W-boson mass projects with ATLAS (and friends)

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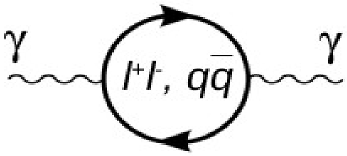
Orsay, Feb. 23, 2023

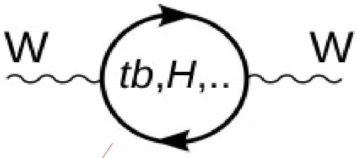
Outline

- Past
  - W-boson mass at 7 TeV : https://arxiv.org/abs/1701.07240
- Future perfect
  - Re-analysis / update of the former
- Future
  - Status of m_W combination project
  - Ongoing measurements with new(er) data : talk by Zhibo Wu tomorrow

Prediction of m_W in the SM - snapshot

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}G_\mu m_Z^2}\frac{1}{1-\Delta r}}\right)$$



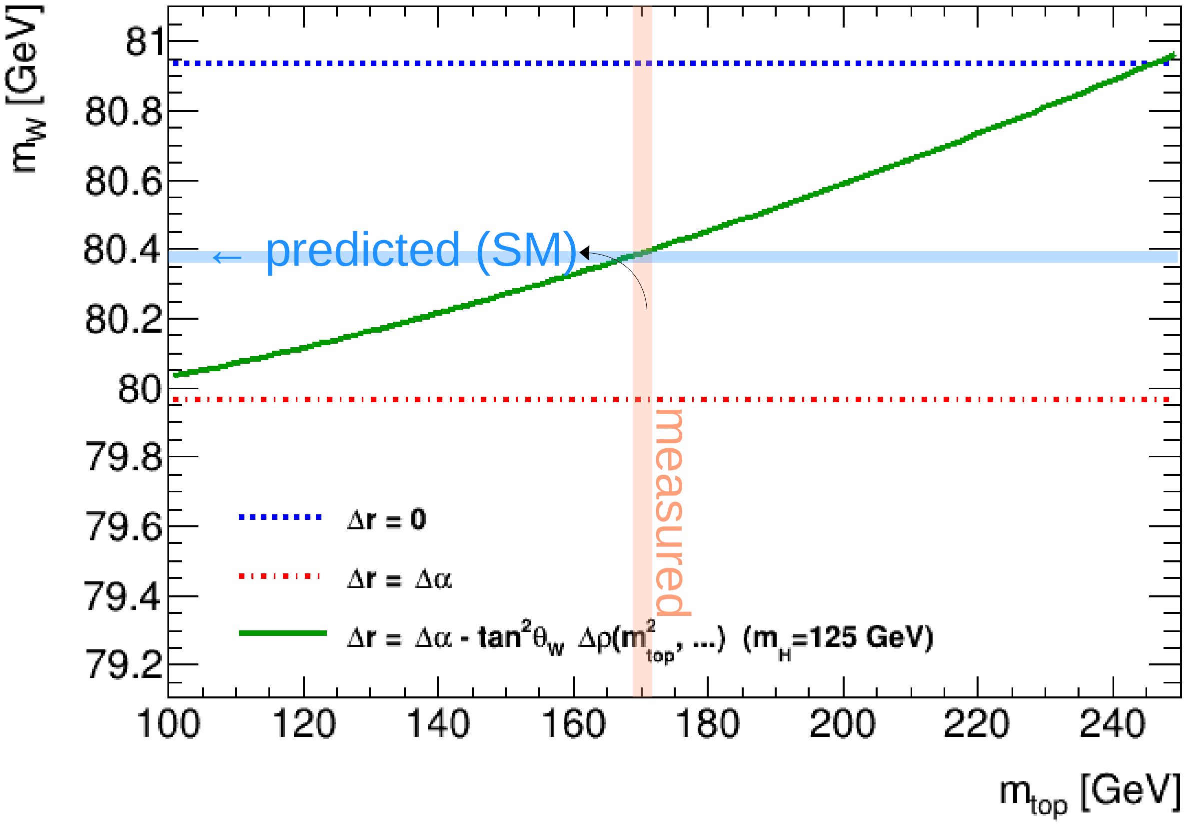


$$\Delta r = \Delta\alpha - \tan^2\theta_W \Delta\rho = \sim 0.059 - \frac{3G_\mu m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_{top}^2}{m_W^2}\cot^2\theta_W - \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots\right]$$

$\alpha(0) \sim 1/137.. \rightarrow \alpha(m_Z) \sim 1/128.9$

→ talk by Chen Wang tomorrow

Prediction of m_W in the SM - snapshot

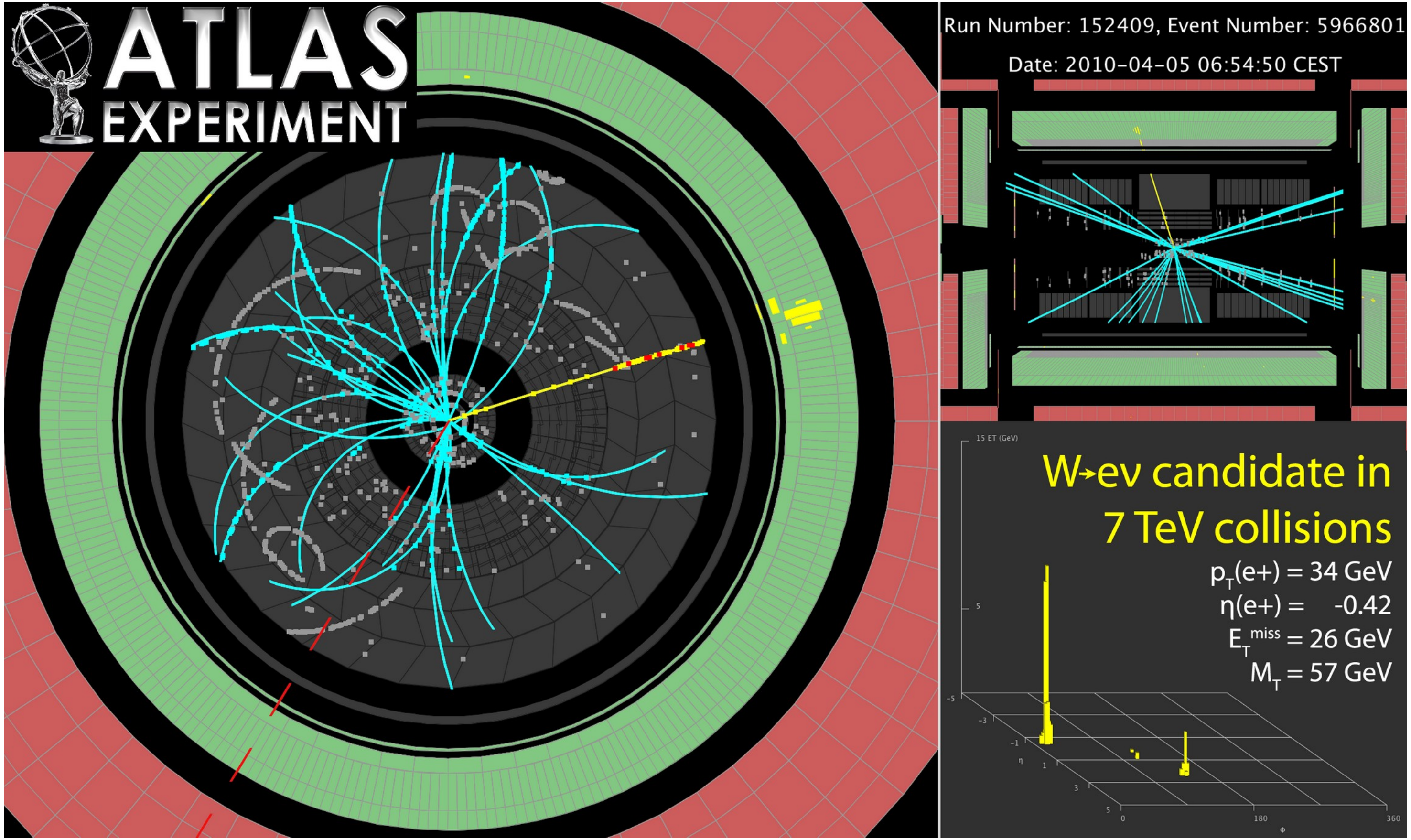


Nowadays:

- Inputs : $\delta m_{top} \sim 0.7$ GeV $\delta m_H < 0.2$ GeV
- Output : **$m_W = 80.356 \pm 0.008$ GeV**

→ talk by Chen Wang tomorrow

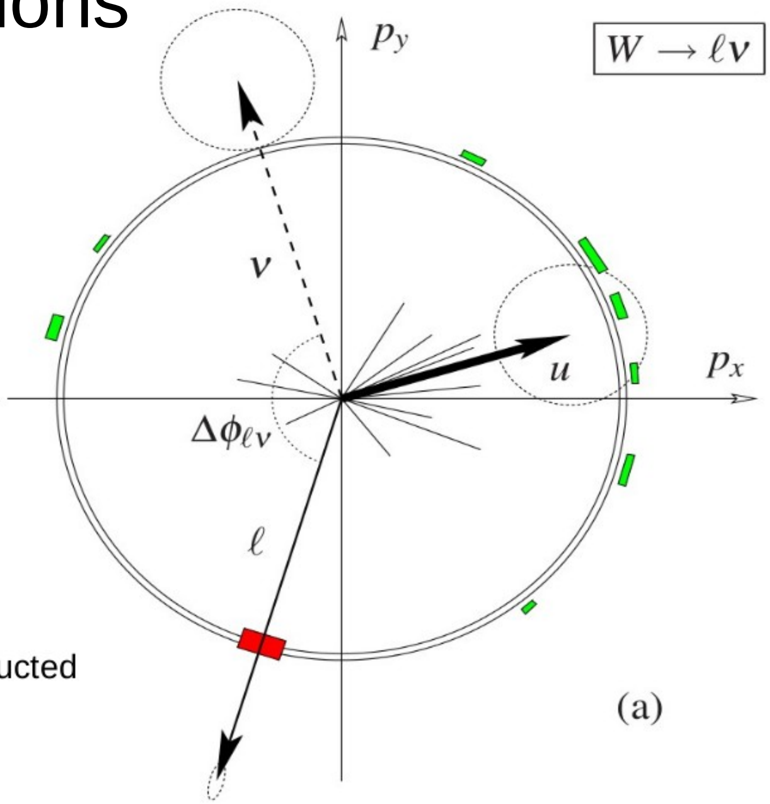
The W boson mass in proton collisions



The W boson mass in proton collisions

- Incomplete kinematics (missing neutrino!)
  → no invariant mass
  → rely on measured quantities, and exploit momentum conservation in the transverse plane

- Event representation :



- Main signature :
  single electron or muon $\vec{p}_T^{\,l}$ p_T^l

- Recoil : sum of "everything else" reconstructed in the calorimeters; a measure of $p_T^{W,Z}$

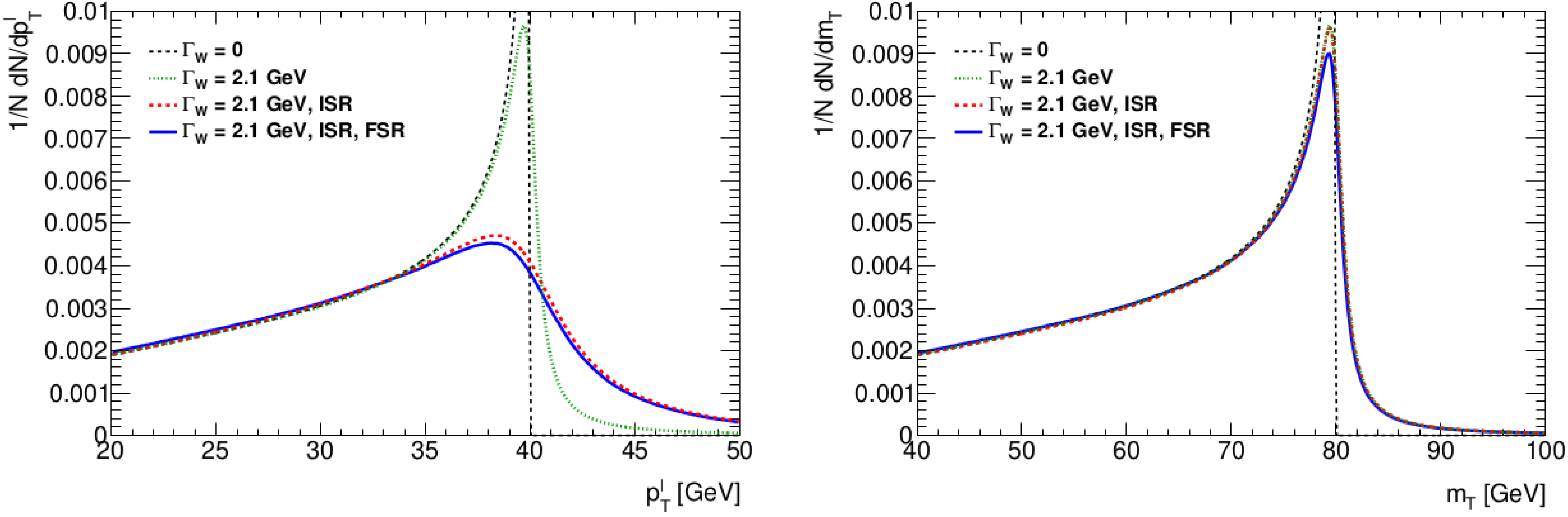
$$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

- Derived quantities : $\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$ $m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos\Delta\phi)}$

The W boson mass in proton collisions

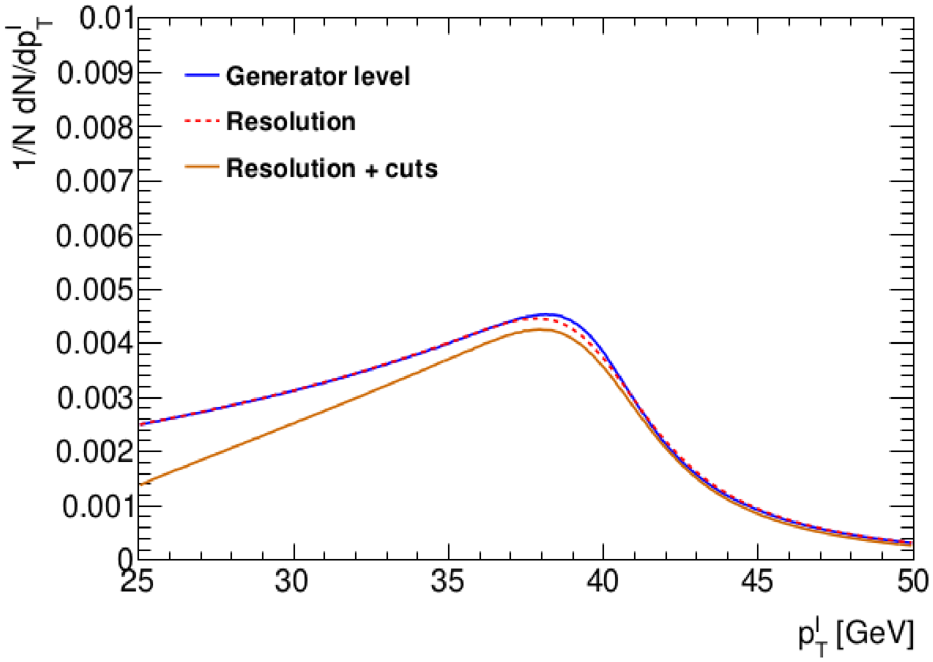
- Physics corrections

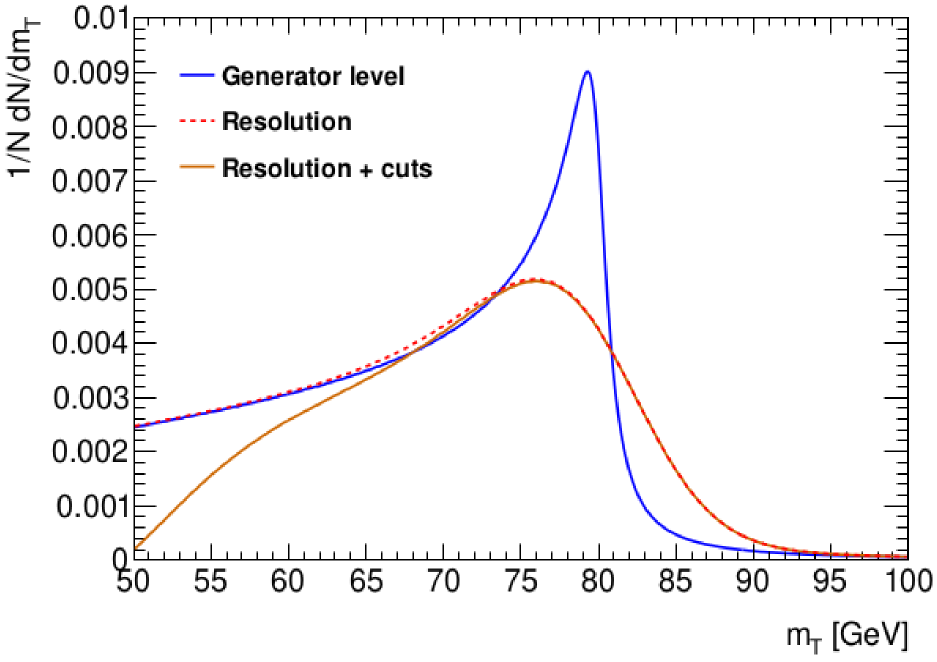
  → all carry uncertainties to be quantified!



The W boson mass in proton collisions

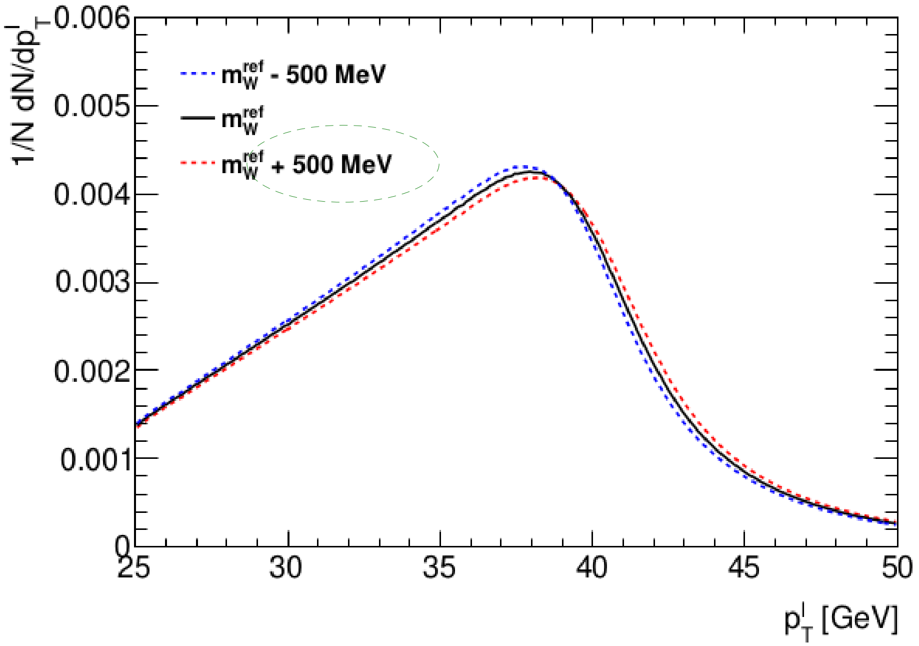
- Detector effects, also with uncertainties :
  - Lepton calibration and resolution;   Missing E_T resolution ~ 5 – 15 GeV
  - Efficiencies and acceptance ~15% (with non-trivial kinematic dependence!)

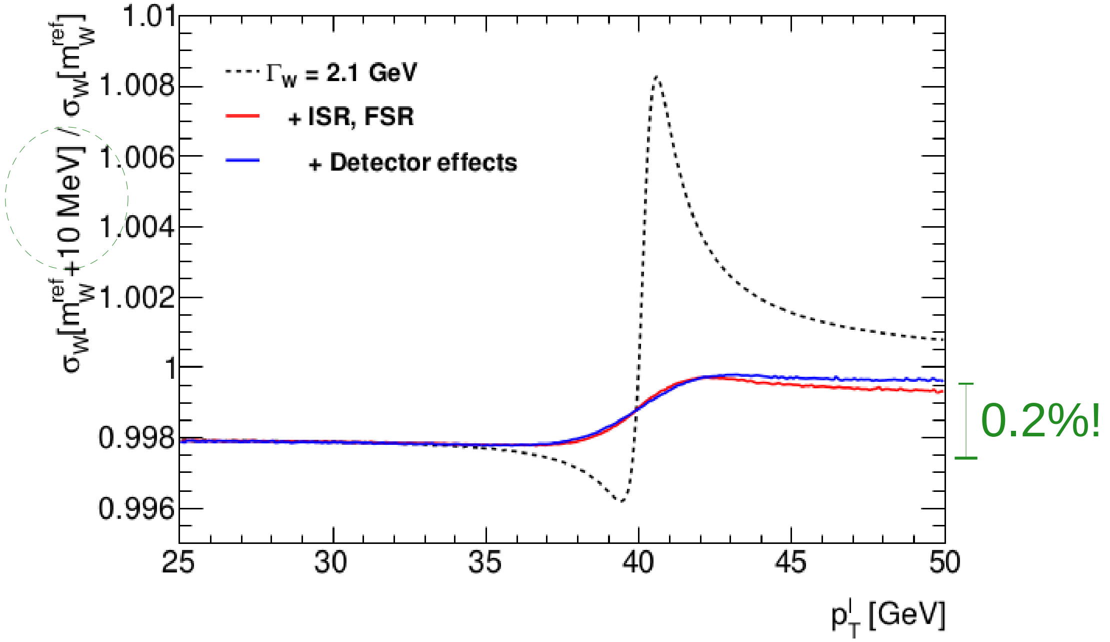




The W boson mass in proton collisions

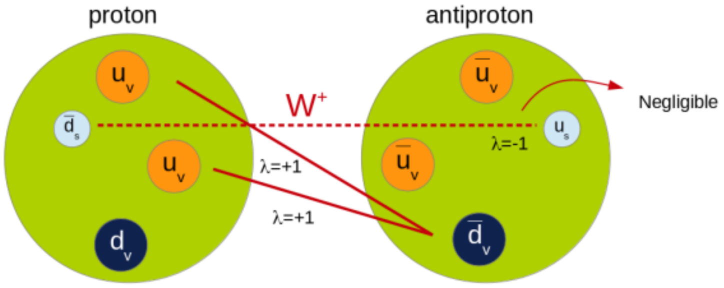
- Mass measurement : produce models ("templates") of the final state distributions for different mass hypotheses; compare to data



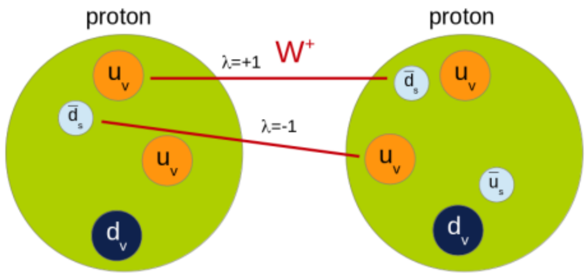


W-boson production at the LHC

A proton-proton collider is the most challenging enviroment to measure m_W, worse compared to e+e- and proton-antiproton



In $p\bar{p}$ collisions W bosons are mostly produced in the same helicity state



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

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

Further QCD complications

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

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

Measurement overview

- Physics modelling
- Calibration
- Z-boson cross checks
- Background
- Combination

- Build the physics modelling by supplementing the MC samples with higher-order corrections and fits to DY ancillary measurements
- Use $Z \rightarrow ll$ events to calibrate the detector response to the energy scales and resolutions of the leptons and of the recoil
- Validate the physics modelling and the calibration by extracting m_Z from p_T lepton and m_T in the Z sample
- Estimate and subtract the backgrounds in the W sample
- Extract m_W in several categories and combine. The categorisation validates the detector calibration and physics modelling and improves the accuracy

Physics modelling strategy

- We call physics modelling the theoretical prediction used to extract the W mass from the observed distributions in data, and the way theory uncertainties are addressed.
- The DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the boson decay:

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

Breit-Wigner

NNLO pQCD

Parton Shower

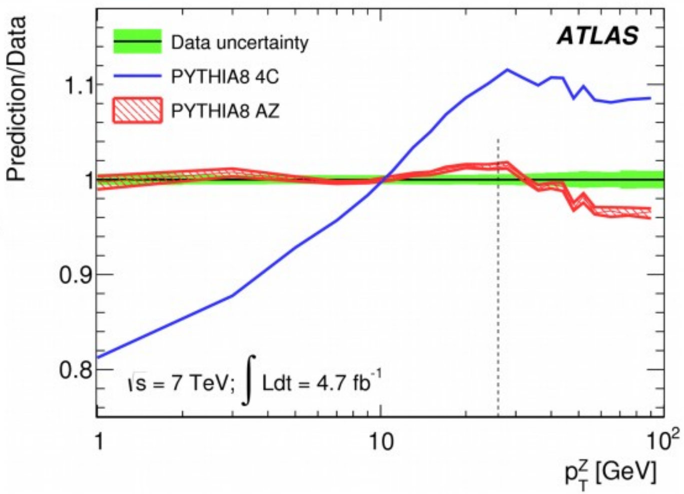
- This factorization allows buliding a composite model, and using the most appropriate or accurate model for each term.
- A fundamental aspect of the model is the use of ancillary DY measurement for validation, and, when possible, to fit the free parameters of the model and assess the uncertainties.
- Within the W-mass analysis, further validation of the model is provided by Z-mass fits, W-boson control plots, and compatibility of m_W categories

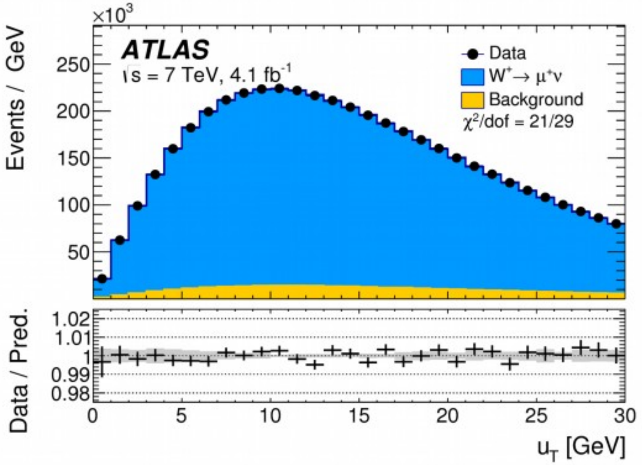
Physics modelling - p_T^W

- The Pythia8 p_T-ordered parton shower is used as model for the p_T W
- The parameters of the model are fit to the p_T Z measurement at 7 TeV (AZ tune)

	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

- The Pythia8 AZ tune describe the p_T Z data within 2% inclusively and in rapidity bins
- Pythia8 is used to transfer from the p_T Z to the p_T W distribution and to evaluate theory uncertainties on the W/Z p_T ratio

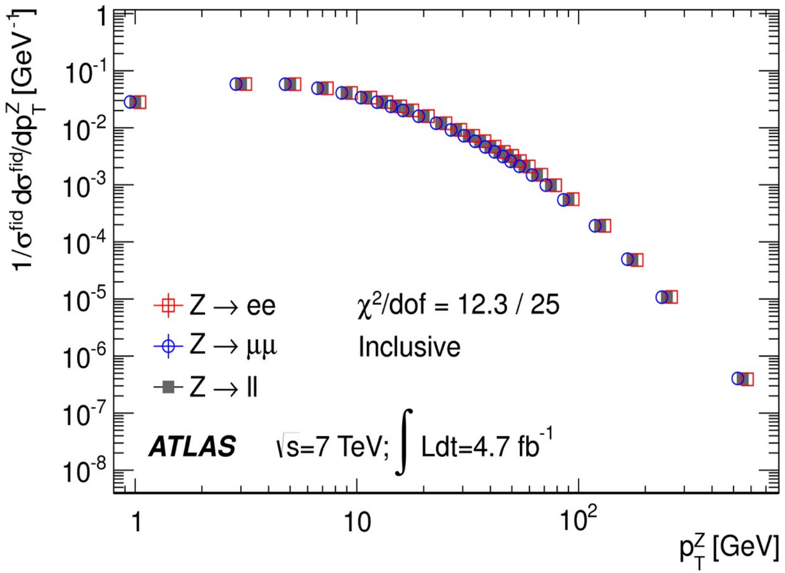


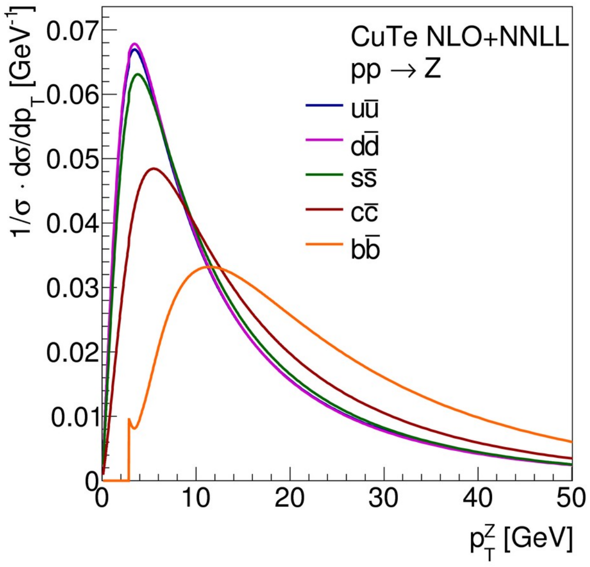


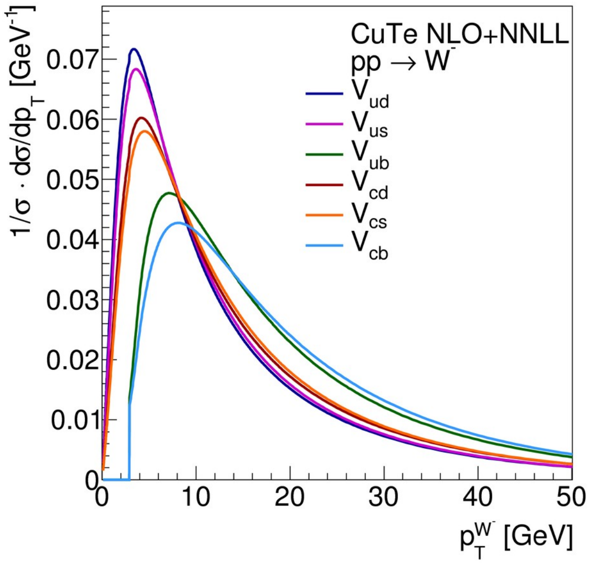
Strong interaction effects

- Transverse momentum distribution
  - Z-based model tuning (Pythia) + Z → W extrapolation uncertainties
    - HQ mass treatment and PDFs

Measurement precision ~0.5%







Summary of QCD uncertainties

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

- PDFs are the dominant uncertainty, followed by p_T W uncertainty due to heavy-flavour-initiated production
- PDF uncertainties are partially anti-correlated between W+ and W-, and significantly reduced by the combination of these two categories.
- p_T W uncertainties are similar for m_W extracted from p_T lepton and from m_T

(CT10nnlo)

Lepton calibration

- The Z boson mass is perfectly well know on this scale of precision, so can be used to calibrate the absolute scale of the momentum measurements

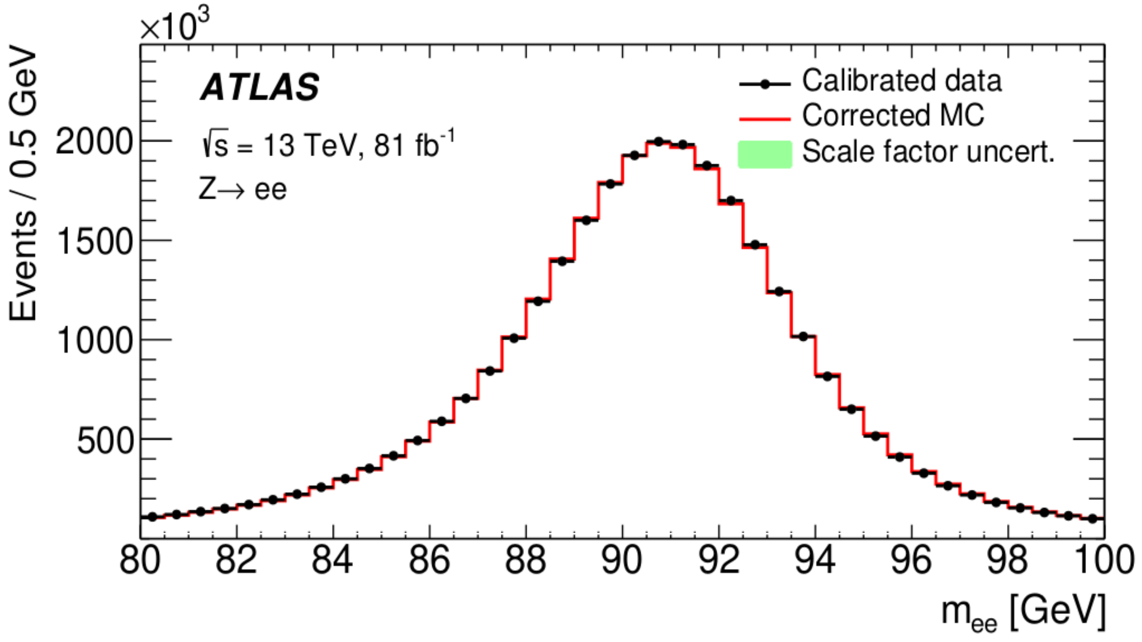
- Detector response derived from first principles to ~0.5% for calorimeters, ~0.05% for tracking detectors.

  ~0.01% is required here

- m_Z is known to ~0.002%,

  $m_{J/psi}$ to ~ 10^{-6}

  → used for final adjustments



Muon calibration

Muon identification using combined ID+MS tracks

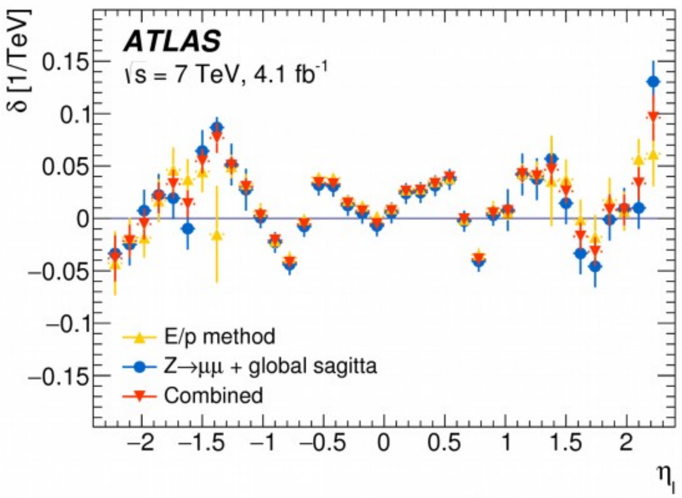
Momentum measurement from ID only

→ simplifies calibration, some loss in resolution

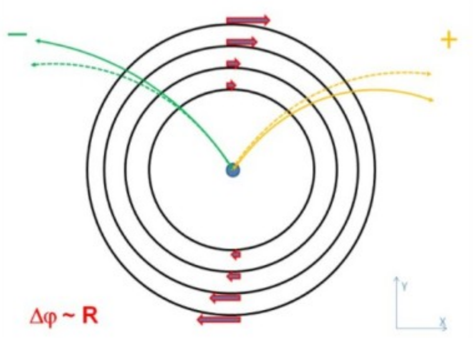
Parameterisation of momentum corrections:

- α: radial bias (scale)
- δ: sagitta bias
- β: resolution correction

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times \frac{1+\alpha(\eta,\phi)}{1+q\cdot\delta(\eta,\phi)\cdot p_{\mathrm{T}}^{\mathrm{MC}}}\left[1+\beta_{\mathrm{curv}}(\eta)\cdot G(0,1)\cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$



Scale calibrated with 10^{-4} rel. unc.



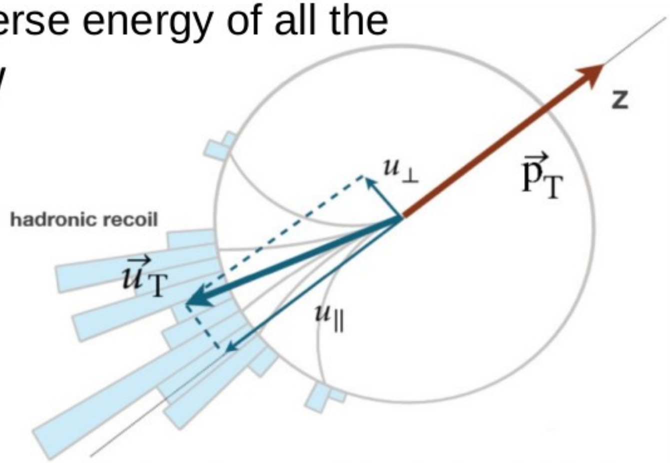
- Charge dependent corrections
- Scale and resolution corrections derived form $Z \rightarrow \mu\mu$ line shape, sagitta bias also from E/p in $W \rightarrow e\nu$

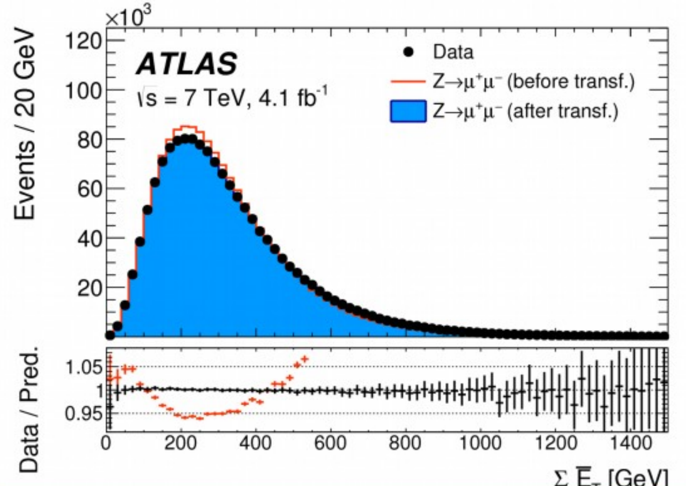
Recoil calibration

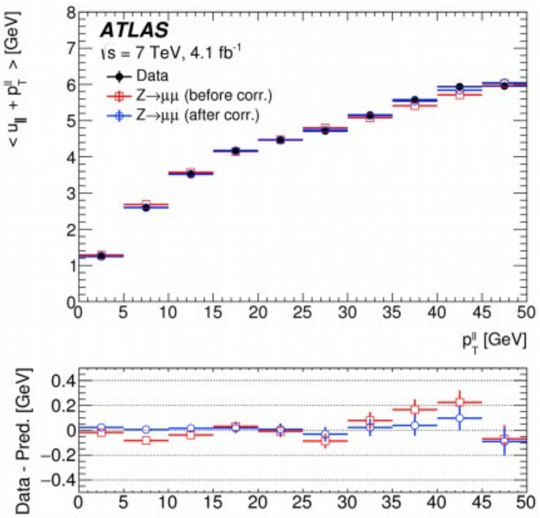
The recoil u_T is the vector sum of the transverse energy of all the calorimeter clusters: u_T is a measure of p_T W

Calibration steps:

- Correct pile-up multiplicity in MC to match the data
- Correct for residual differences in the ΣE_T distribution
- Derive scale and resolution corrections from the p_T balance in Z events

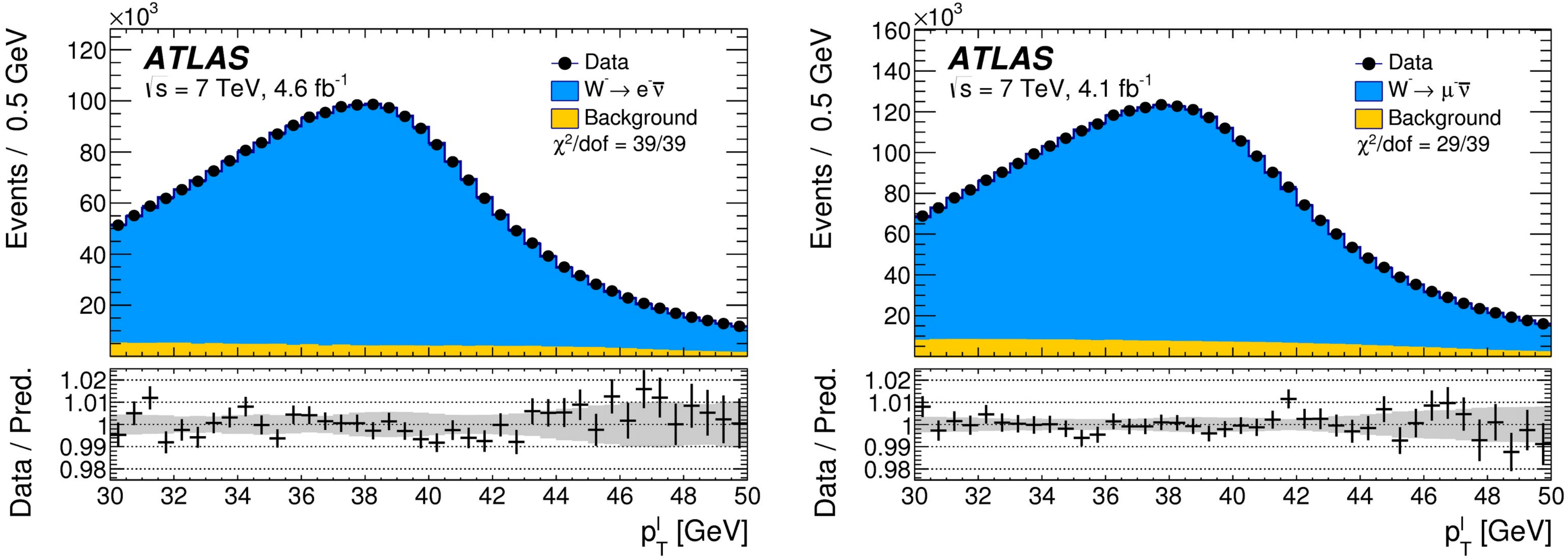






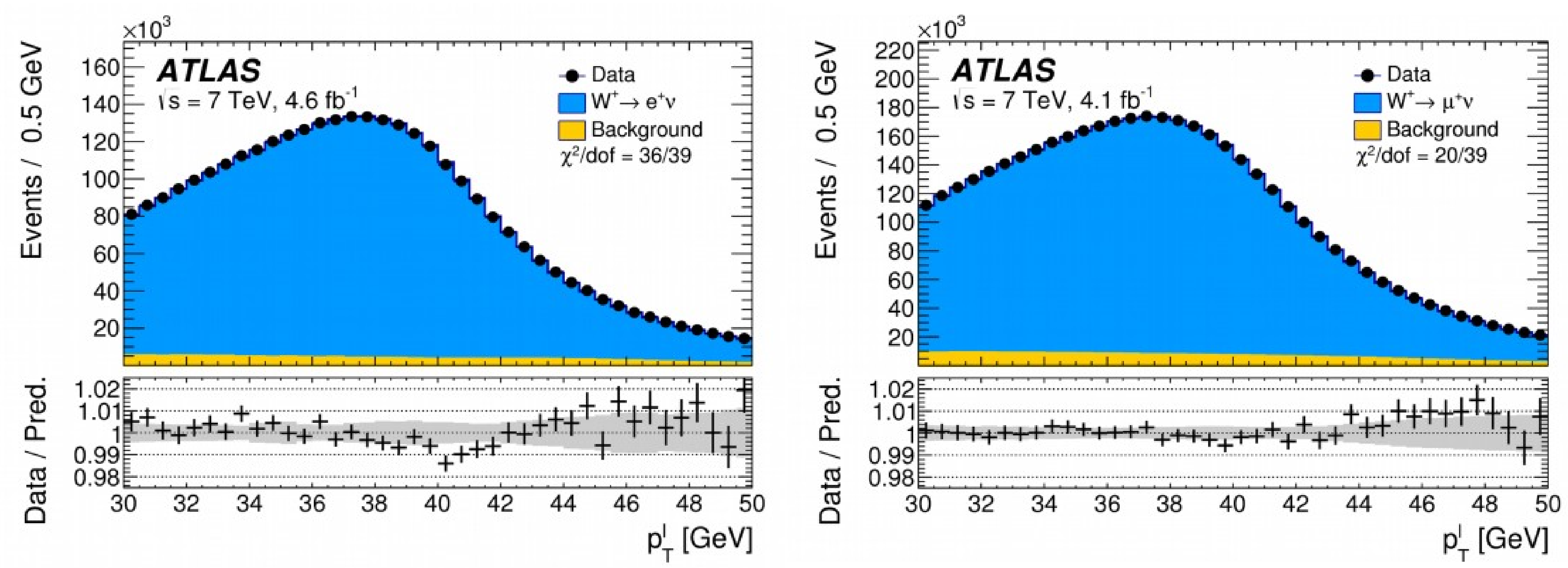
After all is said and done...

- The ~good...

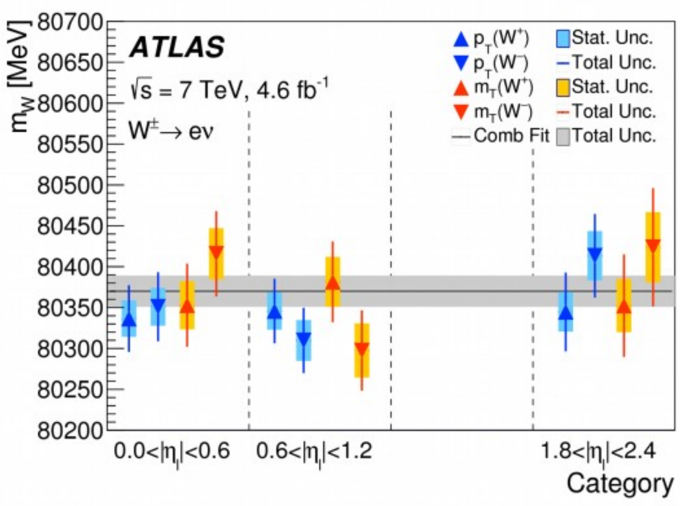


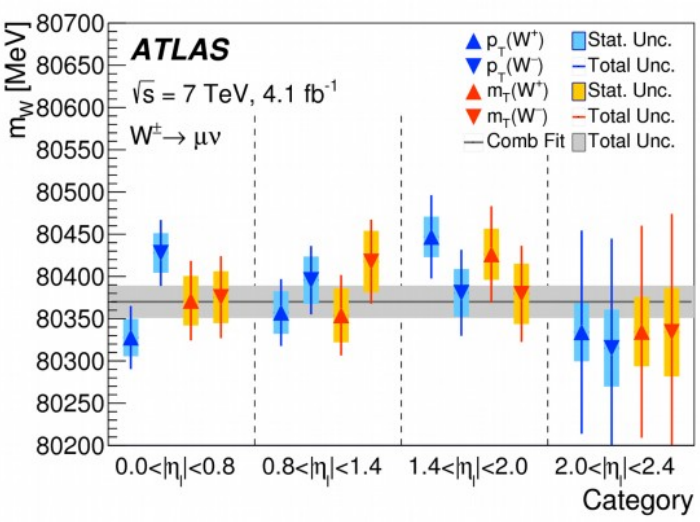
After all is said and done...

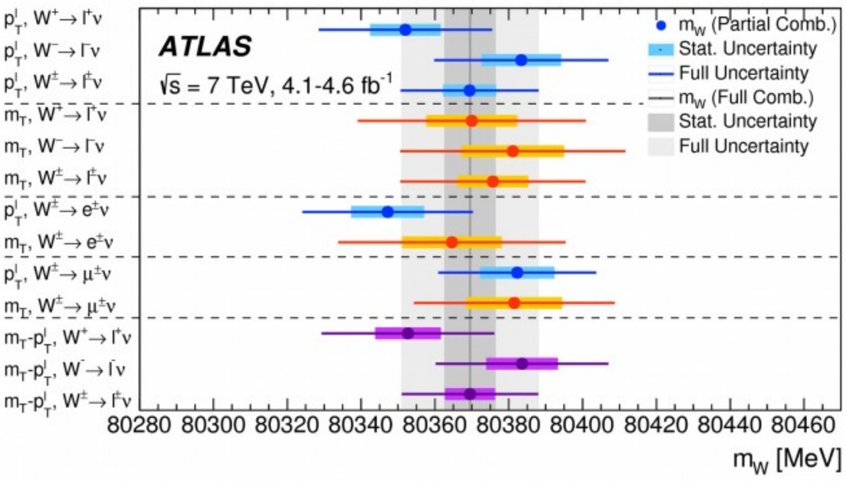
- The ugly



Internal compatibility







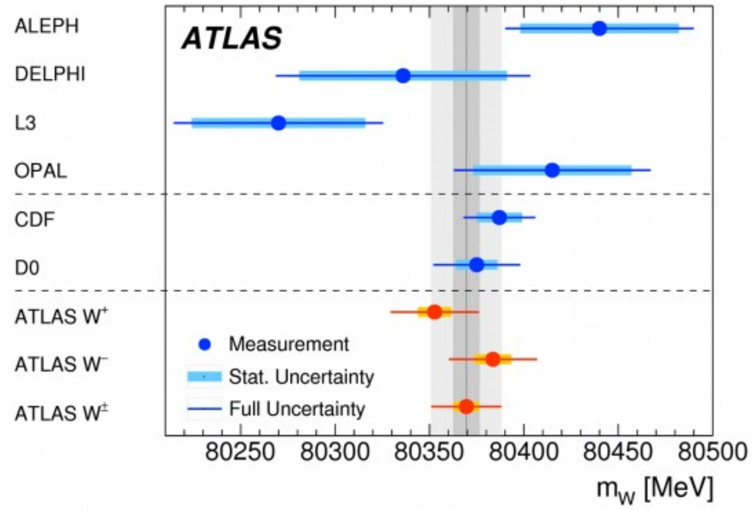
- All categories give consistent extractions of m_W

⬇

- Strong validation of physics modelling and detector calibration

ATLAS result

M_W = 80369.5 ± 18.5 MeV



M_W = 80369.5 ± 6.8 (stat) ± 10.6 (exp.syst.) ± 13.6 (model.syst.) MeV

The dominant uncertainty is due to the physics modelling

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

and the largest contributions are from QCD/PDF

A few comments

- The W-boson mass measurement does typically **not** use state of the art theory… which sounds unfortunate, for such an important test
  - Bad reasons : tradition; sociology; disconnection from theory caused by the lengthy experimental procedures, ….
  - Better reasons : being based on detector-level distributions, the measurement requires a fully exclusive description of the final state (QCD and QED showers, underlying event, …). Such tools are generally behind, in terms of perturbative accuracy
- Recent developments of relevance for the measurement : N^3LO / N^3LL QCD; mixed QCD/EW corrections, new PDFs.
  - When not using this, we at least quote the corresponding uncertainties
- The “dream tool” for this measurement would be a consistent interface between the exclusive MC generators and state-of-the-art pertrbative accuracy. A huge challenge!

A few comments

- The measurement is currently being re-analysed. Objectives :
  - Full review of old analysis by a new team; “resurrect” the analysis and maintain it alive
  - Improvement of a few (sub-leading) systematic uncertainties
  - Improved statistical methods
    - Old : statistical-only template fit; uncertainties from pseudo-data with systematic variations
    - New : profile likelihood fit – impacts uncertainties **and** central value
  - Modern PDF sets
    - CT10 → CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
  - Measurement of Γ_W

→ evaluate measurement stability under change of analysis procedures

→ update our result to state-of-the-art PDF sets and re-evaluate model dependence

Combination of m_W measurements

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

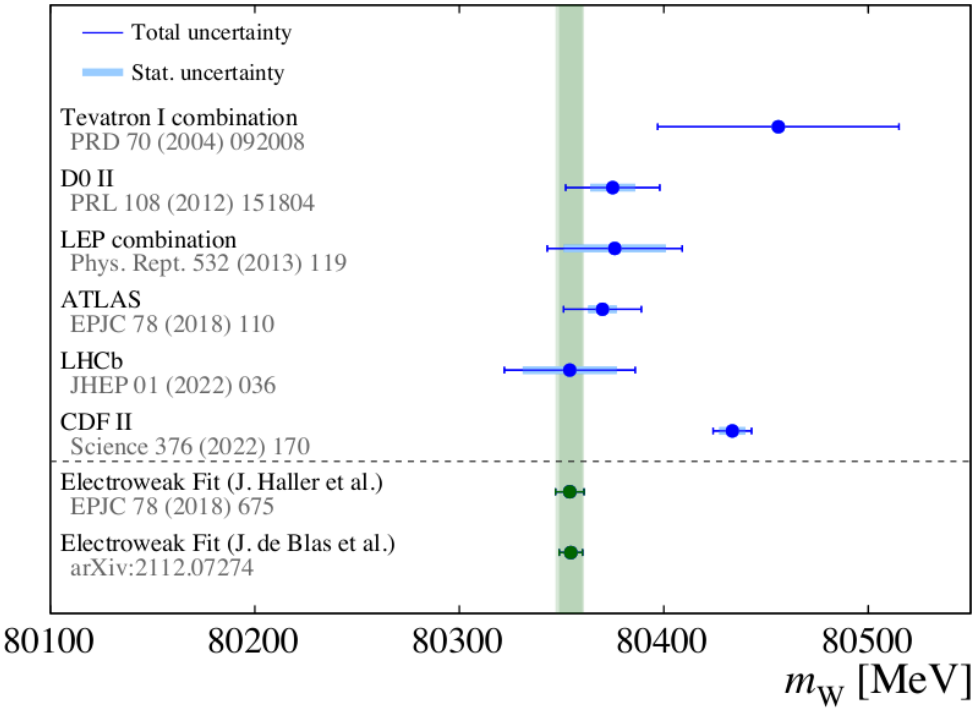
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

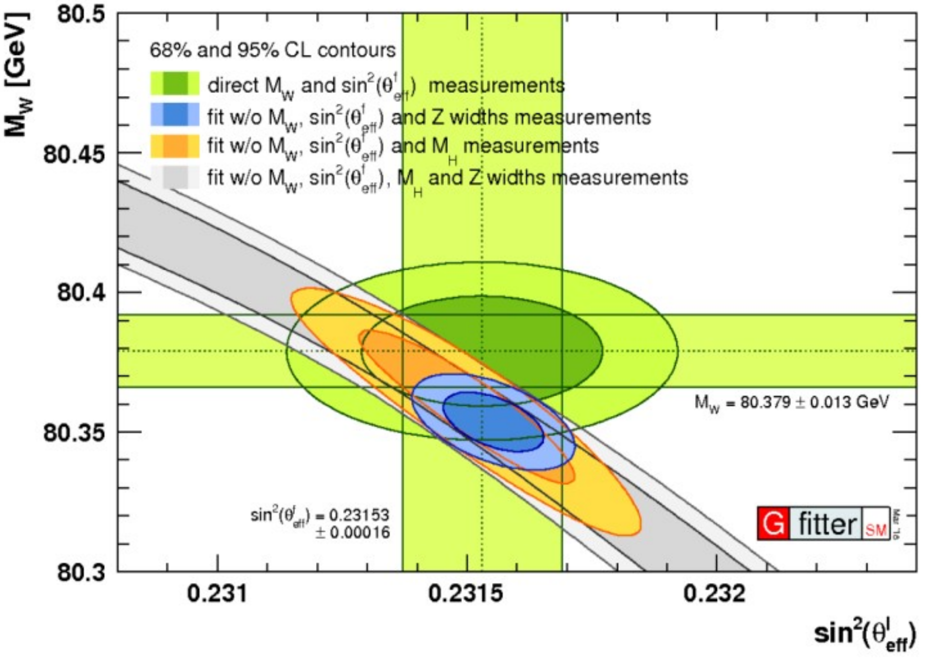
m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV



Objectives

- Provide endorsed **world average combination** of hadron collider m_W results
  - Establish a **methodology** to combine present and future measurements
  - Enable **physics modelling updates** of past measurements (i.e. PDFs, p_T^W)
  - Properly **correlate** m_W **and** $\sin^2\theta^l_{eff}$ measurements in EW fits

[*Eur. Phys. J.* **C74** (2014) 3046]



Combination strategy

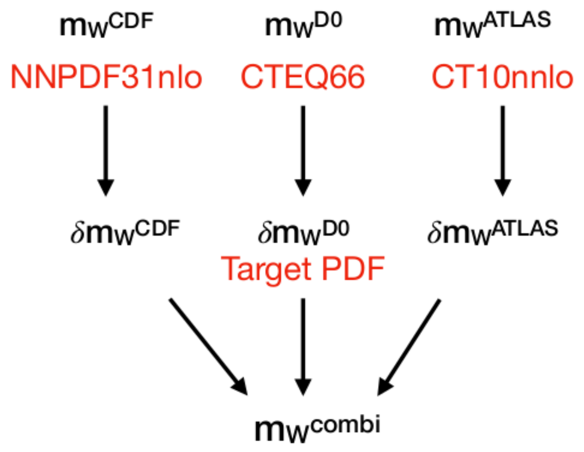
- PDFs main source of correction and uncertainty correlations
  - Other sources very small (EW corrections) or mostly decorrelated (p_T W/Z)

$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

published value | Improved predictions | PDF extrapolation

δm_W^{PDF} correction to reference PDF

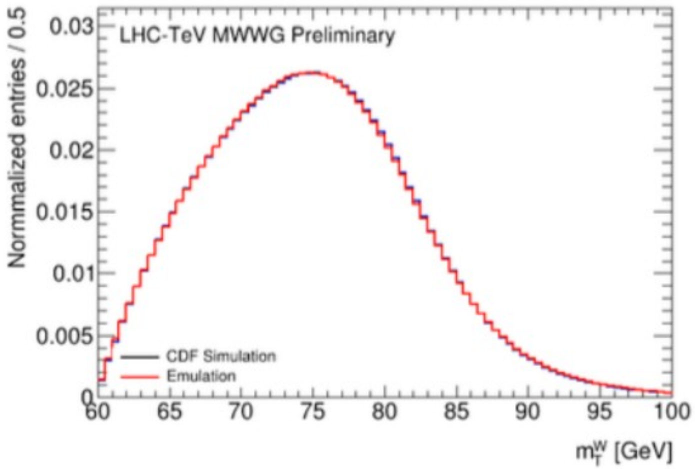
δm_W^{QCD} correction to QCD modelling beyond quoted uncertainties

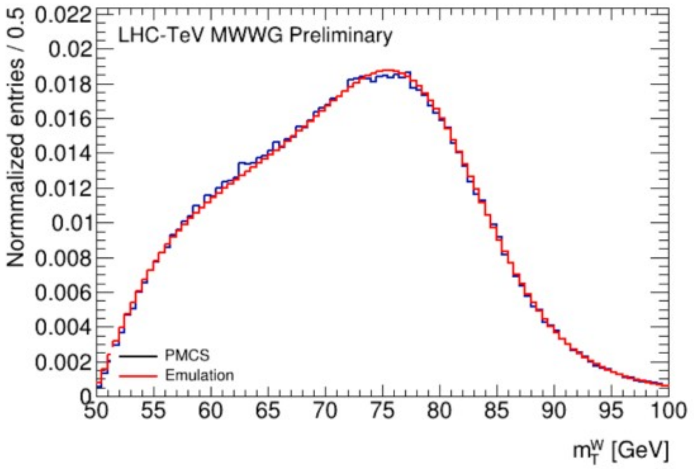


- Correction applied in a two-step procedure:
  1. Correct all measurements to a common PDF/QCD
  2. Combine them properly including correlations

Measurement emulation

- Original analyses and detector simulations cannot be easily reproduced
  - Exception is LHCb for which the analysis will be rerun
- Use **parametrized detector response,** following published information
  - Leptons : η- and p_T-dependent energy/momentum scale as well as resolution and efficiencies
  - Recoil response: include “lepton removal” effects, dependence on boson p_T and event activity
  - Reproduces published distributions at the % level corresponding to **~1-2 MeV precision in $\delta m_W^{QCD,PDF}$**
- Event selection and fit ranges from publications





Event generators

- Fully **reproduced the event generation chain** from the original measurements

  D0: Resbos CP (NNLO+NNLL) generated with CTEQ66 (NLO)

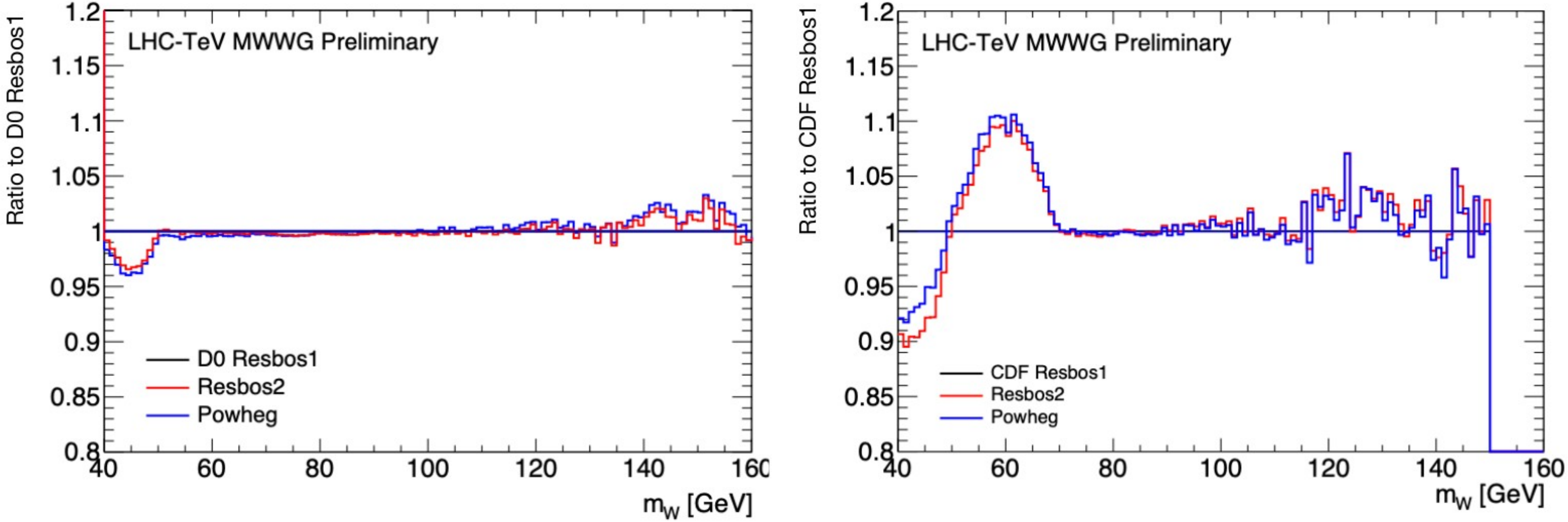
  CDF: Resbos C (NLO+NNLL) generated with CTEQ6M (NLO)

  ATLAS: Powheg+Pythia8 (NLO+PS); y_W + Ai at NNLO with CT10 (NNLO)

  LHCb: Powheg+Pythia8 (NLO+PS); Ai at NNLO,
  as PDF the average of NNPDF3.1,CT18,MSHT20 (NLO)

- Variety of predictions used to validate the PDF shifts and estimate the possible need of QCD correction to published m_W
  - Powheg (NLO+PS), MiNNLOPS (NNLO+PS), DYNNLO (NLO/NNLO F.O.)
  - In addition, updated integration grids from the Resbos authors (dubbed here Resbos2) at NLO+NNLL and NNLO+NNLL with improved treatment of spin correlations [*2205.02788*]

Lineshape



- Invariant mass distribution shows trends wrt modern generators
  - Visible **cut of m_W<150 GeV** in the CDF Resbos sample, small bias on m_W
  - Structures at **low invariant masses** (m_W<50 GeV for D0, m_W< 70 GeV for CDF) and **small overall slope** through the full mass range, negligible impact on m_W

Spin correlations in W-boson decay

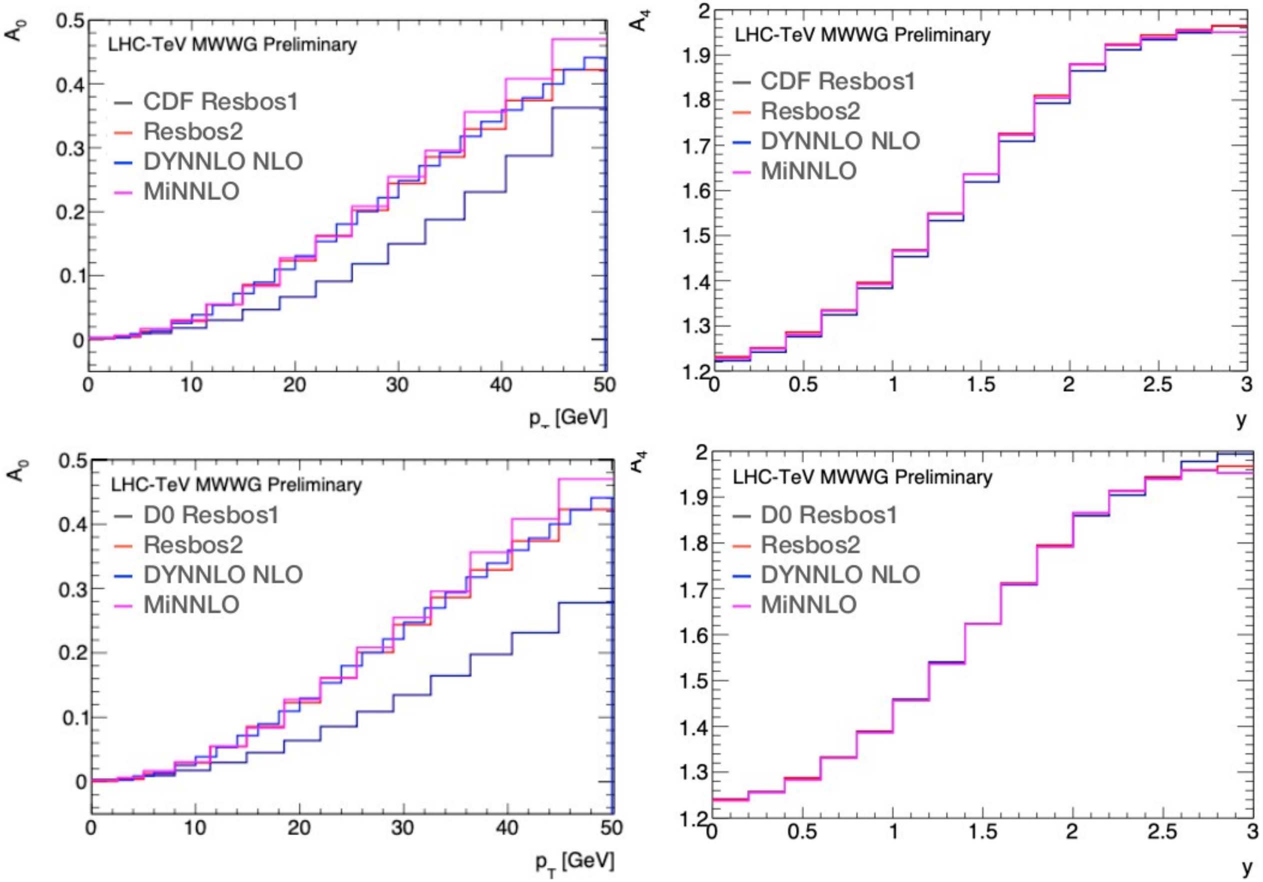
* The cross-section for the production of a spin-1 resonance can be expanded to all-orders in QCD into an **angular coefficients decomposition**:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_{\mathrm{T}}\,dy}\Big[\,(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,\Big],$$

* A_4 the only term at LO QCD; $A_{5,6,7}$ start at $O(\alpha_S^2)$ and remain small
* Measured to high precision in Z events at the LHC [*JHEP* 08(2016) 159, 2203.01602] and well described by fixed-order calculations (known to $O(\alpha_S^3)$ [*JHEP* 11 (2017) 003])

Spin correlations in W-boson decay

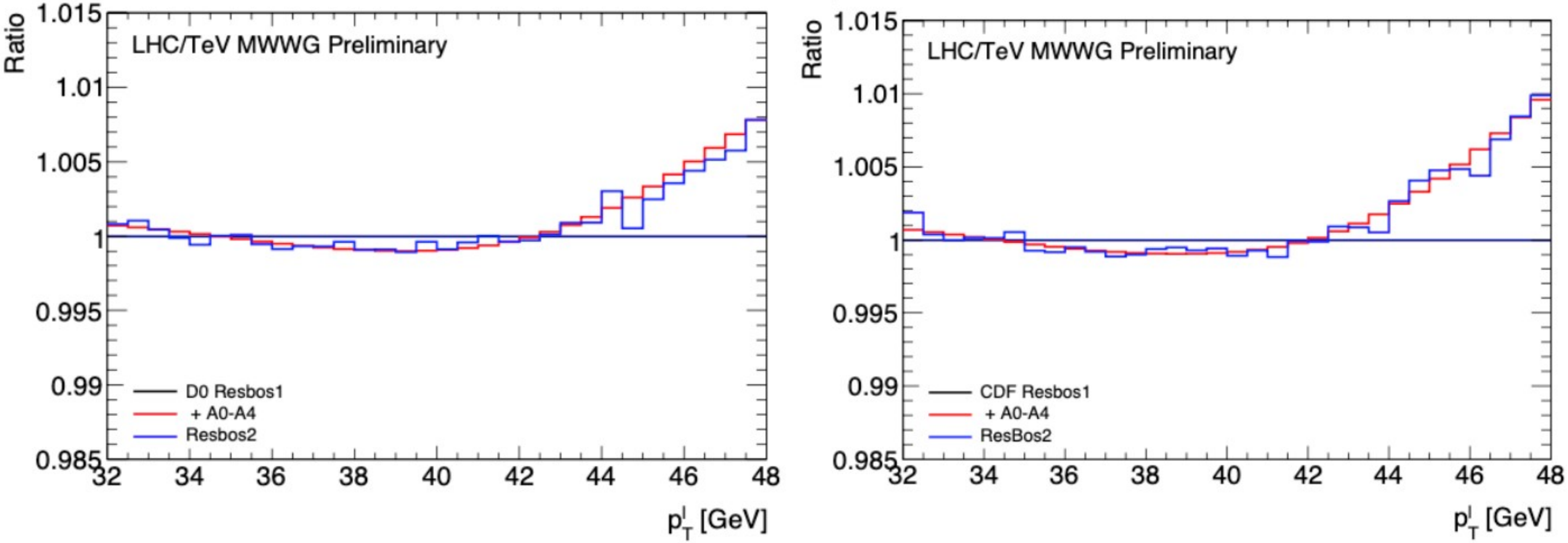
- Boson polarisation in legacy Resbos different from Resbos2 and other codes



- NNLO matching in Resbos not fully differential
  ➜ affects D0
- Issue with Ai resummation,
  ➜ affects CDF/D0
  - Only unpolarised and A_4 resummed, leads to differences from fixed-order Ai
  - Differences visible comparing to DYNNLO or MiNNLOPS
- Motivates a correction of Tevatron measurements to a common QCD calculation

Spin correlations in W-boson decay

- Impact of change in Ai to the new Resbos well-reproduced by reweighting A_{0-4}
  - Effect of up to 1% on detector-level distributions
  - Distributions become harder, m_W in data expected to decrease



- Change in the full phase-space Ai modifies the fiducial $p_T^{W/Z}$ distribution
  - Overestimate δm_W as measurements tune their p_T^W model to data
  - To gauge an uncertainty, change evaluated also constraining the p_T^W distribution

Impact of generator updates

- δm_W^{QCD} reweighing the D0 Resbos-CP NNLO+NNLL predictions to the newer Resbos2 at NLO+NNLL

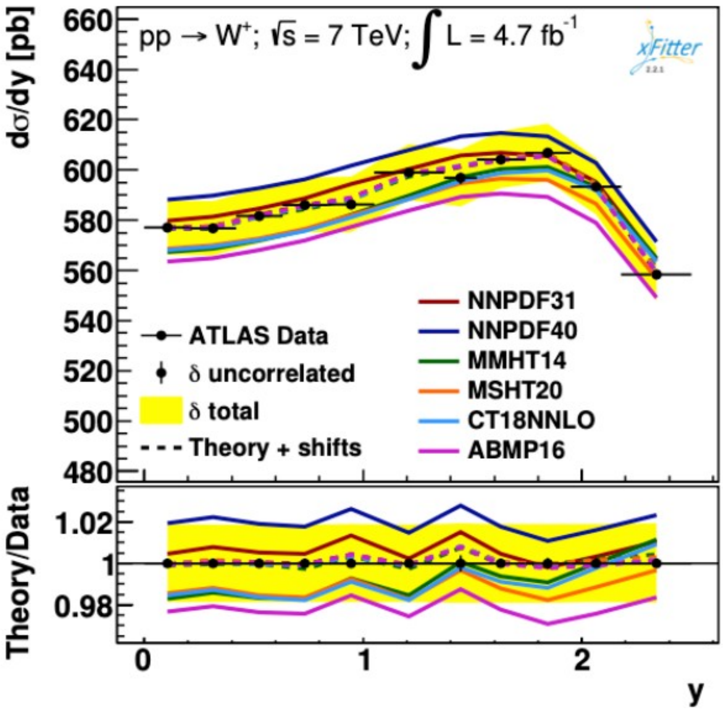
  - Negligible effect of correcting y_W and m_{Inv}
  - Ai-reweighting dominated by A_0 coefficient
  - δm_W about -10 MeV depending on distribution and p_T^W constraint
  - ~2 MeV uncertainty from systematics on the emulation

Correction	δm_W^{QCD} [MeV]					
	p_T^W-constrained			No constraint		
	p_T^ℓ	m_T	p_T^ν	p_T^ℓ	m_T	p_T^ν
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
A_0	7.6	10.0	15.8	16.0	12.6	19.5
A_1	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
A_2	-3.0	-2.6	2.9	-4.2	-3.0	2.3
A_3	2.9	1.6	-0.5	3.5	1.8	-0.2
A_4	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
ResBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

Choice of PDF sets

- Performed a benchmarking of PDF sets against Tevatron and LHC cross-section measurements
  - Considering measurements of W and Z cross-sections from Tevatron and LHC
  - Theory predictions at NNLO QCD x NLO EW

PDF set	Chi2/ndf	PDF set	Chi2/ndf
Cteq66	231/126	CT18NNLO	163/126
CT10	179/126	CT18ANNLO	170/126
NNPDF31	200/126	MSHT20	270/126
NNPDF40	195/126	ABMP16	236/126



- