Measurement of W boson mass at hadron colliders

- **This talk will provide an overview of the recently published measurement of m_W by ATLAS, together with a comparison between the ATLAS and CMS experimental systematics based on Z events measured as if they were W decays**

- **First measurement of m_W at the LHC: quick overview of results**
- **The main challenges at the LHC**

→ historical interlude

- **The modelling of p_T^W and the issues related to using the Z as a reference**

→ experimental interlude

- **What next? Questions for theory**

Important caveat: it is impossible to cover all the subtle points about measuring m_W at the LHC (even in a 90' seminar), so only a few topics will be covered here. See back-up slides for more details.

Precision measurements in the EW sector at the LHC

- At this conference, the word precision has different meanings in different areas (note that mass measurements are a special case):
  - It means sub-percent precision in DY and in some aspects of flavour physics in LHCb
  - It means a few percent at best still for top physics
  - It means 10-40% for Higgs physics (eg couplings), at least for quite a while
- It is not a surprise therefore that DY measurements are the most demanding in terms of theoretical accuracy (far more than Higgs!).
- In a nutshell, there are two key difficulties we are confronted with:

a) The lack of a MC generator tool for DY production which would include N...NLO+N…NLL QCD (and EW/QED) calculations, perfectly matched and merged to PS, with a UE model reproducing the data

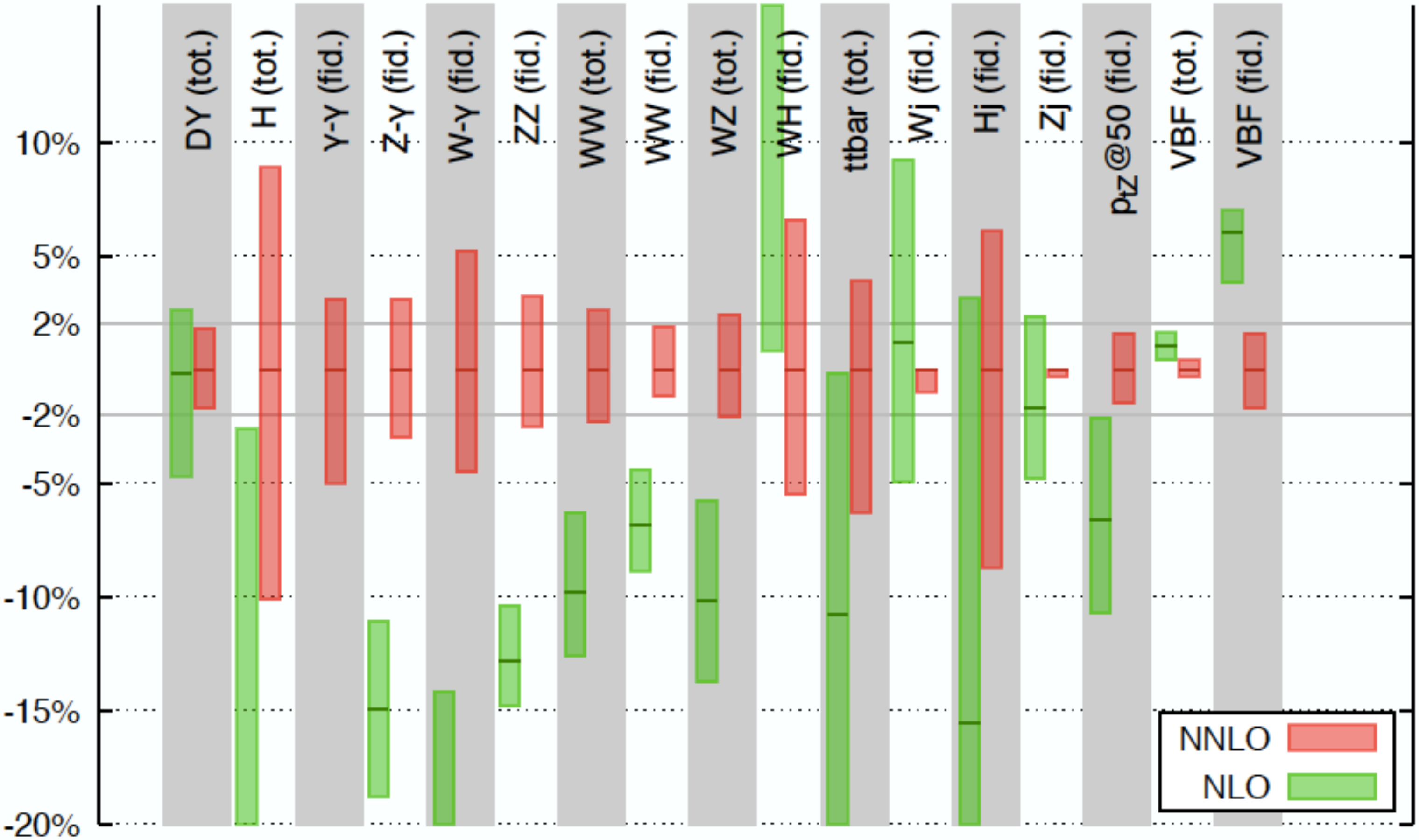
b) The complexity of dealing with a large number of sources of theoretical uncertainty which are not always reliable nor stable

Can we be reasonably certain that full calculation would fall within red bands below?

More importantly, how can we be sure that this would be the case after acceptance cuts, which eg for searches select only small fraction of events?

WHAT PRECISION AT NNLO?

G. Salam



•D. Froidevaux, CERN

Lepton and event selection for measurement of m_W

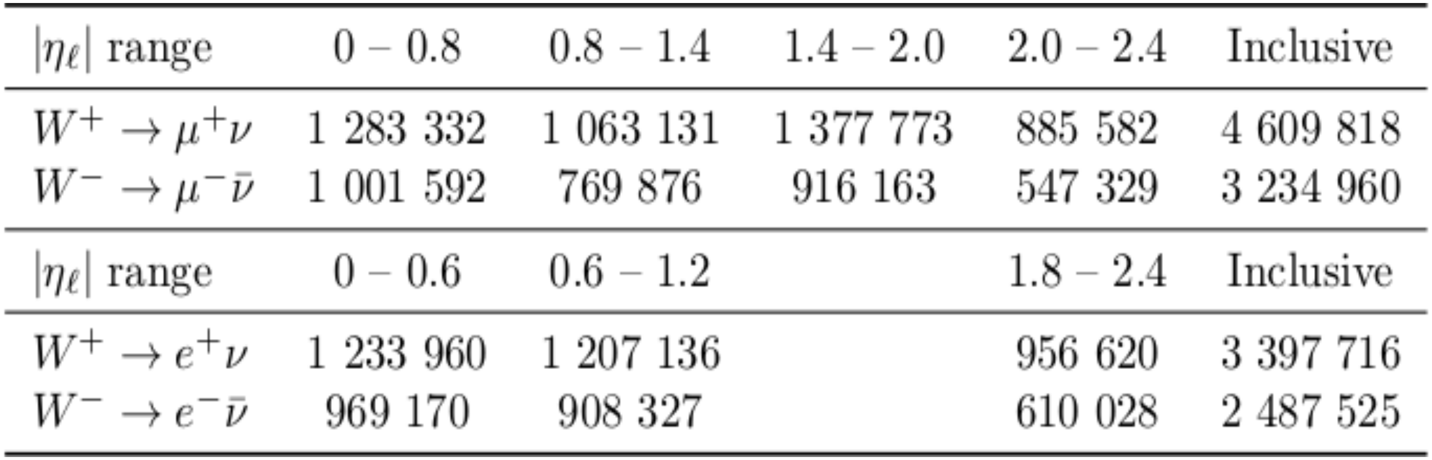
Lepton selections

- Muons : $|\eta| < 2.4$; isolated (track-based)
- Electrons : $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated

Kinematic requirements

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

Measurement categories :

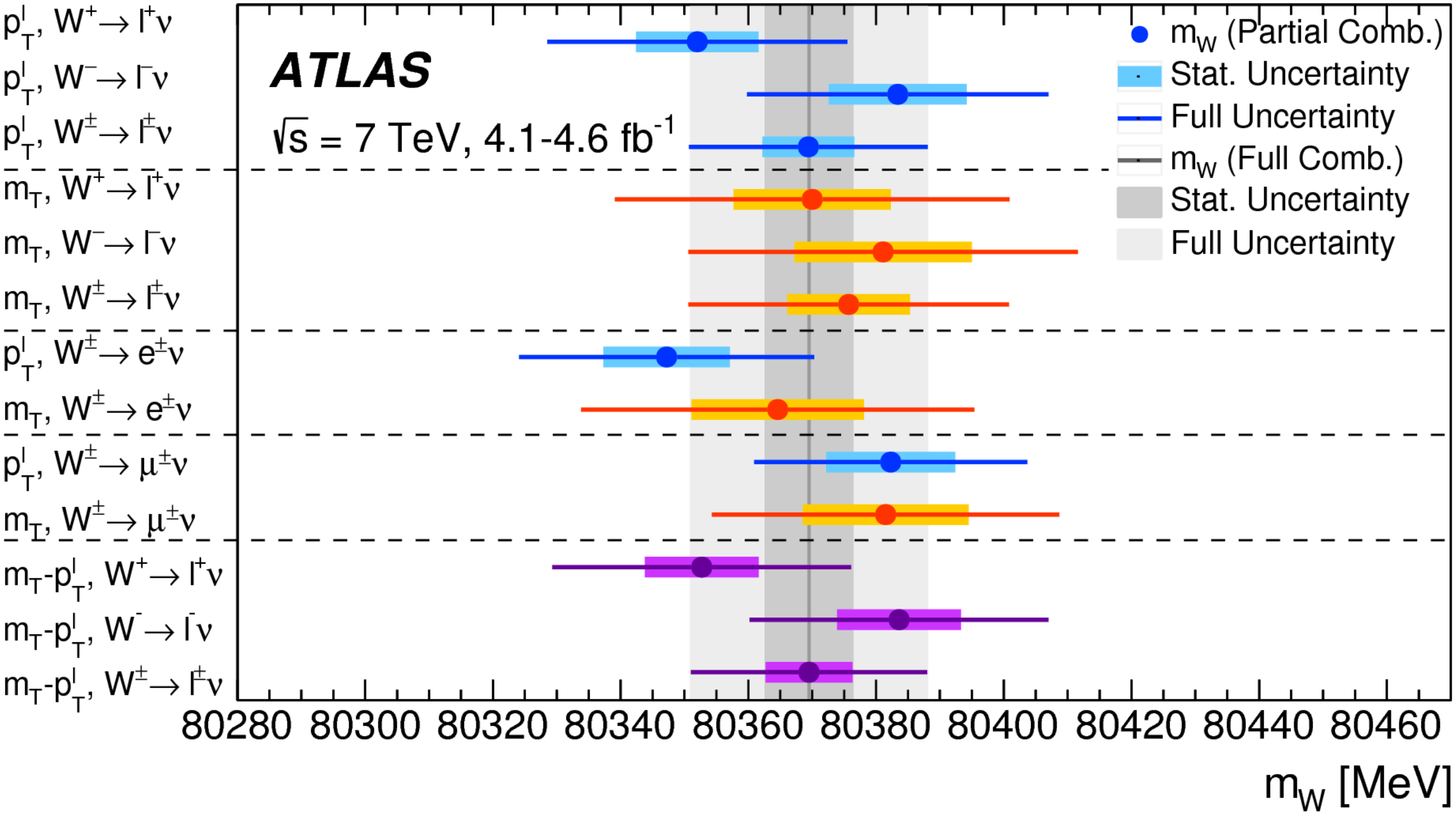


$\lvert\eta_\ell\rvert$ range	0 – 0.8	0.8 – 1.4	1.4 – 2.0	2.0 – 2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\lvert\eta_\ell\rvert$ range	0 – 0.6	0.6 – 1.2		1.8 – 2.4	Inclusive
$W^+ \to e^+\nu$	1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

7.8 M events

5.9 M events

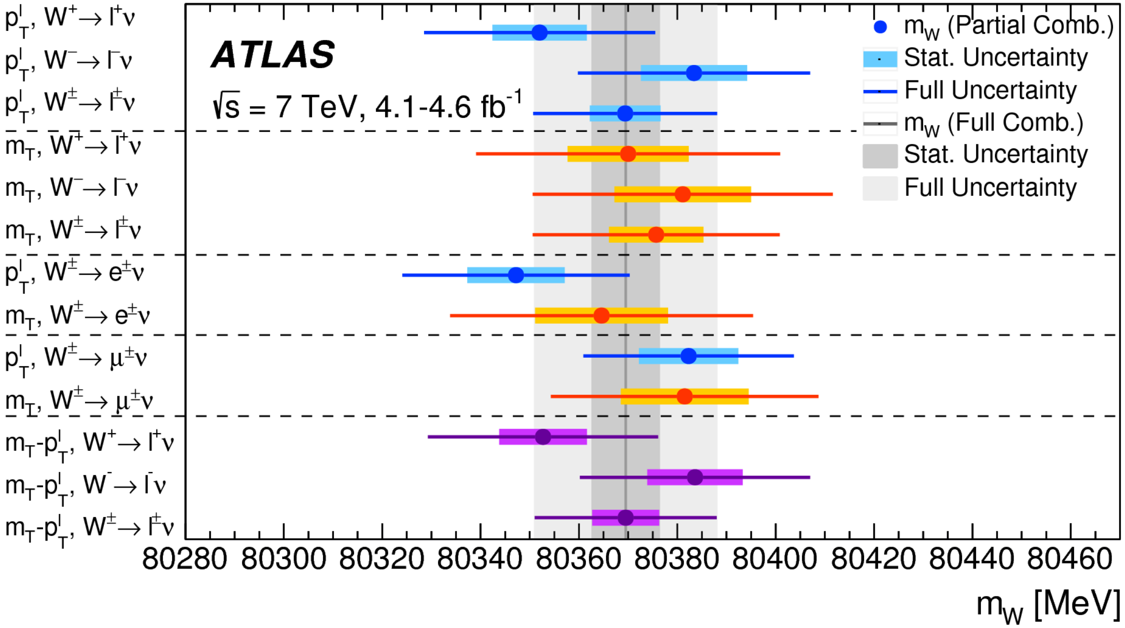
Fit results for m_W



m_W = 80.370 ± 0.007 (stat.) ± 0.011 (exp. syst.) ± 0.014 (mod. syst.) GeV
= 80.370 ± 0.019 GeV

m_{W+} - m_{W-} = -29 ± 13 (stat.) ± 7 (exp. syst.) ± 24 (mod. syst.) MeV
= -29 ± 28 MeV

Relative importance of different measurements

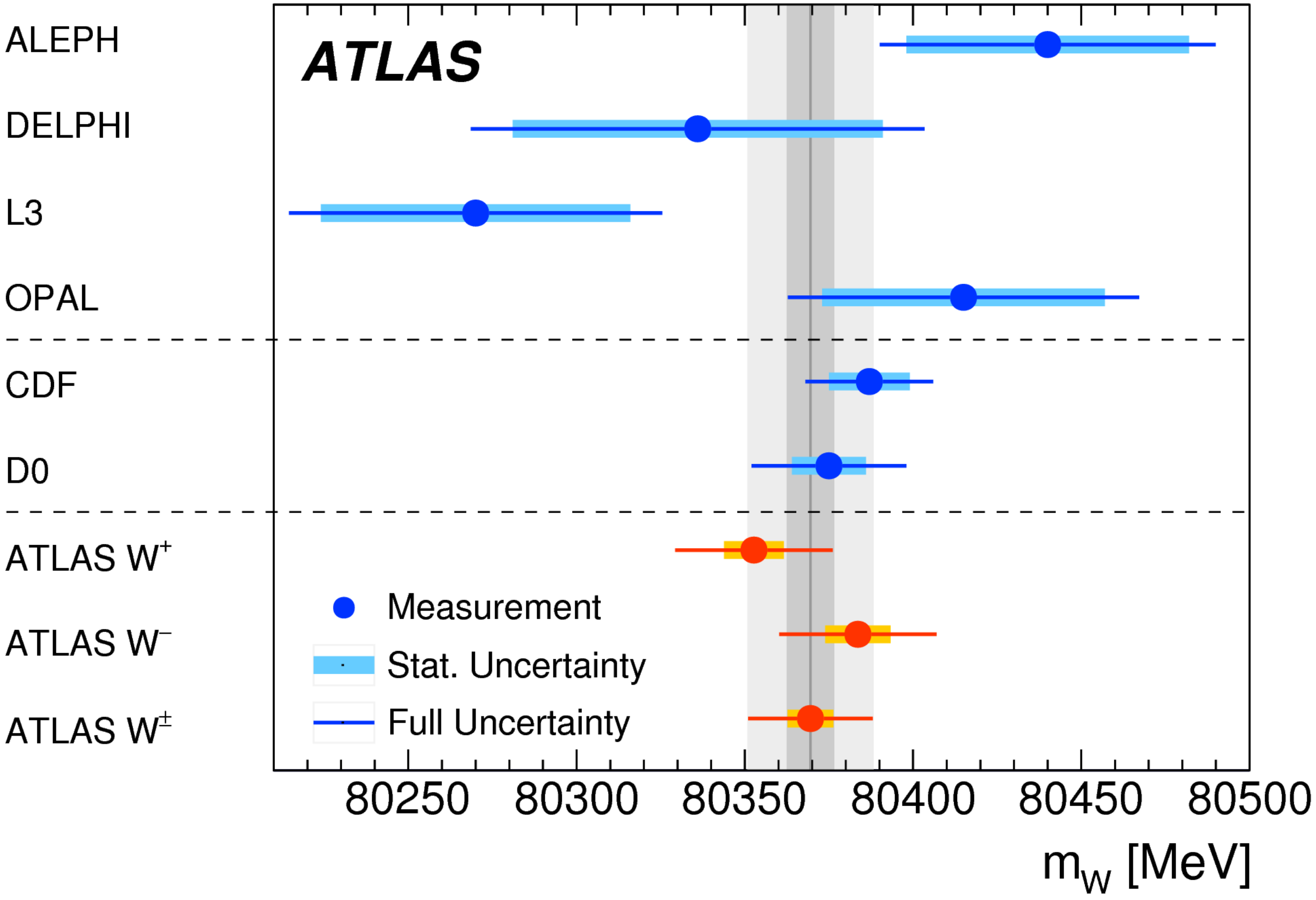


Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481

- **Measuring electrons AND muons provides a crucial set of closure constraints on the experimental systematic uncertainties. A number of experimental issues at the ~ 30-50 MeV level on m_W were resolved in both channels thanks to this.**

