Progress on the measurement of m_W

M. Boonekamp (IRFU)
on behalf of the ATLAS and CMS Collaborations

ATLAS : arXiv:1701.07240

CMS : CMS-PAS-SMP-14-007

Motivation

- The electroweak gauge sector of the Standard Model is constrained by three precisely know parameters:
  - The electromagnetic coupling constant : α = 1 / 137.035999139(31)
  - The muon decay constant : G_μ = 1.16637 (1) $\times$ 10^{-5} GeV^{-2}
  - The Z boson mass : m_Z = 91.1876 (21) GeV

- At leading order, m_W is expressed as

$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}, \quad \sin^2\theta_W = 1 - m_W^2/m_Z^2$$

Higher-order corrections, dominantly W and γ self-energies,

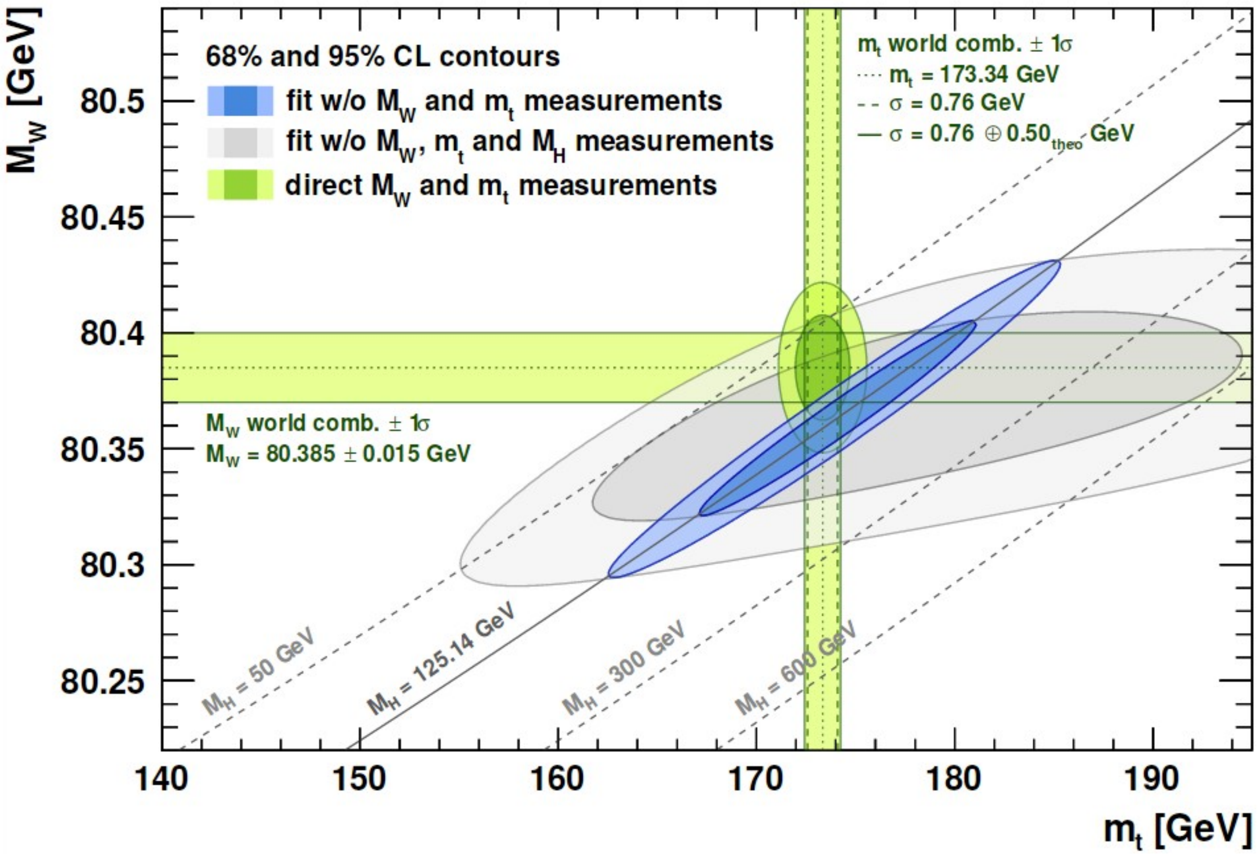
modify this relation to $$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$

Motivation

- Δr incorporates higher-order corrections from the SM and beyond:

$$\Delta r = \Delta\alpha - \tan\theta_W \Delta\rho(m_{top}) + \Delta r_{rem}^{SM}(m_{top}, m_H) + \ldots$$

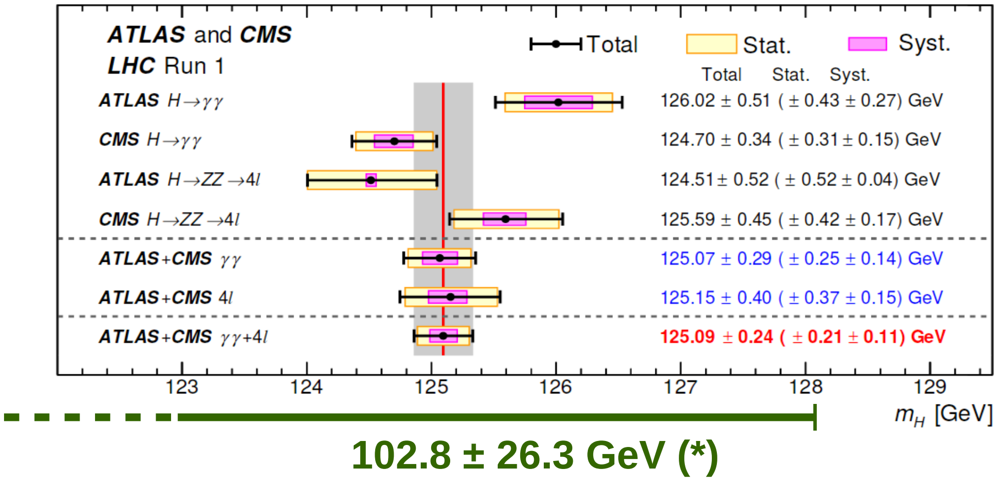
arXiv:1407.3792



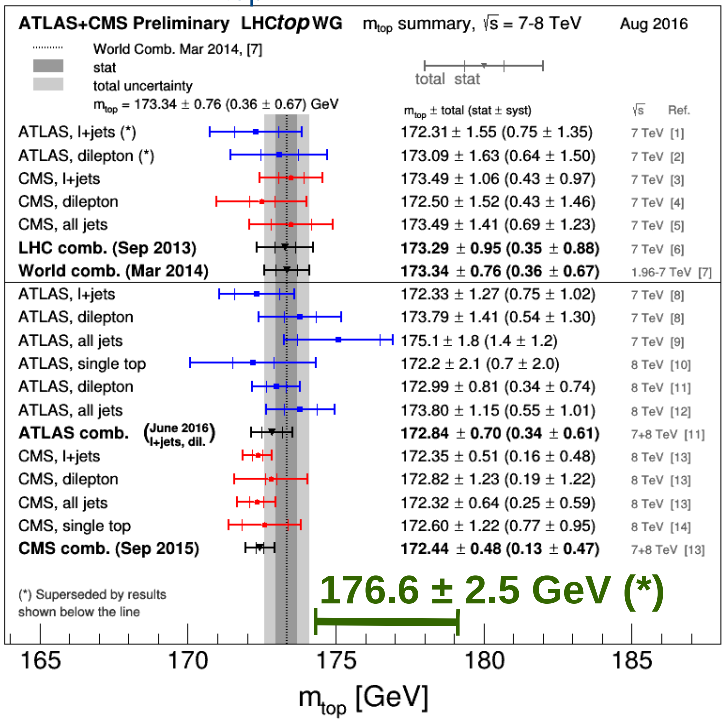
→ Consistency test of the SM, and a probe of BSM physics

Motivation

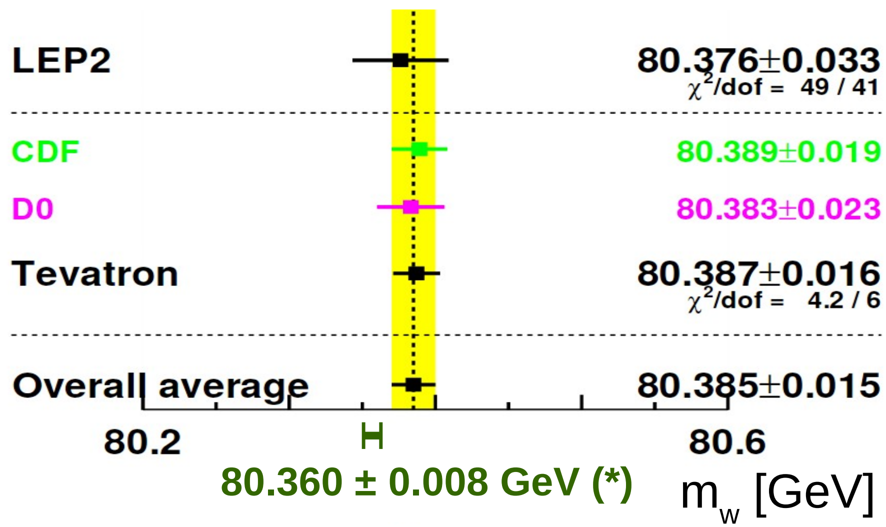
M_H 2014 – 2015, Run 1 (+CMS Run 2!)



m_{top} 2012 – 2016



m_W ≤ 2012 (!)



	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

(*) arXiv:1608.01509

→ m_W has strongest constraining power. Slow progress!

TeVatron results and LHC prospects

arXiv:1203.0293

Source	m_T	p_T^e	$\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$(Experimental)	18	20	24
W Production and Decay Model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$(Model)	13	14	17
Systematic Uncertainty (Experimental and Model)	22	24	29
W Boson Statistics	13	14	15
Total Uncertainty	26	28	33

arXiv:1203.0275

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

D0 5.3 fb^{-1} 1.7×10^6 events, $W\rightarrow e\nu$

$$M_W = 80.375 \pm 0.011\ (\text{stat.}) \pm 0.020\ (\text{syst.})\ \text{GeV}$$
$$= 80.375 \pm 0.023\ \text{GeV}.$$

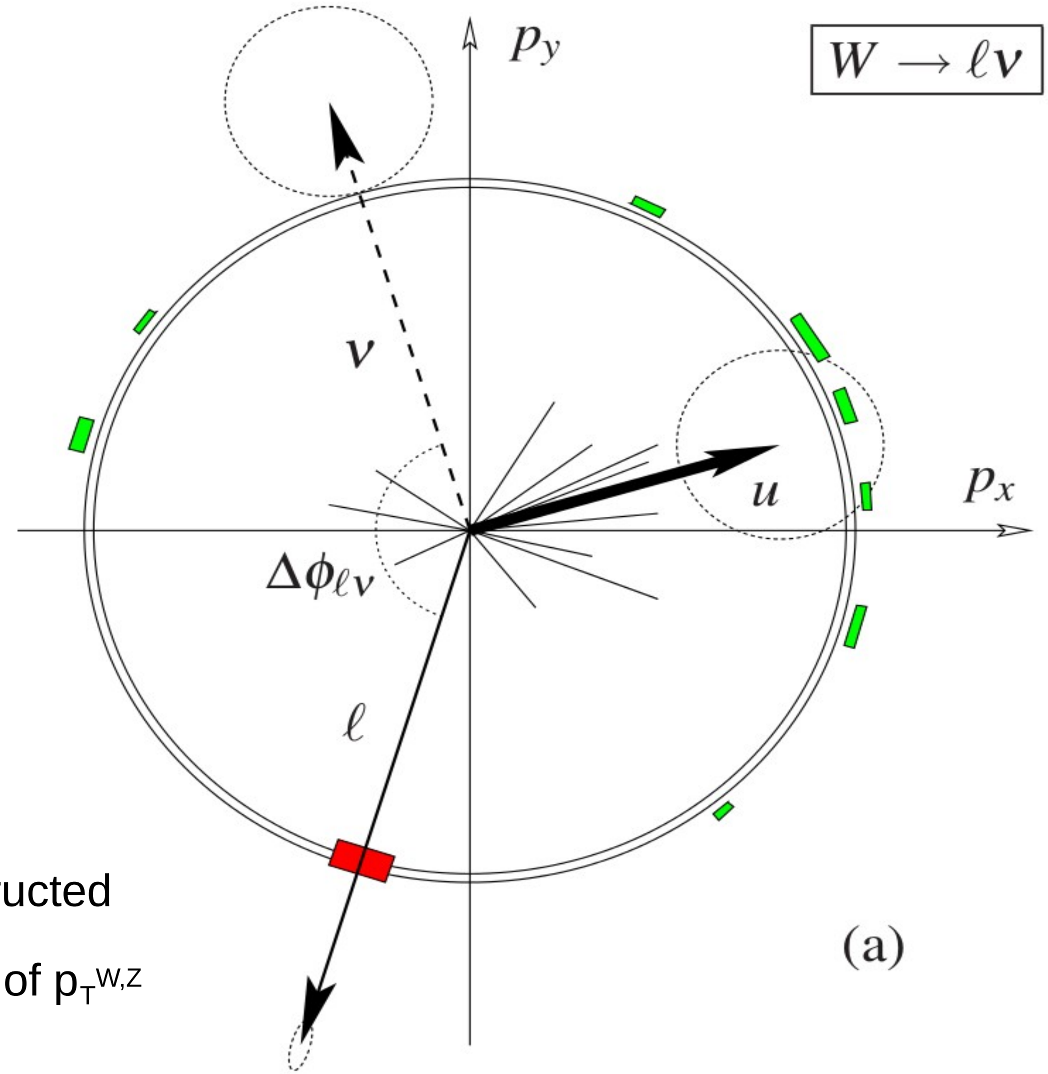
CDF 2.2 fb^{-1} 1.1×10^6 events, $W\rightarrow e\nu,\mu\nu$

$$M_W = 80\,387 \pm 12\ (\text{stat}) \pm 15\ (\text{syst})$$
$$= 80\,387 \pm 19\ \text{MeV}/c^2$$

Expected W samples at ATLAS and CMS ($W\rightarrow e\nu+\mu\nu$) :

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

Event representation



- Main signature :

  single electron or muon $\vec{p}_T^{\,l}$ p_T^{l}

- Recoil : sum of “everything else” reconstructed

  in the calorimeters or tracker; a measure of $p_T^{W,Z}$

  $$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$ + useful projections (see later). No explicit jet reconstruction!

- Derived quantities : $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$. $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$

Event selections

- Kinematic requirements
  - $p_T^l > 30$ GeV $p_T^{miss} > 30$ GeV
  - $m_T > 60$ GeV $u_T < 30$ GeV
- Measurement categories :

W sample (ATLAS)

$\lvert\eta_\ell\rvert$ 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	7.8 M events
$W^- \to \mu^-\bar{\nu}$	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	5.9 M events
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525	

W-like sample (from $Z \to \mu\mu$, CMS)

W-like muon : $|\eta|<0.9$, $p_T^l > 30$ GeV

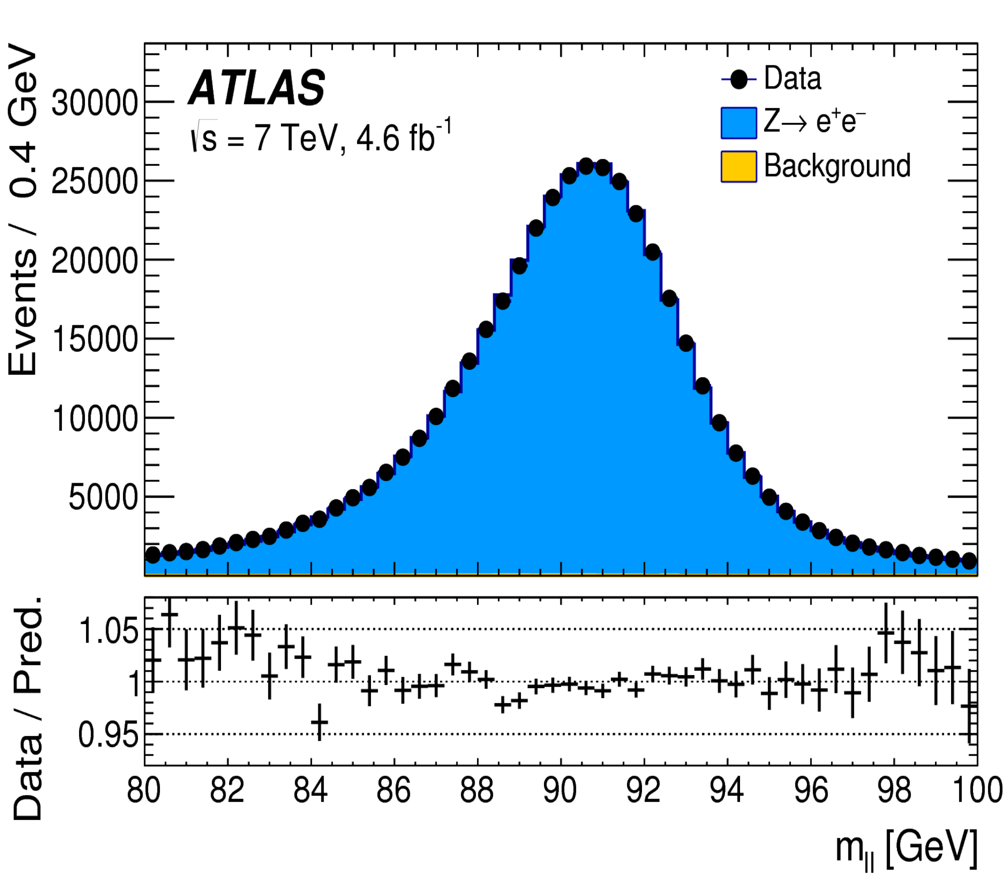
W-like "neutrino" : $|\eta|<2.1$, $p_T^l > 10$ GeV

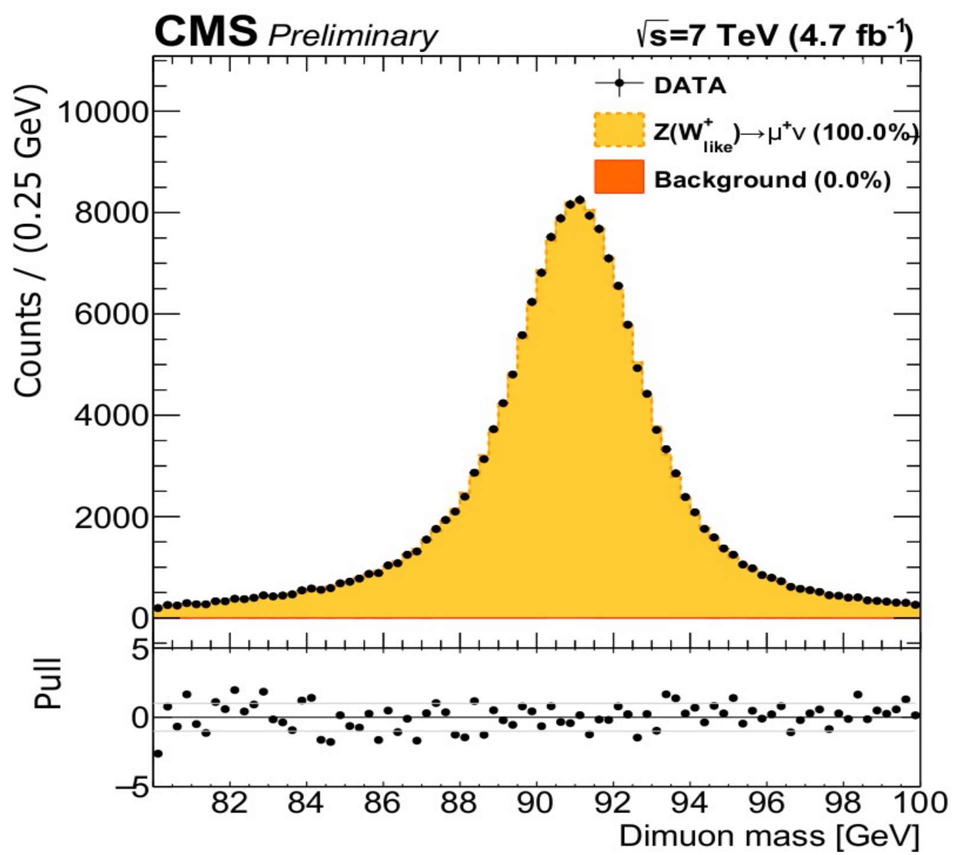
$u_T < 15$ GeV

→ 181 k events for each charge

Analysis overview

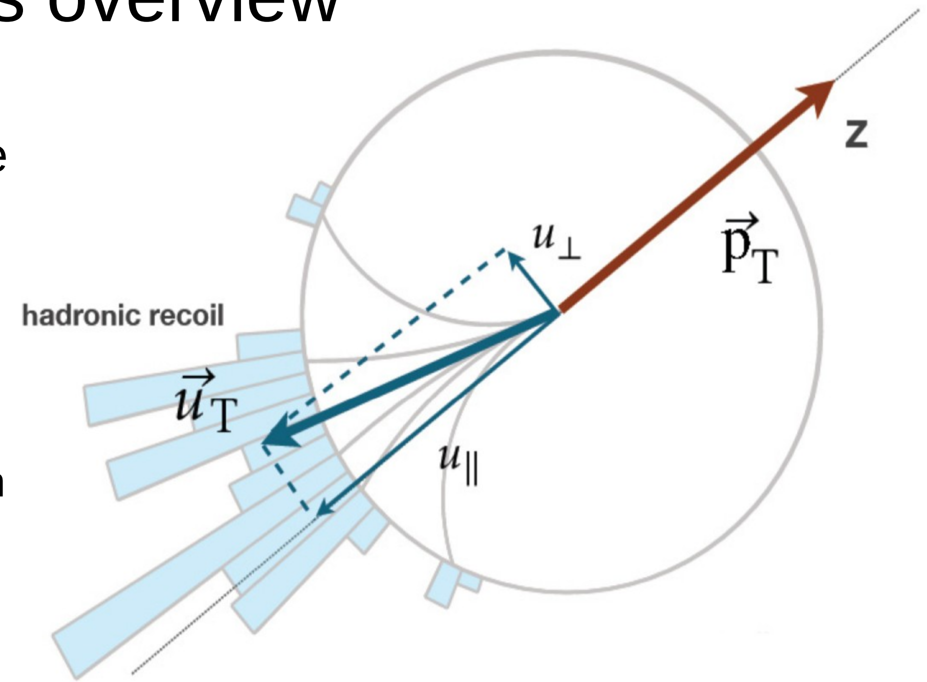
- Lepton calibration : exploit known resonances; typically Z, J/ψ → ll
  - "known" == precisely known mass + accurate theoretical modeling of the resonance (FSR!)

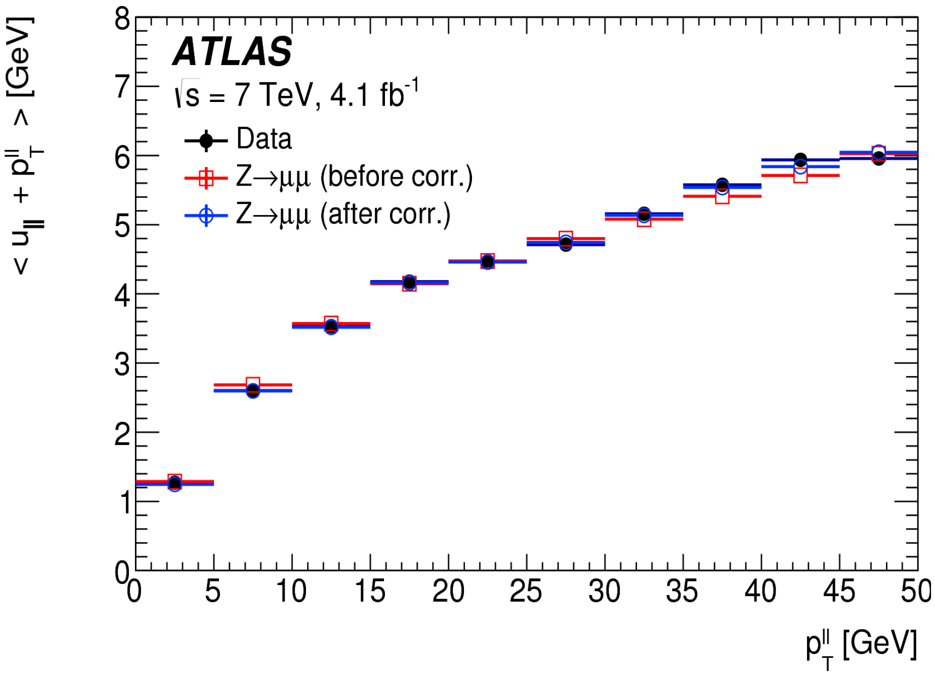


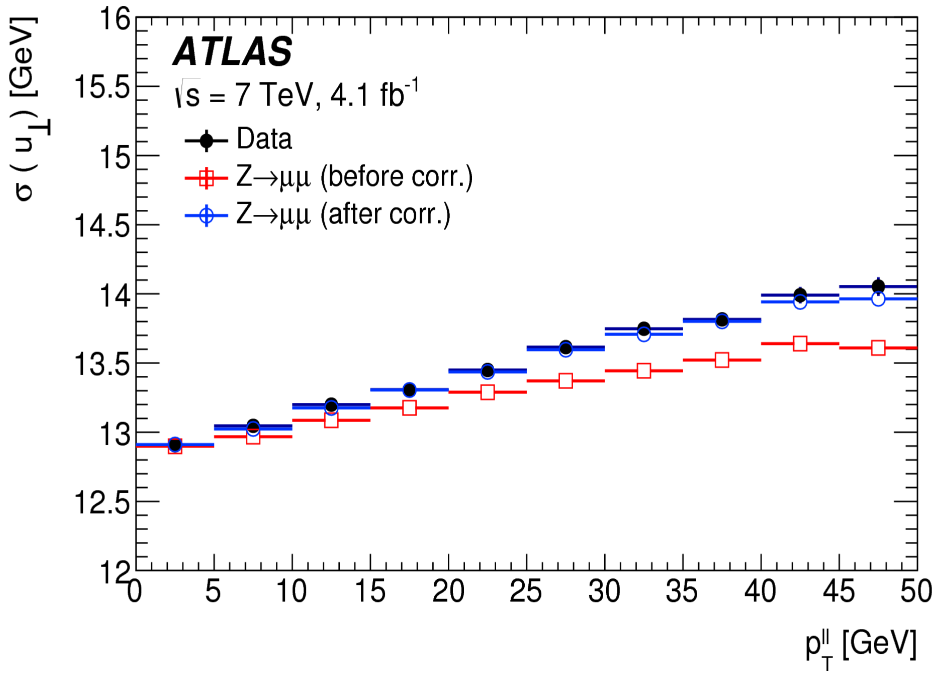


Analysis overview

- Recoil calibration : momentum balance in the transverse plane
- ATLAS : calorimeter clusters
  - Good response, sub-optimal resolution
  - no pile-up mitigation



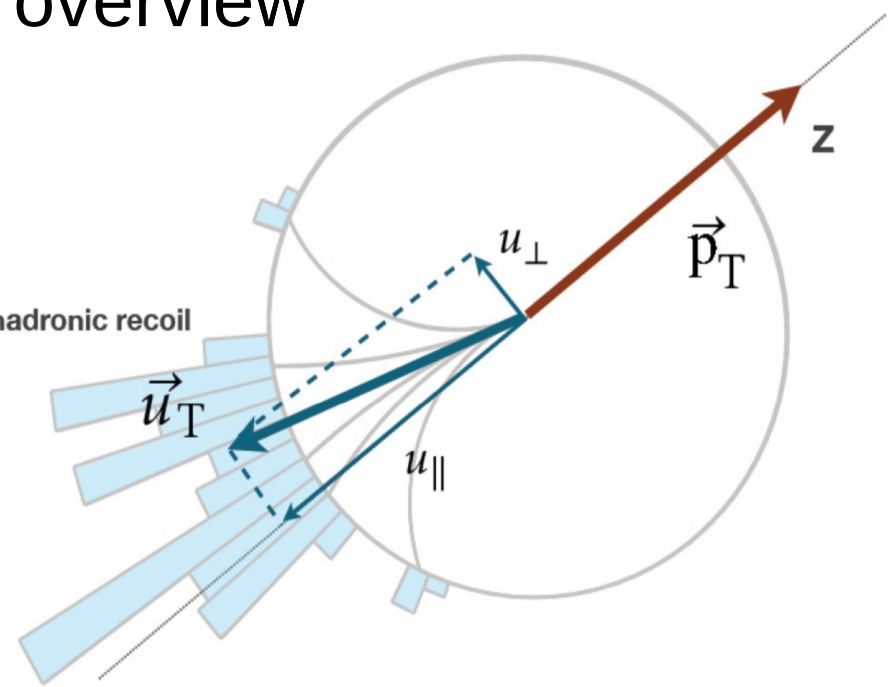


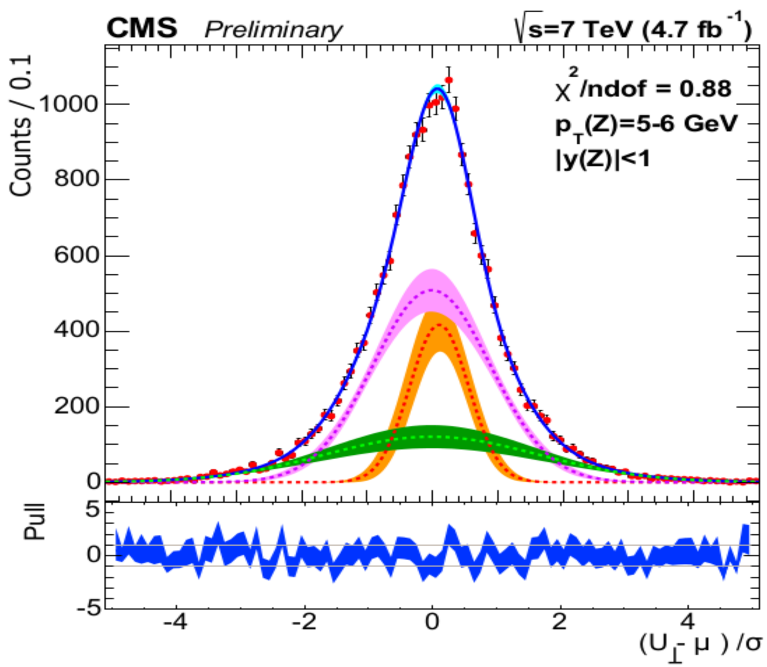


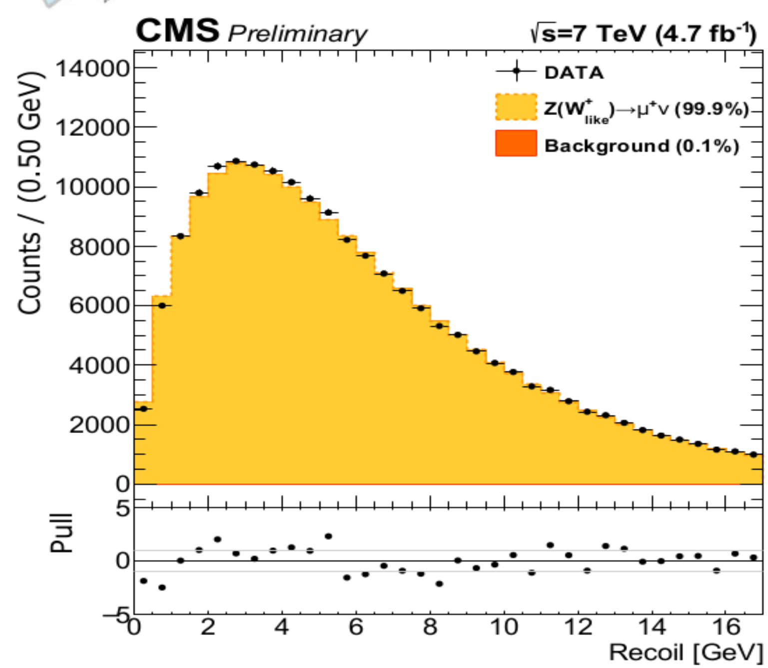
Analysis overview

- Recoil calibration : momentum balance in the transverse plane

- CMS : inner detector tracks
  - Weaker response; better resolution
  - Good pile-up robustness







Analysis overview

- Production and decay : theory + support measurements
  - EW corrections :
    - Baseline simulation : "improved Born" : use physical values for G_μ, m_Z, m_W, $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$
      + FSR (multiple photon emissions)
    - Optimal theory : NLO EW + FSR (multiple photon emissions)

    Full difference taken as systematic uncertainty
  - QCD :

Distribution		*Theory*	*Data*
Rapidity	→	PDFs	σ_W, σ_Z $d\sigma_W/d\eta_l$, $d\sigma_Z/dy_{ll}$
p_T	→	pQCD + p_T resummation	$d\sigma_Z/dp_T^Z$
Decay angle	→	Spin correlations	$A_i^Z(p_T, y)$

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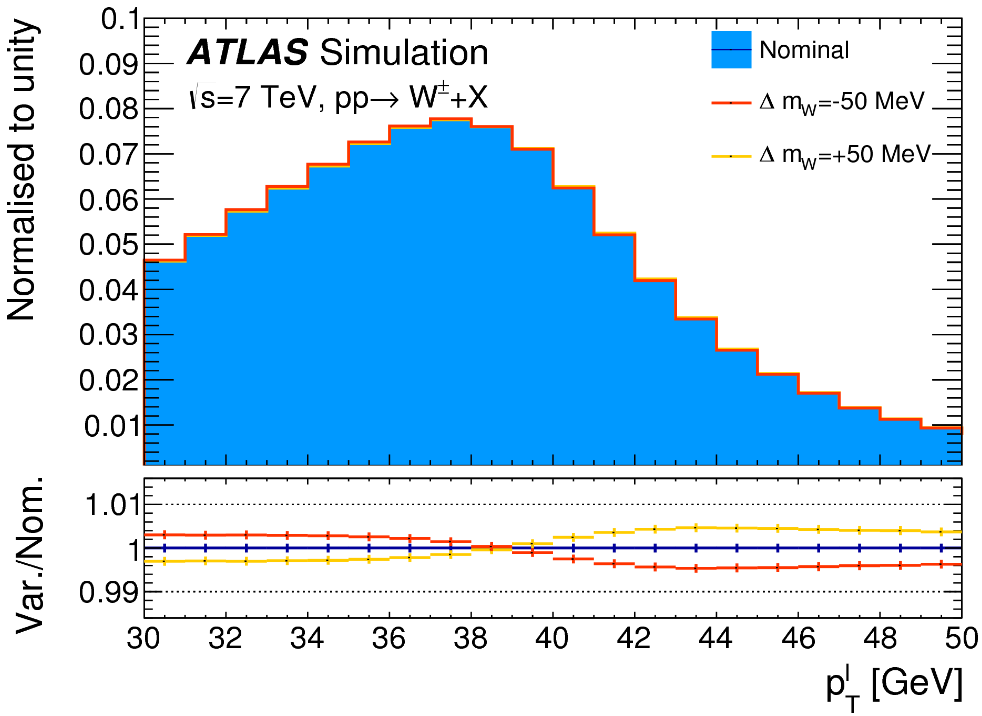
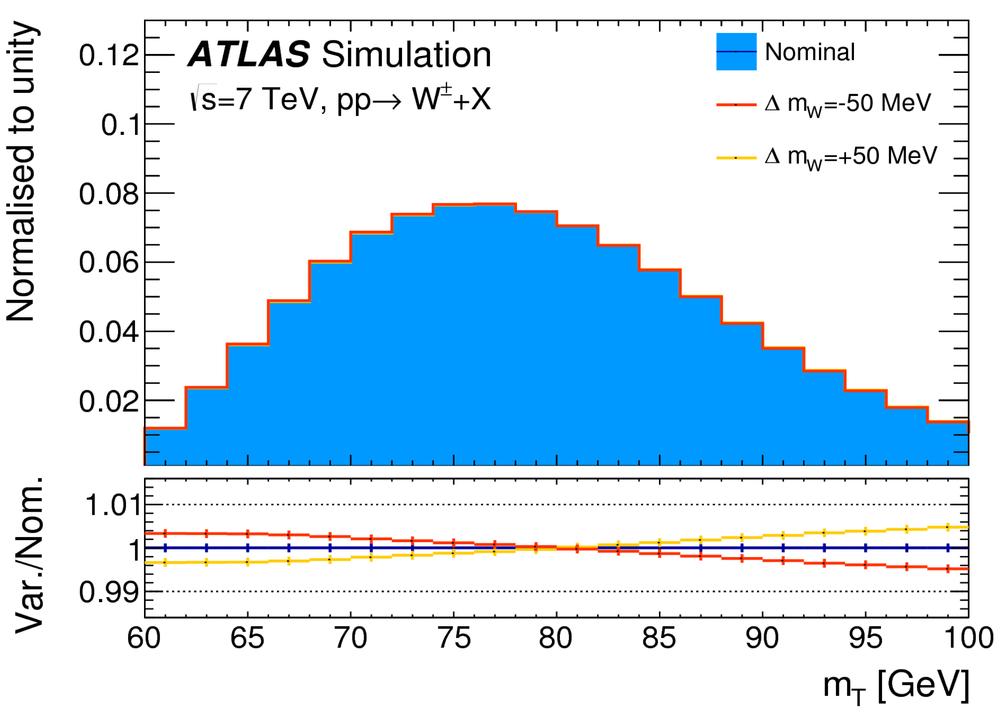
Decay angle	Spin correlations	$A_i^Z(p_T, y)$

Analysis overview

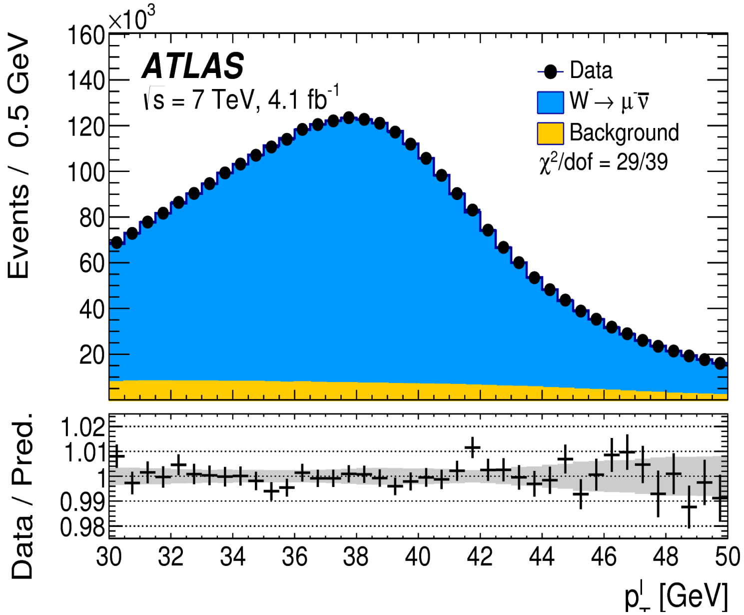
- Sensitive final state distributions : p_T^l , m_T , p_T^{miss}
- Signal distributions contructed from a single Monte Carlo sample, reweighting the boson invariant mass distribution, and compared to data. Mass determination by χ^2 minimization
- Resonance parametrisation : $$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$

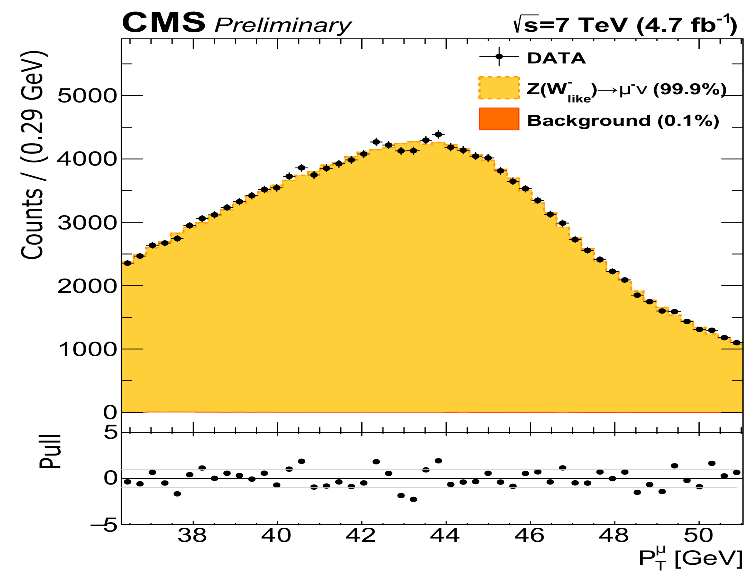




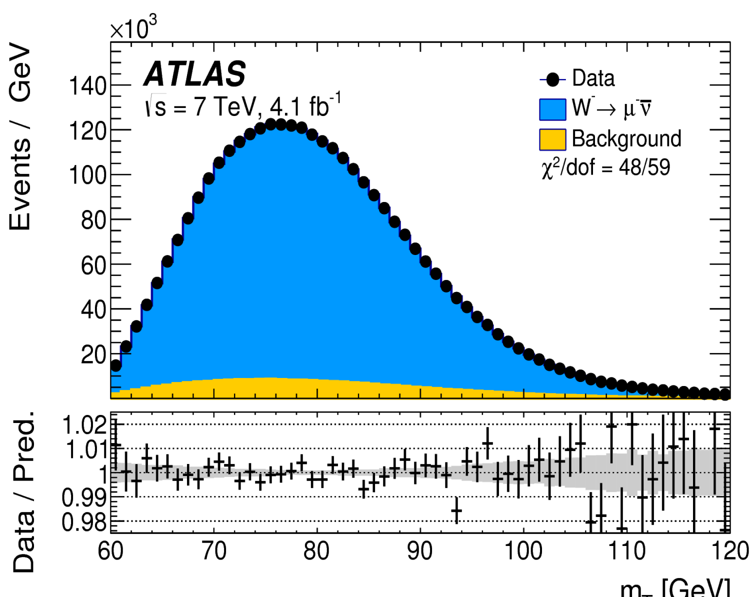
Mass-sensitive distributions

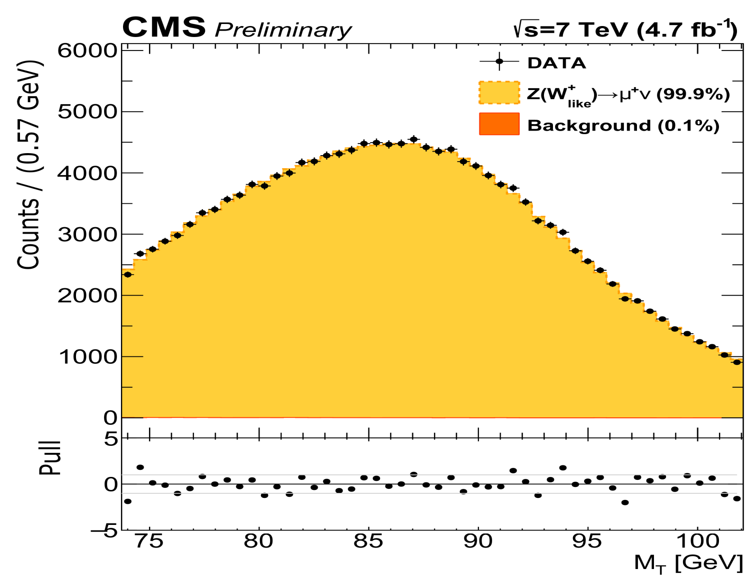
p_T





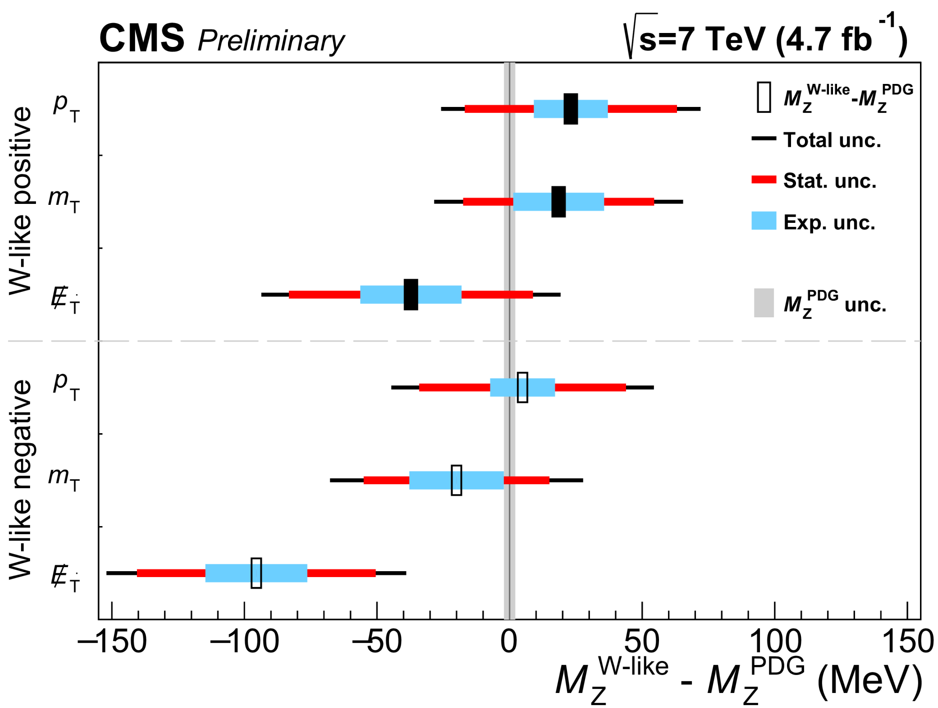
M_T

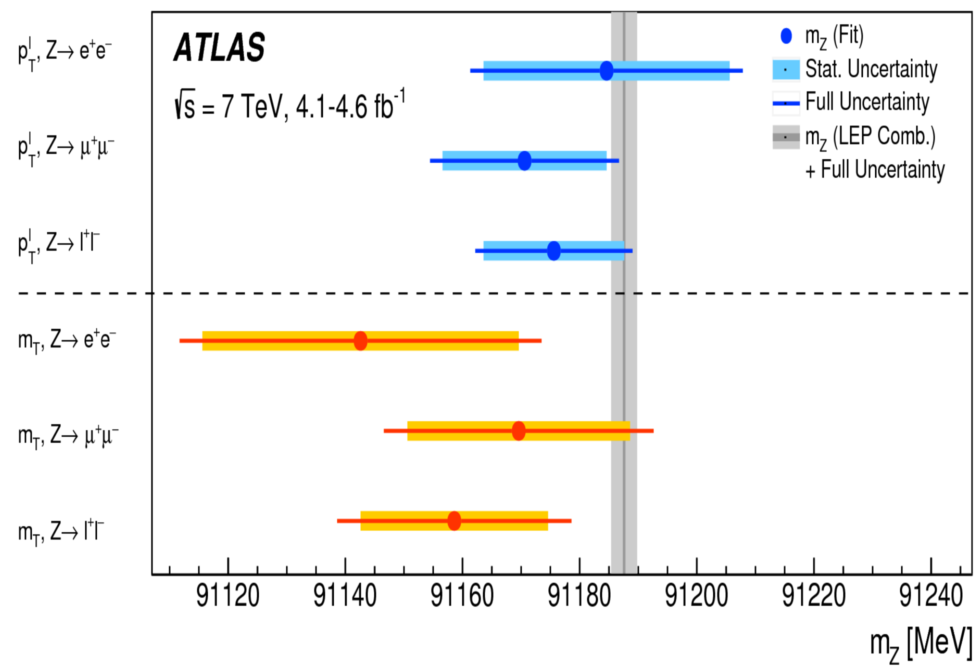




Cross checks using the Z sample

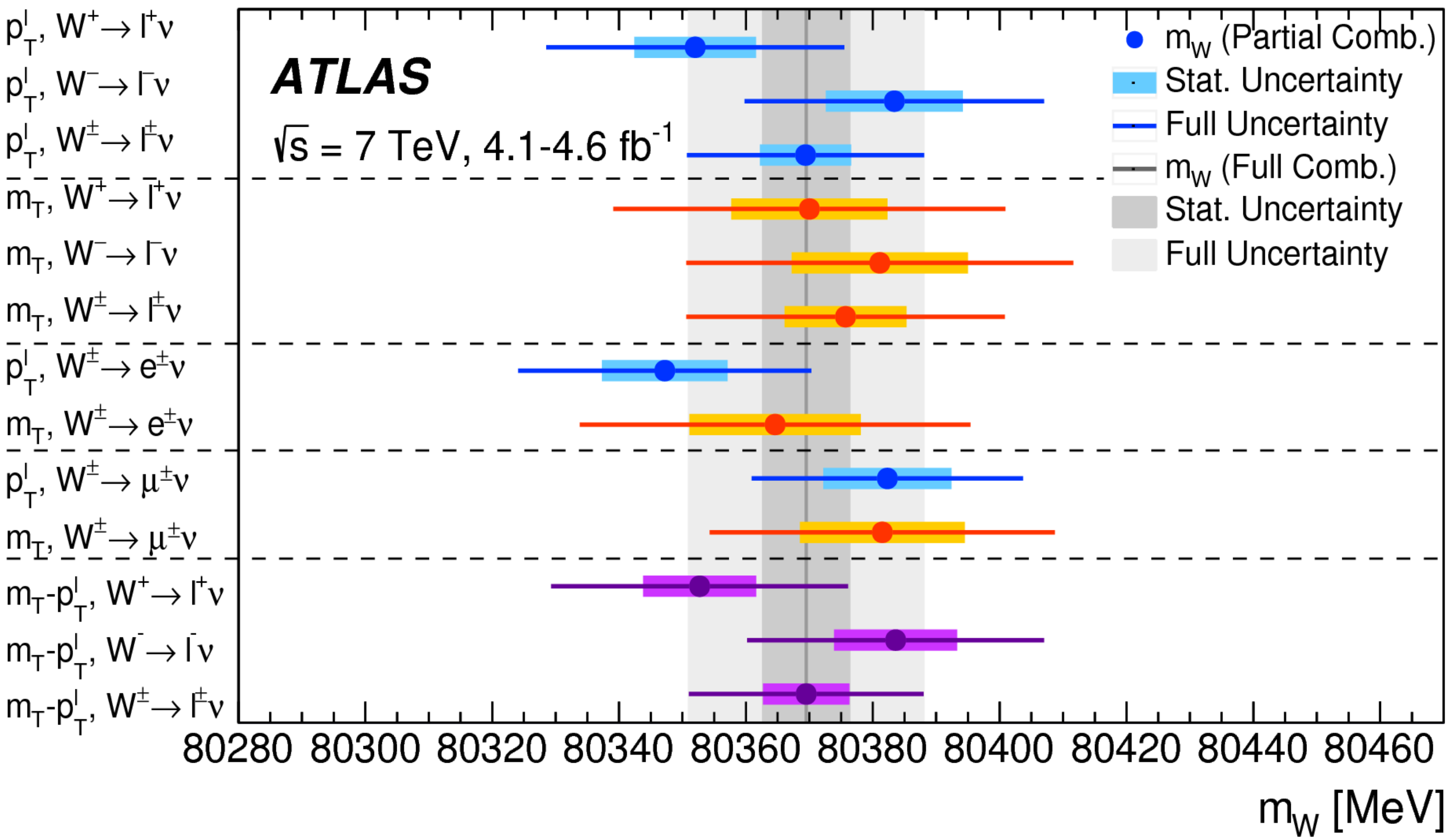
Z boson events can be used to test the analysis techniques, calibration procedures, …
Idea : reconstruct a Z event as a W, ie remove one lepton from the event and reconstruct transverse mass, missing E_T as in W production





Very useful exercise, but does not address several significant sources of uncertainty:
- experimental (W backgrounds; extrapolation of Z-based calibrations to W)
- W production model

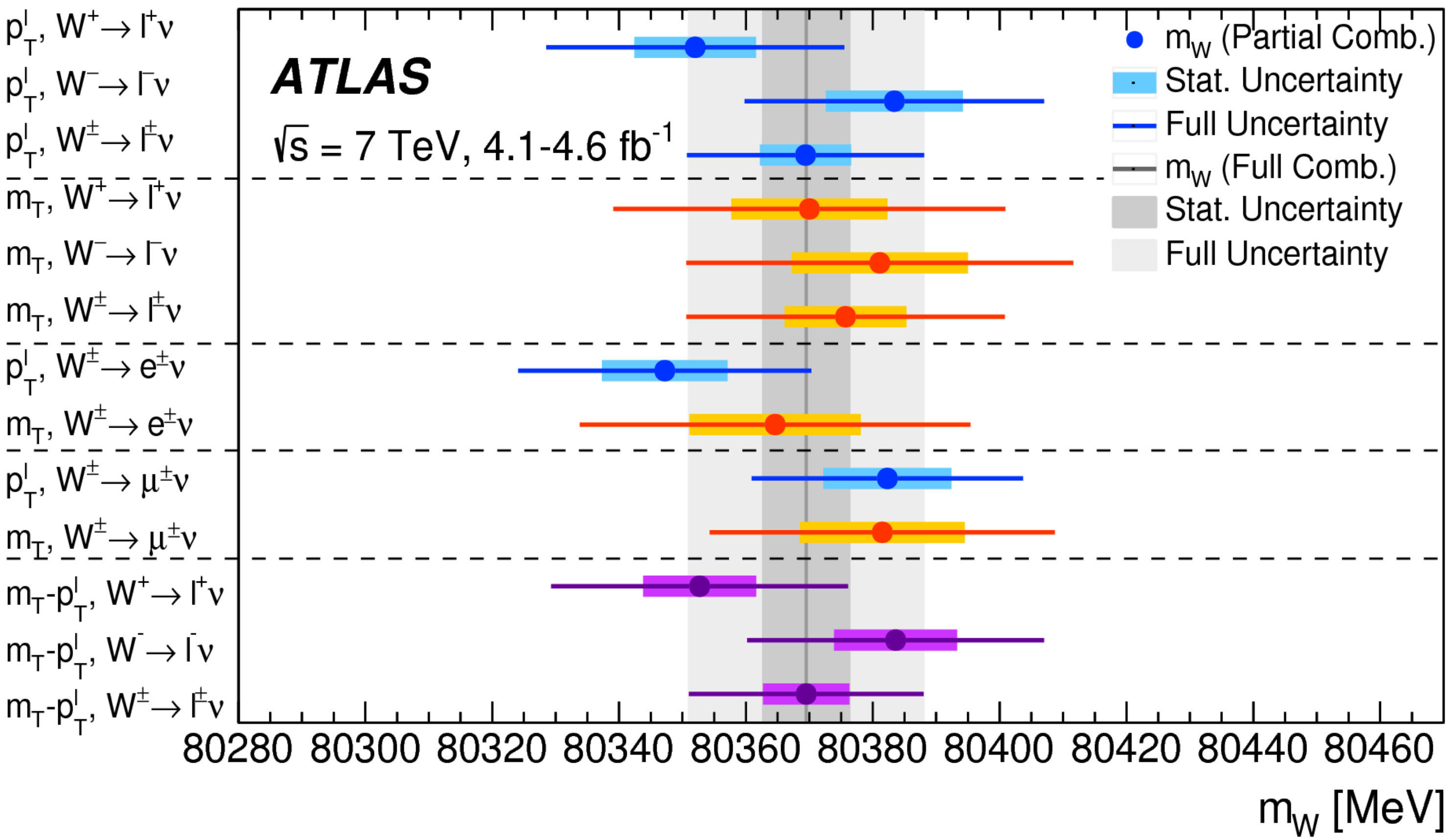
Results



$$m_W = 80.370 \pm 0.007\ (\text{stat.}) \pm 0.011\ (\text{exp.syst.}) \pm 0.014\ (\text{mod.syst.})\ \text{GeV}$$
$$= \underline{80.370 \pm 0.019\ \text{GeV}}$$

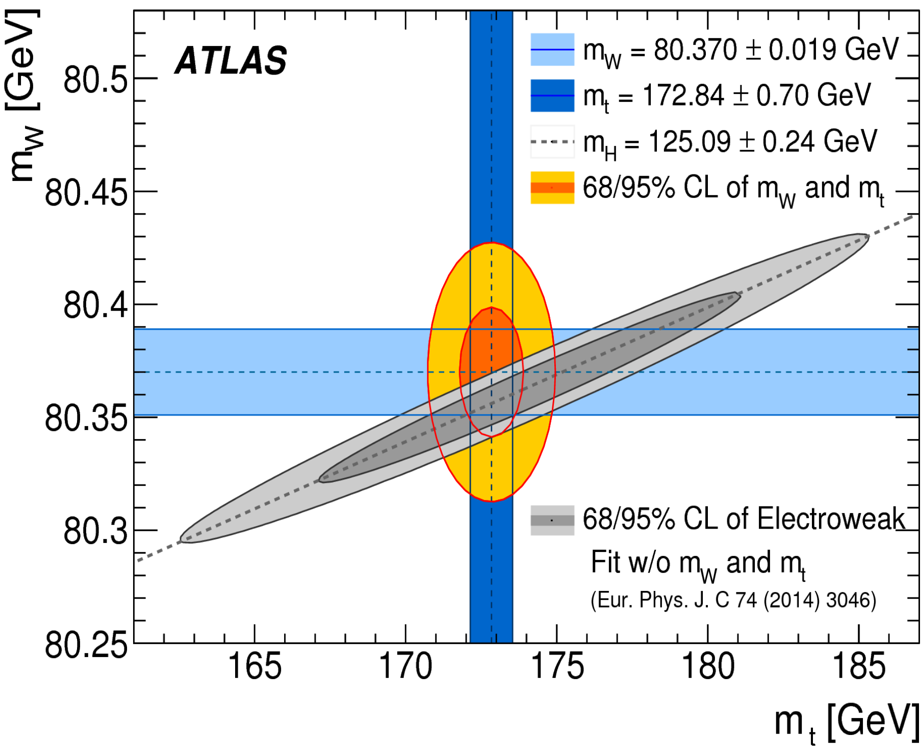
δm_W (mod.syst) ~ 6 (EW) $\oplus$ 8 (QCD) $\oplus$ 9 (PDF) MeV

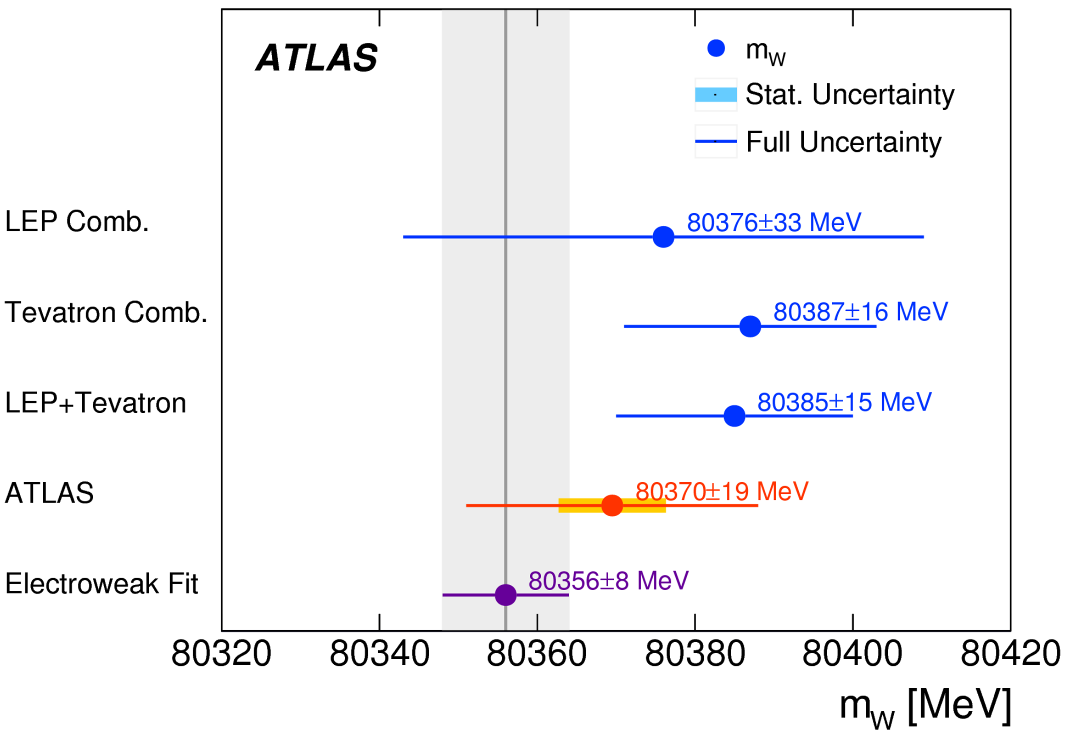
Results



$$m_{W+} - m_{W-} = -29 \pm 13\ (\text{stat.}) \pm 7\ (\text{exp.syst.}) \pm 24\ (\text{mod.syst.})\ \text{MeV}$$
$$= \underline{-29 \pm 28\ \text{MeV}}$$

Standard Model consistency



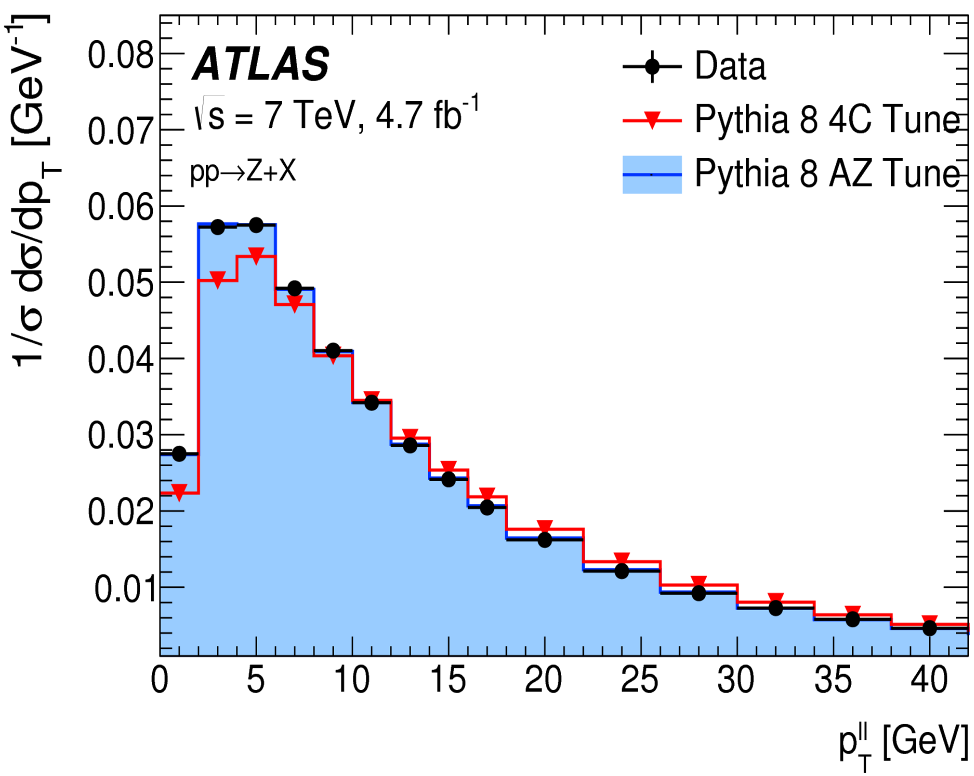


SM prediction for m_W vs m_t, assuming $m_H = 125.09 \pm 0.24$ GeV

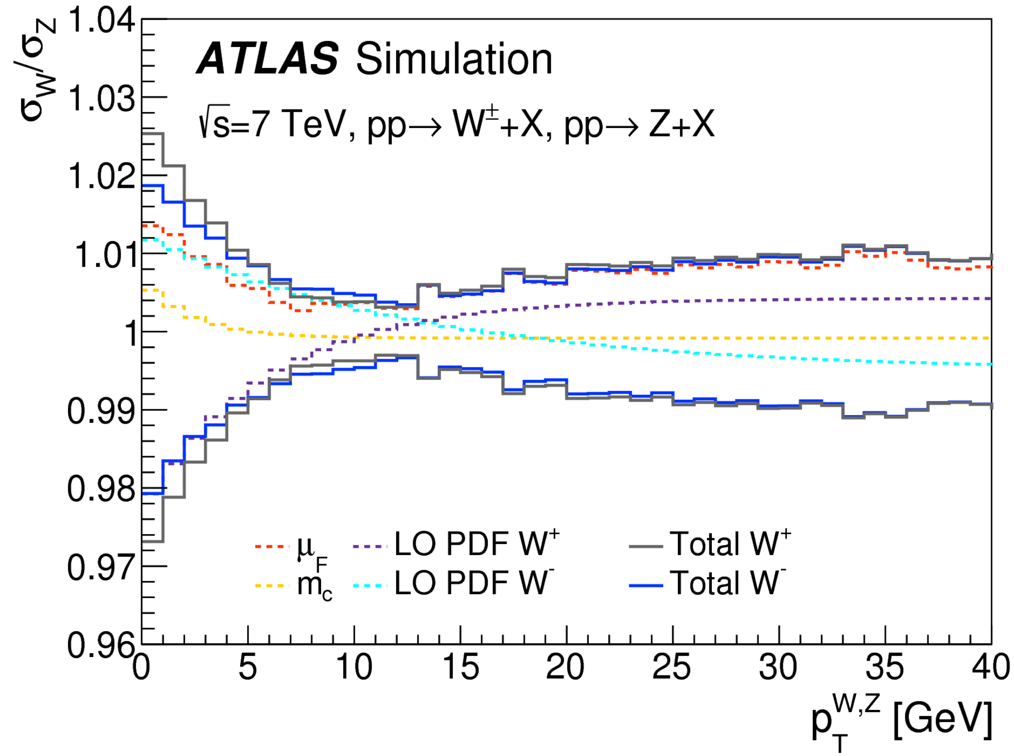
SM prediction for m_W, assuming
$m_H = 125.09 \pm 0.24$ GeV
$m_t = 172.84 \pm 0.70$ GeV

Selected topic : boson p_T distribution

- Traditional approach : fit predictions to Z data, apply to W
  - Pythia8 parton shower describes data best
  - Z → W extrapolation uncertainty : mostly heavy-quark mass effects and PDFs
    - For a more detailed discussion, cf talk by O.Arnaez tomorrow



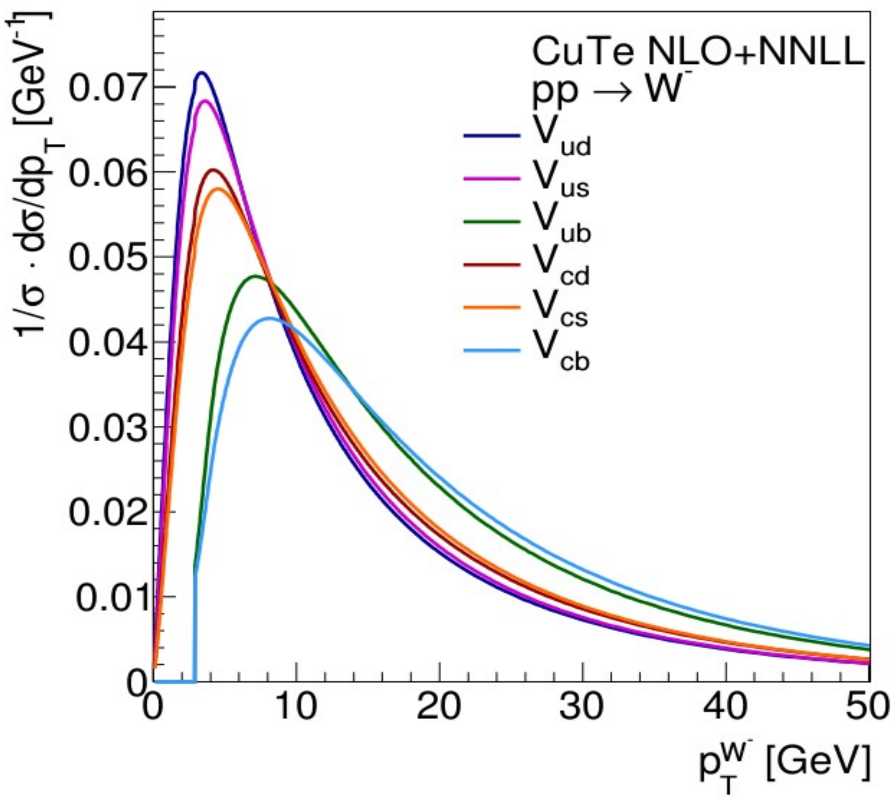
Tuned agreement ~0.5% for p_T^Z < 30 GeV

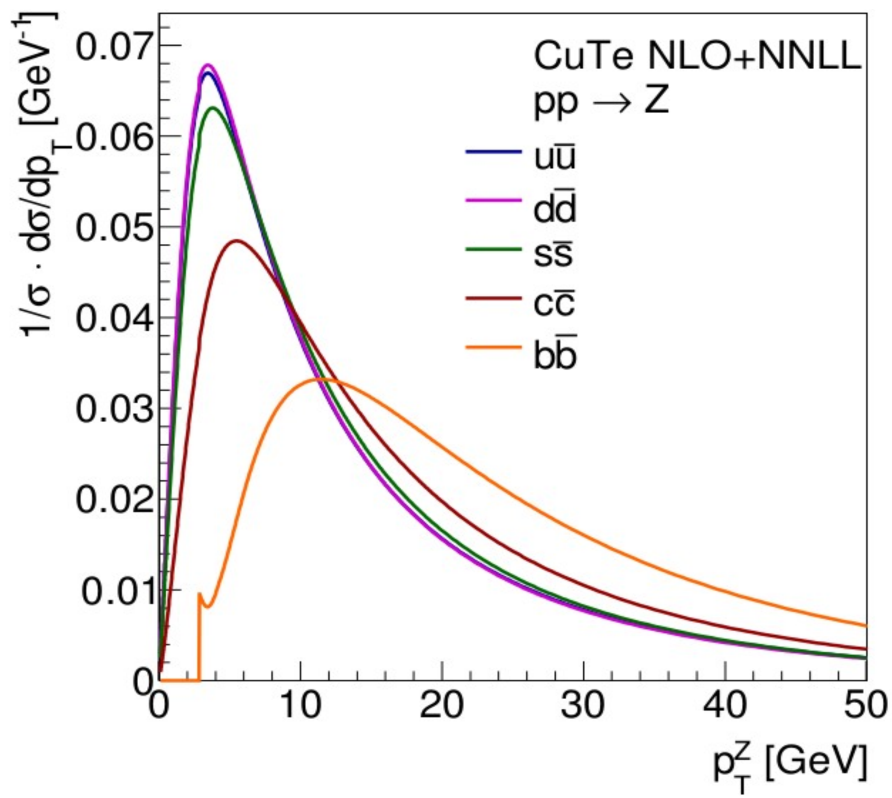


1-2% additional uncertainty on the prediction of $d\sigma/dp_T^W$

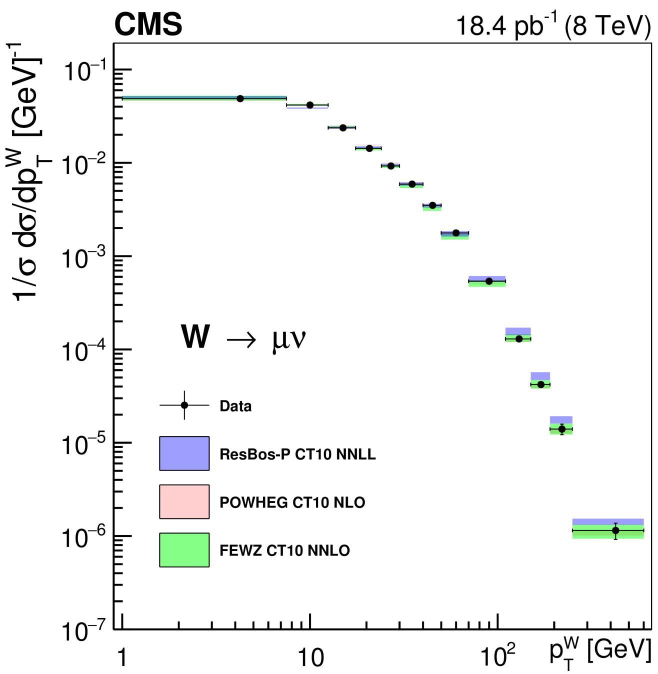
Boson p_T distribution

- Traditional approach : fit predictions to Z data, apply to W
  - Pythia8 parton shower describes data best
  - Z → W extrapolation uncertainty : mostly heavy-quark mass effects and PDFs
    - Highlight in particular the role of the strange quark density, probed via W/Z cross section ratios and W+c production





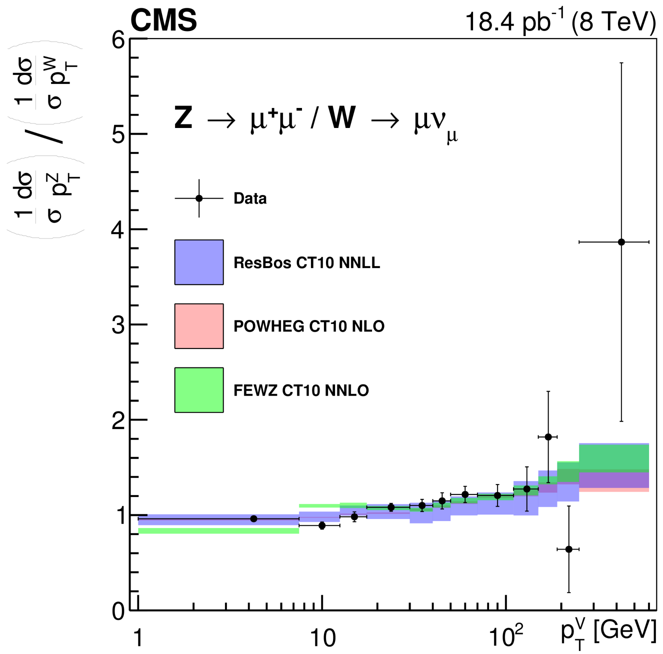
Alternative : direct masurement

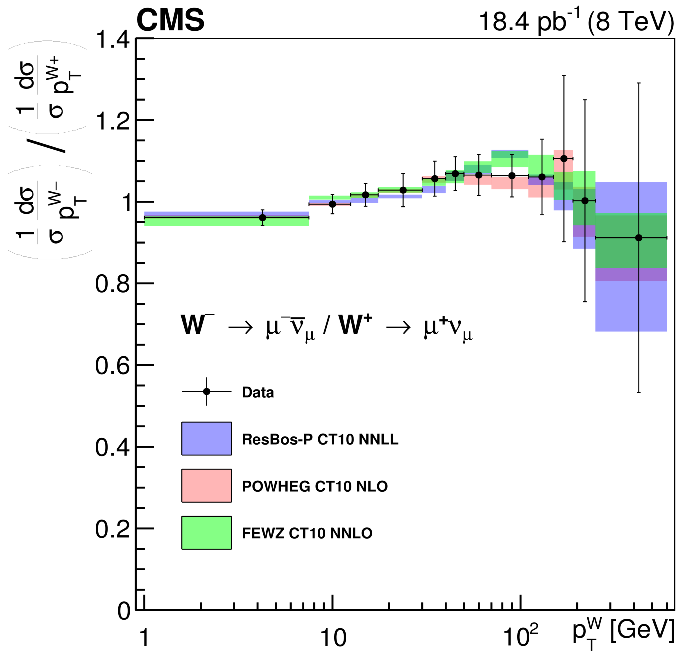


Unfolded measurement of the recoil p_T distribution.

CMS : 18.4 +- 0.5 pb^{-1} ; μ~4

Repeating these measurements would be useful:
Target : ~1% accuracy in ~5 GeV bins
Ideal sample : 100 pb^{-1} ; μ~1
Data taking would take about 1 week in Run2 conditions





Allows two important tests:
- Z → W extrapolation
- W$^+$/W$^-$ distribution ratio

Boson p_T distribution : ways forward

$$\frac{\partial \sigma_W^{\mathrm{True}}}{\partial p_{\mathrm{T}}} \sim \frac{\partial \sigma_W^{\mathrm{TH}}}{\partial p_{\mathrm{T}}}$$

2-5% (NNLO+NNLL)

$$\sim \frac{\partial \sigma_Z^{\mathrm{Exp}}}{\partial p_{\mathrm{T}}} \times \frac{\partial \sigma_W^{\mathrm{TH}} / \partial p_{\mathrm{T}}}{\partial \sigma_Z^{\mathrm{TH}} / \partial p_{\mathrm{T}}}$$

0.5% ⊕ 1-2% ? (NLL!)

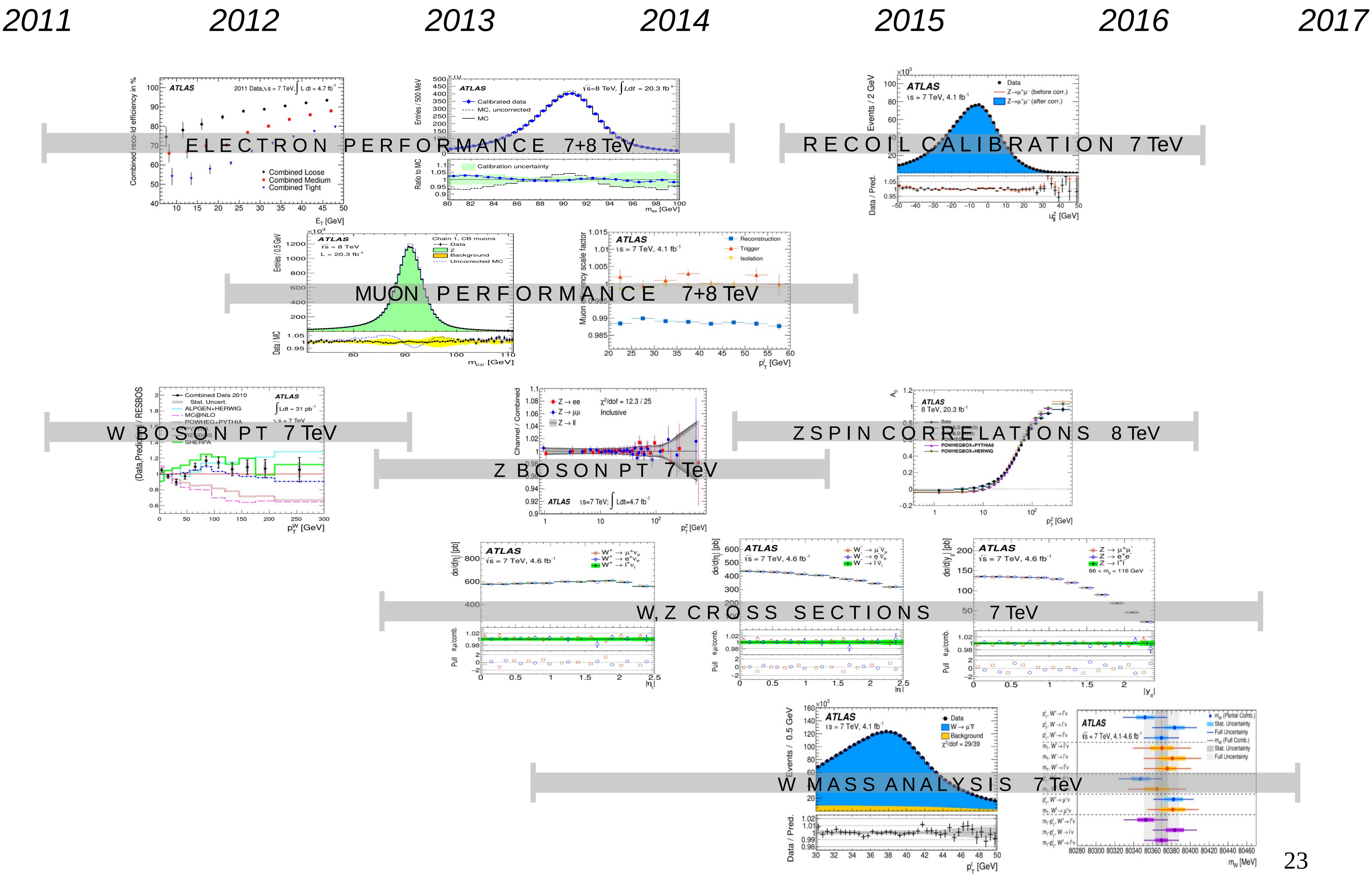
$$\sim \frac{\partial \sigma_W^{\mathrm{Exp}}}{\partial p_{\mathrm{T}}}$$

~1% ? (experimental)

Need progress!
(note : Tevatron counts no uncertainty here)

Need data – 100 pb^{-1} before the end of Run 2?

Inputs to the ATLAS analysis



Summary

- Results
  - First measurement of m_W at the LHC, by ATLAS : **m_W = 80.370 ± 0.019 GeV**
    - A competitive measurement, dominated by physics modeling uncertainties as expected
    - One of the projects that ties the entire body of ATLAS data togethe
  - A result from CMS is eagerly awaited – progressing well!
- Perspectives
  - World average : expect 11 – 13 MeV total uncertainty, depending on the correlations of PDF uncertainties at the Tevatron and LHC
  - **Fantastic W and Z samples made available by the LHC at 8 and 13 TeV**. Modelling uncertainties need to be reduced in order to fully exploit these data.

- The path to δm_W~5 MeV : modelling uncertainties
  - Electroweak corrections well understood; complete mixed QCDxEW corrections are the next theoretical milestone
  - Bottlenecks on PDF uncertainties, given always more constraints from data?
  - Boson p_T distribution : need dedicated theoretical studies and a direct measurement!

Back up

Main systematic 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										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	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

|η| comb e → ~15 MeV
μ → ~11 MeV

Strongly correlated

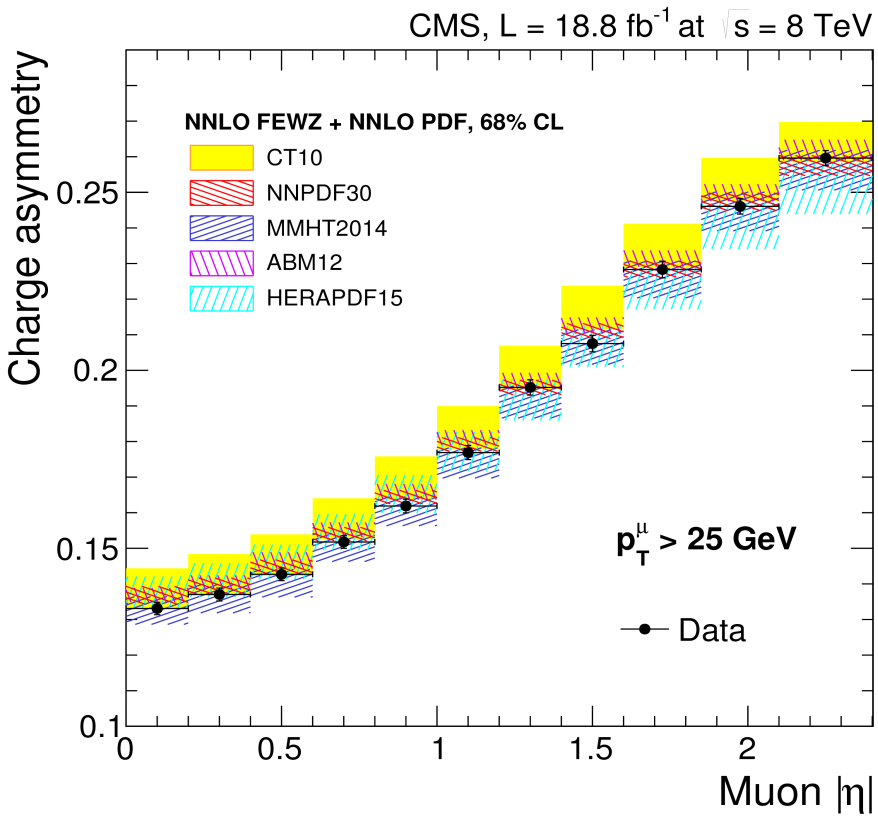
Strongly correlated

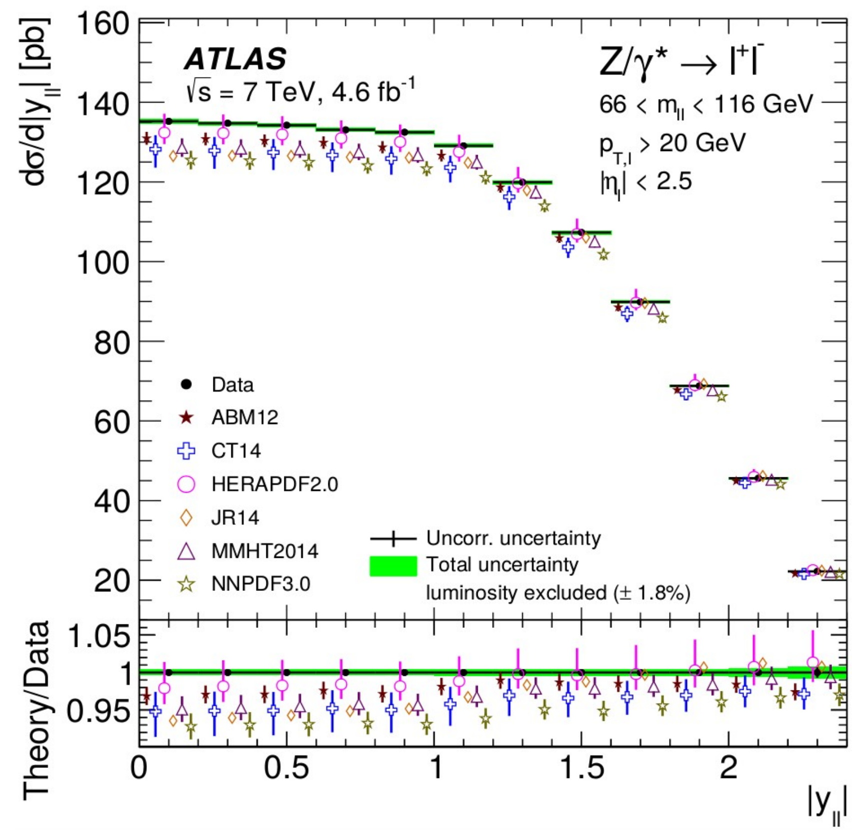
|η| comb. → ~14 MeV
W+/W- comb → ~8 MeV

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

Rapidity distribution

- Recent ATLAS and CMS results on W, Z cross section measurements:
  - arXiv:1612.03016
- Integrated and differential measurements with sub-% precision
- High sensitivity to PDFs; critical to validate the predictions used for the m_W analysis





Higher-order EW effects

- QED effects included in the simulation : ISR using Pythia8, and FSR using Photos
  - Negligible uncertainty
- Missing effects
  - NLO EW effects, evaluated in presence of QCD corrections. Available from Powheg-EW and Winhac (uncertainties from the latter).

    Impact on p_T and m_T distributions calculated in two schemes (α_0, G_μ); undertainty defined from the largest effect
  - QED emission of pairs : formally of higher order, but a significant additional source of momentum loss

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

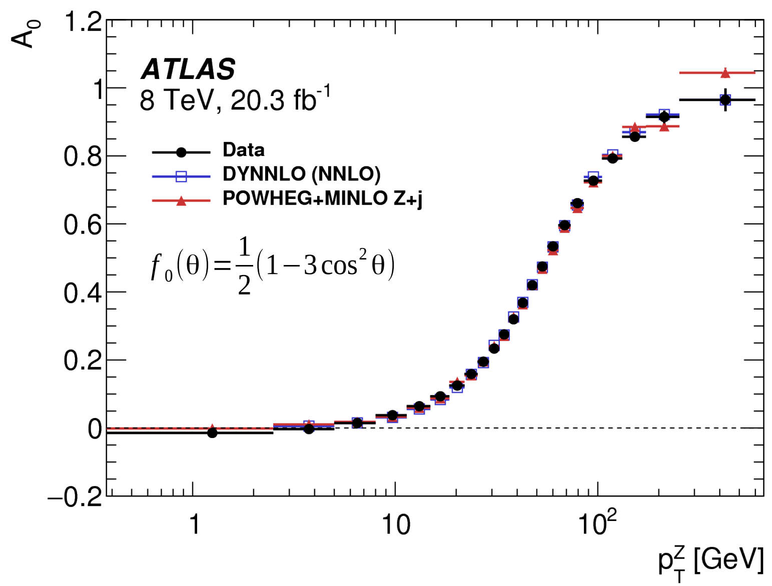
Angular distributions

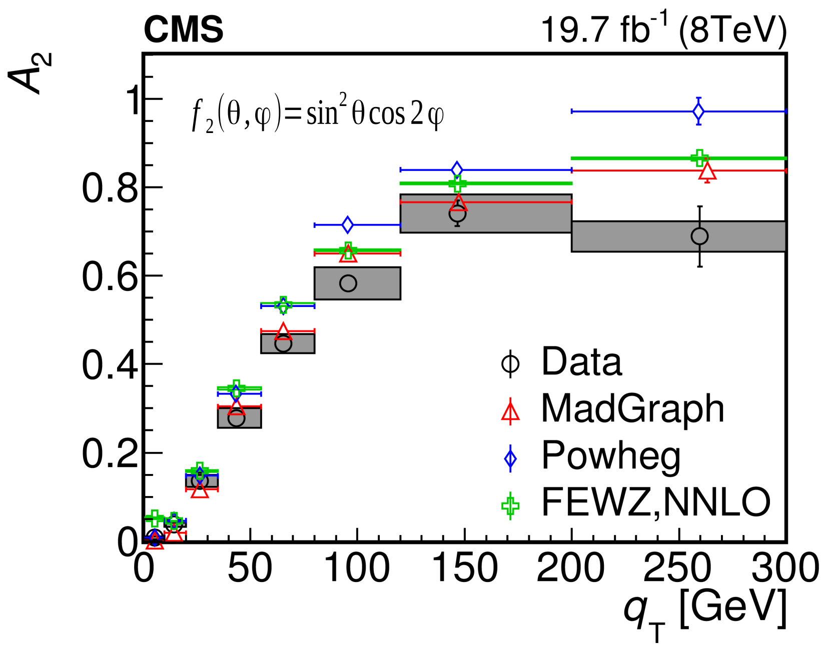
- Fully differential cross section for spin-1 boson production, to all orders:

$$\frac{d\sigma}{dm\,dy\,dp_T\,d\cos\theta\,d\varphi} = \frac{d\sigma}{dm\,dy\,dp_T}\left[(1+\cos^2\theta) + \sum_i A_i(m, p_T, y) f_i(\cos\theta, \varphi)\right]$$

how accurate is the theoretical description of the A_i coefficients?

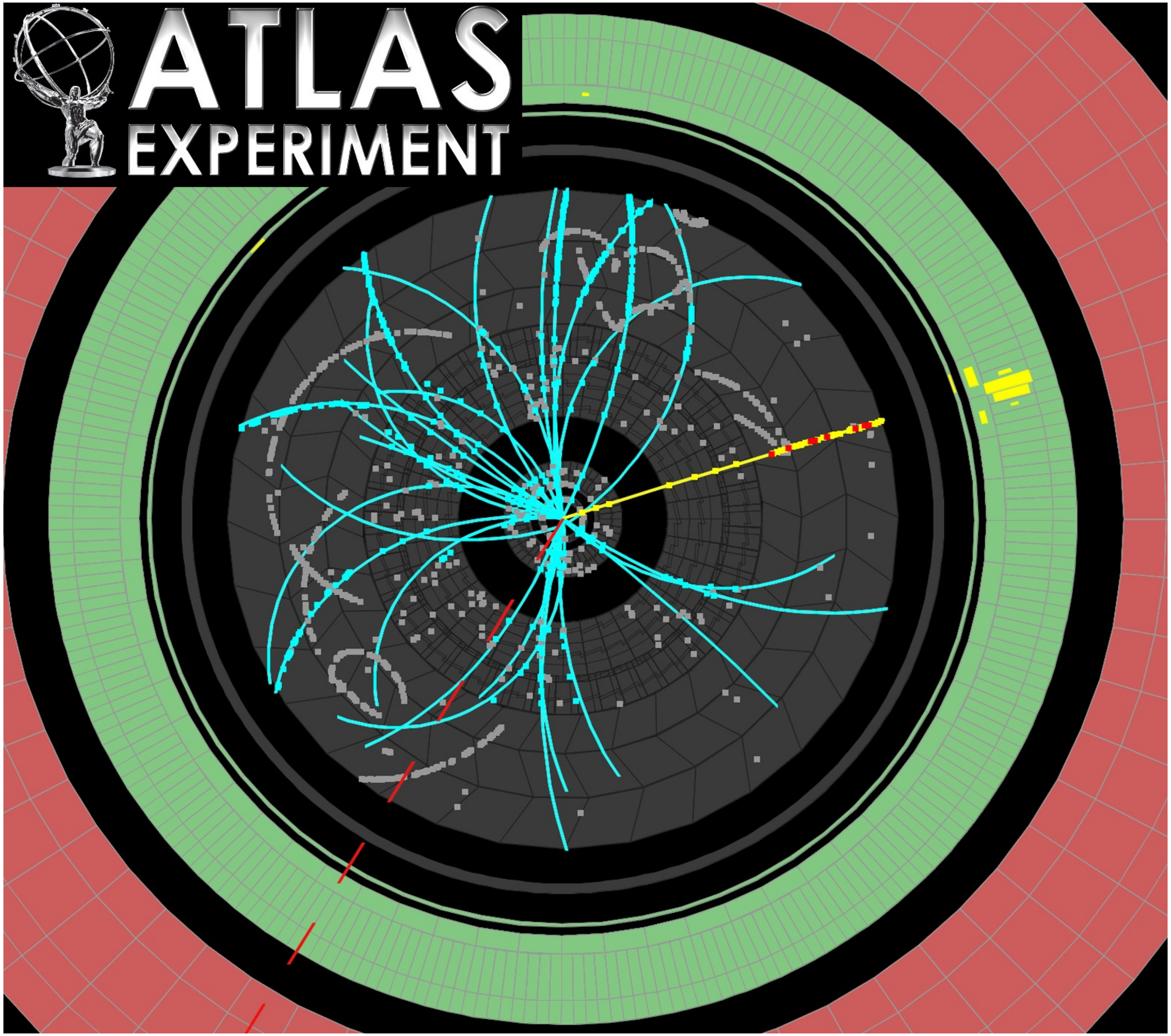
  – eg. fixed-order and resummed calculations disagree, at least at NLO (ResBos)





- The data validate fixed-order perturbative QCD, within the measurement uncertainties

W candidate events



W candidate events