Measurement of the W-boson mass at the ATLAS experiment

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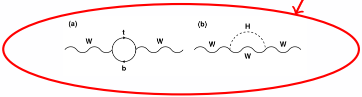
Motivation

- Relation in EW sector of the SM:

$$M_W^2(1 - M_W^2/M_Z{}^2) = \frac{\pi\alpha}{\sqrt{2}G_F} \cdot \frac{1}{1-\Delta r}$$

- Loop corrections



$$\Delta r(m_t^2, \ln(M_H), M_W, M_Z, \dots)$$

Current world average exp.
$M_W = 80.385 \pm 0.015$ GeV

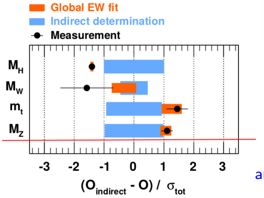
- Probe consistency of the SM via M_W

	measurement [GeV]	**prediction** [GeV]
M_H	125.09±0.24	102.8±26.3
m_t	172.84±0.70	176.6±2.5
M_W	80.385±0.015	80.360±0.008

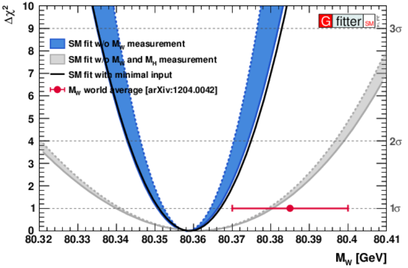
- **Objective:** experimental precision of about 8 MeV
- Sensitive to several BSM scenarios

Global EW fit

→ Measure SM observables
→ Fit SM relations to precision data



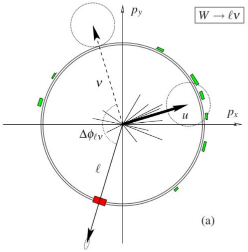
arXiv:1407.3792



Strategy of W-mass measurement

- **Basic objects:** single isolated lepton $\vec{p}_T^{\ell}$, recoil $\vec{u}_T = \sum \vec{E}_T$ (a measure of p_T^W)
- Observables sensitive to M_W:

Lepton transverse momentum	p_T^{ℓ}
(Neutrino transverse energy)	$E_T^{\nu} = \lvert\vec{p}_T^{\nu}\rvert, \vec{p}_T^{\nu} = -(\vec{p}_T^{l} + \vec{u})$
Transverse mass	$m_T^W = \sqrt{2p_T^{\ell}p_T^{\nu}(1 - \cos\Delta\phi_{\ell\nu})}$

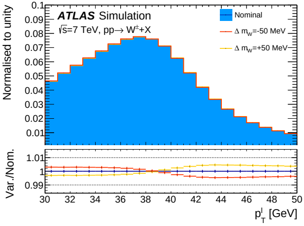


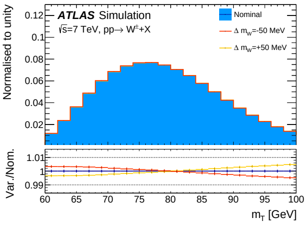
$p_T^{\ell} > 30$ GeV, $E_T^{\nu} > 30$ GeV

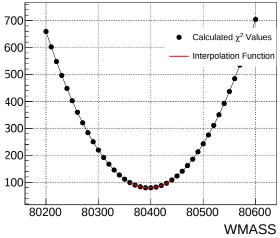
$u < 30$ GeV, $m_T^W > 60$ GeV

Template fit method:

- The p_T^{ℓ}, m_T^W and E_T^{miss} distributions are computed with MC for different values of M_W
- Each template is compared to data by means of χ^2
- The preferred value of M_W corresponds to minimum of the χ^2 function







$\delta M_W^{stat} = 10/13$ MeV for p_T^{ℓ} / m_T^W

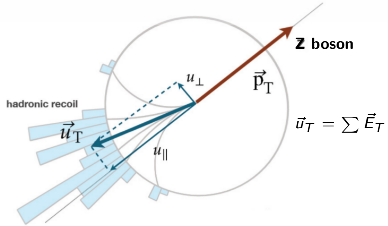
Experimental corrections

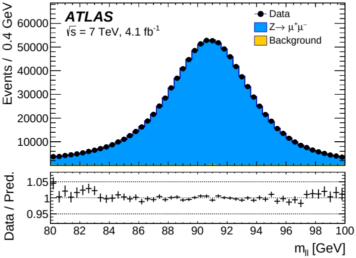
Lepton calibration

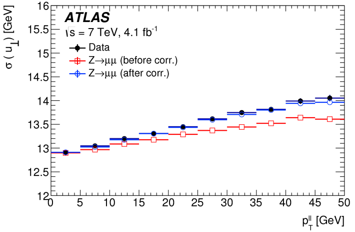
- **Momentum scale and resolution** corrected to match well-known M_Z distribution in $Z \to \ell\ell$ resonance
- Lepton reconstruction and selection requirements corrected using $Z \to \ell\ell$ via Tag-and-Probe method

Recoil calibration

- Event activity correction (Nb of pile-up interactions, ΣE_{T})
- Recoil response calibrated using p_T balance between lepton-pair and u_T in $Z \to \ell\ell$



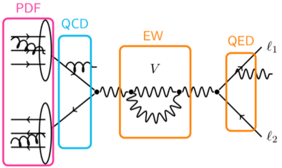


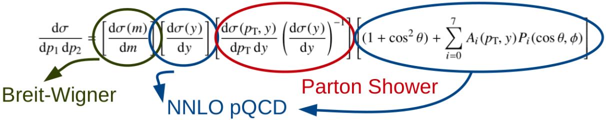


Total lepton uncertainty: 10/14 MeV for muons/electrons

Recoil uncertainty: 2.6/13.0 MeV for p_T^{ℓ}/m_T^W

Physics modeling





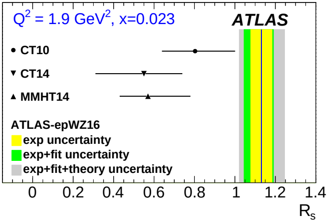
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

- No available generator can describe all these effects
- As starting point, we use **PowhegPythia** generator
- Corrections to **PowhegPythia** are based on factorization of fully differential leptonic DY cross section into 4 pieces:
  - Variation of $d\sigma/dm$ is modeled with Breit-Wigner+EW corrections
    $$\frac{d\sigma}{dm} \sim \frac{m^2}{(m^2-m_V^2)^2+m^4\Gamma_V^2/m_V^2}$$
  - The $d\sigma/dp_T$ is modeled with parton shower MC
  - The $d\sigma/dy$ and A_i (describe spin correlations) are modeled with NNLO QCD predictions
- A model in each part is constrained using experimental measurements of Z and W production

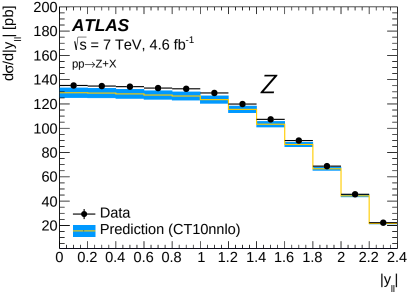
Rapidity and pseudorapidity distributions

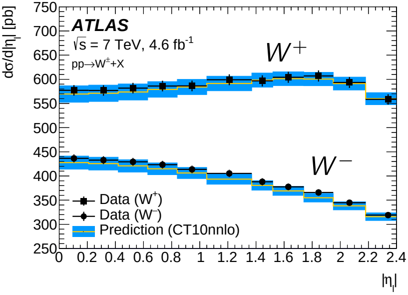
- Modeled with NNLO QCD predictions using **DYNNLO**
- PDF set **CT10nnlo**: best agreement with 7 TeV data (sub-% precise measurement)
- Predictions validated with W^+, W^- and Z data: $\chi^2 = 45/34$ satisfactory
- **Uncertainty:** from CT10nnlo, envelope of CT14 and MMHT

arXiv:1612.03016



$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

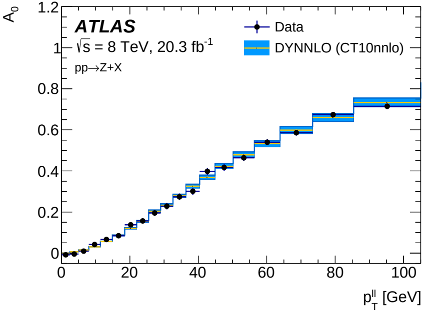


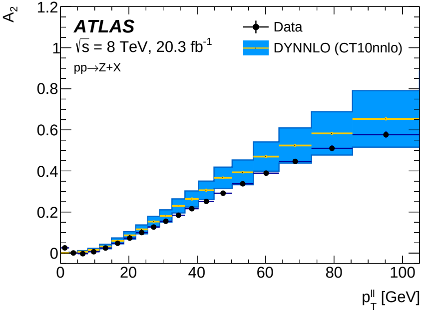


Angular coefficients A_i

- Fully differential cross section for spin-1 boson production, to all orders:
- A_i's are modeled with NNLO QCD predictions using **DYNNLO**
- Predictions are validated by comparisons to the Z measurement at 8 TeV (arXiv:1606.00689)
- **Uncertainty:** experimental uncertainty + observed discrepancy for A_2

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

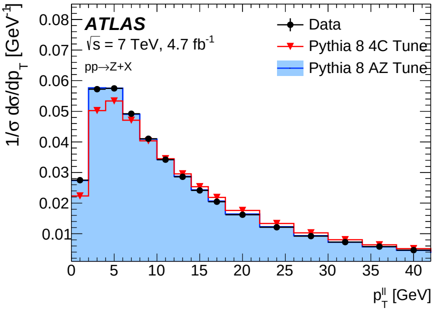


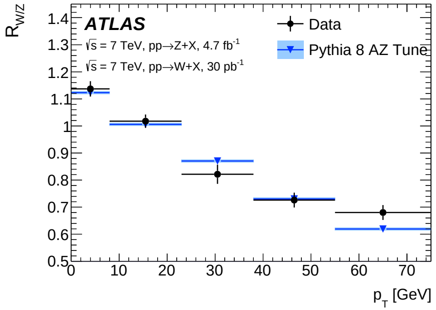


p_T^W modeling

- p_T^V easy to measure in $Z \to ll$ events, but hard for $W \to l\nu$
- Calibration W with Z: $\frac{d\sigma(W)}{dp_T} = \left[\frac{d\sigma(W)/dp_T}{d\sigma(Z)/dp_T}\right]_{pred} \times \left[\frac{d\sigma(Z)}{dp_T}\right]_{meas}$
- Use **Pythia8** parton shower, tuned to p_T^Z data at 7 TeV (AZ tune) $\to$ tuned parameters: α_s, intrinsic k_T, Q_0
- Apply model to W relying on good prediction of W/Z ratio $\to$ **validated on data**
- More advanced DYRES, Resbos, Powheg MiNLO+Pythia8 are disfavoured by data
- **Uncertainty:** p_T^Z data, PS parameters, μ_F, heavy quark masses

	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
χ^2_{min}/dof	45.4/32

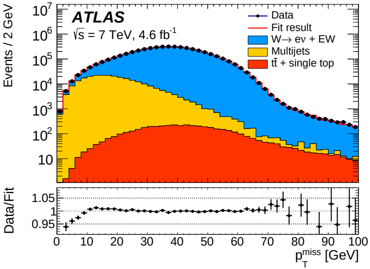




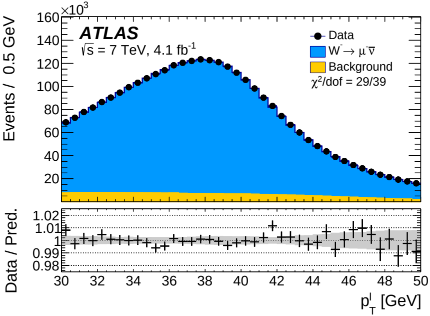
Backgrounds and distributions

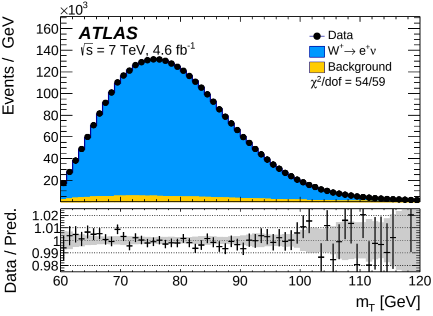
Missing part: **backgrounds**

- EW and top backgrounds are from MC
- Multijets background is estimated from data
  → from control region with large activity around leptons
  → normalized in jet-enriched region with relaxed kinematic cut(s)



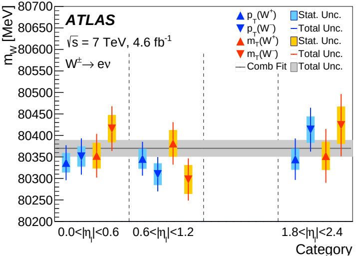
$W-$**mass sensitive distributions:**

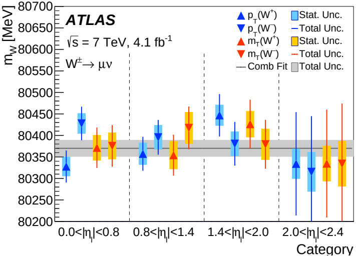




Mass measurements

- A crucial aspect is the **categorisation** (p_T^ℓ, m_T^W; electrons, muons; W^+/W^-; $|\eta|$−bins)
- Consistent results → validates the detector calibration and physics modeling
- Compatibility test: $\chi^2/n_{dof} = 29/27$
- Precision compatible to the single most precise measurement (CDF)





Results

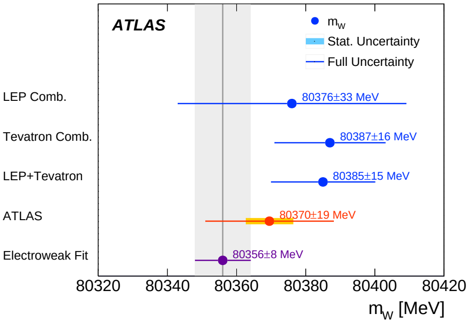
$$m_W = 80369.5 \pm 6.8\,\text{MeV(stat.)} \pm 10.6\,\text{MeV(exp. syst.)} \pm 13.6\,\text{MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

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

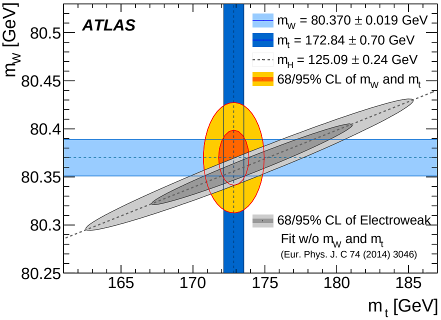
$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}$$

Standard Model consistency

- **Consistent** with the SM prediction and with the current world average value
- No signs of new physics



SM prediction for m_W assuming
$m_H = 125.09 \pm 0.24$ GeV
$m_t = 172.84 \pm 0.70$ GeV



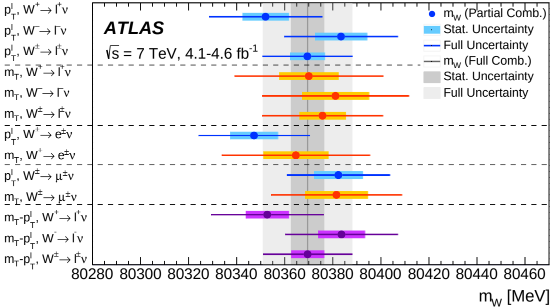
SM prediction for m_W vs m_t
assuming $m_H = 125.09 \pm 0.24$ GeV

BACKUP

Combined results

- Good compatibility between partial combinations
- Dominant contribution from p_T^ℓ
- Significant contribution from electron channel

Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481



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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

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}$$

Multijet background

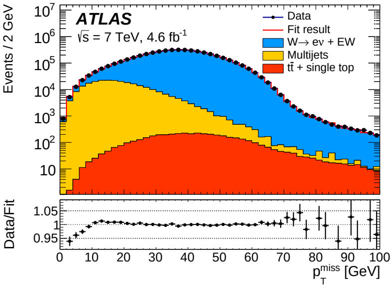
EW and top backgrounds are from MC; MJ background is estimated from data

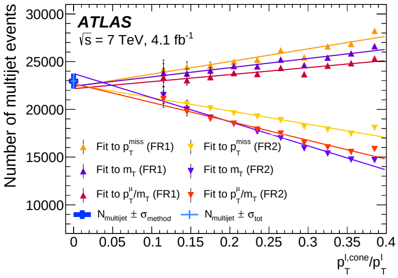
- **General method:**
  - Define a background dominated fit region with relaxed kinematic cut(s)
  - Signal distribution from MC; background from control region with inverted lepton isolation cut (large activity around leptons)
  - The multijet background is normalized with fraction fit
- **Variations:**
  - 3 observables (p_T^{miss}, m_T^W, p_T^{ℓ}/m_T^W); 2 fitting regions
  - Different isolation criteria $\rightarrow$ extrapolate to the signal region
- **Uncertainty:** $\sim$ 4 MeV (mu); $\sim$ 8 MeV (e)

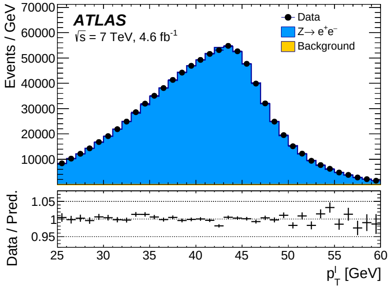
Fraction

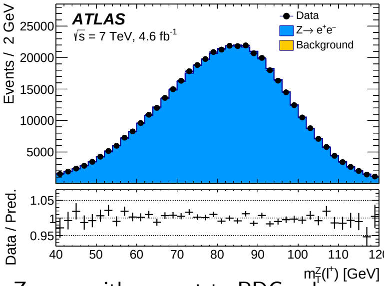
0.5-0.7% (muons)

0.6-1.7% (electrons)

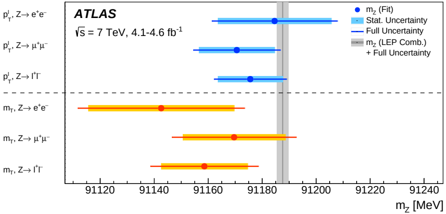








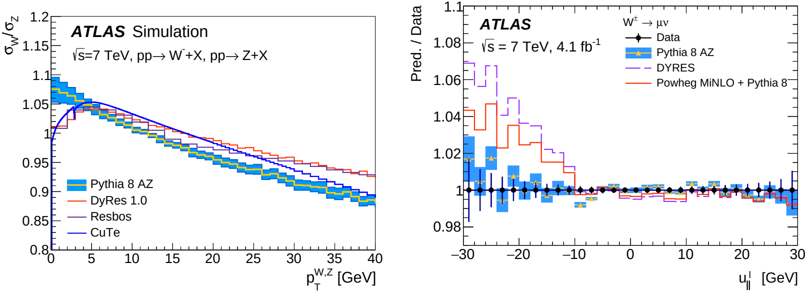
Z mass with respect to PDG value



- W-like transverse mass $m_T(l)$:
  - Reconstructed from recoil and lepton
- Calibration is verified with M_Z $\rightarrow$ compatibility within $< 1\sigma$ (p_T^l) and 1.4σ (m_T^Z) with the PDG value

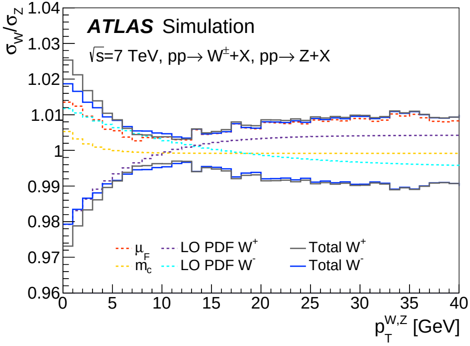
p_T^W modeling

- Theoretically more advanced resummed predictions were also tried (DYRES, ResBos, Cute)
- They predict harder p_T spectrum wrt Pythia
- Such behaviour is strongly disfavoured by the $u_{||}(l)$ distribution in data → not used



p_T^W modeling uncertainty

- Difference between W and Z: PDF and heavy-quark effects
- $Z \rightarrow W$ extrapolation uncertainty:
  - variation of remaining parton shower parameters
  - choice of LO parton shower PDF: CTEQ6L1, CT14, MMGT2014 and NNPDF2.3
  - factorization scale (decorrelated between light and heavy quark induced production)
  - heavy quark masses ($\delta m_c = \pm 0.5$ GeV)



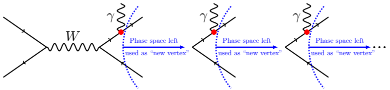
Summary of modeling uncertainties

- CT10nnlo PDFs (synchronized in DYNNLO and Pythia) + envelop CT10 to CT14 and MMHT: dominant uncertainty, followed by p_T^W uncertainty due to heavy-flavour-initiated production
- PDF uncertainty are **anti-correlated** between W^+ and W^- $\rightarrow$ significant reduction from the combination
- AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
- A_i uncertainties from Z data + envelope for A_2 discrepancy

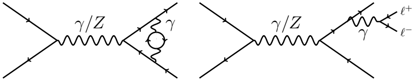
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9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

Electroweak corrections

- **Effects present in MC simulation:**
  → FSR modeled with Photos (dominant effect)
  → ISR modeled in Pythia PS



- **Missing effects:**
  → fermion pair emmision
  → NLO EW corrections



- Related uncertainties estimated using dedicated MC (Winhac)

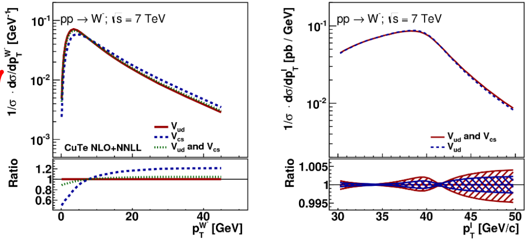
Kinematic distribution	p_T^e	$m_T^{e\nu}$	p_T^ν	p_T^μ	$m_T^{\mu\nu}$
δm_W [MeV]					
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
FSR (pair production)	3.6	0.8	< 0.1	4.4	0.8
Pure weak and IFI corrections	3.3	2.5	0.6	3.5	2.5
Total [MeV]	4.9	2.6	0.6	5.6	2.6

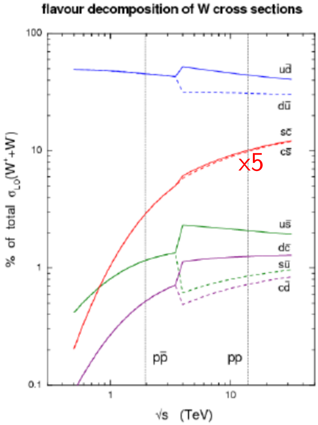
Challenges @LHC

Additional complications at LHC wrt TeVatron

- Higher **pile-up** enviroment complicates the **hadronic recoil** calibration
- Larger role of sea-quarks in W-boson production $\rightarrow$ implies larger uncertainty on the p_T^l distribution
- Assymetric production of W^+ and W^- $\rightarrow$ charge-dependent analysis
- Large role of heavy 2^{nd}−genereation quarks $\rightarrow$ implies larger uncertainty from modeling of p_T^W and W-polarisation

PDF uncertainty $\rightarrow$ W polarization $\rightarrow$ uncertainty on p_T^l





Summary of uncertainties

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

|η| comb e → ~15 MeV
μ → ~11 MeV

Strongly correlated

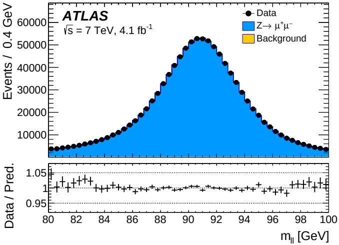
Strongly correlated

|η| comb. → ~14 MeV
W+/W- comb → ~8 MeV

Fit ranges : $32<p_T^l<45$ GeV; $66<m_T<99$ GeV, minimizing total expected measurement uncertainty

Lepton calibration

Correct for imperfect knowledge of magnetic field, material, detector alignment, response:

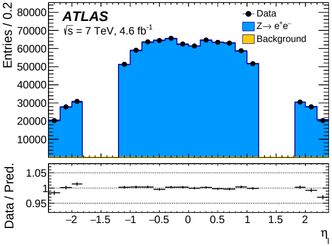


Momentum corrections

- **Momentum scale and resolution** corrected to match well-known M_Z distribution in $Z \to \ell\ell$ resonance

Efficiency corrections

- Lepton reconstruction and selection requirements are corrected in MC using $Z \to \ell\ell$ with Tag-and-Probe method



Total lepton uncertainty:

10 MeV (muon) and 14 MeV (electron)

Hadronic recoil corrections

Calibration relies on momentum balance in the transverse plane

- Match event activity in data and MC (Number of pile-up interactions, ΣE_{T})
- Residual recoil scale and resolution corrections based on parallel and perpendicular projections to Z direction

Uncertainty: 2.6/13.0 MeV with p_T^ℓ / m_T^W