- **Even though the weight of the m_T measurement is much smaller than that of p_T^l, it plays an important role in the understanding of the theoretical modelling uncertainties on p_T^W**

Consistency of experimental results



Results in the various measurement categories

Channel m_T-Fit	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	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

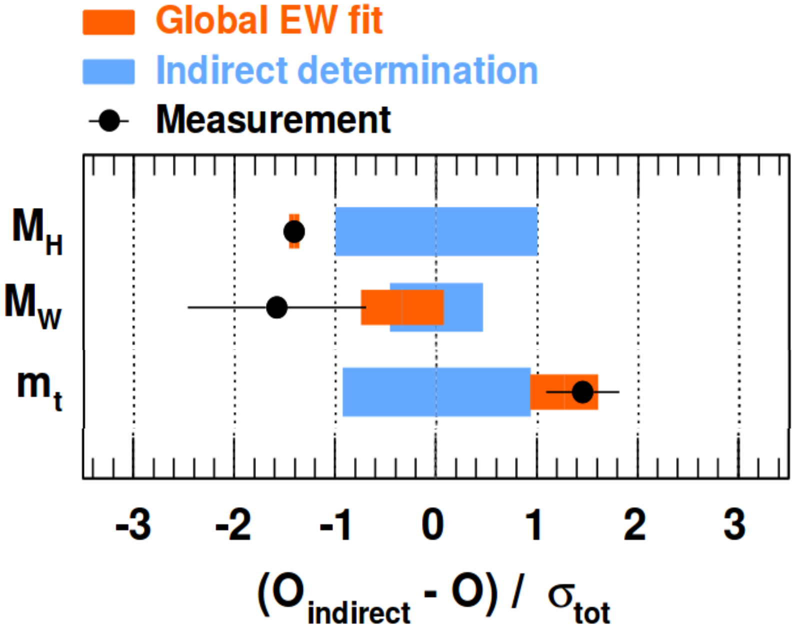
Strongly correlated

Strongly correlated

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

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

Relation between top, Higgs and W masses



	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

The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables

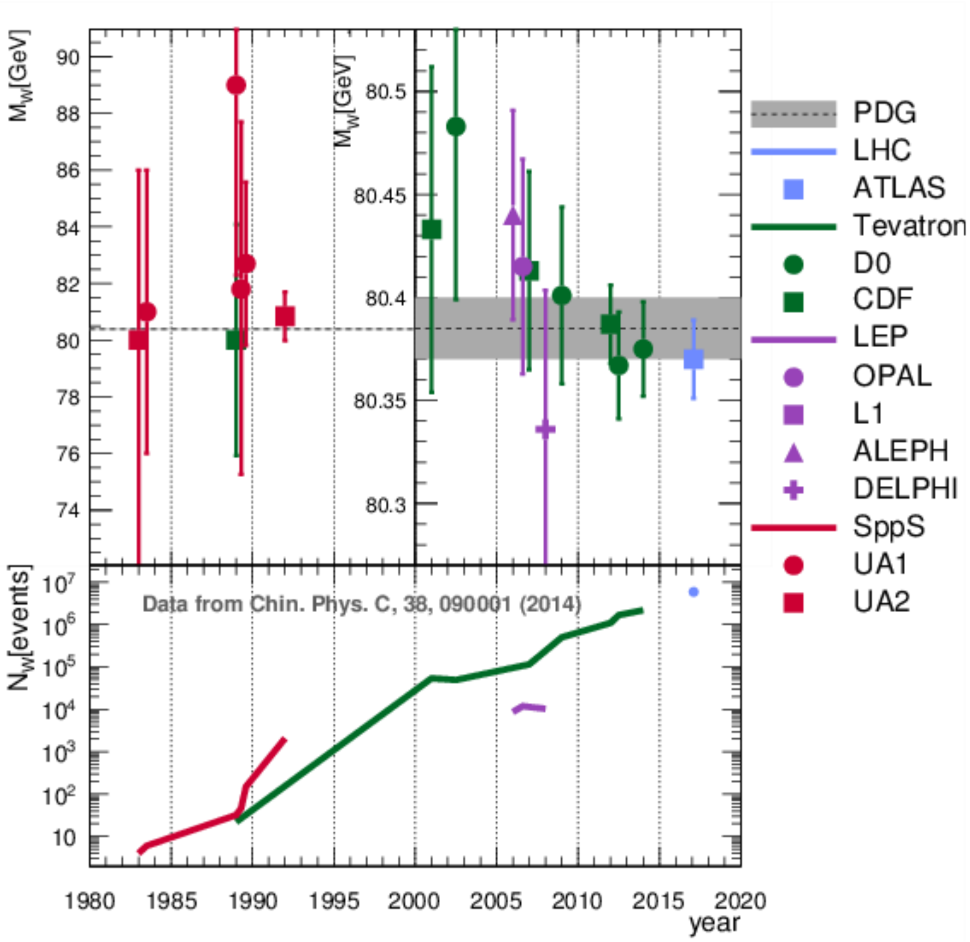
Improving precision will not increase sensitivity to new physics

Indirect determination of m_W (±8 MeV) is more precise than the experimental measurement

Call for $\delta m_W < 10$ MeV

The W mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics

W-boson mass history



1983 CERN SPS – W discovery
UA1/UA2
$m_W = 81 \pm 5$ GeV

1992 UA2 (with m_Z from LEP)
$m_W = 80.35 \pm 0.37$ GeV

2013 LEP combined
$m_W = 80.376 \pm 0.033$ GeV

2013 Tevatron combined
$m_W = 80.387 \pm 0.016$ GeV

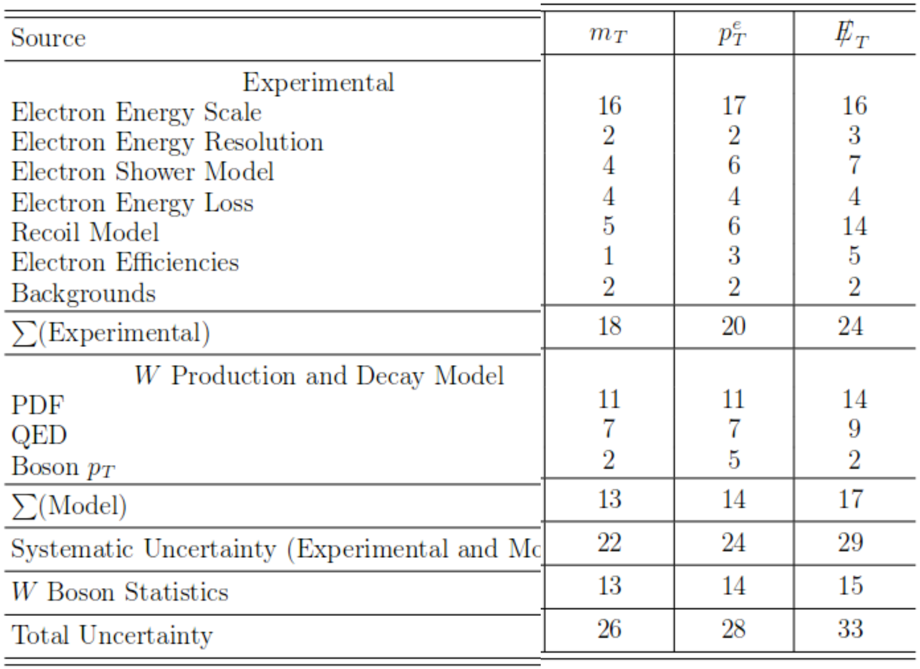
2017 LHC (ATLAS)
$m_W = 80.370 \pm 0.019$ GeV

Only four W-boson mass measurements in the last 7 years

→ **Complex measurements which require O(5-7) years**

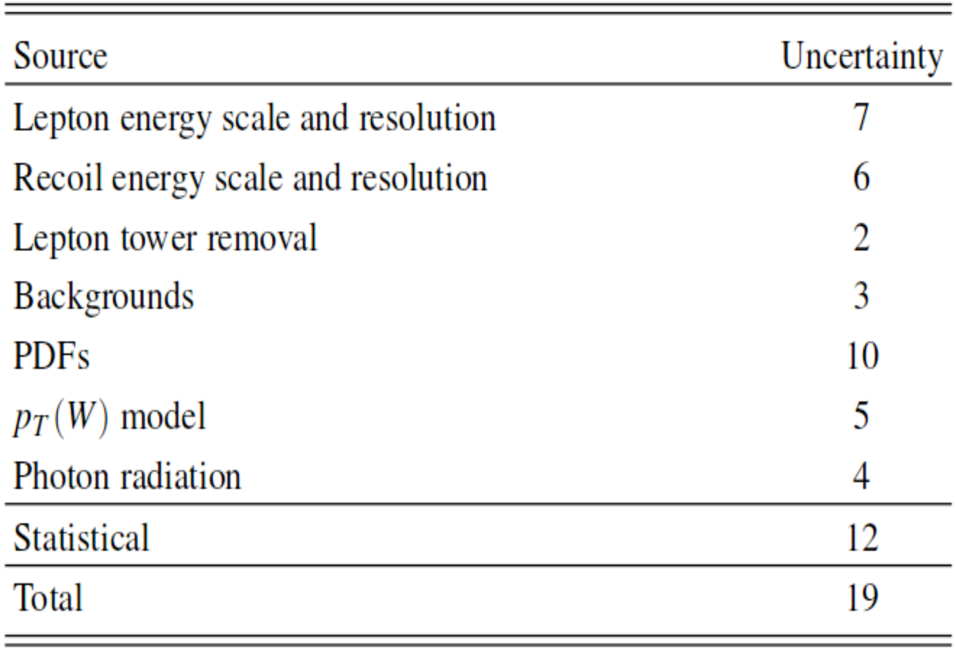
TeVatron results/prospects and LHC prospects

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 Mc	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} W→eν

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

CDF 2.2 fb^{-1} 1.1×10^{6} events, W→eν,μν

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

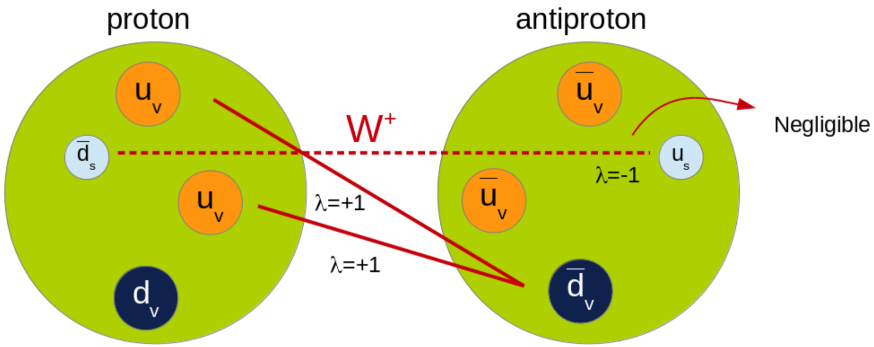
Tevatron prospects: full dataset (10 fb^{-1}) + end-cap W→eν for D0 (?)

W samples in ATLAS (W→eν, μν) :

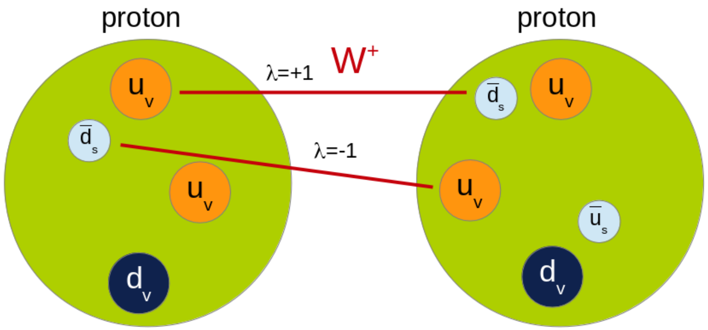
7 TeV	8 TeV	13 TeV
~4.5 fb^{-1}	~20.3 fb^{-1}	~30 fb^{-1}
15×10^{6}	80×10^{6}	190×10^{6}

W-boson mass measurement at the LHC

A proton-proton collider is the most challenging environment to measure m_W, worse than e^+e^- and also worse than proton-antiproton



In ppbar collisions, W bosons are mostly produced in the same helicity state



In pp collisions, they are equally distributed between positive and negative helicity states

Further QCD complications:

- Heavy-flavour-initiated processes
- W^+, W^- and Z are produced by different light-flavour fractions
- Larger gluon-induced W production

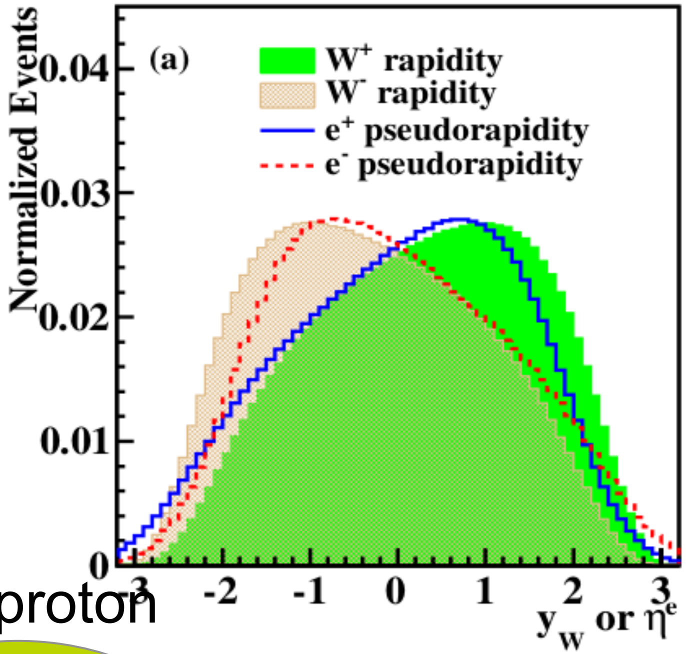
Large PDF-induced W-polarisation uncertainty affecting the lepton p_T distribution

Very large Z samples, available for detector calibration given the precisely known Z mass → most of the measurement is then the transfer from Z to W

PDF uncertainties in W mass measurement

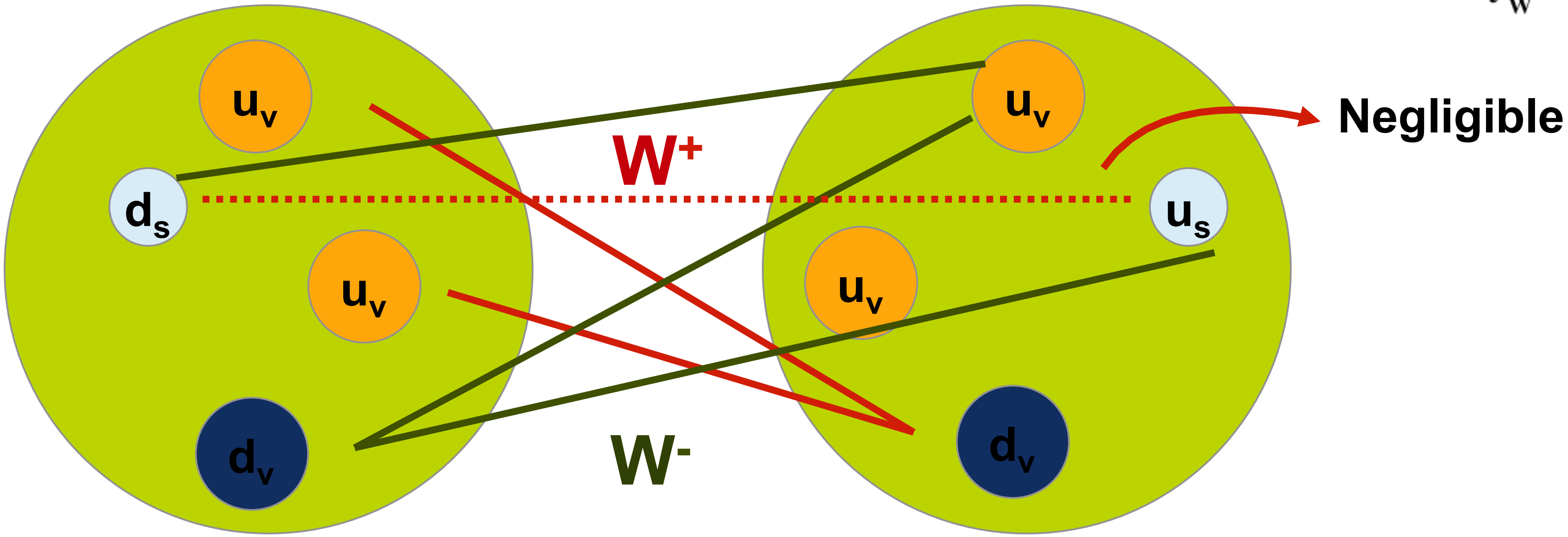
In proton-antiproton collisions:

- Asymmetry of the W rapidity
- Same cross section for W^+ and W^-
- Valence-dominated production
- Very small ambiguity for the incoming partons: quark from proton, antiquark from antiproton



Proton

Antiproton



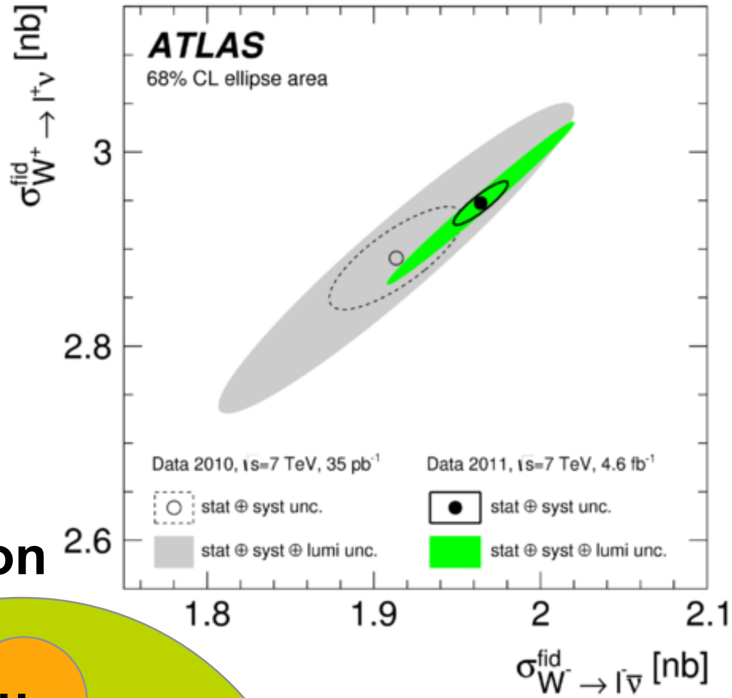
PDF uncertainties in W mass measurement

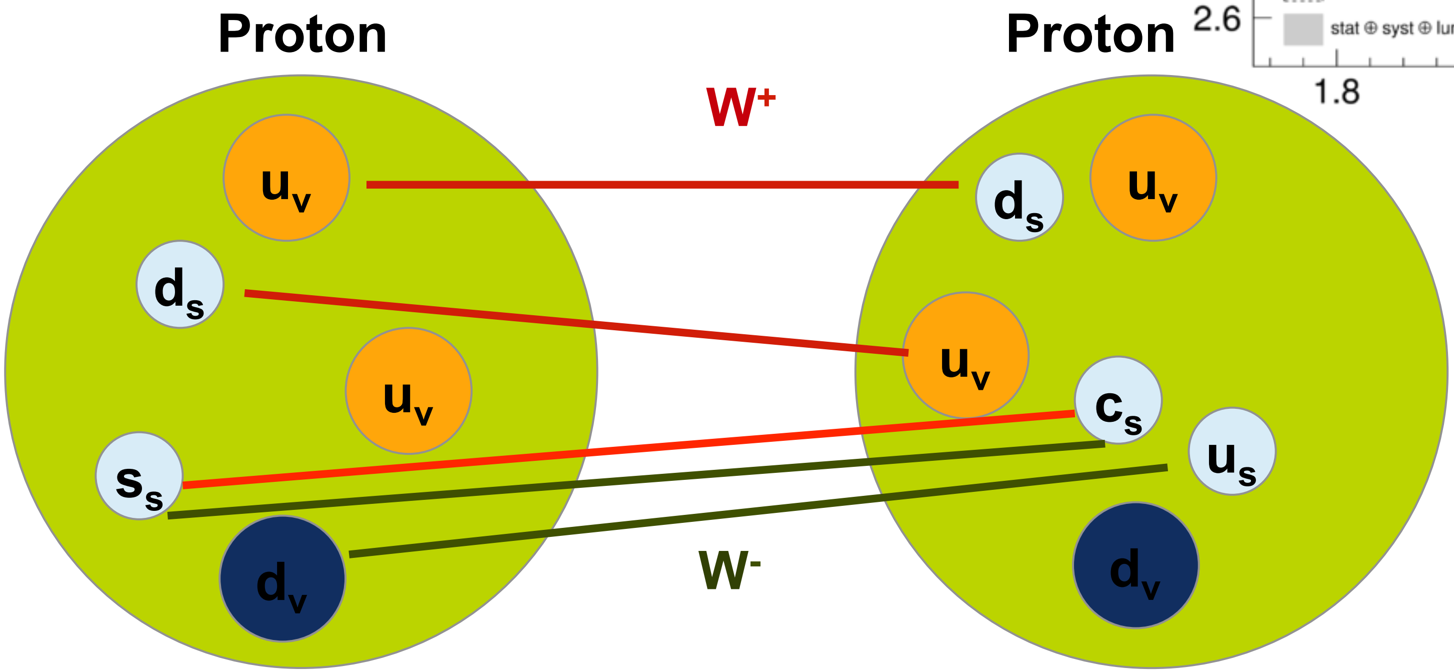
In proton-proton collisions:

- **Different cross section for W^+ and W^-**
- **Large ambiguity in the direction of the incoming quark**

→ Will need to exploit difference between W^+ and W^-

https://arxiv.org/abs/1612.03016





Historical interlude: the 80's in UA1/UA2 at the SppS

From the beginning, with the observation of two-jet dominance and of 4 W → eν and 8 Z → e^+e^- decays

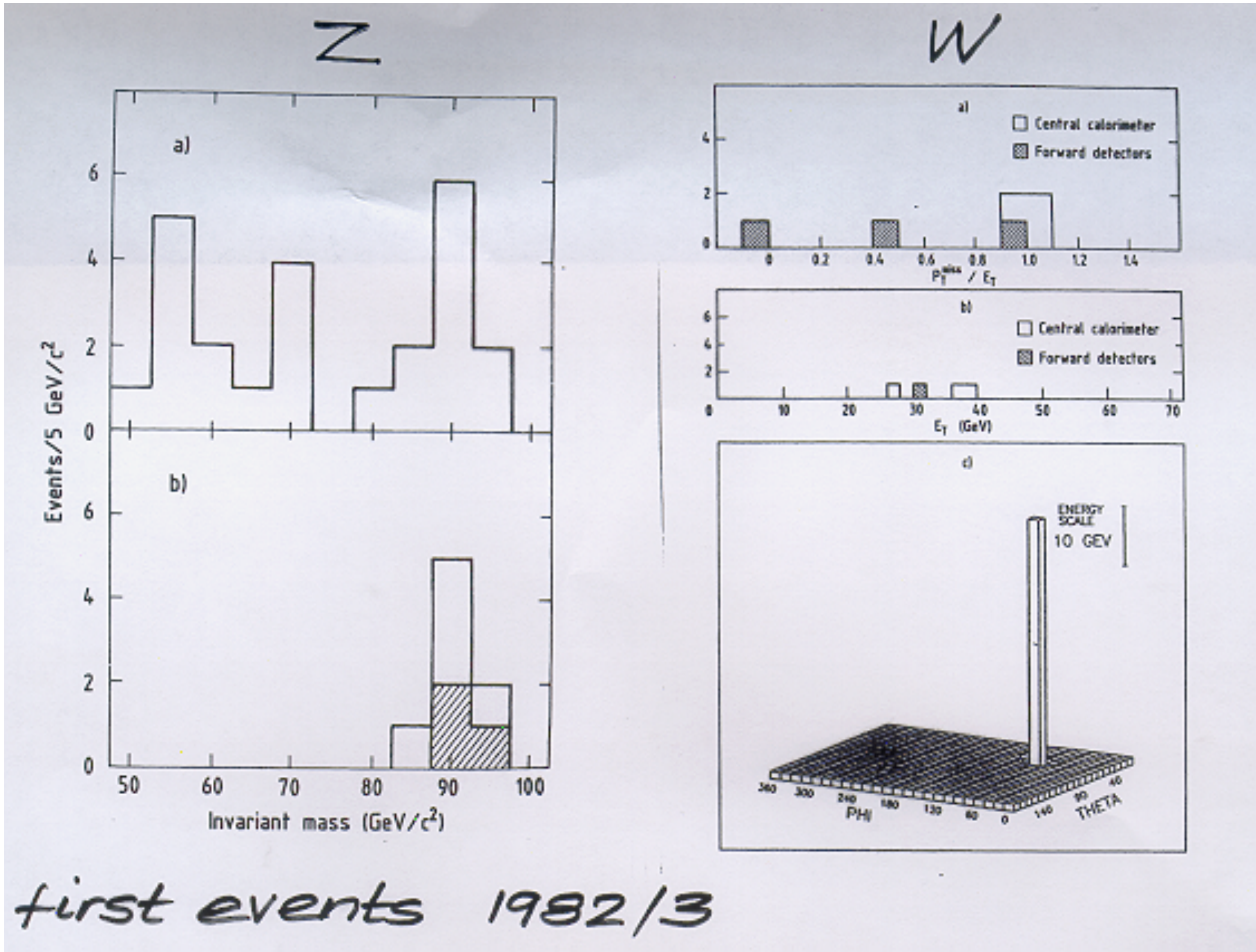
$\sqrt{s} = 546$ GeV, L ~ 10^{29} $cm^{-2}s^{-1}$

UA2 was perceived as large at the time:

- ♥ 10-12 institutes
- ♥ from 50 to 100 authors
- ♥ cost ~ 10 MCHF
- ♥ duration 1980 to 1990

Physics analysis was organised in two groups:

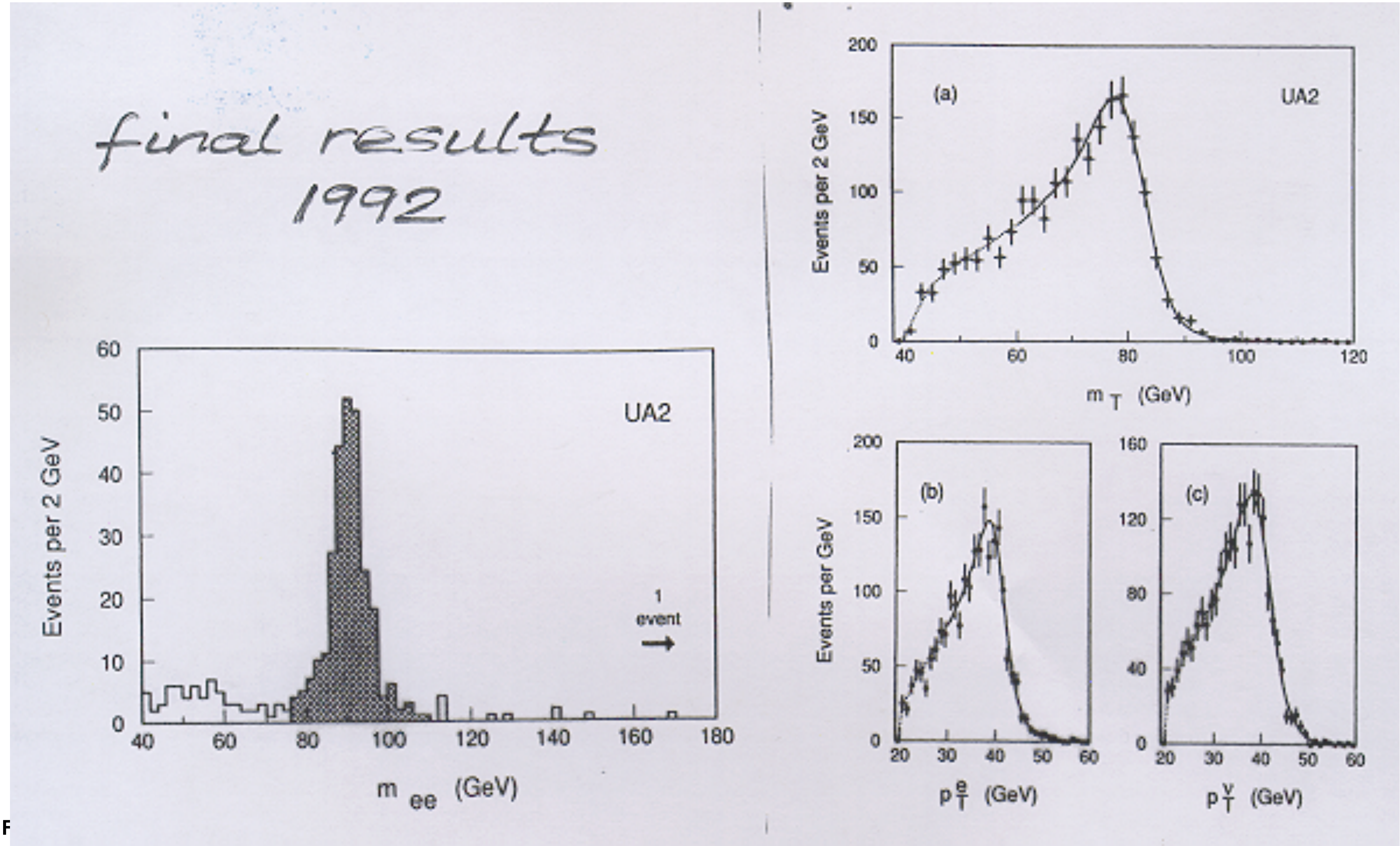
1. Electrons → electroweak
2. Jets → QCD



first events 1982/3

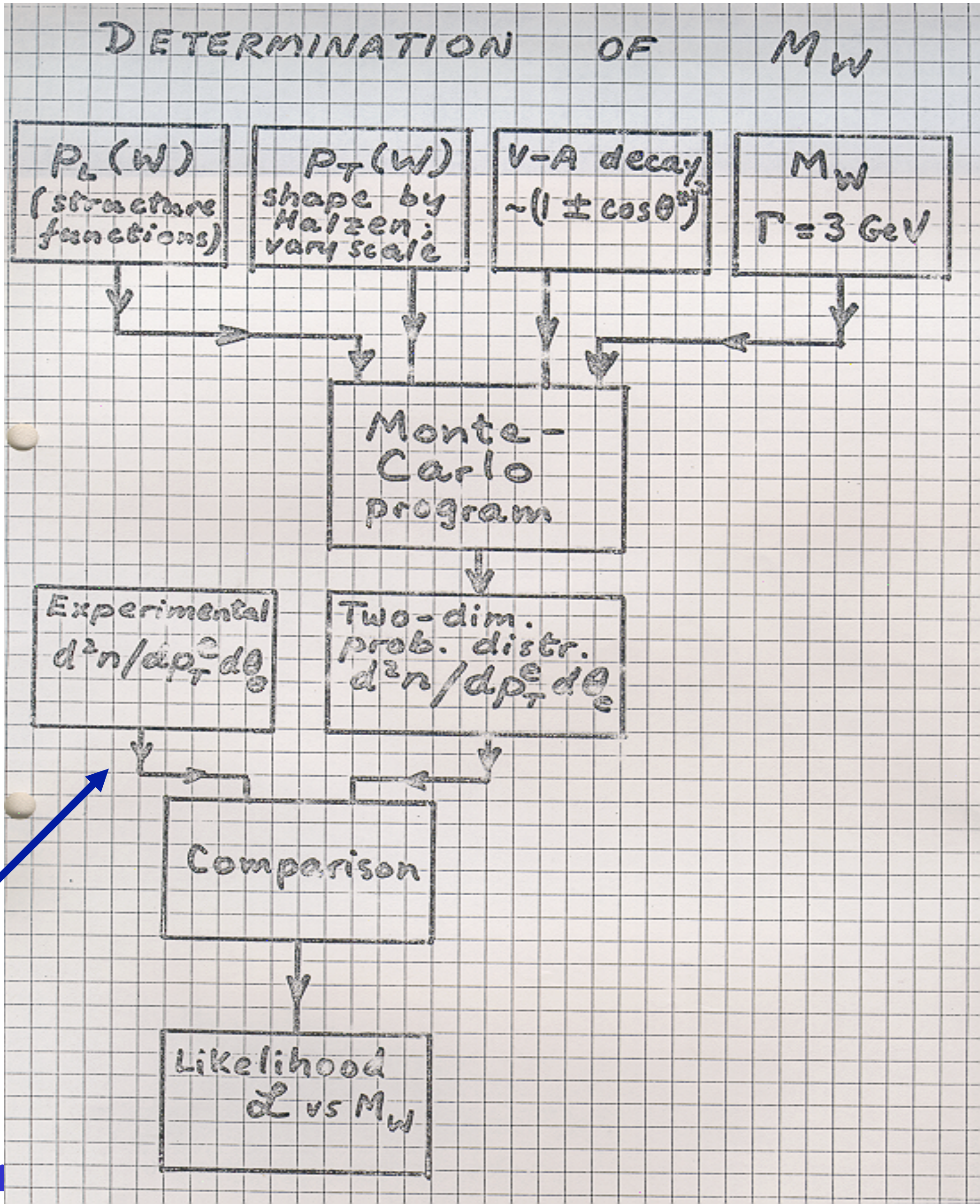
Historical perspective: the 80's in UA1/UA2 at the SppS

To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry



final results
1992

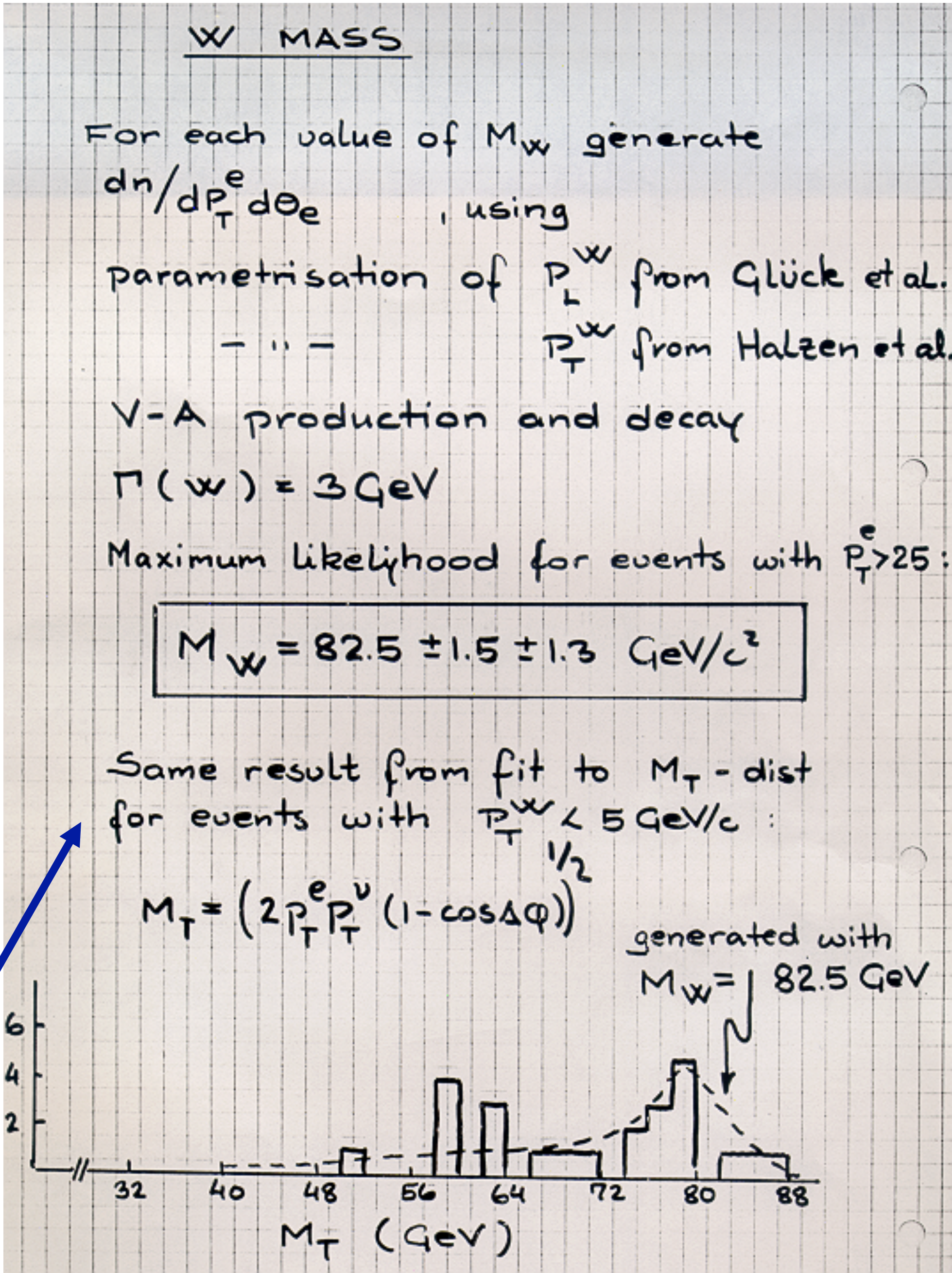
Historical perspective: the 80's in UA1/UA2 at the SppS



Software design in UA2

Historical perspective: the 80's in UA1/UA2 at the SppS

Software documentation in UA2



W MASS

For each value of M_W generate $dn/dP_T^e d\theta_e$, using

parametrisation of P_L^W from Glück et al.

— " — P_T^W from Halzen et al.

V-A production and decay

$\Gamma(W) = 3$ GeV

Maximum likelihood for events with $P_T^e > 25$:

$$\boxed{M_W = 82.5 \pm 1.5 \pm 1.3 \text{ GeV}/c^2}$$

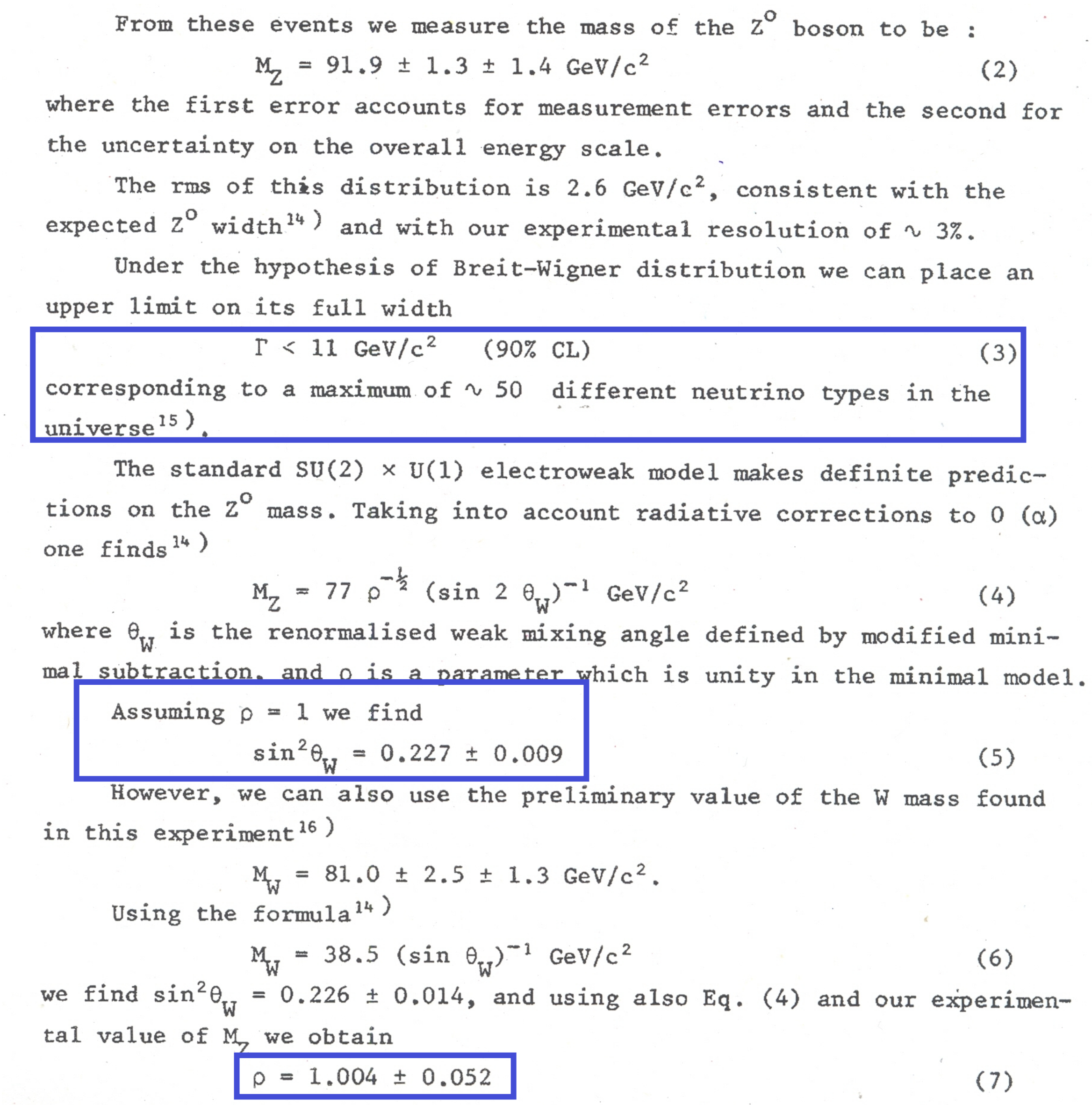
Same result from fit to M_T - dist for events with $P_T^W < 5$ GeV/c :

$$M_T = \left(2 P_T^e P_T^\nu (1 - \cos\Delta\varphi)\right)^{1/2}$$

generated with $M_W = 82.5$ GeV

Historical perspective: the 80's in UA1/UA2 at the SppS

First ever EW fits in UA2 before LEP turned on



From these events we measure the mass of the Z^o boson to be :

$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV/c}^2 \qquad (2)$$

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

The rms of this distribution is 2.6 GeV/c^2, consistent with the expected Z^o width¹⁴⁾ and with our experimental resolution of ∿ 3%.

Under the hypothesis of Breit-Wigner distribution we can place an upper limit on its full width

$$\Gamma < 11 \text{ GeV/c}^2 \quad (90\% \text{ CL}) \qquad (3)$$

corresponding to a maximum of ∿ 50 different neutrino types in the universe¹⁵⁾.

The standard SU(2) × U(1) electroweak model makes definite predictions on the Z^o mass. Taking into account radiative corrections to 0 (α) one finds¹⁴⁾

$$M_Z = 77 \rho^{-\frac{1}{2}} (\sin 2 \theta_W)^{-1} \text{ GeV/c}^2 \qquad (4)$$

where θ_W is the renormalised weak mixing angle defined by modified minimal subtraction, and ρ is a parameter which is unity in the minimal model.

Assuming ρ = 1 we find

$$\sin^2\theta_W = 0.227 \pm 0.009 \qquad (5)$$

However, we can also use the preliminary value of the W mass found in this experiment¹⁶⁾

$$M_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV/c}^2.$$

Using the formula¹⁴⁾

$$M_W = 38.5 (\sin \theta_W)^{-1} \text{ GeV/c}^2 \qquad (6)$$

we find $\sin^2\theta_W = 0.226 \pm 0.014$, and using also Eq. (4) and our experimental value of M_Z we obtain

$$\rho = 1.004 \pm 0.052 \qquad (7)$$

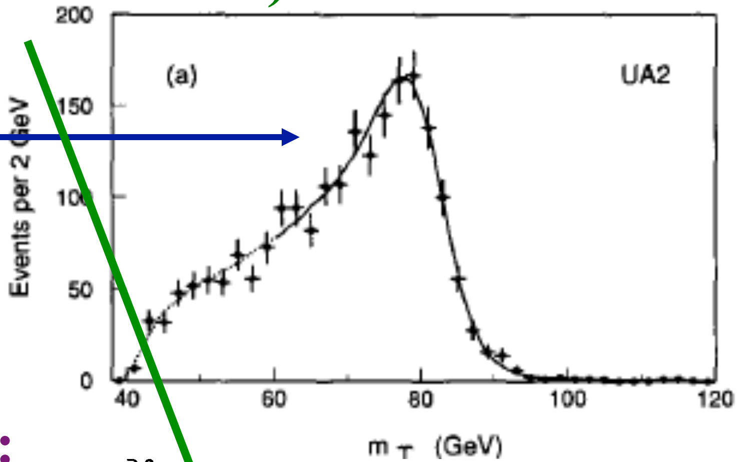
Historical perspective: the 80's in UA1/UA2 at the SppS

Most important results from 1987-1990 campaign with UA2:

precise measurement of m_W/m_Z

and direct limit on top-quark mass ($m_{top} < 60$ GeV)

Transverse mass distribution for electron-neutrino pairs



$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

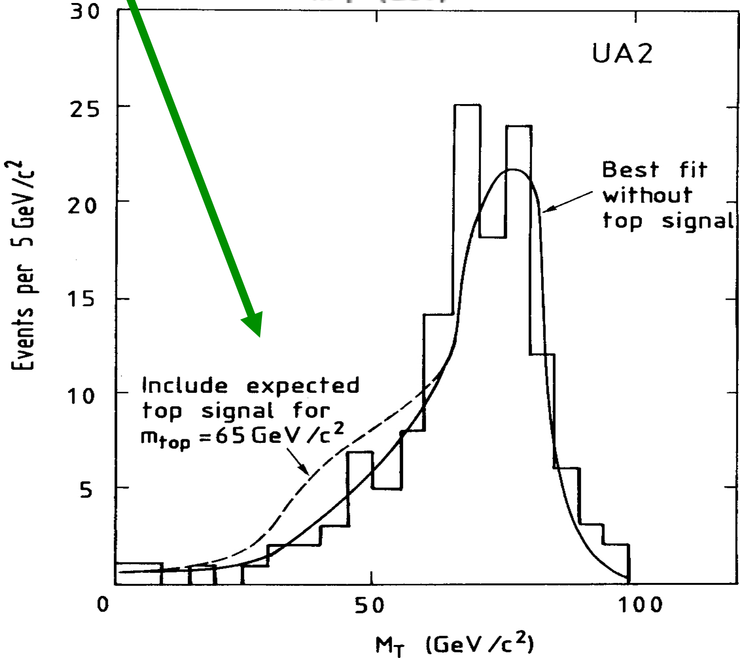
Using the precise measurement of m_Z (LEP):

$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

Indirect limits on top-quark mass in the context of the Standard Model:

$$m_{top} = 160^{+50}_{-60} \text{ GeV}$$

(four years before the discovery of the top quark at Fermilab)



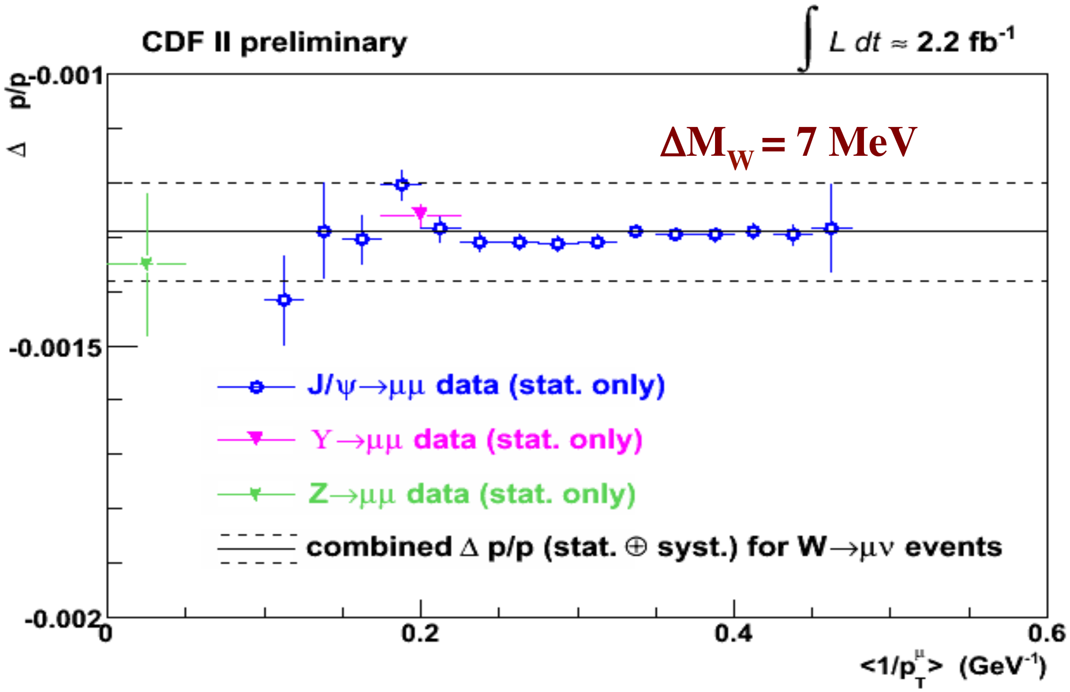
W-boson mass measurements: Tevatron vs LHC

CDF: Tracker Linearity Cross-check & Combination

Final momentum calibration using the J/ψ, ϒ and Z bosons

Combined momentum scale correction:

- $\Delta p/p = (-1.29 \pm 0.07_{\text{independent}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}}) \times 10^{-3}$

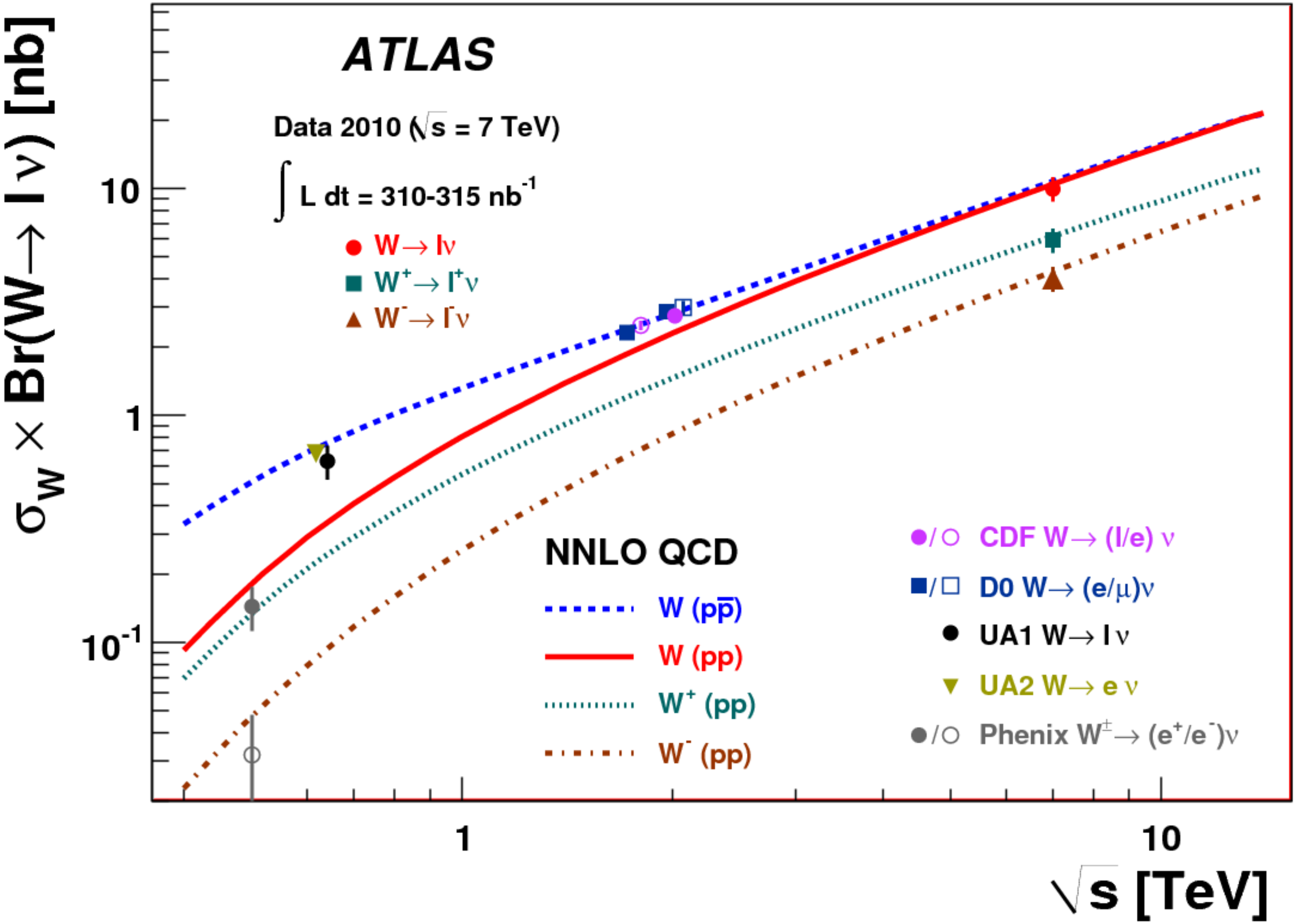


$\Delta M_W = 7$ MeV

<u>Note</u>: this paves the way to a precision measurement of m_Z at hadron colliders, can LHC do better than LEP?

Historical perspective: first run at 7 TeV in 2010

First W/Z events seen in April-May 2010 were very exciting!



