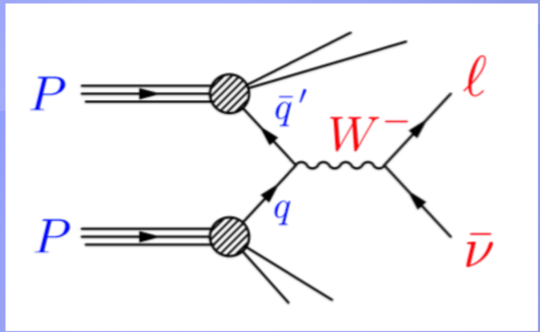
W mass at LHC

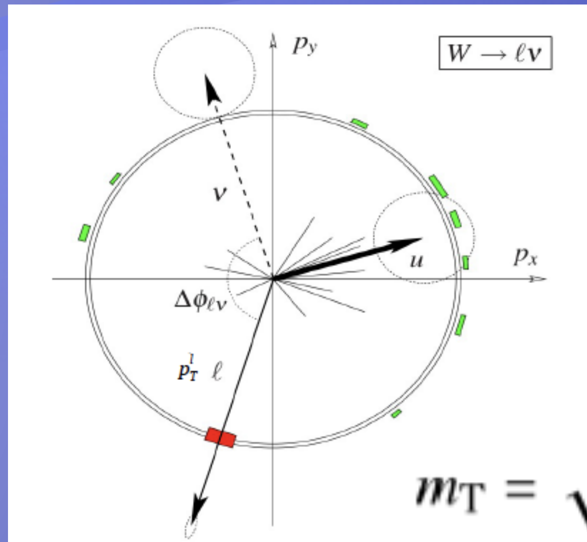


Source	reference
m_W paper	EPJC 78 (2018) 110
CERN Seminar	M. Boonkamp (2016.12.13)
Physics Modelling	ATL-PHYS-PUB-2014-015
Eletron calibration	EPJC 74 (2014) 3017
Muon calibration	EPJC 74 (2014) 3130
Z pT (Z) Pythia Tune	JHEP09 (2014) 145

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

How to measure the W mass

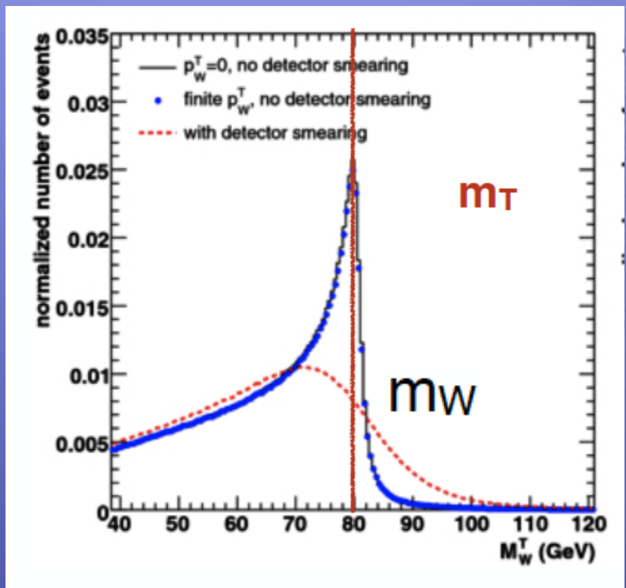


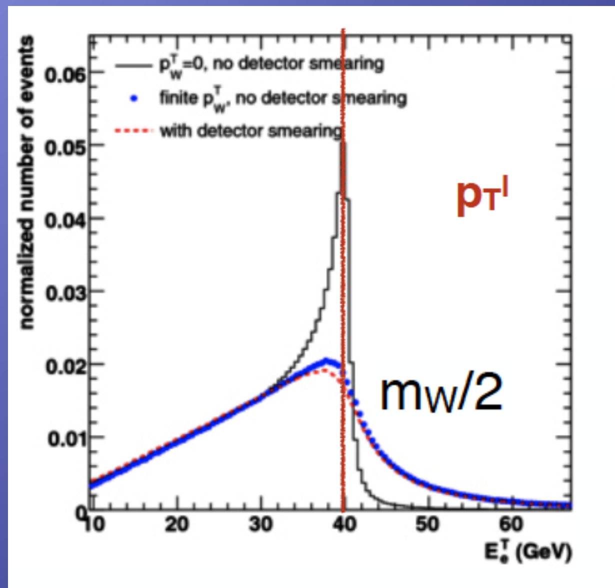


$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$

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

- Use leptonic decay e/μ channels
- Sensitive variables to W mass: $p_T(e/\mu)$, m_T, $p_T(MET)$:
  Jacobian edge provides the mass of W

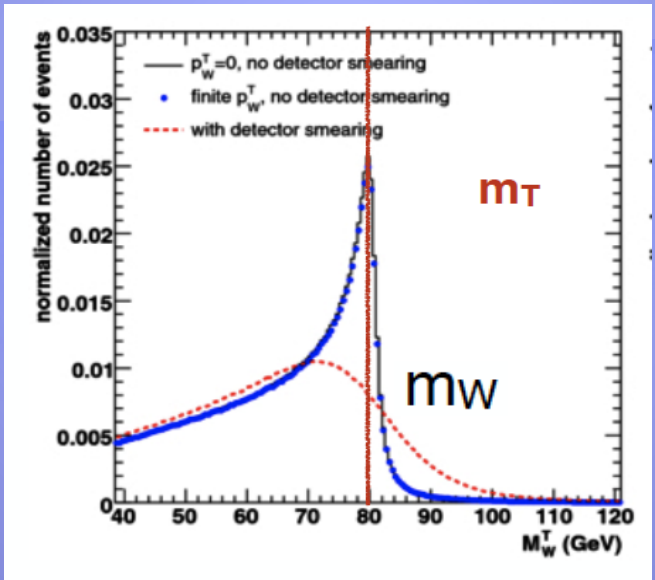




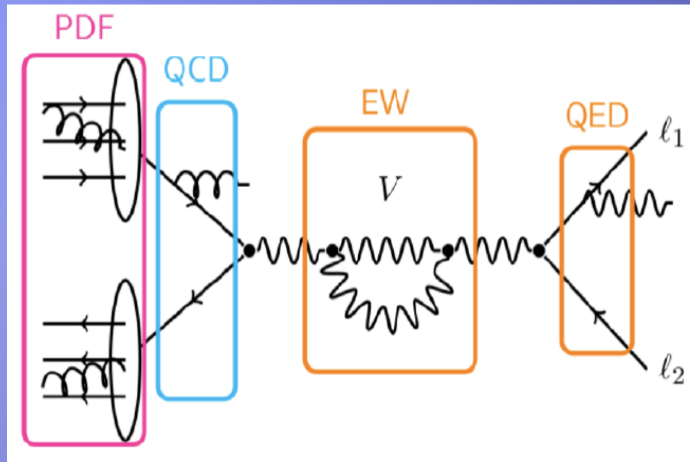
$$\frac{d\sigma}{dp_t} = \frac{d\sigma}{d\cos\theta} * \frac{d\cos\theta}{dp_t}$$

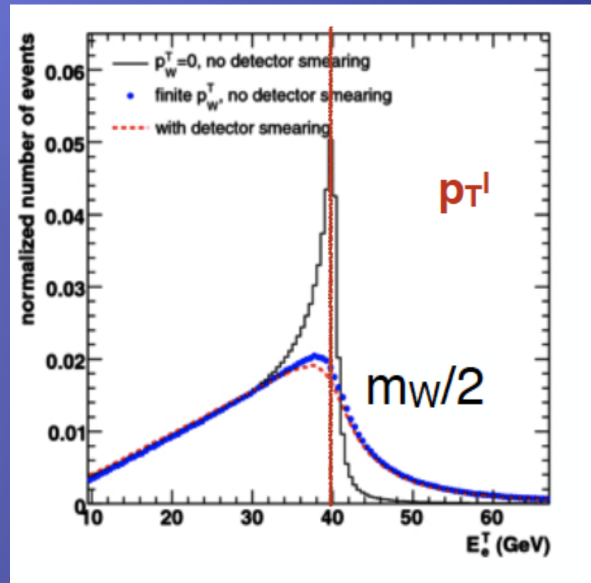
$$= \frac{d\sigma}{d\cos\theta} * \frac{2p_t}{M_W} * \frac{1}{\sqrt{(\frac{M_W}{2})^2 - p_t^2}}$$

How to measure the W mass



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

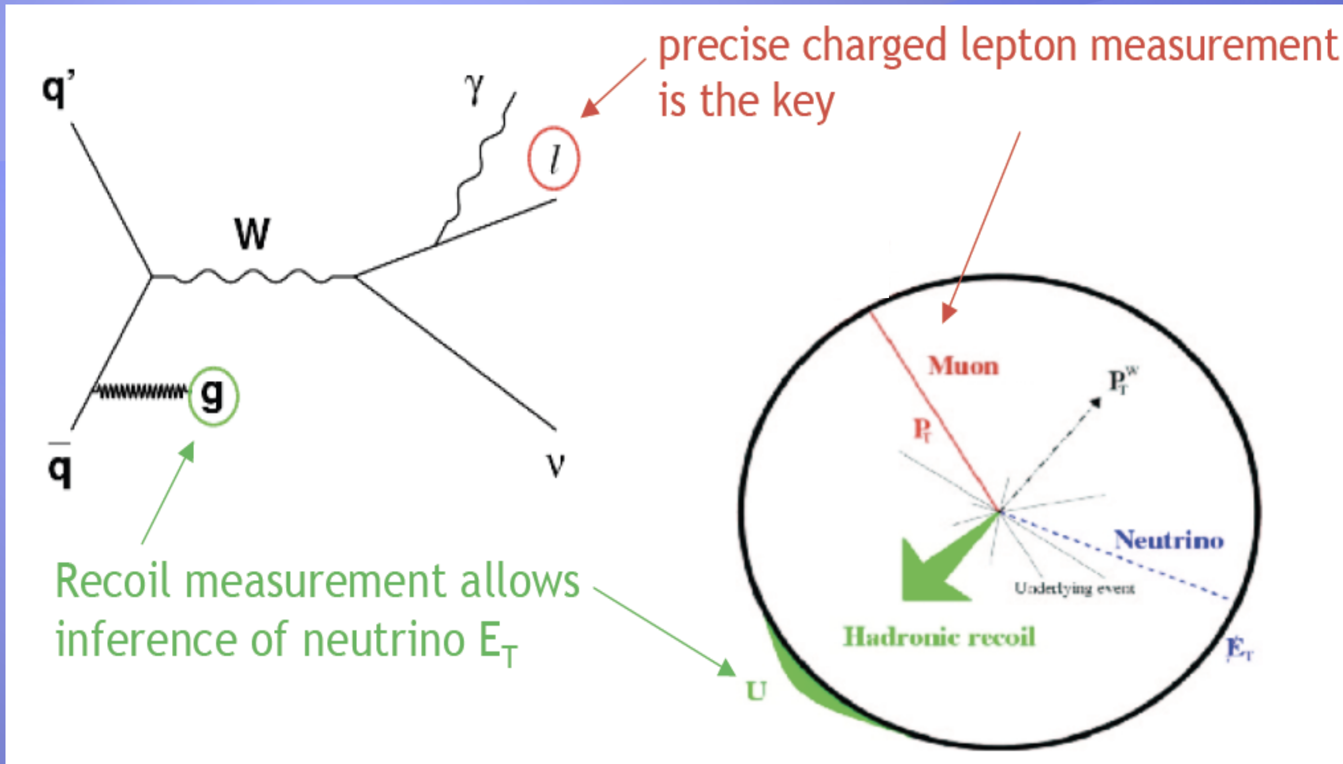




- **m_T method:**
  - **Insensitive to p_T(W)**
  - **Reconstruction of $p_T(\nu)$ sensitive to hadronic response and multiple interactions**

- **$p_T(l)$ method:**
  - **Sensitive to p_T(W): PDF, PS,UE**
  - **Sensitive to W helicity (+1,-1,0) (different from Tevatron)**

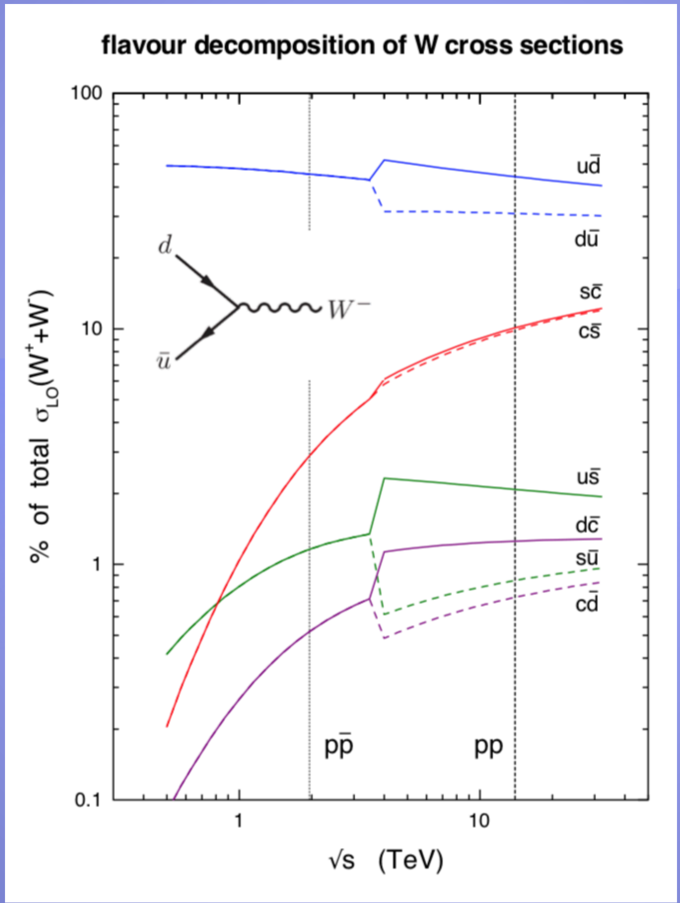
Measurement Overview



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

- Use Z (-->ee,μμ) to derive "physics model" for recoil and lepton calibration
- Validate the physics model by extracting m_z from $p_T(l)$ and m_T
- Extract m_W in several categories and combine

Why tough at LHC?



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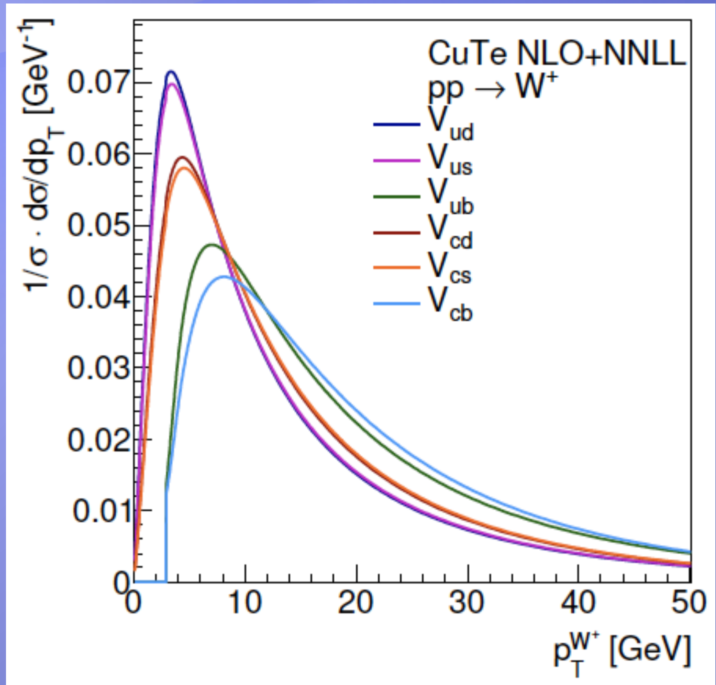
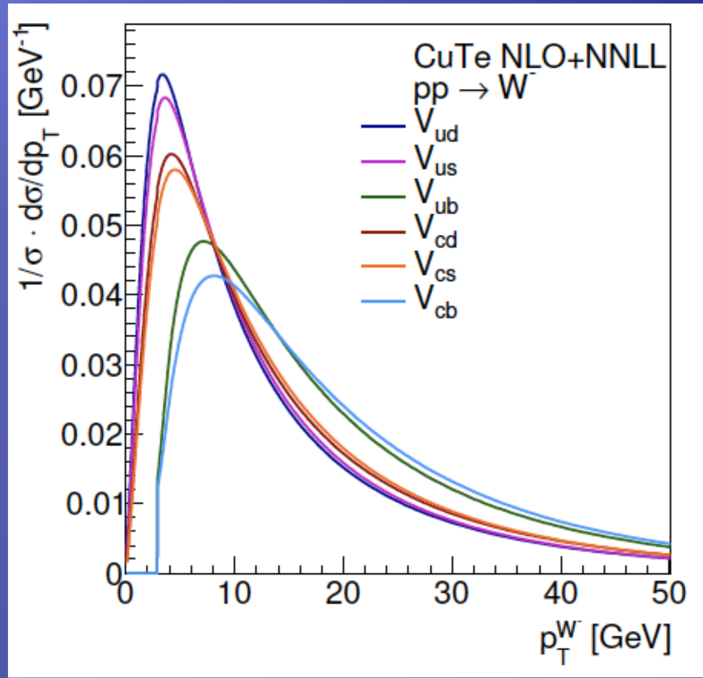




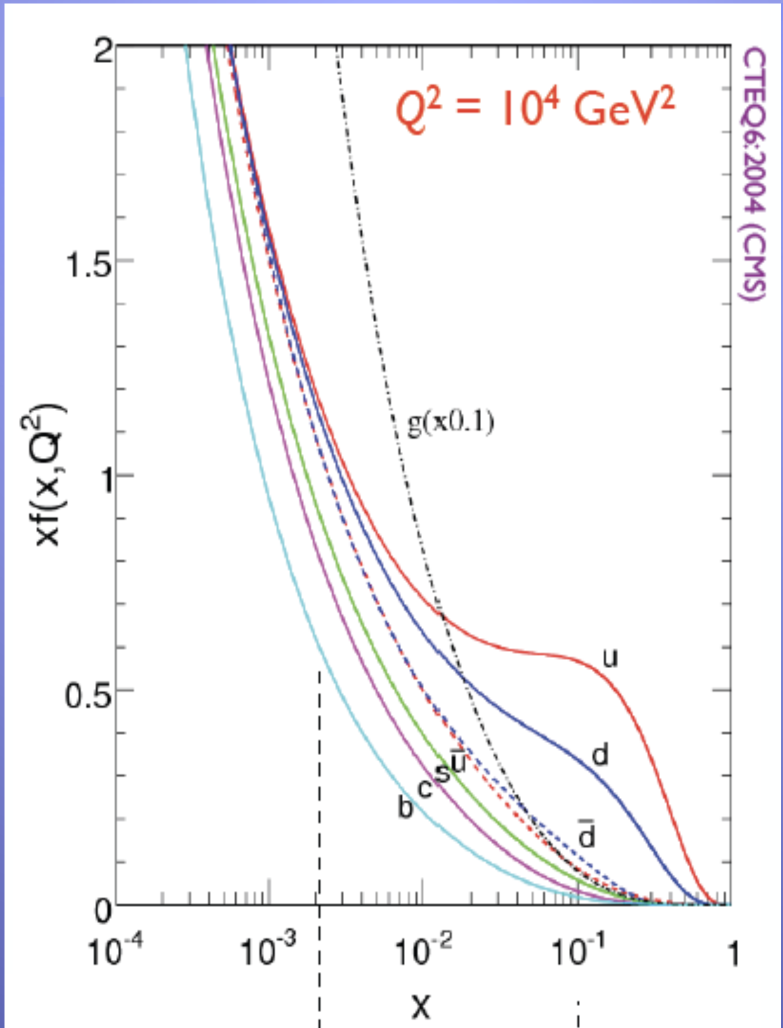
$p_T(W)$

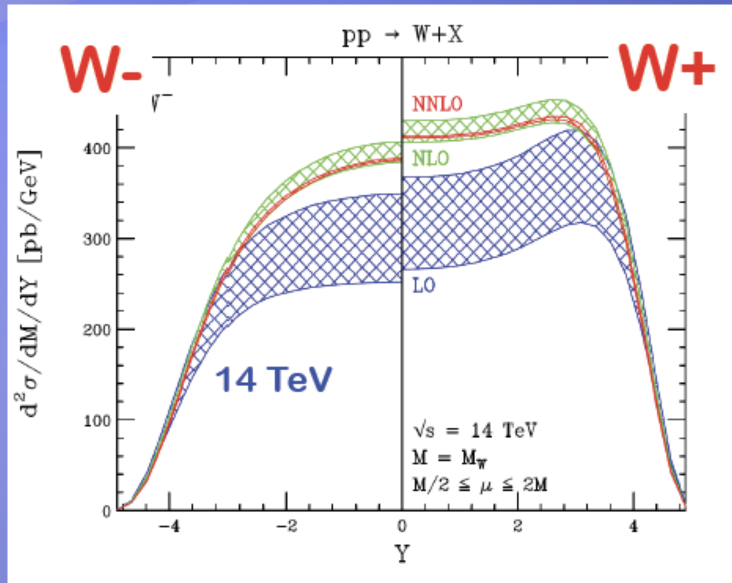
- Heavy-flavor-initiated processes play a larger role (25%): 5% at Tevatron, especially due to strange sea PDF
- Different rapidity dist. for W^+, W^- (larger gluon-quark contribution too)
- Hard to extrapolate to W from $p_T(Z)$ data

$p_T(l)$

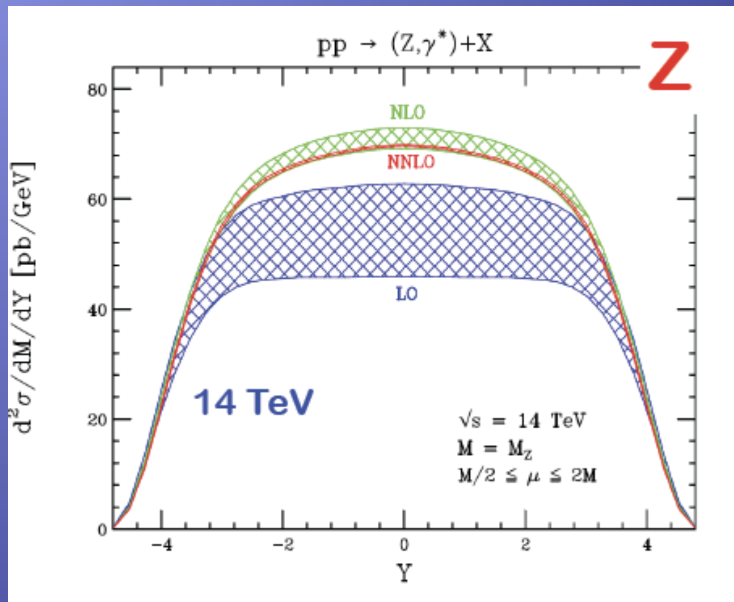
- Tevatron: mostly one polarization +1 for W+, -1 W- , but at LHC, (+1,-1,0) for W+

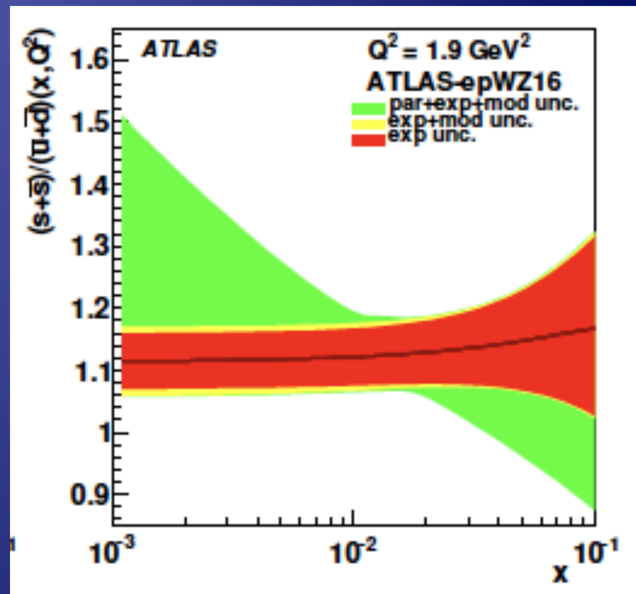
Why tough at LHC?





- Symmetric at Tevatron



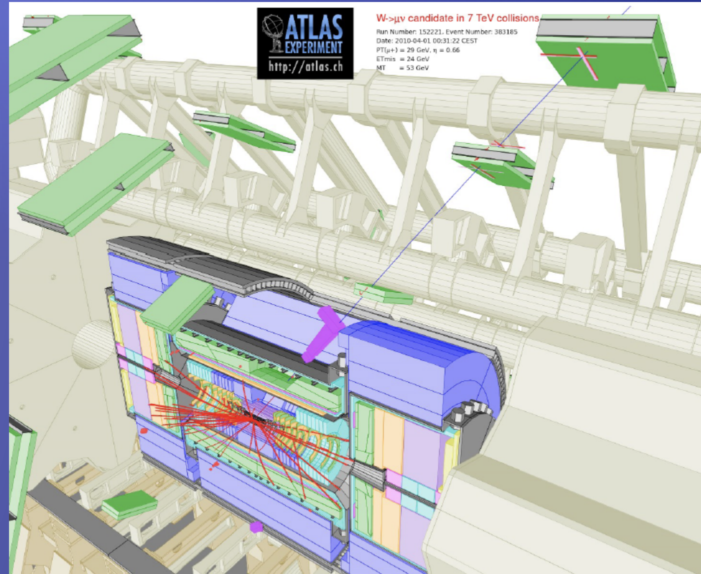


Event sample at ATLAS

Lepton selections:

- muons isolated (track-based) $|\eta|<2.4$
- electrons isolated (track+calorimeter-based) tight identified $0<|\eta|<1.2$, $1.8<|\eta|<2.4$

Kinematic requirements: $p_T^l>30$ GeV, $m_T>60$ GeV, MET>30 GeV and recoil(u_T)<30 GeV



~6M/8M observed in the electron/muon channel

$\|\eta_\ell\|$ 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
$\|\eta_\ell\|$ 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

CDF	ATLAS	LHCb
6.4	6.8	23
2.4M (μ) 1.8M (e)	8M (μ) 6M (e)	2.4M (μ)

W samples at ATLAS ($W\to e\nu, \mu\nu$) :

7 TeV	8 TeV	13 TeV
~4.5 fb^{-1}	~20.3 fb^{-1}	~30 fb^{-1}
15×10^6	80×10^6	190×10^6

Electron Calibration

- Electron energy measurement from the EM calorimeter
- Corrections for scale and resolution are derived from the Z events: phi dependent corrections are important for MET
- Validations using J/Psi→ee, Z→eeγ (~0.05%)

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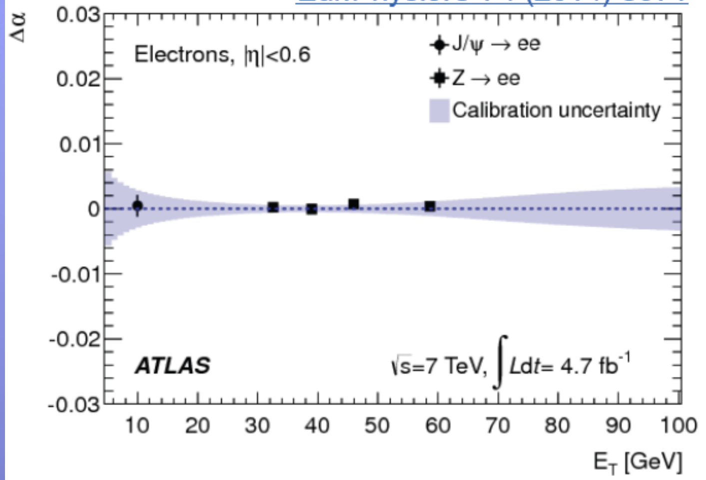
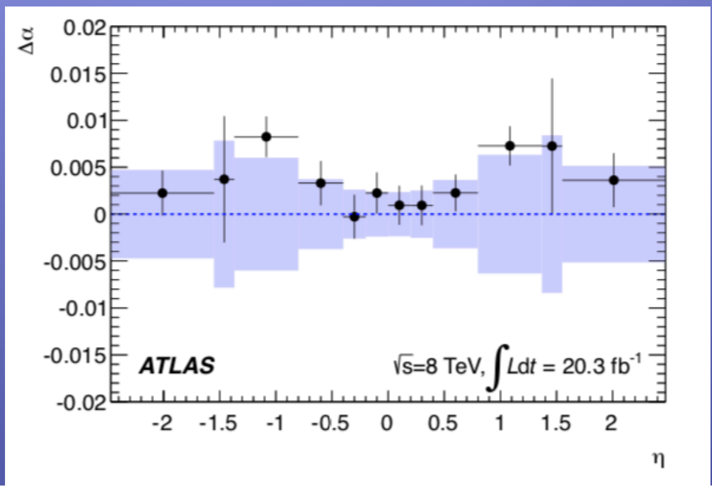
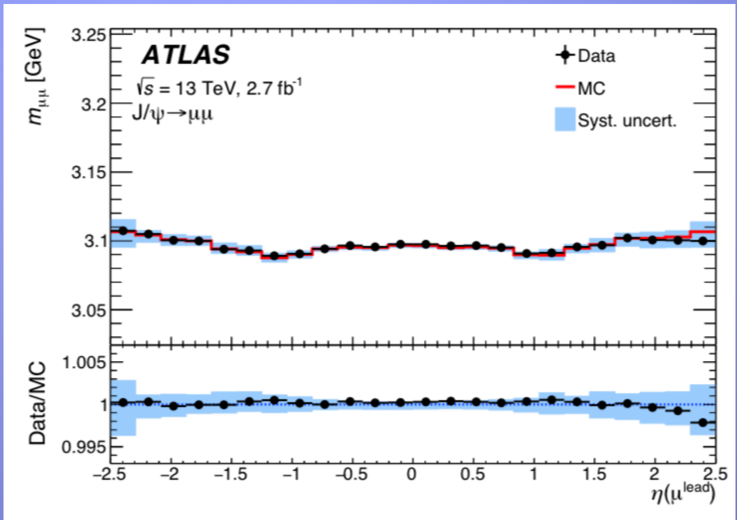




$\|\eta_\ell\|$ range	Combined	
Kinematic distribution	p_T^ℓ	m_T
δm_W [MeV]		
Energy scale	8.1	8.0
Energy resolution	3.5	5.5
Energy linearity	3.4	5.5
Energy tails	2.3	3.3
Reconstruction efficiency	7.2	6.0
Identification efficiency	7.3	5.6
Trigger and isolation efficiencies	0.8	0.9
Charge mismeasurement	0.1	0.1
Total	14.2	14.3

Muon Calibration

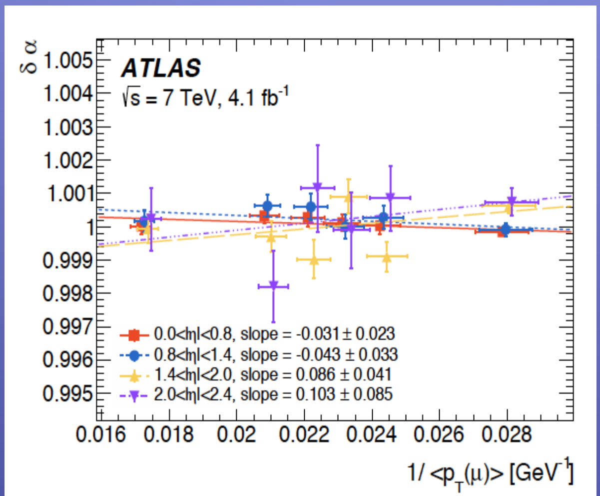
- Muon identified from combined ID+MS tracks, but momentum measurment from ID only simplifies calibration
- Calibration factors from ID-only muons from $Z \rightarrow \mu\mu$ and sagitta bias from $Z \rightarrow \mu\mu$ and E/p of $W(+,-) \rightarrow e\nu$ (~0.05%)

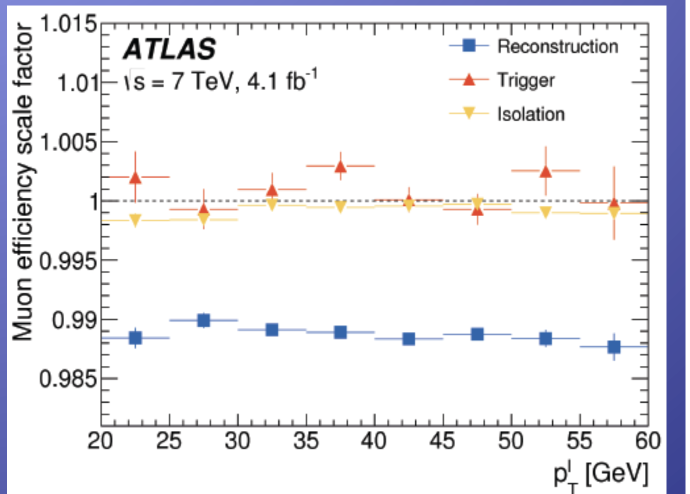


$$p_T^{MC,corr} = p_T^{MC} \times [1 + \alpha(\eta, \phi)] \times \left[1 + \beta_{curv}(\eta) \cdot G(0,1) \cdot p_T^{MC}\right],$$

$$p_T^{data,corr} = \frac{p_T^{data}}{1 + q \cdot \delta(\eta, \phi) \cdot p_T^{data}},$$

$\lvert\eta_\ell\rvert$ 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

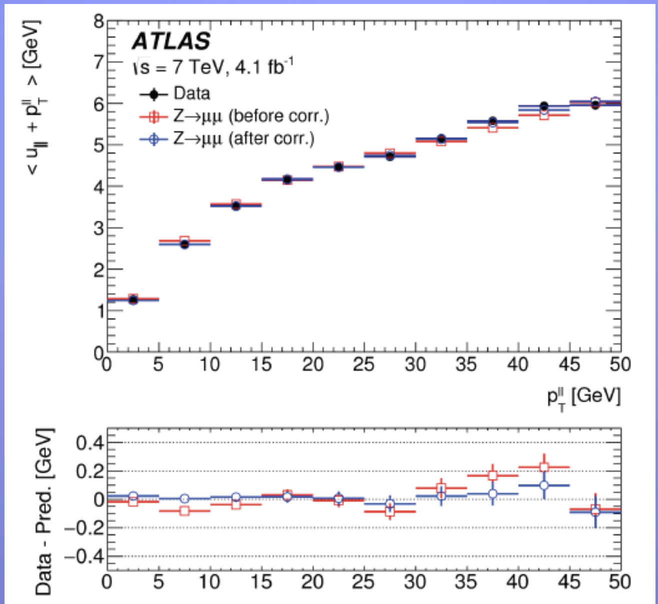


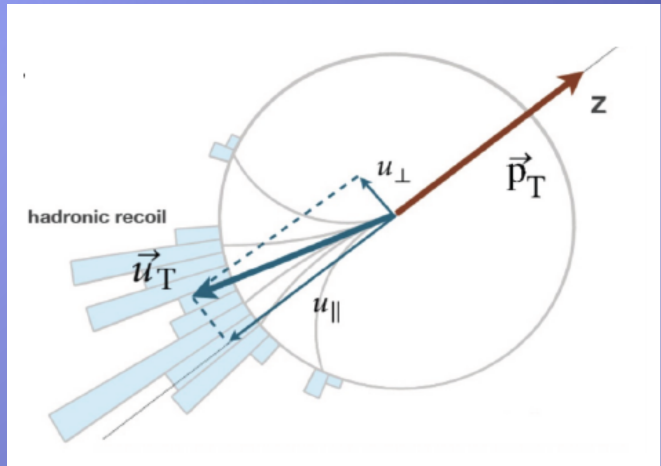


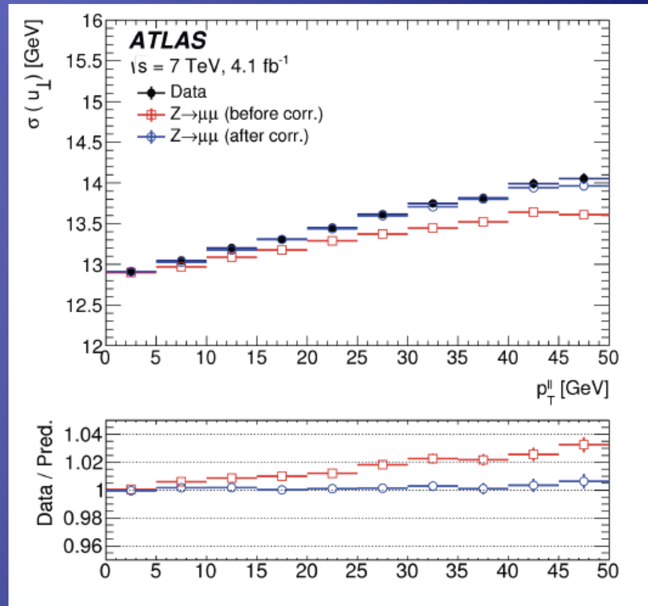
$\lvert\eta_\ell\rvert$ range	Combined	
Kinematic distribution	p_T^ℓ	m_T
δm_W [MeV]		
Momentum scale	8.4	8.8
Momentum resolution	1.0	1.2
Sagitta bias	0.6	0.6
Reconstruction and isolation efficiencies	2.7	2.2
Trigger efficiency	4.1	3.2
Total	9.8	9.7

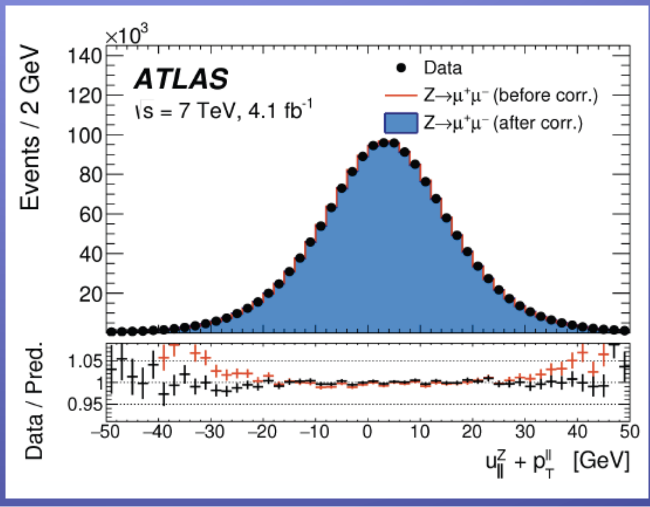
Recoil Calibration

- Vector sum of the all cluster momenta→a measure of $p_T(W)$
- Calibrate the scale and resolution corrections from the p_T balance in Z events





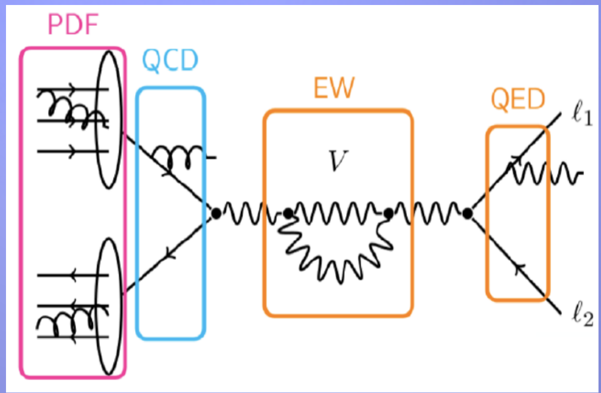




W-boson charge	Combined	
Kinematic distribution	p_T^ℓ	m_T
δm_W [MeV]		
$\langle\mu\rangle$ scale factor	0.2	1.0
ΣE_T^* correction	1.0	11.2
Residual corrections (statistics)	2.0	2.7
Residual corrections (interpolation)	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.1
Total	2.6	13.0

Physics modelling

- W, Z samples are generated by Powheg + Pythia 8.
- Each event is reweighted to include the higher-order QCD and EWK corrections, as well as the fit results to match kinematic distributions



- EWK corrections:
  QED I/FSR and missing higher order
- QCD corrections:
  $p_T(W)$, W polarisation and rapidity

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

Breit-Wigner

NNLO pQCD

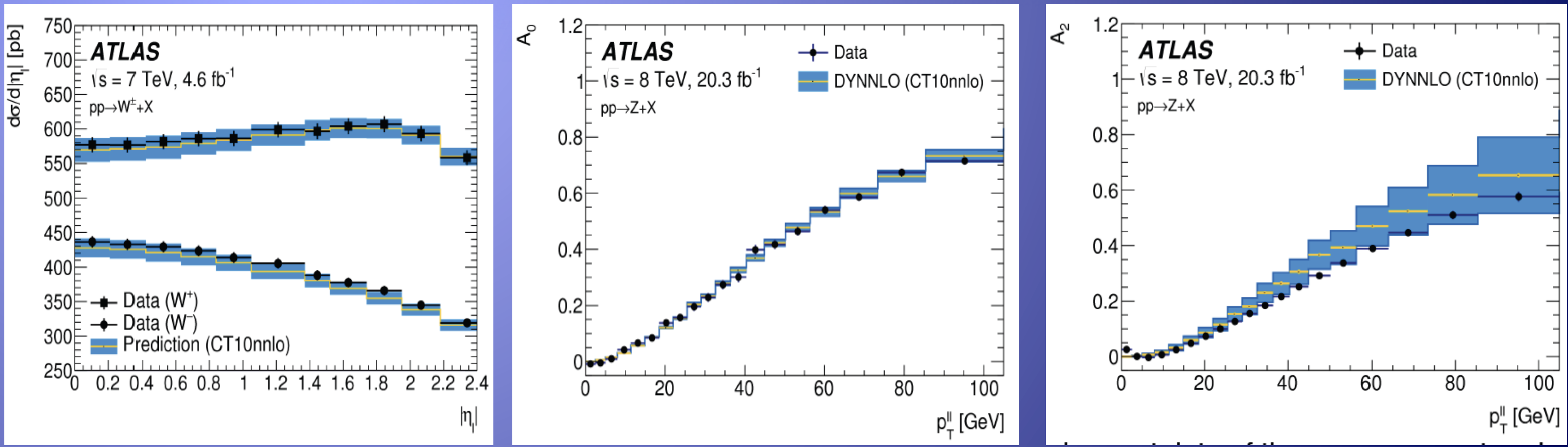
Parton Shower

$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$

- The Z cross section is reorganized by factorizing the dynamics of the boson production and kinematic of the boson decay
- Use this model to fit the free parameters of the model using Z events

Rapidity and angular coefficients

- The rapidity dist. and Ai coefficients modelled with NNLO predictions and the CT10nnlo PDF: validated by 8 TeV Z data
- The rapidity dist. is very sensitive to PDF. (the CT10nnlo PDF is consistent with the unsuppressed strange quark PDF.

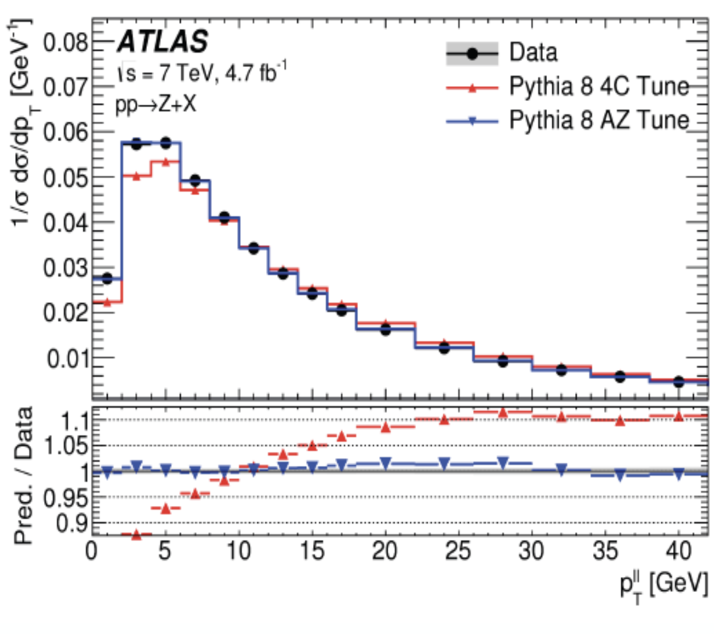


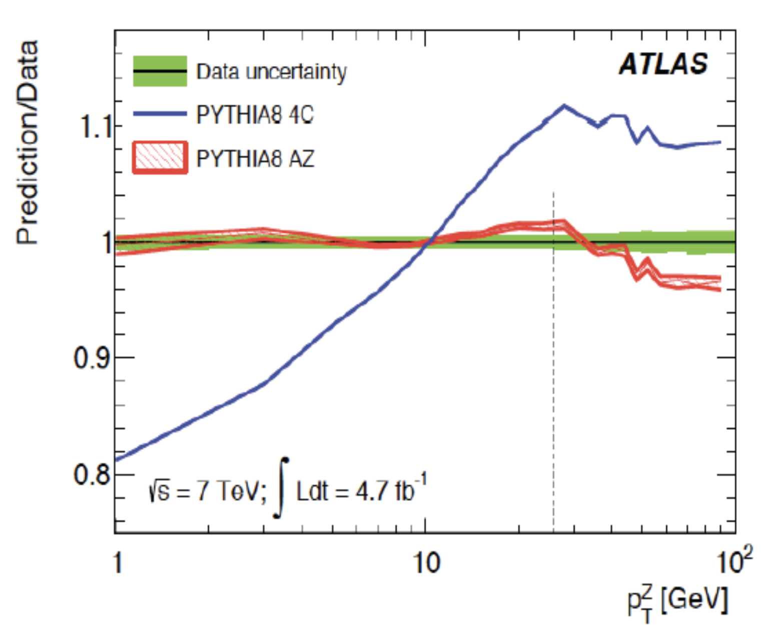
- Good agreement
- An observed discrepancy for A_2

W-boson charge	Combined	
Kinematic distribution	p_T^ℓ	m_T
Angular coefficients	5.8	5.3

Z transverse momentum

- Parton shower MC Pythia 8 tuned to the $p_T(Z)$ data – AZ tune
- Better than 1% for $p_T(Z) < 40$ GeV





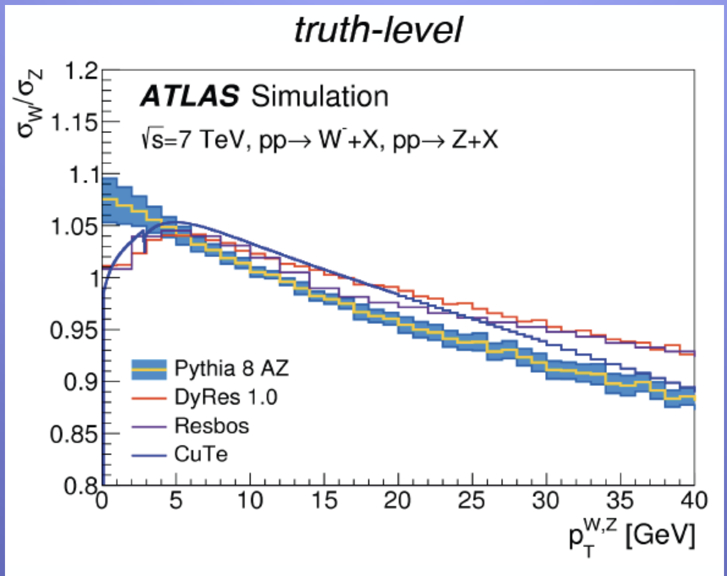
	PYTHIA8
Tune Name	AZ
Primordial k_T [GeV]	1.71 ± 0.03
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002
ISR cut-off [GeV]	0.59 ± 0.08
$\chi^2_{min}/\mathrm{dof}$	45.4/32

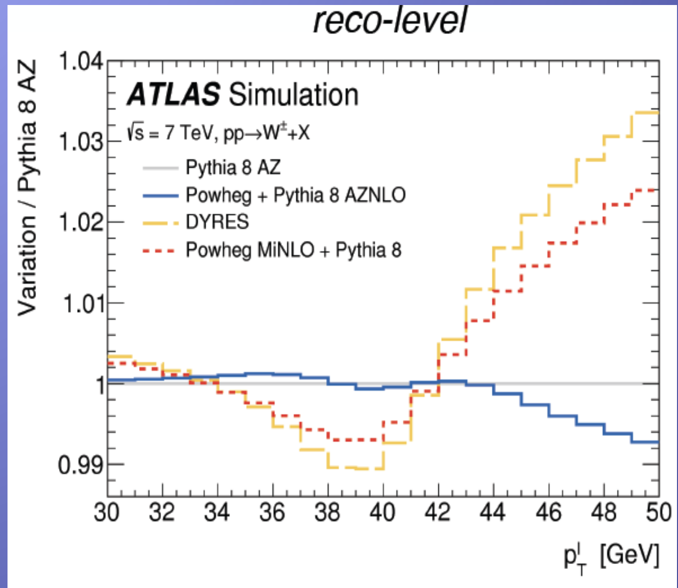
- Pythia 8 is used to transfer from the $p_T(Z)$ to the $p_T(W)$ dist. and to evaluate the theory uncertainty on the W/Z p_T ratio

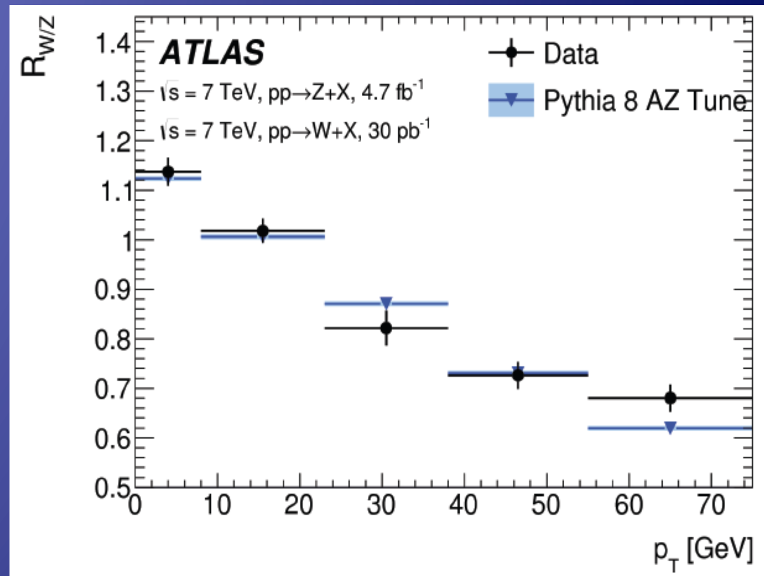
W-boson charge	Combined	
Kinematic distribution	p_T^ℓ	m_T
AZ tune	3.0	3.4

W transverse momentum

- The Pythia 8 AZ tune is used to extrapolate to W, considering relative variations of the W and Z p_T distributions
- The Pythia 8 predictions are softer than the NNLL resummed predictions (DYRES,Resbos, CuTE) for a give Z p_T distribution
- But the resummed predictions disfavored by the data, and the Pythia is in a good agreement: the extrapolation works!



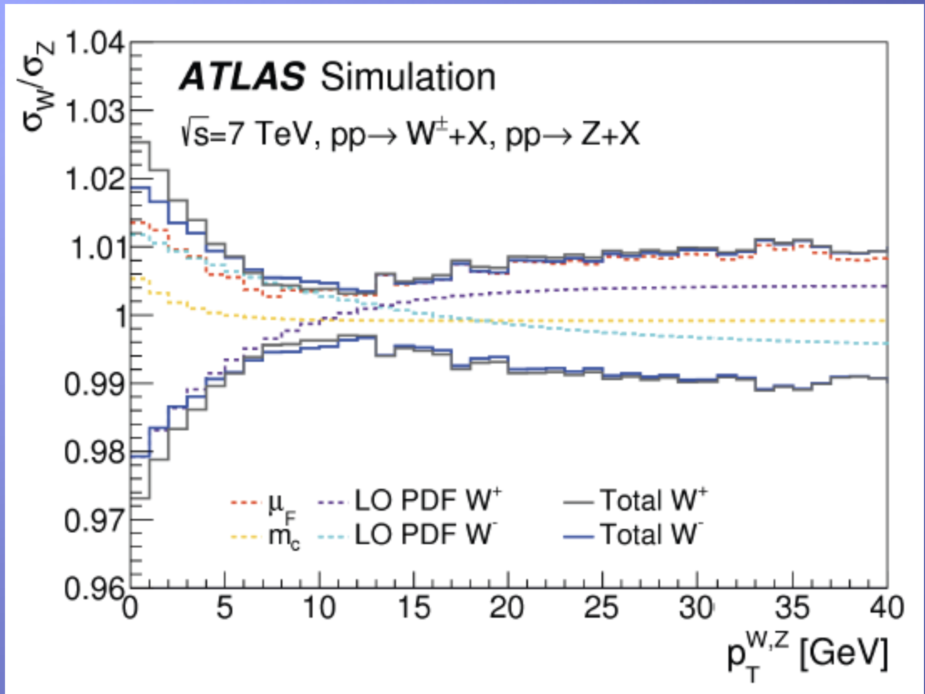




- Current precision of the data (~3%) and broad bin size (~8 GeV) limit in reducing syst. uncertainty
- Measurements with ~ 5 GeV bin size with ~1% precision will be useful

W p_T uncertainties

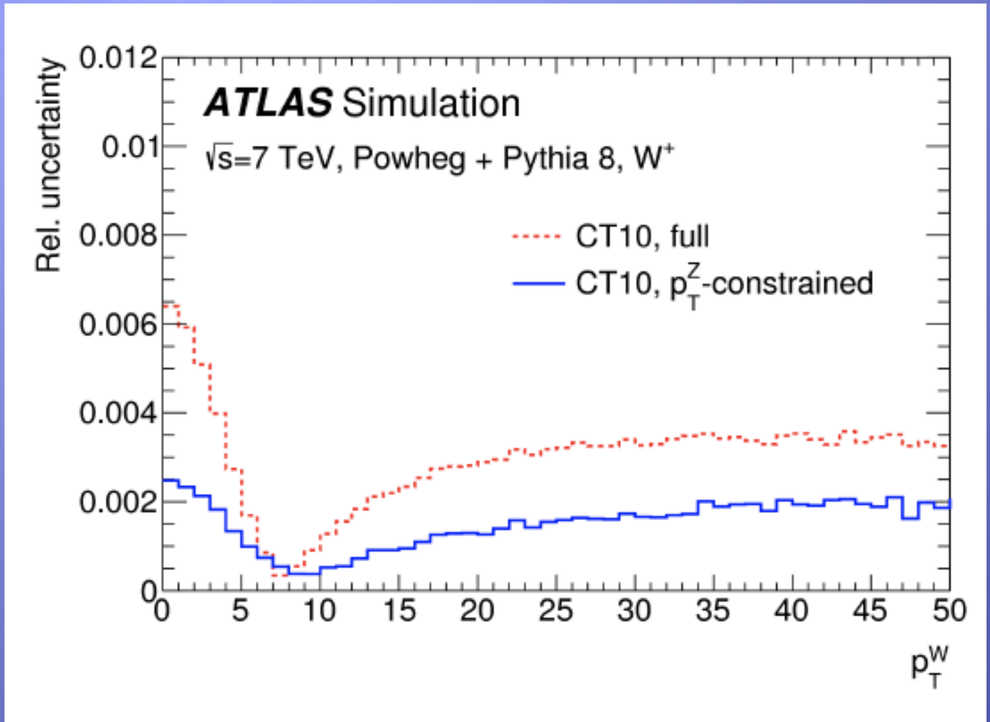
- **Production with heavy flavor quarks makes a difference between W and Z**
- **But higher-order QCD effects are mostly correlated between W and Z produced by light quarks**



W-boson charge	Combined	
Kinematic distribution	p_T^ℓ	m_T
Charm-quark mass	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9
Parton shower PDF uncertainty	1.0	1.6

PDF uncertainties

- **PDF uncertainty series of CT10nnlo are applied simultaneously to the boson rapidity, Ai, and p_T distributions**
- **Only relative variations of the pT(W) and pT(Z) induced by the PDFs are considered as the PDF uncertainty**



- **PDF uncertainties are anti-correlated between W+ and W-**

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7

Summary of physics modelling

QCD

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

- **PDF uncertainties is the dominant followed by pT(W) uncertainty due to the heavy-flavor initiated production**

ISR using Pythia8,
and FSR using Photos

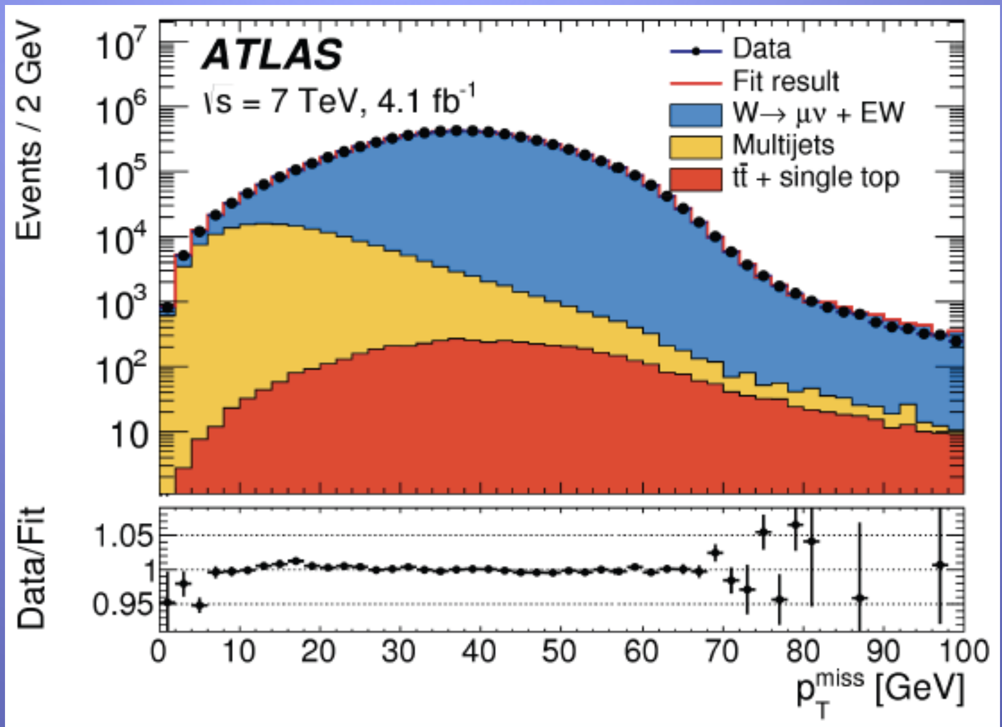
EW

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

QED emission of pairs : formally of higher order, but a significant additional source of momentum loss

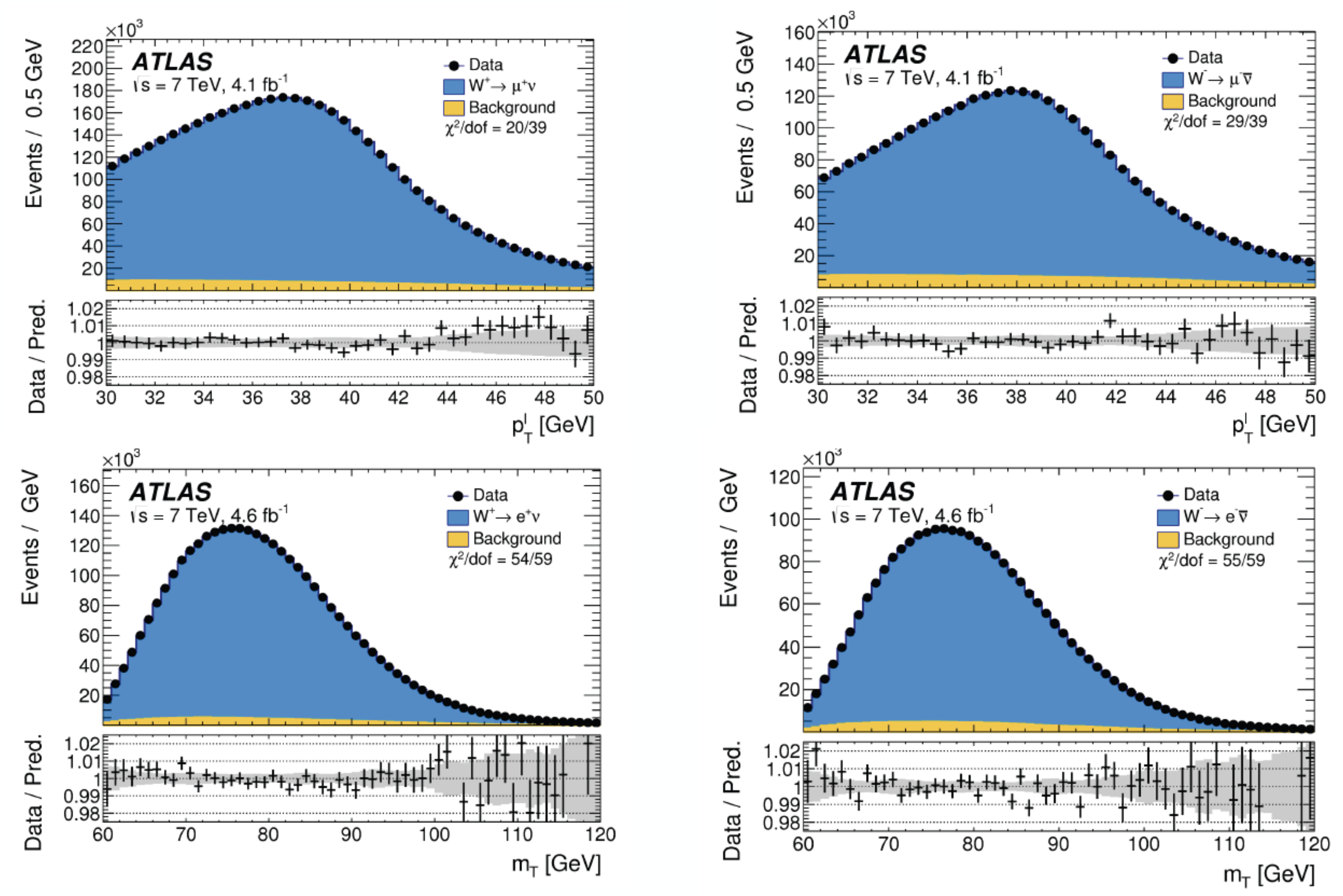
Backgrounds

- **EWK and top bkgds are estimated by using MC**
- **Multijet bkgds is done using data-driven techniques**



Kinematic distribution	p_T^ℓ				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	3.5	4.5	–	–	4.3	5.2
$Z \to \tau\tau$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
WW, WZ, ZZ (fraction)	0.1	0.1	0.1	0.1	0.4	0.4	0.3	0.4
Top (fraction)	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
Multijet (fraction)	3.2	3.6	1.8	2.4	8.1	8.6	3.7	4.6
Multijet (shape)	3.8	3.1	1.6	1.5	8.6	8.0	2.5	2.4
Total	6.0	6.8	4.3	5.3	12.6	13.4	6.2	7.4

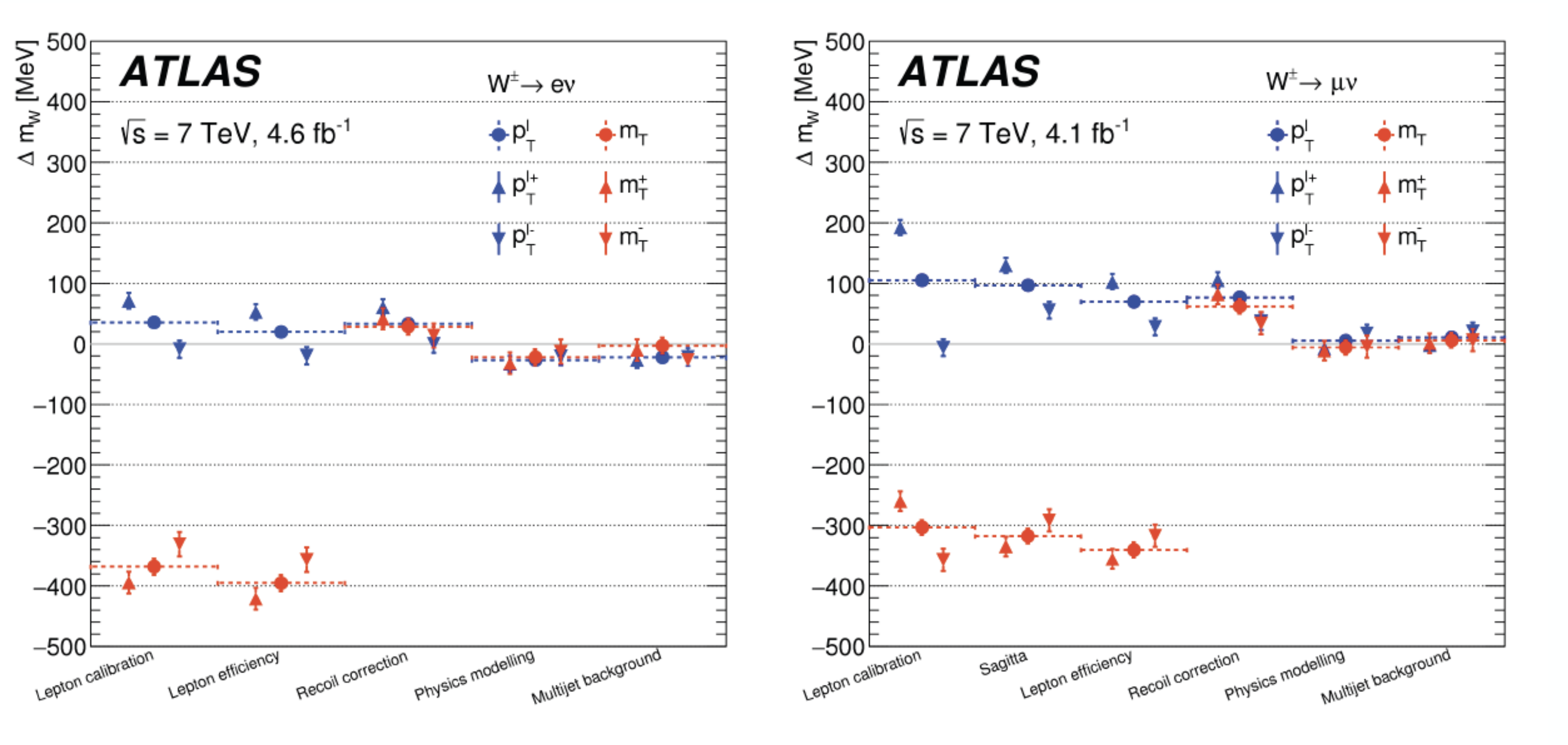
W p_T and m_T distributions



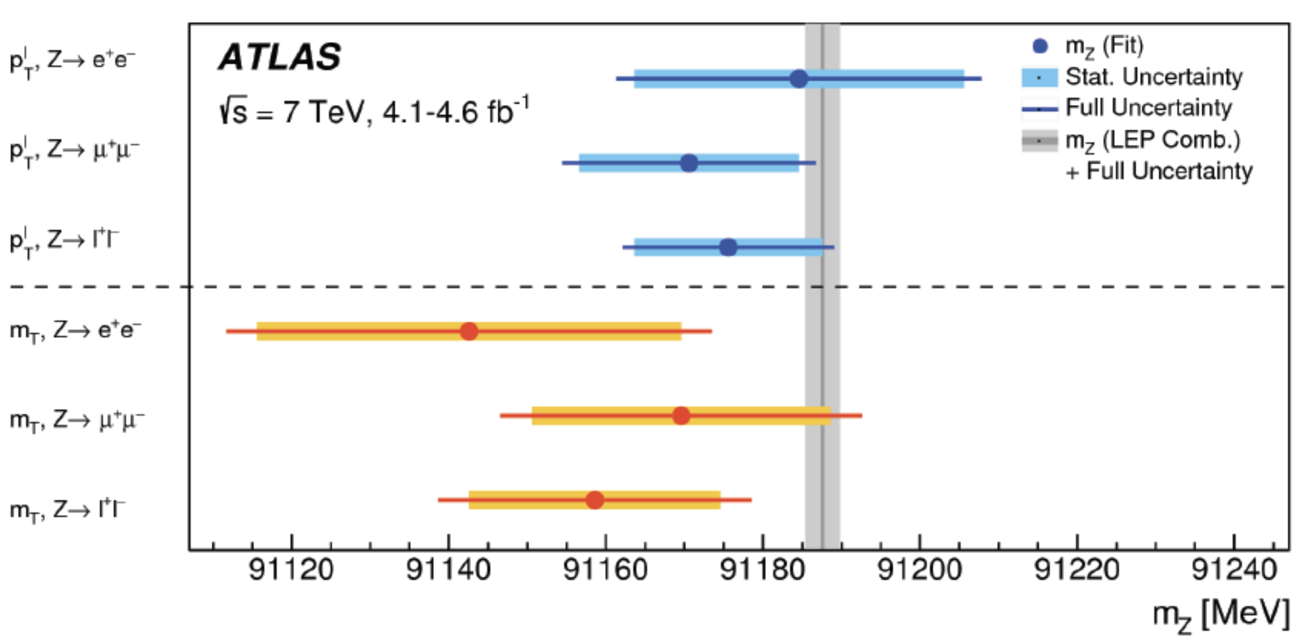
Fitting ranges:
$32<p_T^l<45$ GeV,
$66<m_T<99$ GeV

Summary of corrections

- After all corrections are applied, consistent results are obtained



Test on Z Mass using one lepton

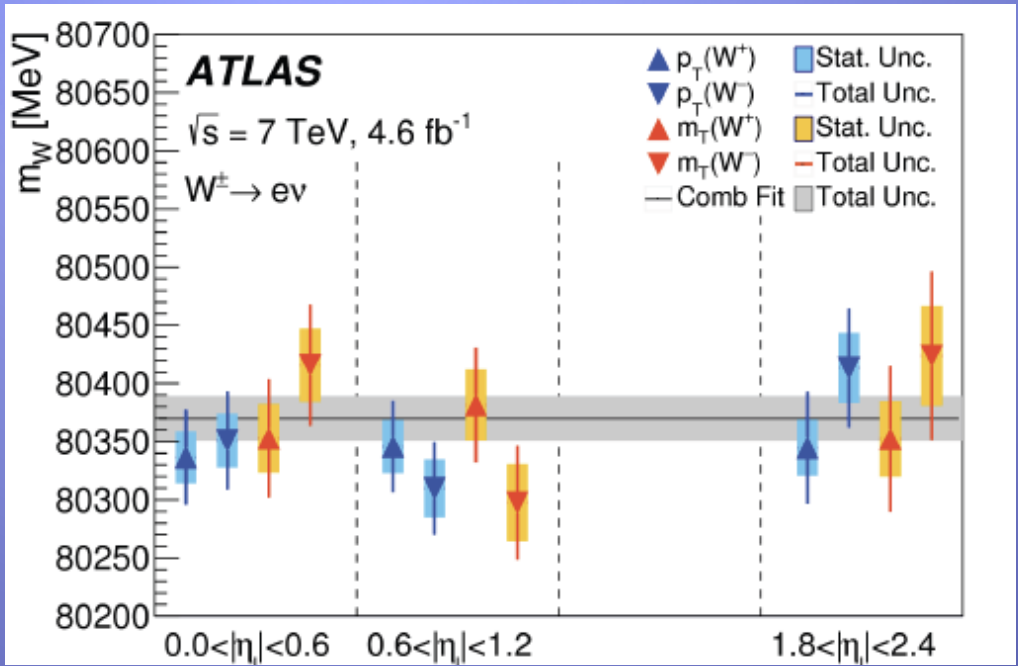


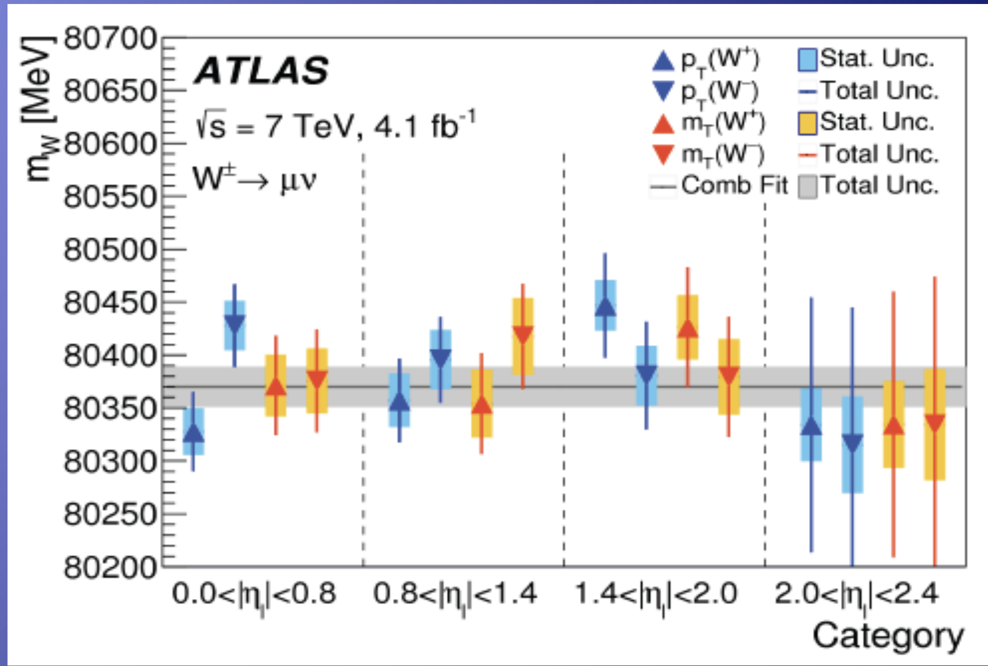
Lepton charge Distribution	ℓ^+ p_T^ℓ	ℓ^+ m_T	ℓ^- p_T^ℓ	ℓ^- m_T	Combined p_T^ℓ	Combined m_T
Δm_Z [MeV]						
$Z \to ee$	$13 \pm 31 \pm 10$	$-93 \pm 38 \pm 15$	$-20 \pm 31 \pm 10$	$4 \pm 38 \pm 15$	$-3 \pm 21 \pm 10$	$-45 \pm 27 \pm 15$
$Z \to \mu\mu$	$1 \pm 22 \pm 8$	$-35 \pm 28 \pm 13$	$-36 \pm 22 \pm 8$	$-1 \pm 27 \pm 13$	$-17 \pm 14 \pm 8$	$-18 \pm 19 \pm 13$
Combined	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

- **Results are consistent with the combined LEP values within uncertainties**
- **m_T method slightly lower due to recoil modeling?**

Consistency Checks

- Results were checked in different categories, but also in different pile-up and u_T bins





W mass

Channel	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80371.3	29.2	12.4	0.0	15.2	8.1	9.9	3.4	28.4	47.1
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80354.1	32.1	19.3	0.0	13.0	6.8	9.6	3.4	23.3	47.6
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80426.3	30.2	35.1	0.0	14.3	7.2	9.3	3.4	27.2	56.9
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.6	40.9	112.4	0.0	14.4	9.0	8.4	3.4	32.8	125.5
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80375.5	30.6	11.6	0.0	13.1	8.5	9.5	3.4	30.6	48.5
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80417.5	36.4	18.5	0.0	12.2	7.7	9.7	3.4	22.2	49.7
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80379.4	35.6	33.9	0.0	10.5	8.1	9.7	3.4	23.1	56.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.2	52.4	123.7	0.0	11.6	10.2	9.9	3.4	34.1	139.9
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80352.9	29.4	0.0	19.5	13.1	15.3	9.9	3.4	28.5	50.8
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80381.5	30.4	0.0	21.4	15.1	13.2	9.6	3.4	23.5	49.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80352.4	32.4	0.0	26.6	16.4	32.8	8.4	3.4	27.3	62.6
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80415.8	31.3	0.0	16.4	11.8	15.5	9.5	3.4	31.3	52.1
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80297.5	33.0	0.0	18.7	11.2	12.8	9.7	3.4	23.9	49.0
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80423.8	42.8	0.0	33.2	12.8	35.1	9.9	3.4	28.1	72.3
p_T-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80327.7	22.1	12.2	0.0	2.6	5.1	9.0	6.0	24.7	37.3
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80357.3	25.1	19.1	0.0	2.5	4.7	8.9	6.0	20.6	39.5
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80446.9	23.9	33.1	0.0	2.5	4.9	8.2	6.0	25.2	49.3
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.1	34.5	110.1	0.0	2.5	6.4	6.7	6.0	31.8	120.2
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80427.8	23.3	11.6	0.0	2.6	5.8	8.1	6.0	26.4	39.0
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80395.6	27.9	18.3	0.0	2.5	5.6	8.0	6.0	19.8	40.5
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80380.6	28.1	35.2	0.0	2.6	5.6	8.0	6.0	20.6	50.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80315.2	45.5	116.1	0.0	2.6	7.6	8.3	6.0	32.7	129.6
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80336.5	22.2	0.0	20.1	2.5	6.4	9.0	5.3	24.5	40.7
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80345.8	22.8	0.0	21.4	2.6	6.7	8.9	5.3	20.5	39.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80344.7	24.0	0.0	30.8	2.6	11.9	6.7	5.3	24.1	48.2
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80351.0	23.1	0.0	19.8	2.6	7.2	8.1	5.3	26.6	42.2
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80309.8	24.9	0.0	19.7	2.7	7.3	8.0	5.3	20.9	39.9
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80413.4	30.1	0.0	30.7	2.7	11.5	8.3	5.3	22.7	51.0

- **W pT(l):**
  lepton calib. (15~35 MeV)

- **mT(l):**
  recoil calib. (15 MeV)

W mass combination

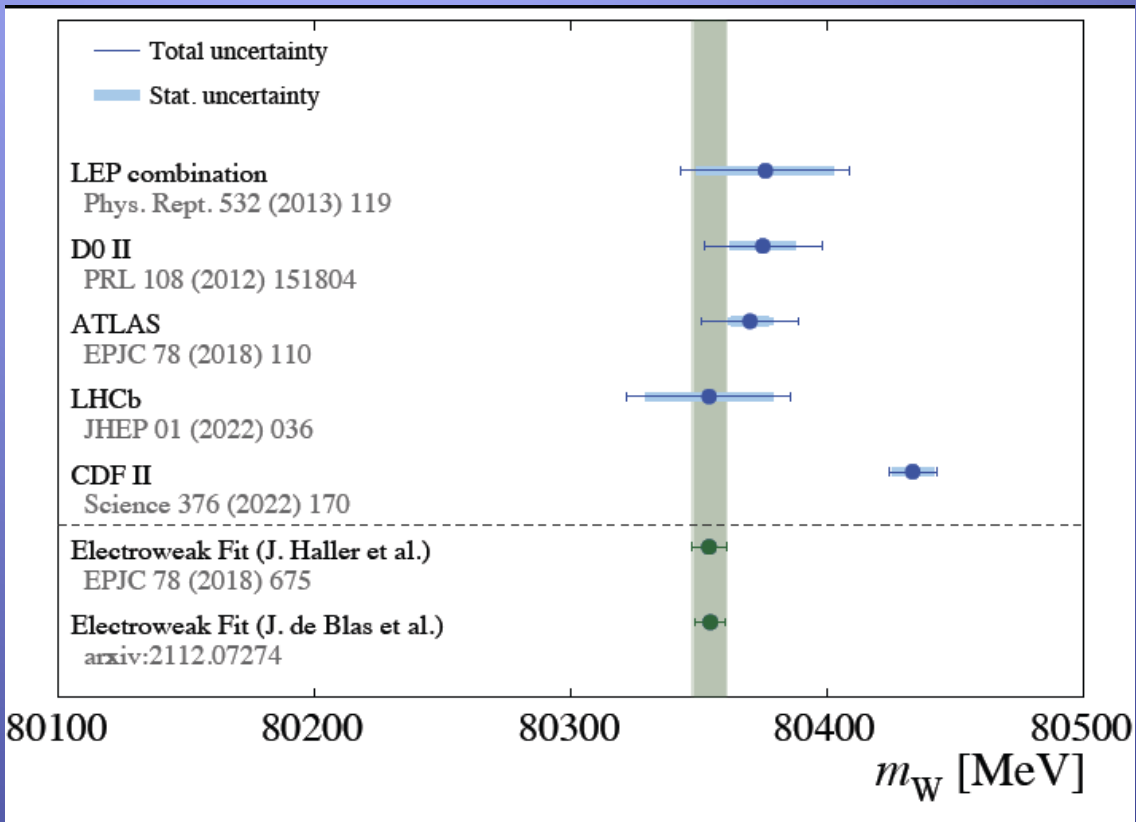
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
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

- **Lepton & pT(l), mT(W) correlated: lepton effect is reduced**
- **PDF anti-corr. for W+ and W-**

ATLAS W mass results

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK 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

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



Comparison with CDF

Modeling

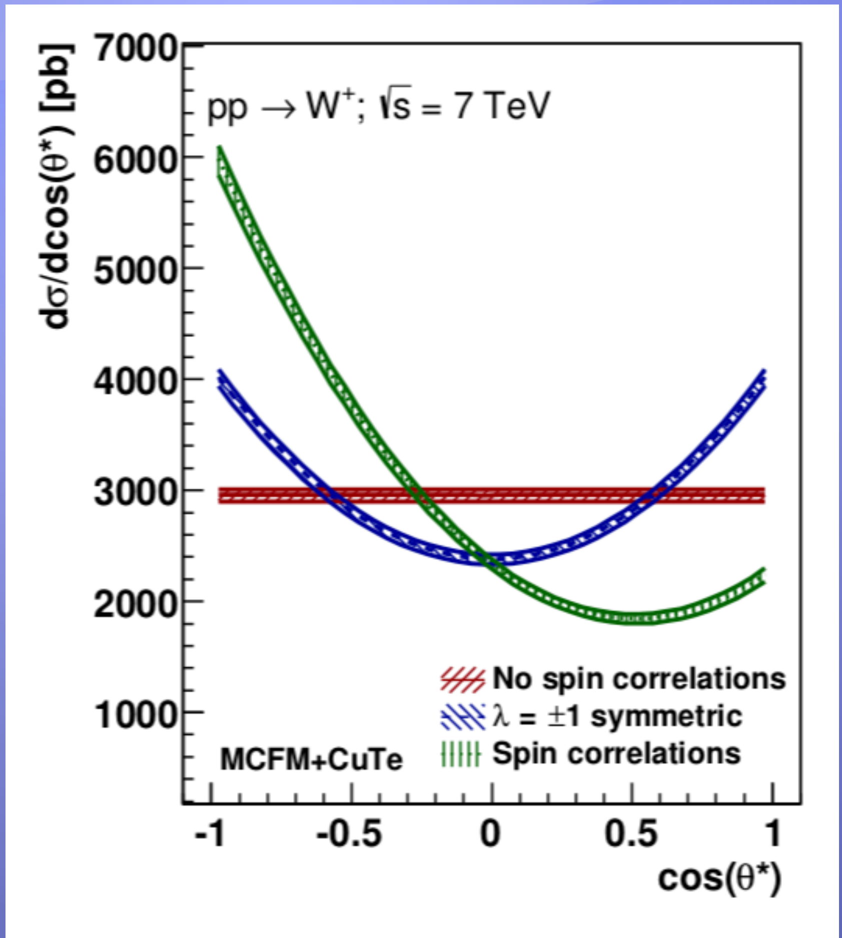
	CDF	ATLAS	LHCb
Baseline	RESBOS	Powheg+Pythia	Powheg+Pythia
Reweight	-	DYNNLO	DYTURBO
Parton shower	data-driven	data-driven	data-driven
QED	PHOTOS+HORACE	PHOTOS	Pythia+PHOTOS+Herwig

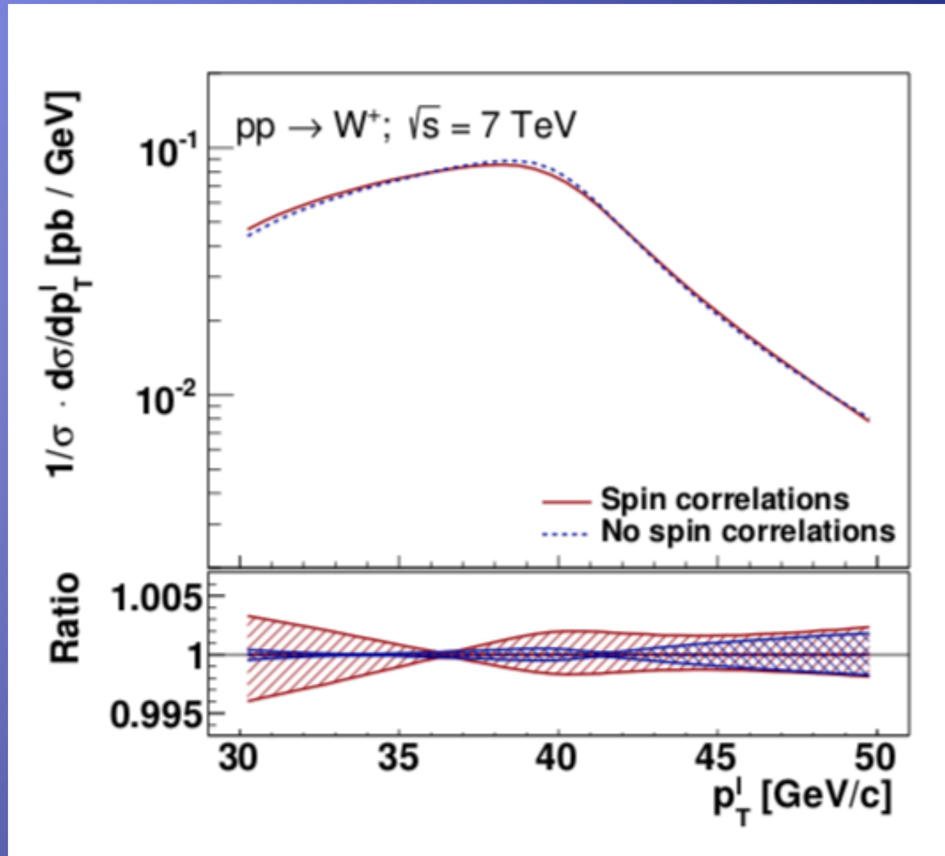
Uncertainties (in MeV)

	CDF	ATLAS	LHCb
Statistical	6.4	6.8	23
Lepton energy/ momentum scale	2 (μ) + 6 (e)	7* (μ) + 7* (e)	7 (μ)
PDFs	4	7*	9
Model (excl. PDFs)	3.5	8*	17
Total	9.4	18.5	31.4

Backup slides

W boson helicity





Flavor decomposition