W-boson mass measurement at the LHC

The measurement of m_W at the LHC is extremely challenging and prone to many potential biases due to QCD effects

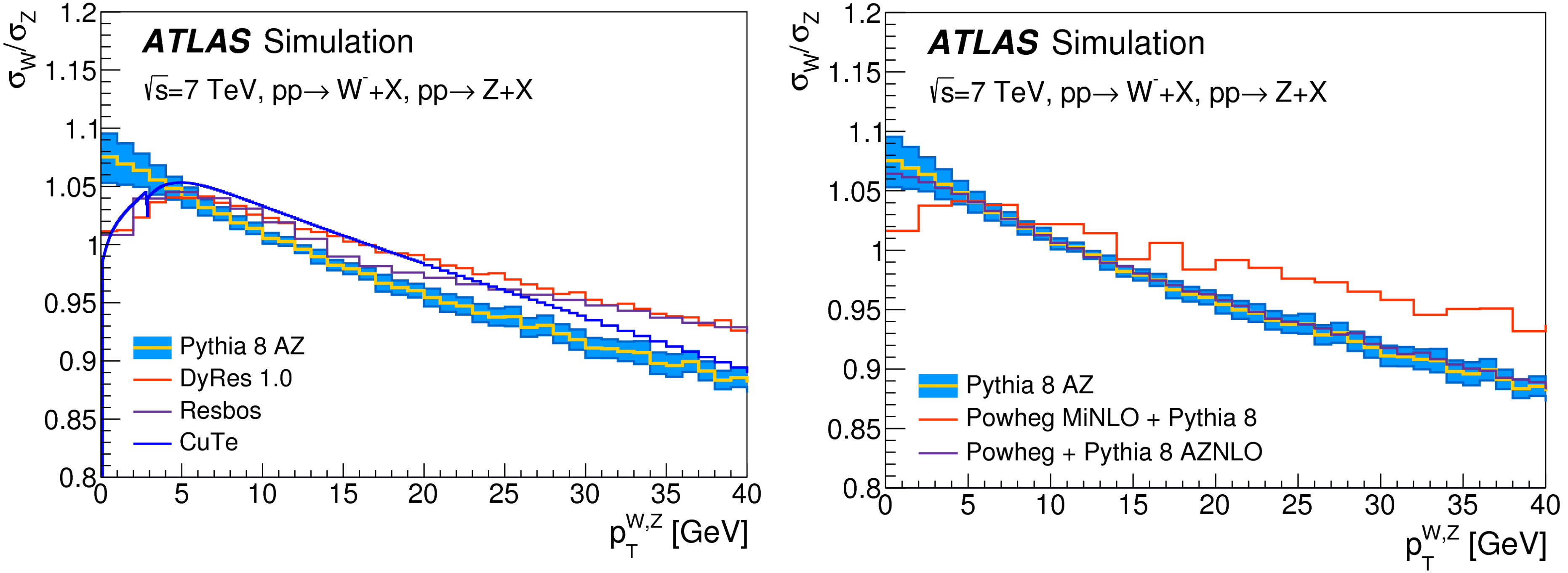
These affect all aspects of the measurement: detector calibration, transfer of theory predictions tuned to data from Z to W,
PDF uncertainties, W polarisation, modelling of p_T^W

Need to design the measurement to be “as waterproof as possible” from the point of view of detector calibration and physics modelling

At the same time, the challenge makes the measurement hugely interesting, and provides a great occasion to improve the understanding of the detector performance and of QCD beyond that achieved by any other measurement or search at the LHC

Transverse momentum distribution

- Theoretically more advanced calculations were also attempted
  - DYRES (and other resummation codes : ResBos, CuTe)
  - Powheg MiNLO + Pythia8
- All predict a significantly harder p_T^W spectrum for given p_T^Z distribution :

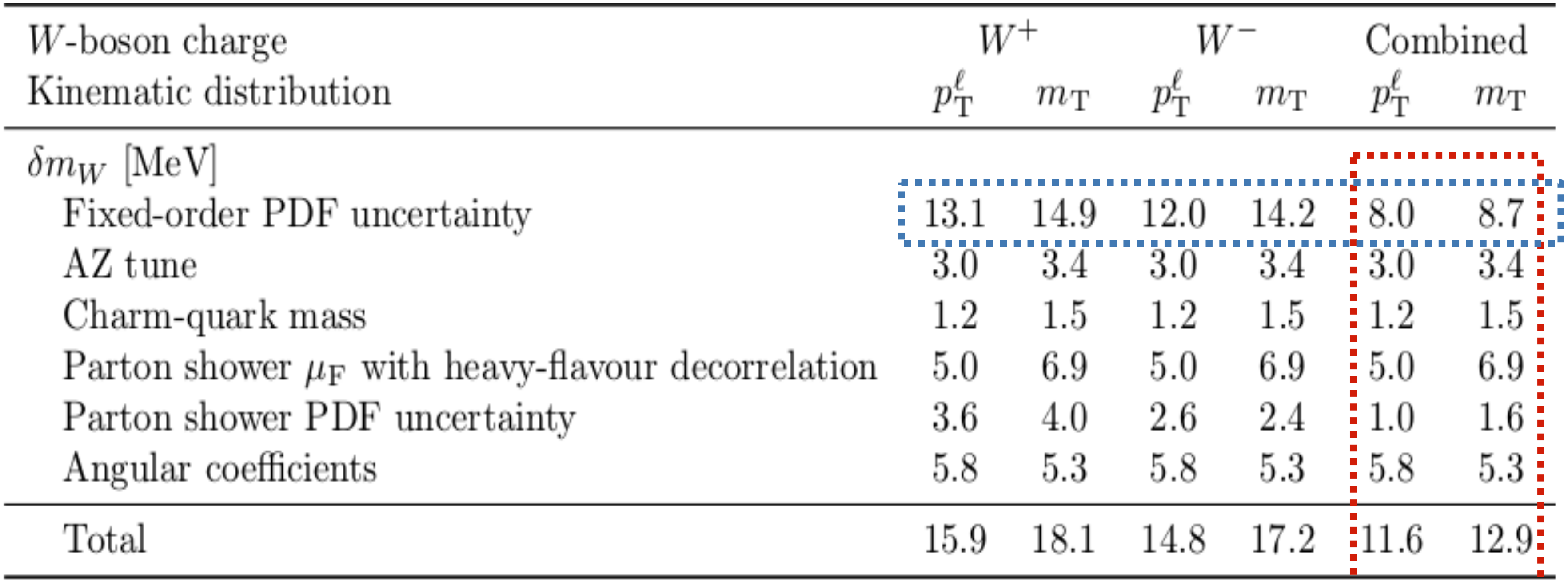


- This behaviour is disfavoured by data (see later); predictions discarded for now. As a result, no explicit uncertainty from missing fixed-order terms at $O(\alpha_s^2)$, but use data to place an upper bound on this effect.

Summary of QCD predictions and uncertainties

- **Baseline**
  - $d\sigma/dy$, $A_i(p_T,y)$: DYNNLO+CT10nnlo (fixed-order)
  - At given y, $d\sigma/dp_T$ is predicted using Pythia8 AZ
- **Uncertainties**
  - CT10nnlo uncertainties (synchronised in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT. Strong anti-correlation of uncertainties for W^+ and W^-!
  - AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
  - A_i uncertainties from Z data; envelope for A2 discrepancy

Validated by the data:
σ_W, σ_Z, p_T^Z, A_i ; also η_l, u_T, $u_{||}$



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

Summary of QCD predictions and uncertainties

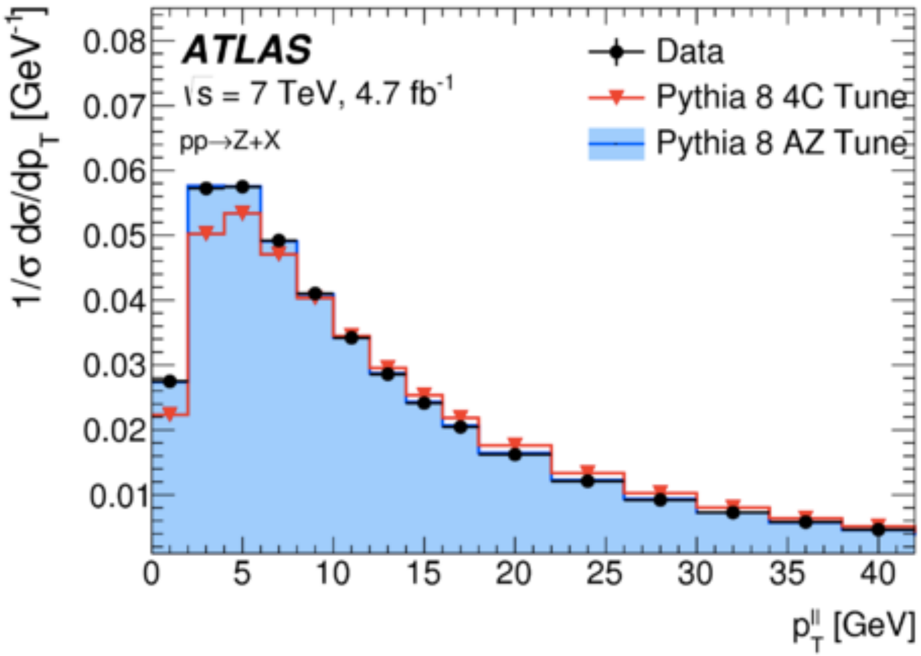
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

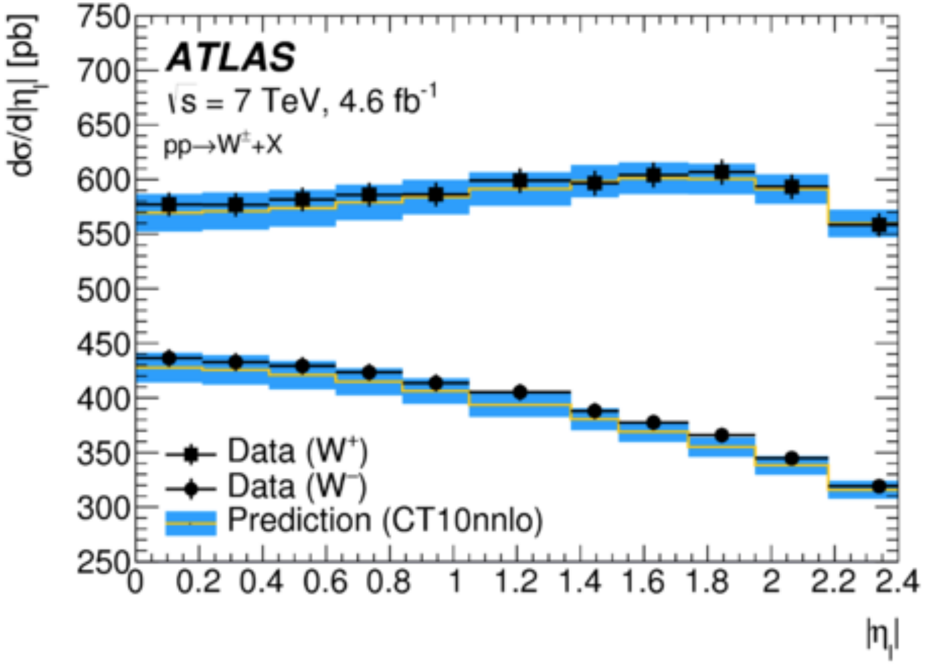
Breit-Wigner

Parton Shower

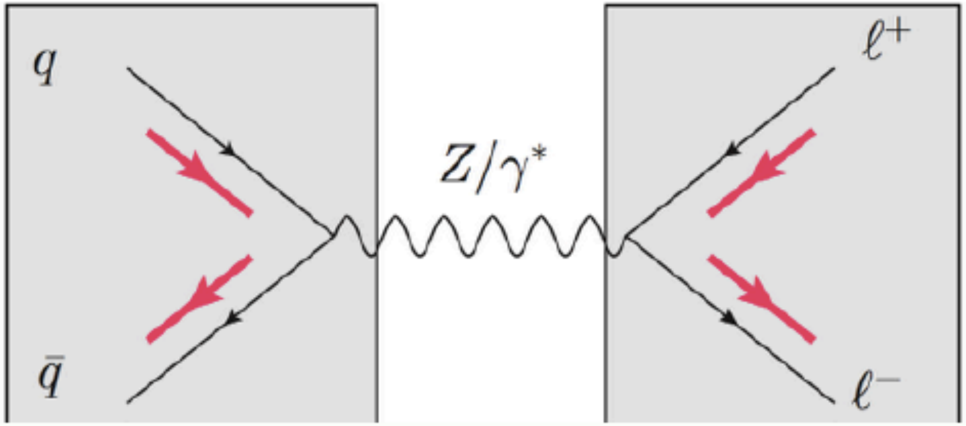
NNLO pQCD

- **Baseline**
  - $d\sigma/dy$, $A_i(p_T,y)$: DYNNLO+CT10nnlo (fixed-order)
  - At given y, $d\sigma/dp_T$ is predicted using Pythia8 AZ





Measurement of angular coefficients in Z(W) decays to leptons



- Angular distributions of leptons from Z-boson decays are a portal to its production dynamics via polarisation
- Exploit decomposition of cross-section into only nine terms at all orders in QCD
  - Angular dependence is fully analytical for 2 -> 2 process
  - Higher order effects absorbed into behavior of $\boxed{\text{Ai}}$ coefficients
- These measurements…
  - Probe dynamics of QCD
  - Allow us to test and improve Monte Carlo implementations
  - Are a critical ingredient for future precision EW measurements

What is measured?

Primary: Eight Ai(p_T^Z) …

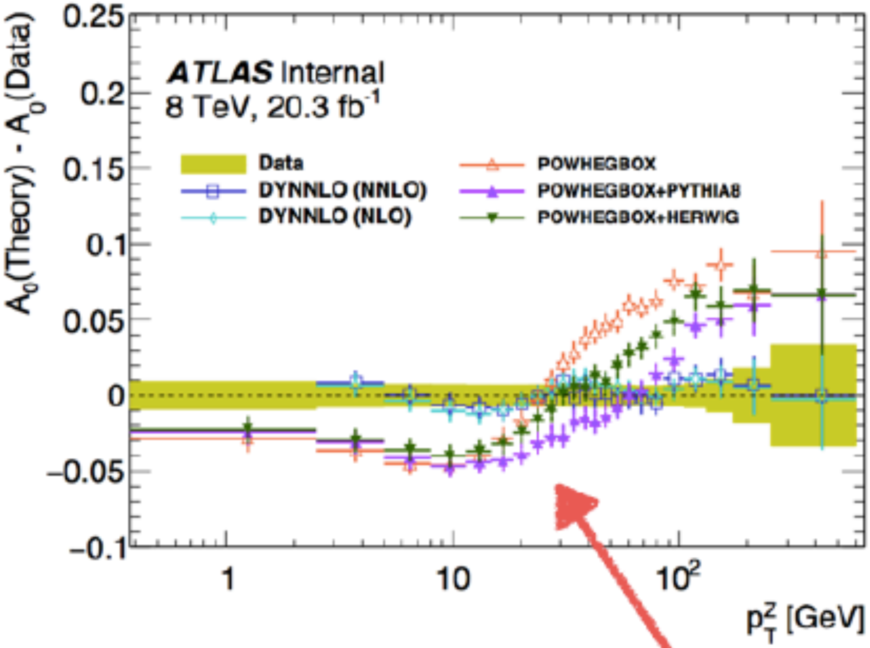
Secondary: Eight Ai(p_T^Z, y^Z) …

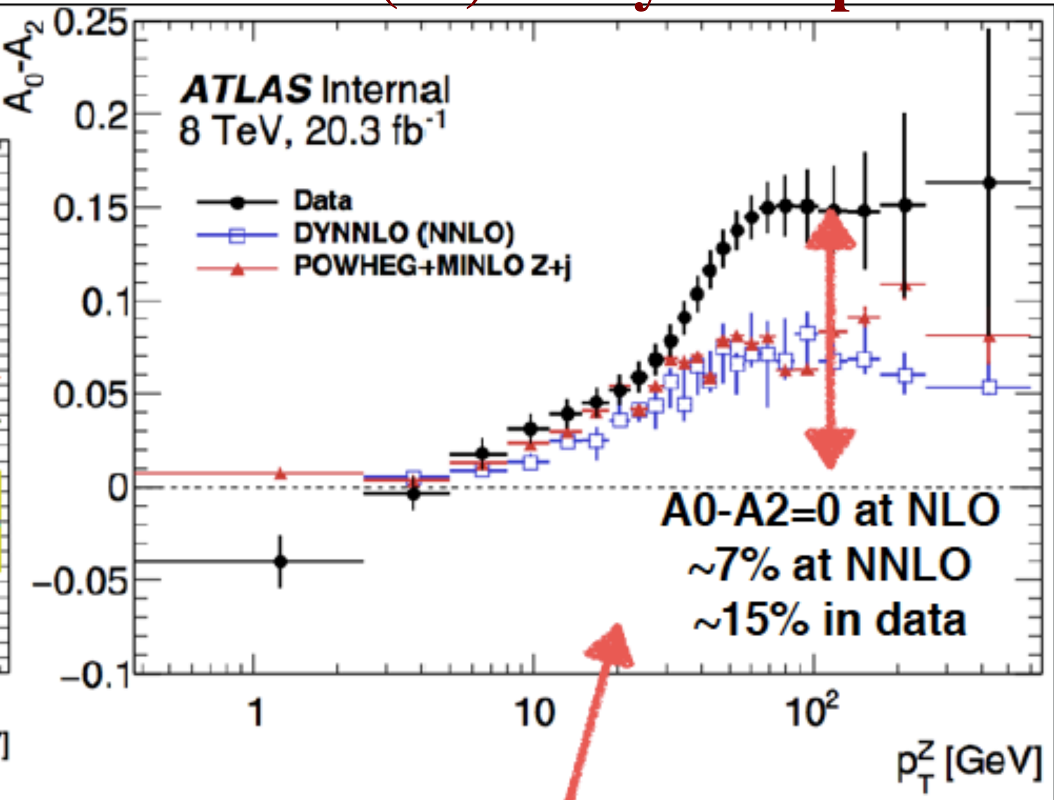
… Integrated over m^Z

$$\begin{aligned}\frac{d^5\sigma}{\boxed{dp_T^Z\, dy^Z\, dm^Z}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{\boxed{dp_T^Z\, dy^Z\, dm^Z}} \times \\ \{\boxed{(1+\cos^2\theta)} + 1/2\,\boxed{A_0}\boxed{(1-3\cos^2\theta)} + \boxed{A_1}\boxed{\sin 2\theta\, \cos\phi} \\ +1/2\,\boxed{A_2}\boxed{\sin^2\theta\, \cos 2\phi} + \boxed{A_3}\boxed{\sin\theta\, \cos\phi} + \boxed{A_4}\boxed{\cos\theta} \\ +\boxed{A_5}\boxed{\sin^2\theta\, \sin 2\phi} + \boxed{A_6}\boxed{\sin 2\theta\, \sin\phi} + \boxed{A_7}\boxed{\sin\theta\, \sin\phi}\}.\end{aligned}$$

Measurement of angular coefficients in Z(W) decays to leptons

Comparisons to theory





A0-A2=0 at NLO
~7% at NNLO
~15% in data

A_0, A_0-A_2

- Powheg completely mismodels A_0 (important for m_W discussion)
  - Related to implementation of Sudakov form factors and cutoffs in b-quark mass
  - Fixed in Powheg+MiNLO

A_0-A_2 (Lam-Tung) sensitive to higher order corrections

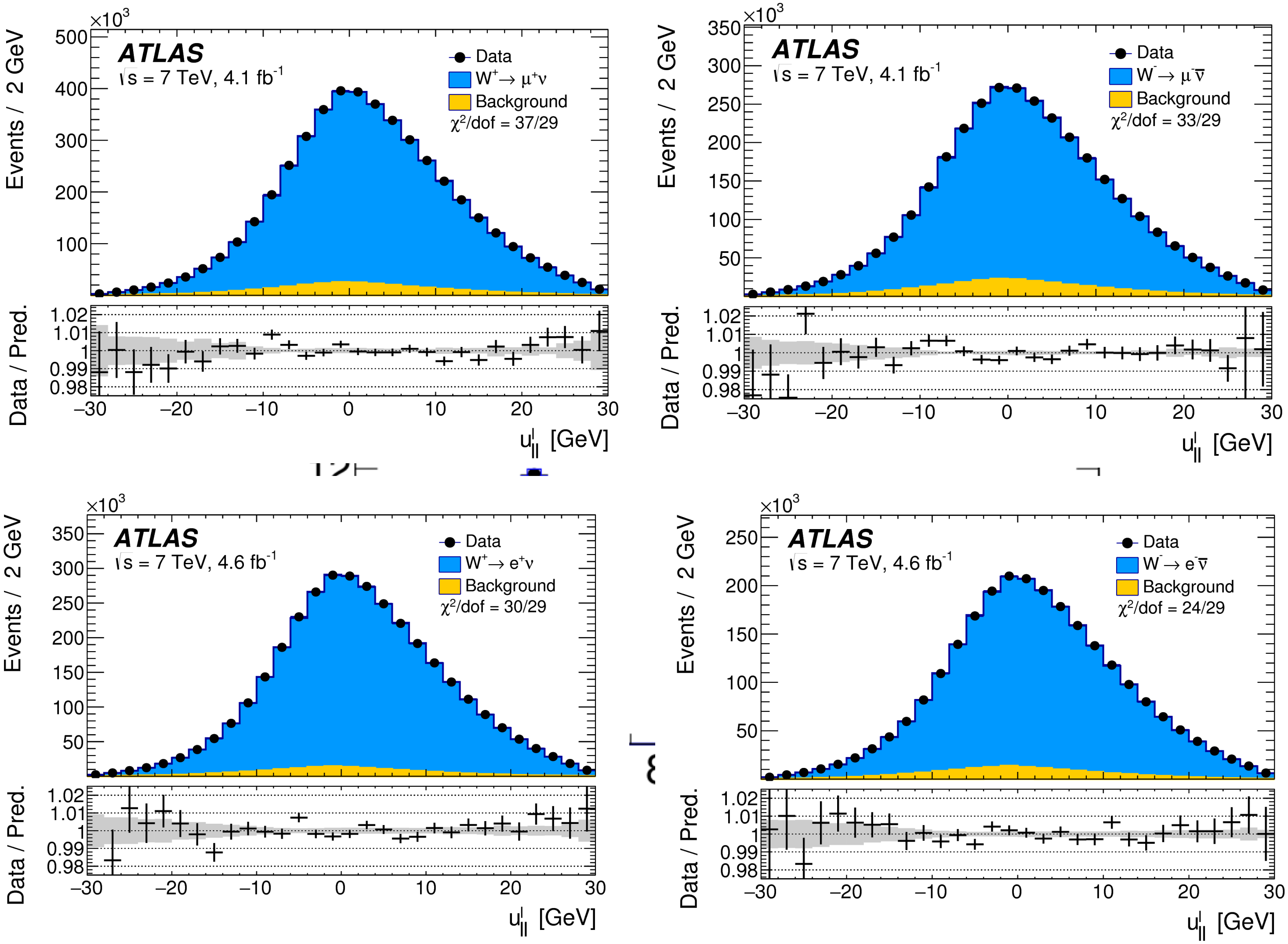
First ever observation of significant deviation from NNLO predictions

Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$

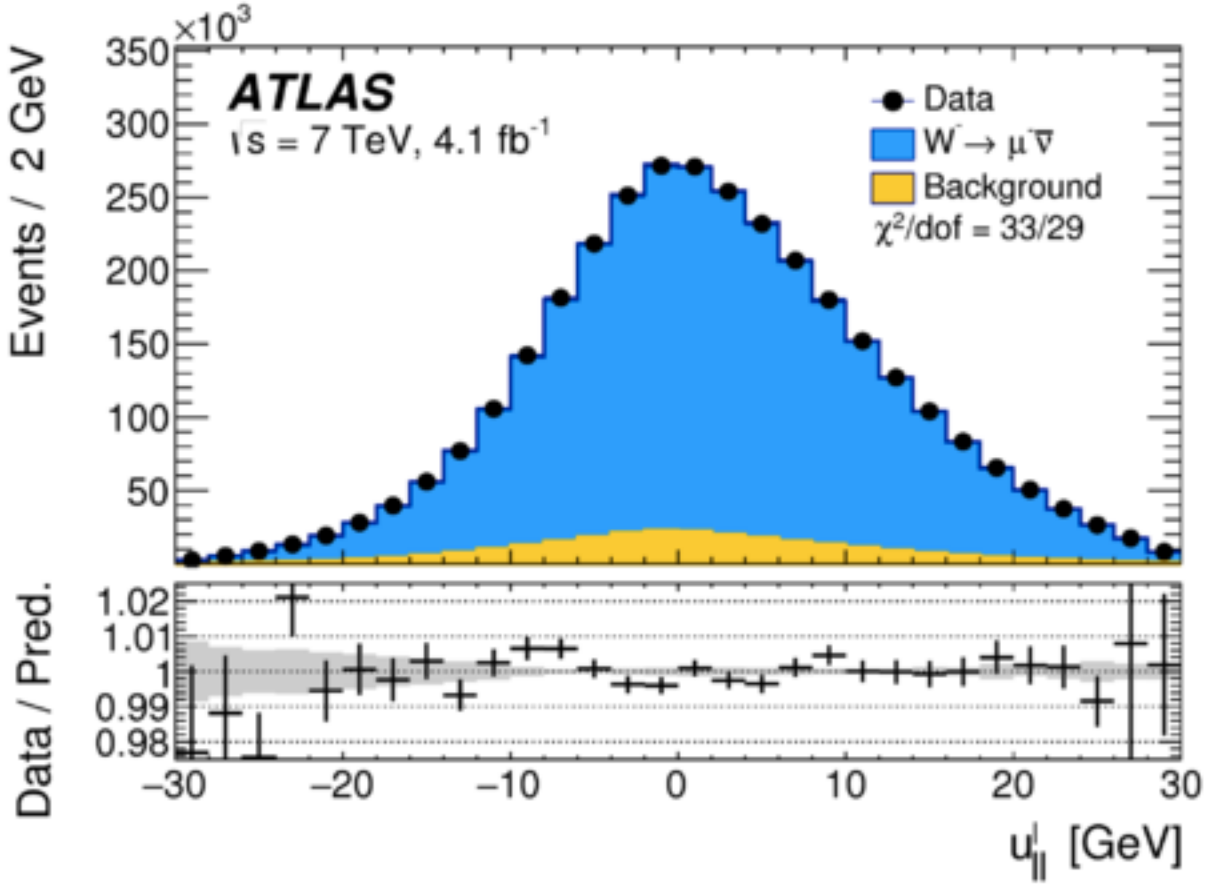
W^+ **W^-**

Muons

Electrons



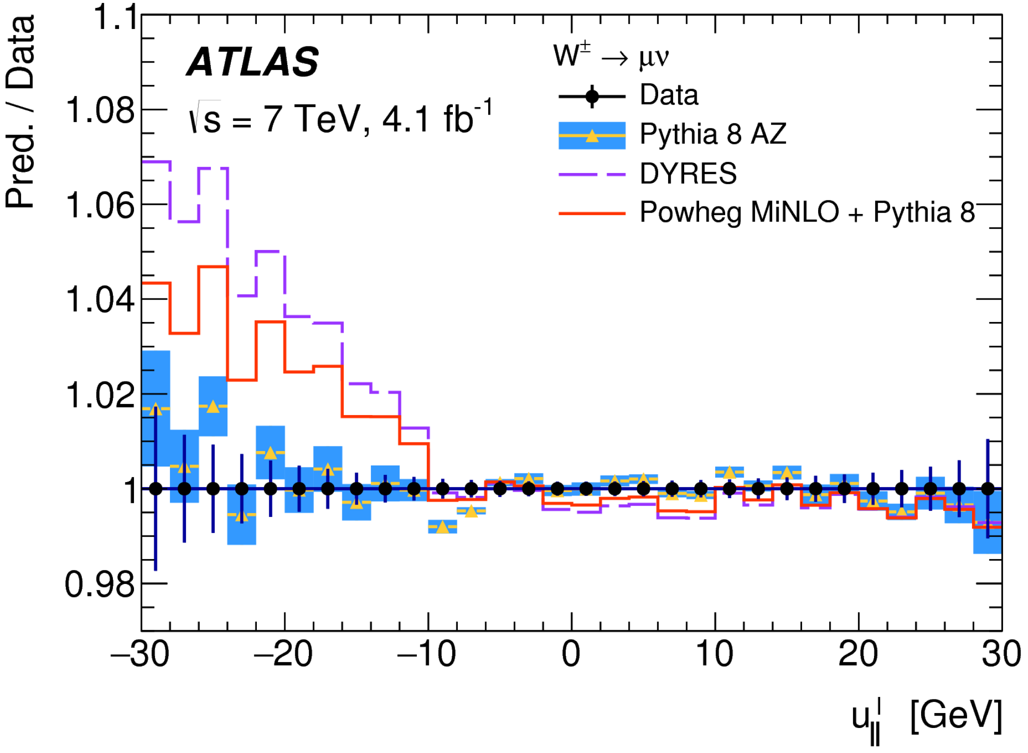
Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$

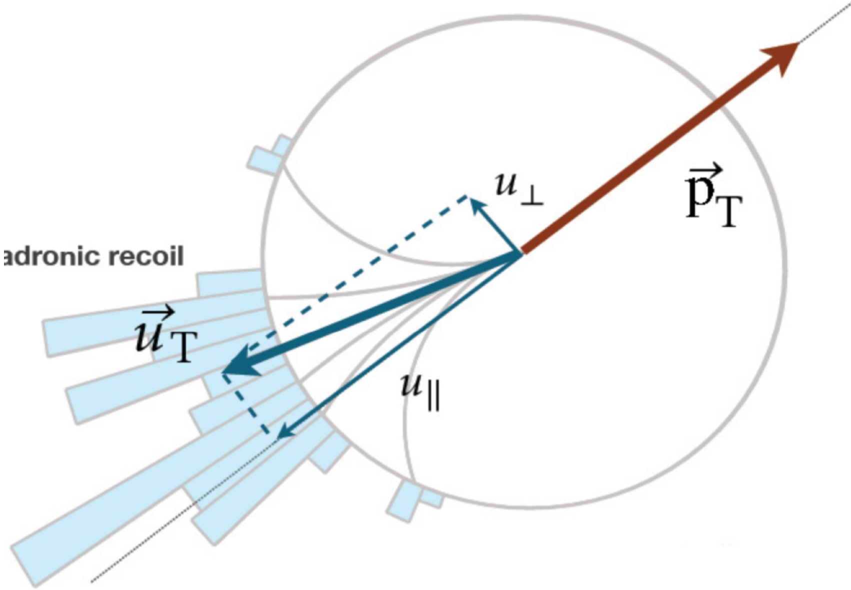


- The region $u_{//}^{l} < -10$ GeV is sensitive to the physics modelling of the soft part of the p_T^W spectrum
- With a total of e.g. ~ 0.8M W to $\mu\nu$ decays, one can constrain modelling uncertainties to ~ 10 MeV

Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$

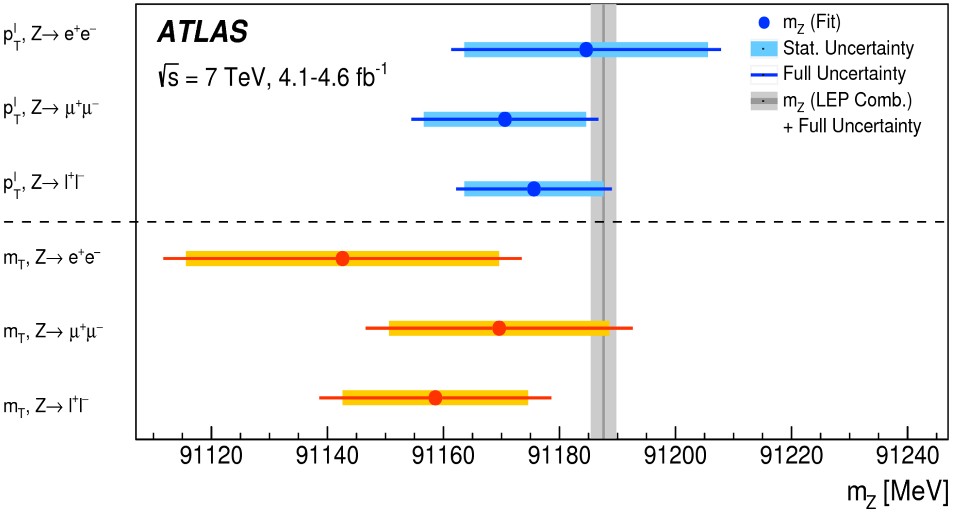
The $u_{||}^l$ distribution is very sensitive to the underlying p_T^W distribution, for $u_{||}^l < 0$. This feature can be exploited, even in a high pile-up environment to verify the accuracy of the baseline model, and to compare to alternative (more state-of-the-art?) models

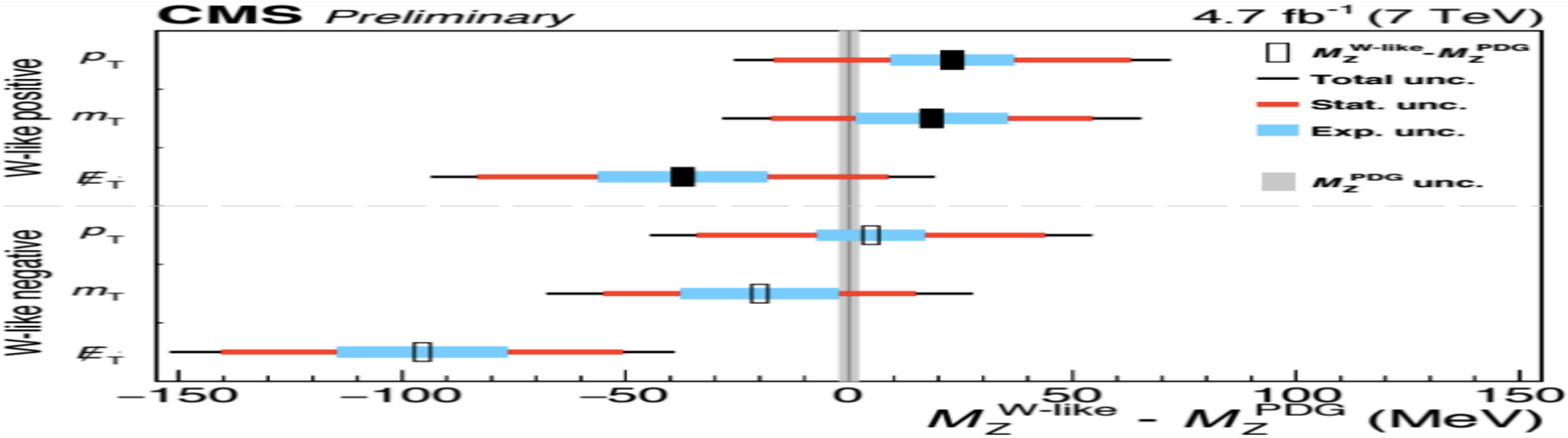




Pythia 8 tuned to Z OK; DYRES, Powheg MiNLO disfavoured

Experimental interlude: cross-checks with Z events (ATLAS and CMS)





Cross-checks with Z events (ATLAS and CMS 7 TeV)

Source of uncertainty (values in MeV for m_T meas.)	**CMS muons**	**ATLAS muons**	**ATLAS electrons**
Lepton efficiencies	**1**	**3.9**	**8.2**
Lepton calibration	**14**	**8.9**	**11.6**
Recoil calibration	**9**	**12.0**	**12.0**
Statistics	**35**	**28**	**38**

Remarks

1. **The CMS measurement is less precise statistically than the ATLAS one for muons for several reasons (only muons with $|\eta| < 0.9$ used in CMS, half of the sample used for the recoil calibration and the other half for the measurement)**
2. **The lepton calibration in ATLAS is more precise because it is based on the full run-1 dataset (7 and 8 TeV)**
3. **The recoil calibration in CMS appears more precise than the ATLAS one (particle flow versus 3D topological clusters) but the response of the recoil in CMS is ~30%, to be compared to ~70% in ATLAS**
4. **The efficiency systematics for CMS are much smaller (stats insufficient?)**

Prospects on measurements at 8 and 13 TeV

- **Larger data samples allow (in principle) more precise calibrations of detector response, provided material, alignment, geometry, etc… are all well understood.**

- **However, these larger data samples come with higher pile-up, which deteriorates recoil resolution. This will compromise the m_T measurement, and reduce our ability to control and validate modelling uncertainties through the recoil distributions.**

- **In order to benefit from the larger 8 and 13 TeV data samples, it is therefore crucial to improve the methodology used for the recoil calibration in order to mitigate pile-up effects as much as possible while preserving small systematics from extrapolation from Z to W.**

- **The single lepton triggers are also a concern, especially for the electrons, since the trigger turn-on curve extends in 2016 into the fit region, while this was not the case in 2011. The improved phase-1 calorimeter trigger for run 3 should solve this important concern for the run-2 data.**

Prospects on physics modelling

- PDF uncertainties can be reduced by the inclusion in the fit of precise W, Z inclusive rapidity measurements with ATLAS/CMS run-1 data
- p_T^W uncertainties can be reduced by using higher-order predictions based on analytical resummation, and with fits to Z p_T 8 TeV measurement, which is more precise than the 7 TeV measurement, and has low- and high-mass distributions which can constrain heavy-flavour-initiated production.
- Much work was already done on the two points above, and there are plans to update the 7 TeV ATLAS measurement with improved physics modelling tools and fits.
- Thanks to the precise measurements at 8 TeV, uncertainties on the angular coefficients are currently not a limiting factor. In the future, they can be reduced with more precise predictions and more precise measurements.

- For the physics modelling, ultimately, we need to perform precise and direct measurements of the W p_T, angular coefficients, and underlying event, either with dedicated low pile-up runs, or with new methodologies. This will remove the most difficult source of systematic uncertainty, which otherwise will remain a source of endless debate.

Questions to theory colleagues

- Can one really extrapolate from Z to W assuming certain cancellations of theory uncertainties (in particular the dreaded scale variations, where resummation needs to be added to the usual suspects)?

- Why are NNLO+NNLL calculations worse than simple parton shower when compared to data? Could this be due to oversimplication of ansatz assuming a sophisticated calculation of a single observable provides more accuracy than a model generating event-by-event kinematics of multiple soft gluon emission? Or is this mostly due an as yet poorly understood treatment of heavy flavours? These play an important role at the LHC, and the contributions are not at all the same for W (charm, strangeness) and Z (bottom).

- How can one solve the bottlenecks in the theory used by PDF fits? Scale variations, parton shower effects, etc

- Is there a way to extrapolate the discrepancies seen between NNLO QCD and data for the Z angular coefficients to the W boson? Presumably experiments need to do the W measurements themselves but the accuracy will always be worse than for Z bosons.

Back-up slides

Lepton and event selection for measurement of m_W

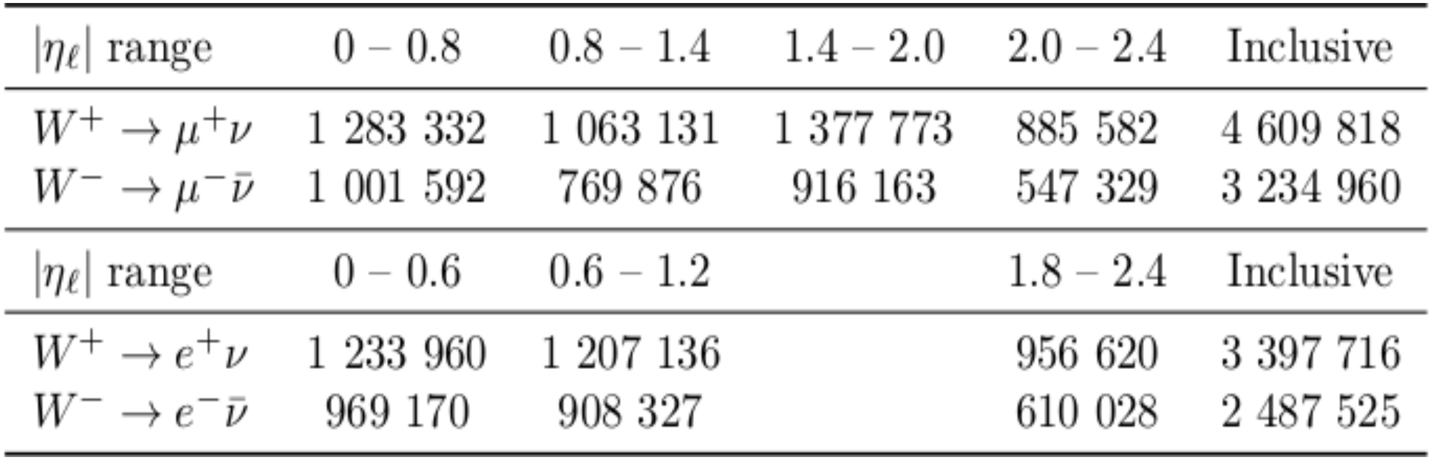
Lepton selections

- Muons : $|\eta| < 2.4$; isolated (track-based)
- Electrons : $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated

Kinematic requirements

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

Measurement categories :

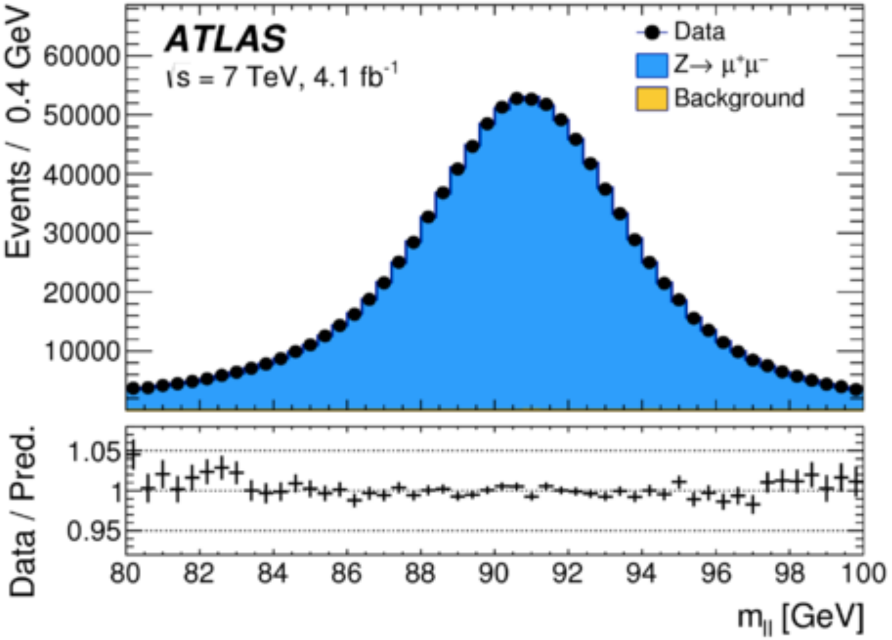


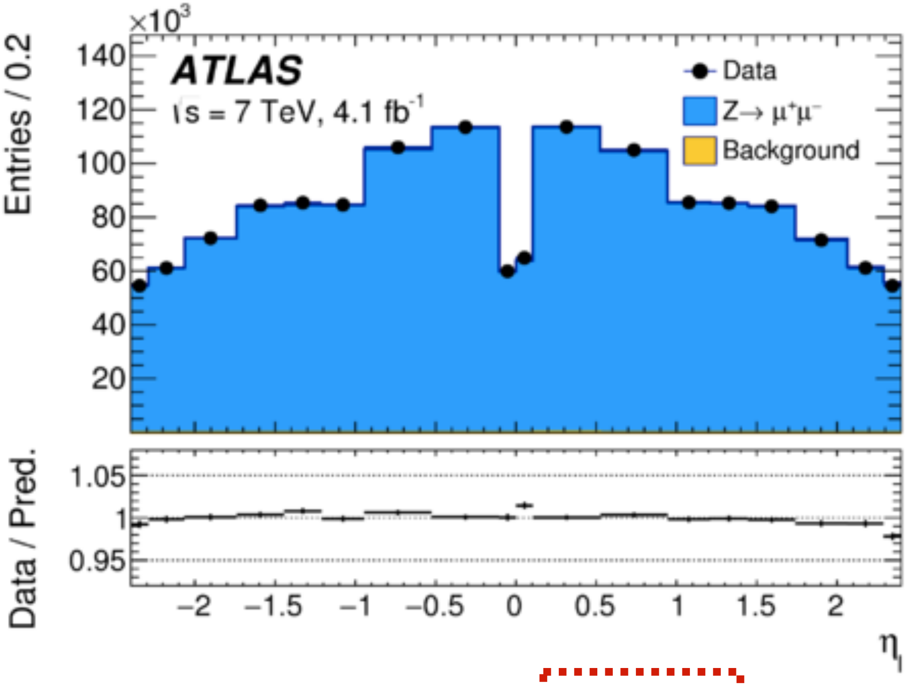
$\|\eta_\ell\|$ range	$0 - 0.8$	$0.8 - 1.4$	$1.4 - 2.0$	$2.0 - 2.4$	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	$0 - 0.6$	$0.6 - 1.2$		$1.8 - 2.4$	Inclusive
$W^+ \to e^+\nu$	1 233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

7.8 M events

5.9 M events

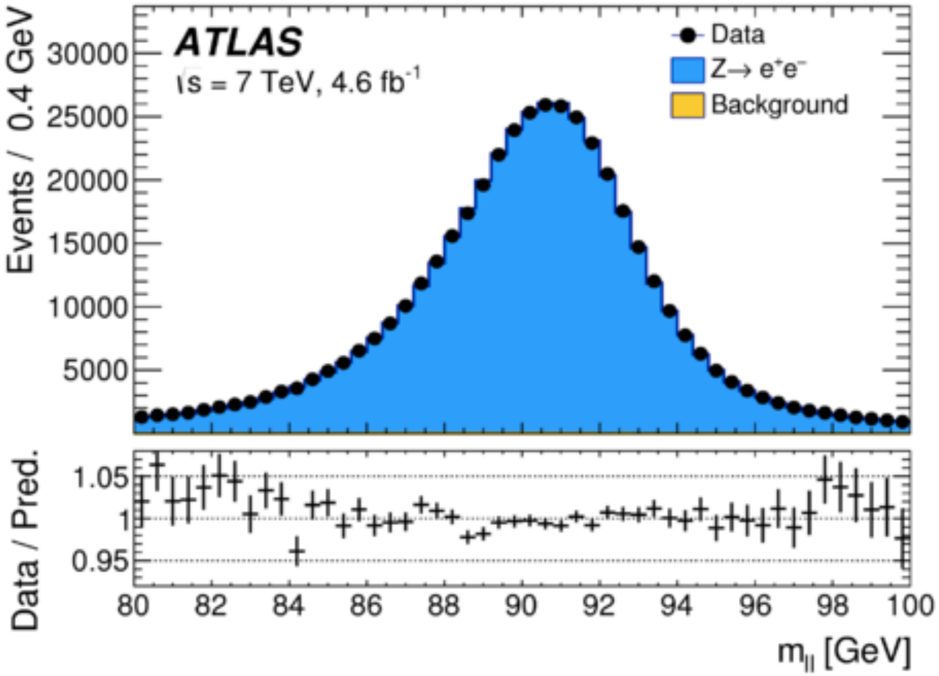
Muon calibration : performance and results

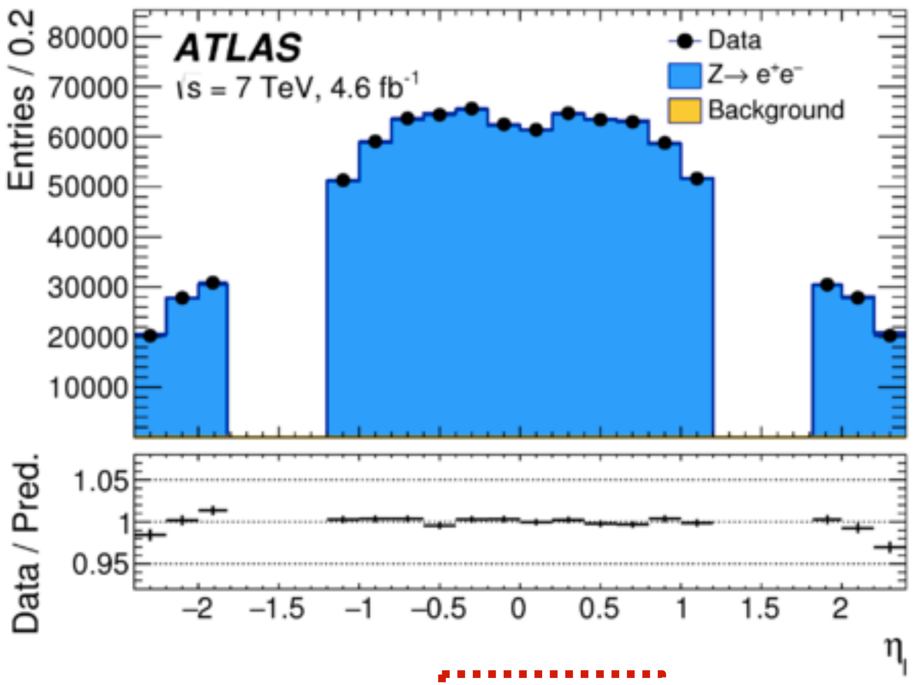




$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0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

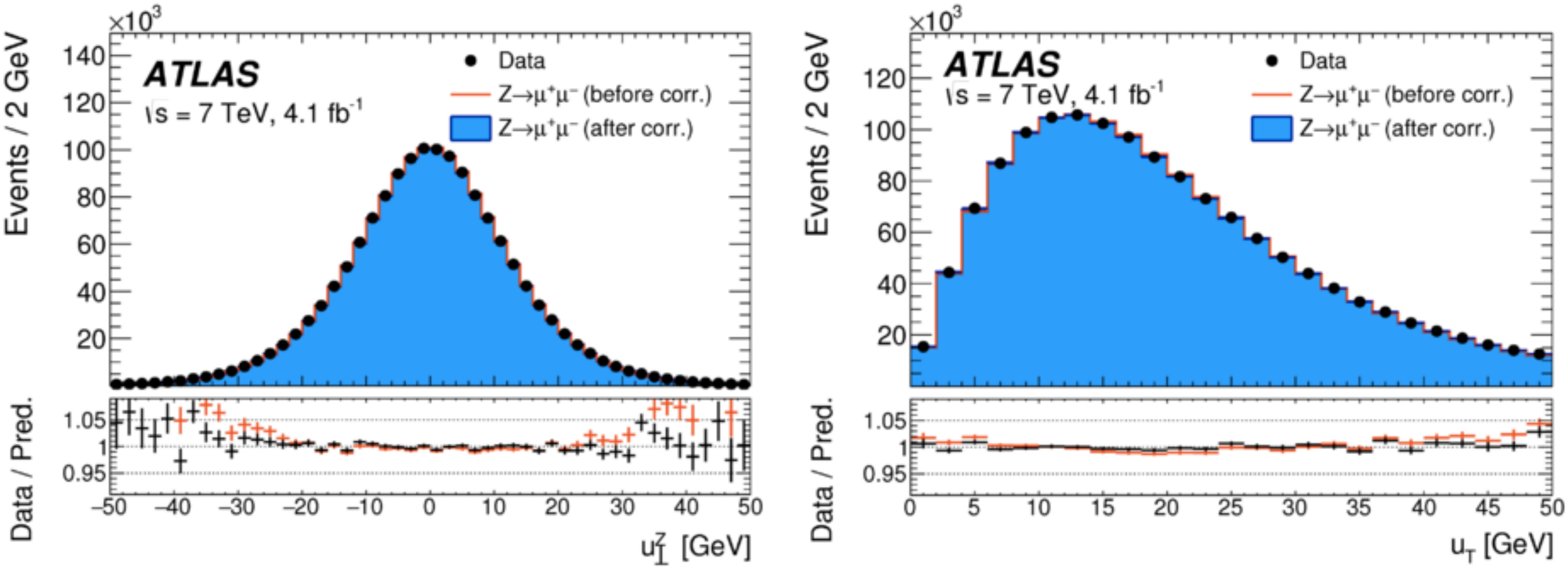
Electron calibration : performance and results





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

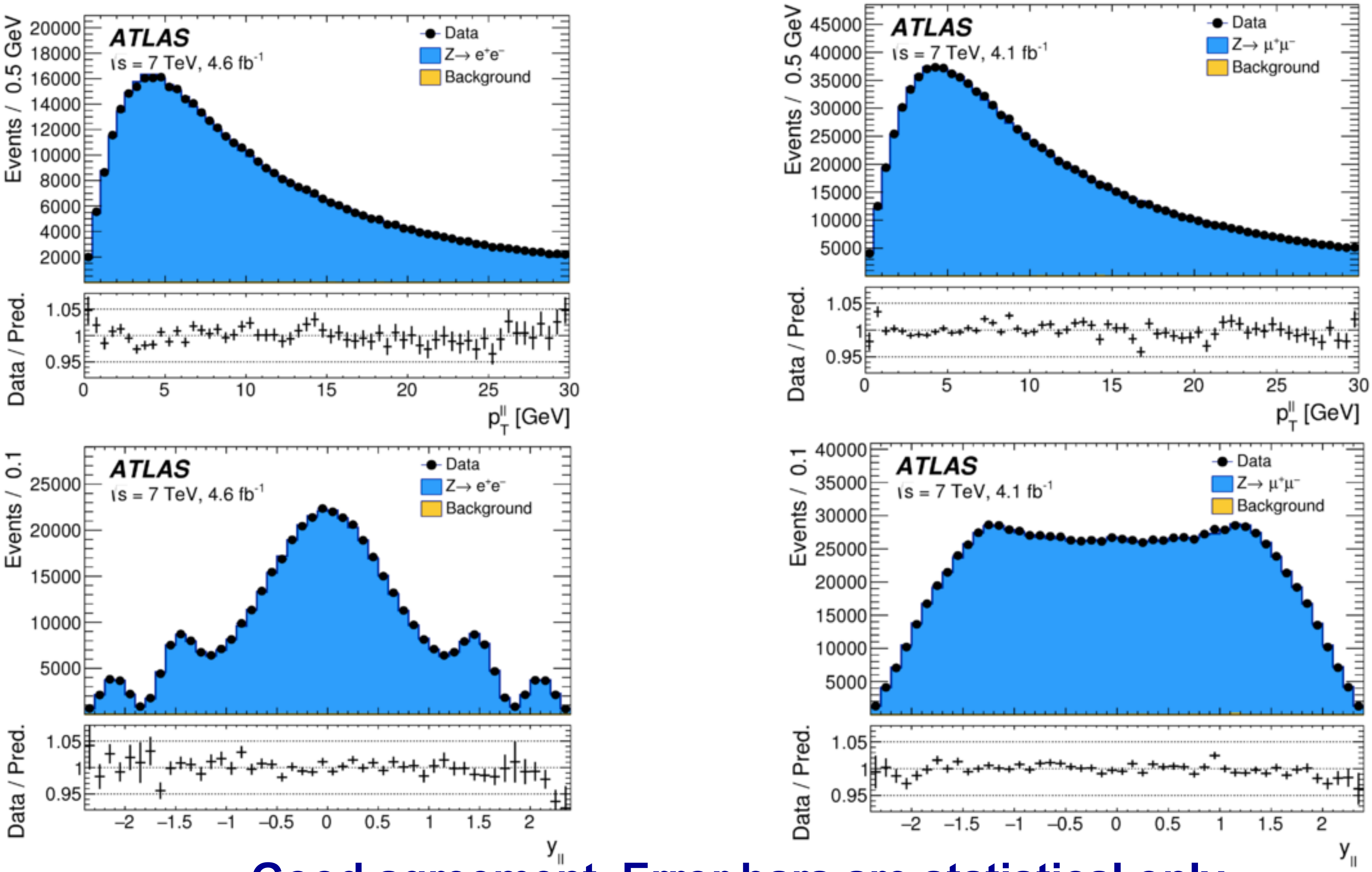
Recoil calibration : performance and results



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

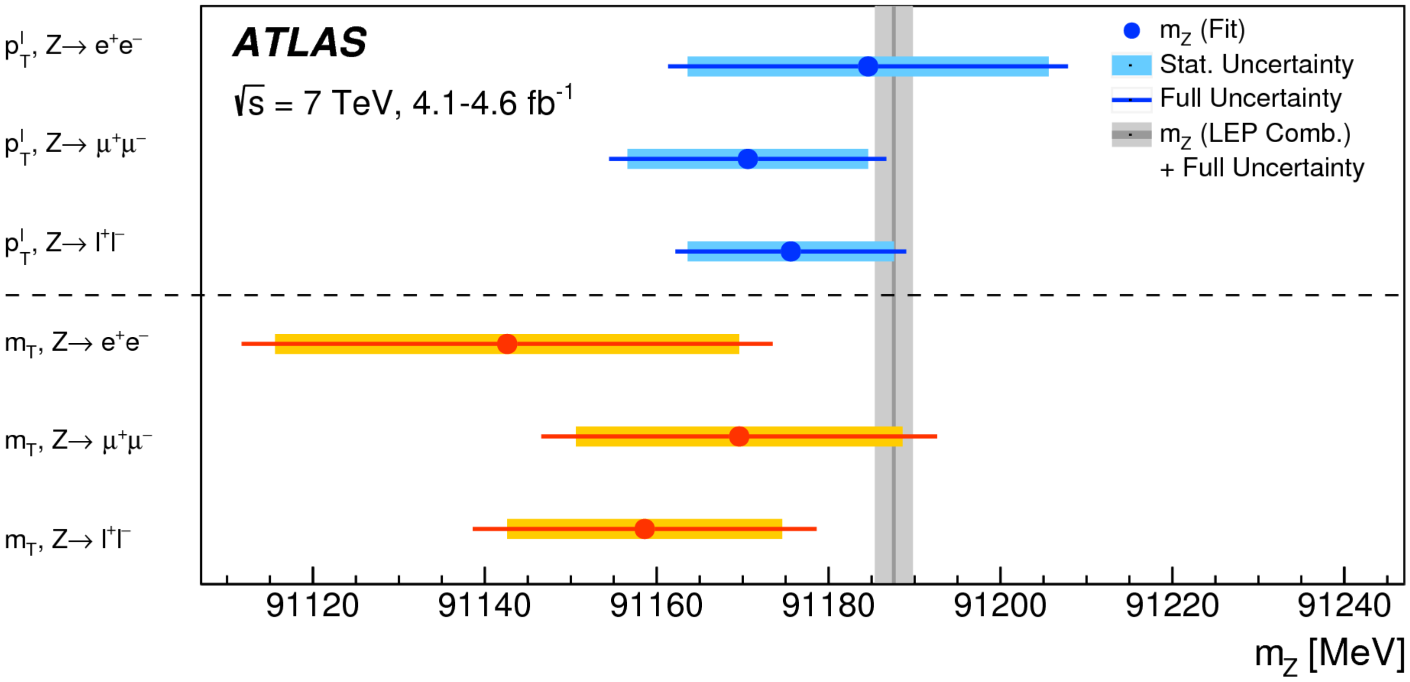
Cross-checks with Z events

Z boson rapidity and p_T distributions :



Good agreement. Error bars are statistical only

Cross-checks with Z events



Lepton charge	ℓ^+		ℓ^-		Combined	
Distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	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	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

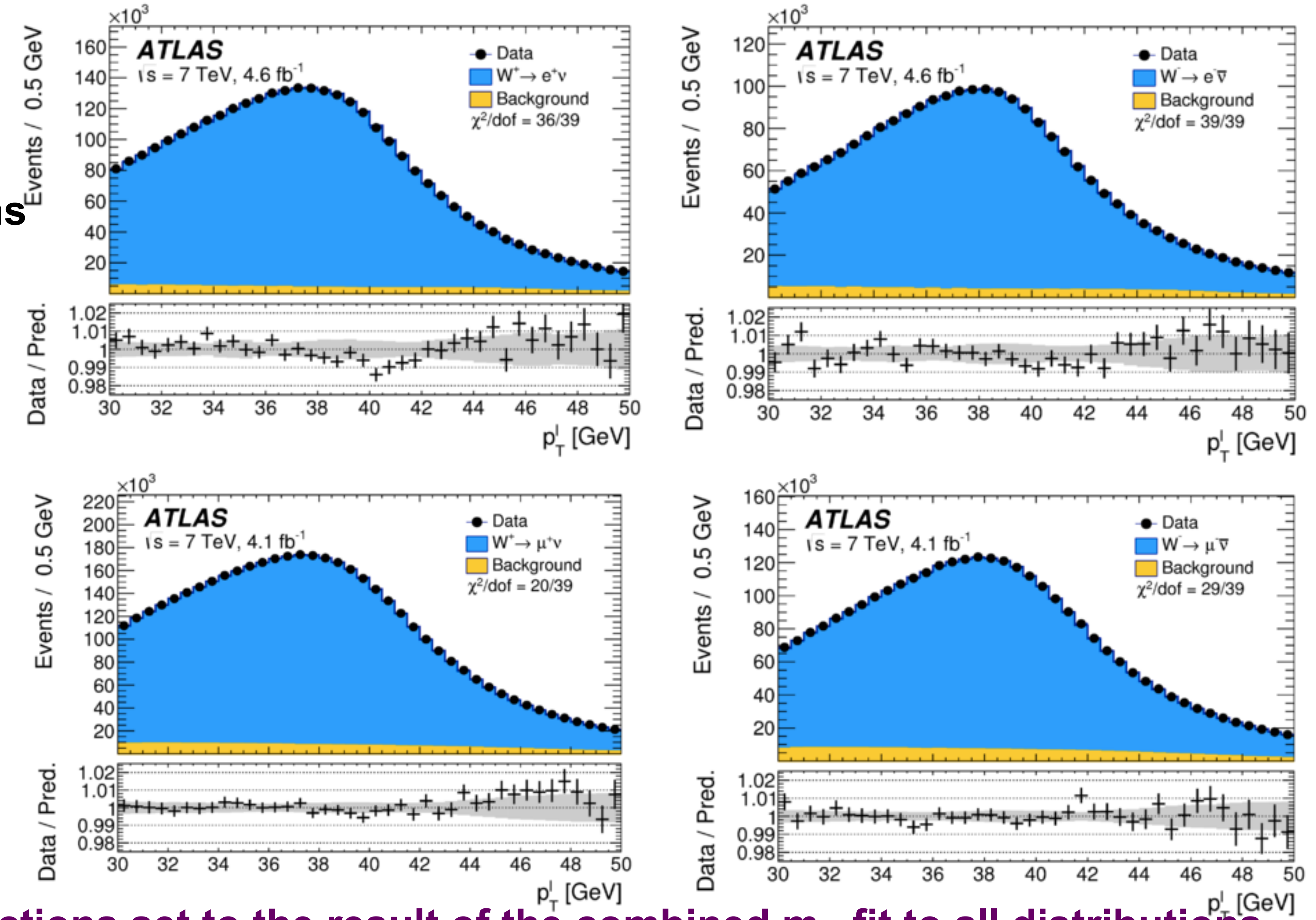
Results are consistent with m_Z within experimental uncertainties.
Fitted values are a bit low on average, but they are all from the same events

Post-fit distributions: lepton p_T

W^+ **W^-**

Electrons

Muons



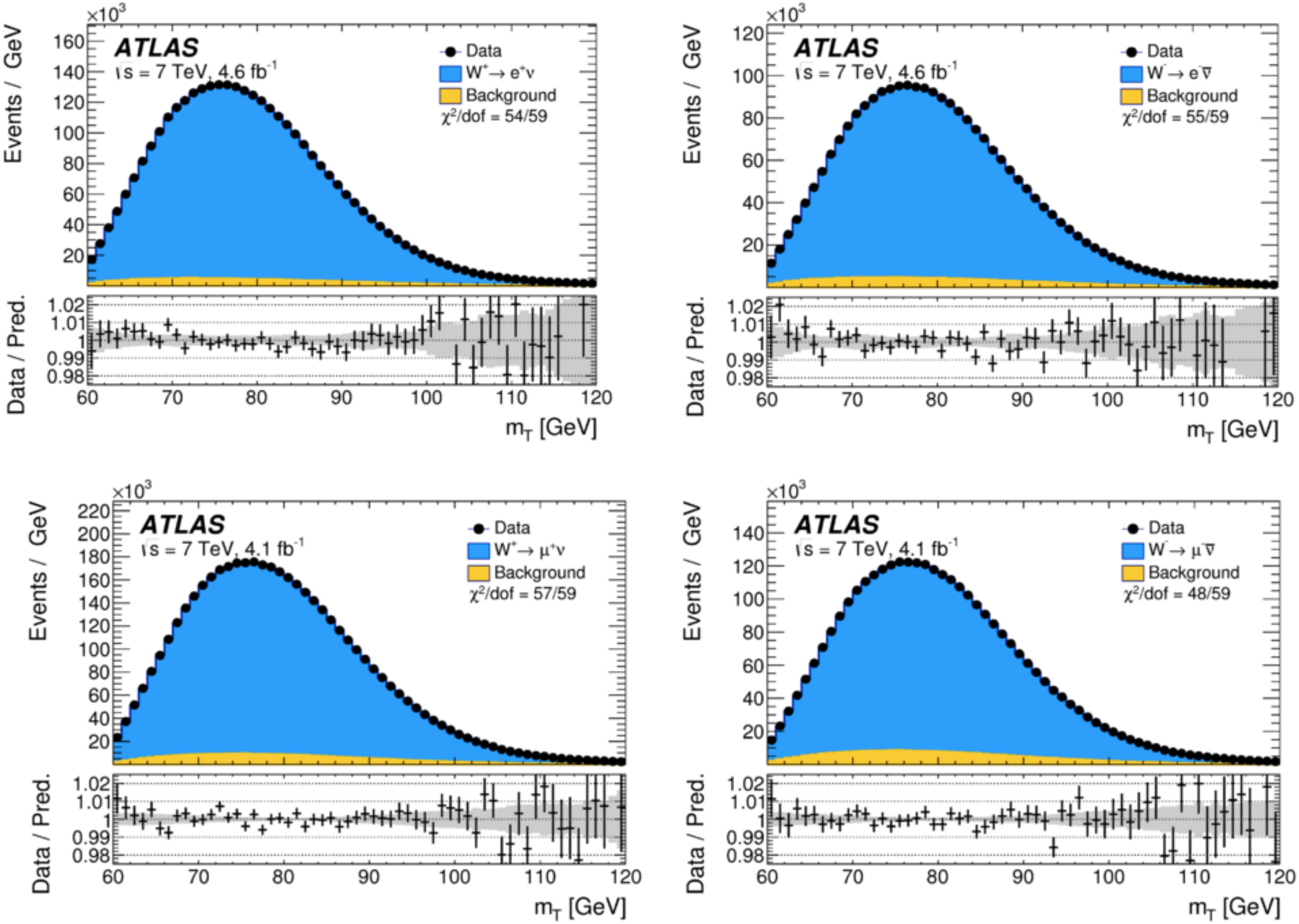
Predictions set to the result of the combined m_W fit to all distributions

Post-fit distributions: transverse mass m_T

W^+ **W^-**

Electrons

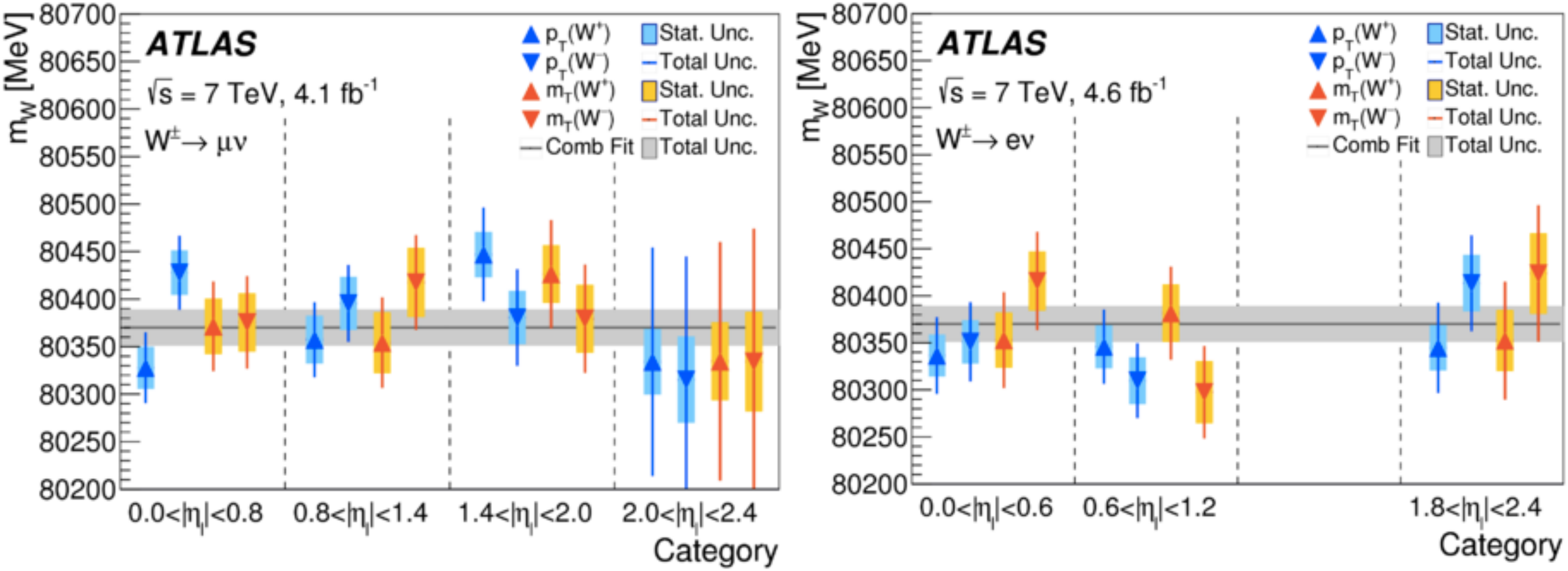
Muons



Predictions set to the result of the combined m_W fit to all distributions

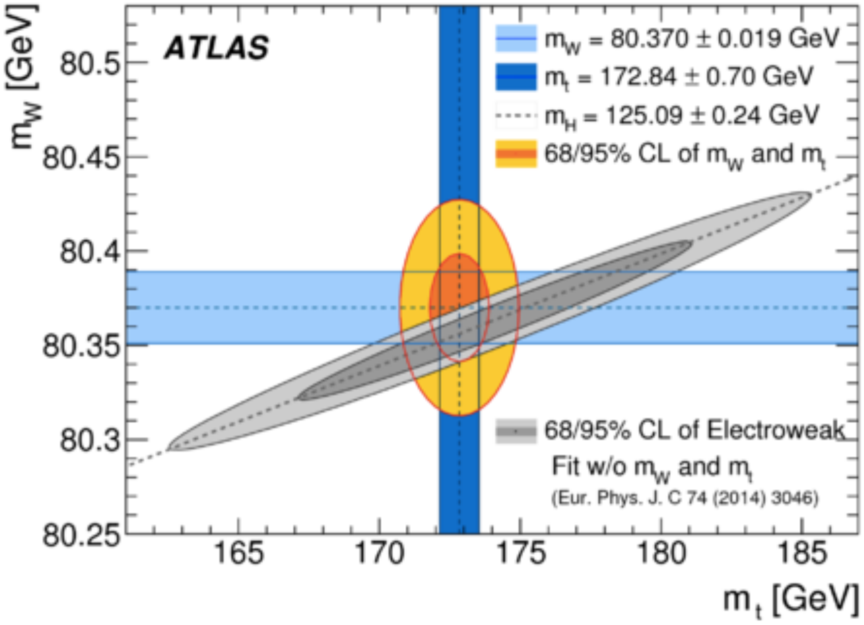
Fit results for m_W

Compatibility tests, performed before unblinding

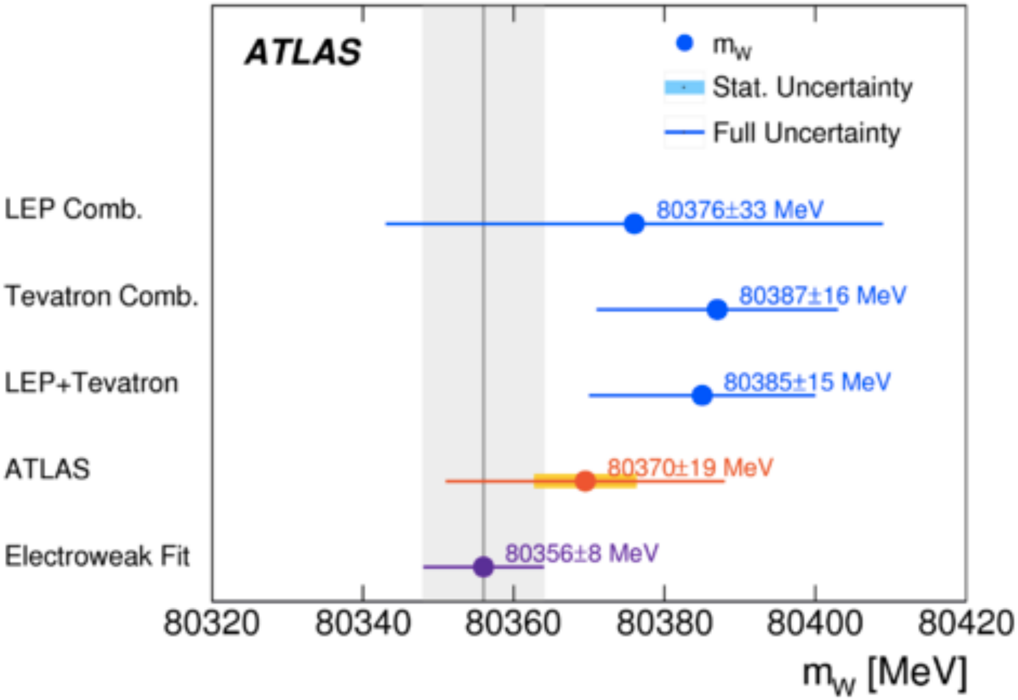


χ^2 / n_{dof} = 29 / 27

Consistency of Standard Model



SM prediction for m_W vs m_t, assuming m_H = 125.09 ± 0.24 GeV



SM prediction for m_W, assuming
m_H = 125.09 ± 0.24 GeV
m_t = 172.84 ± 0.70 GeV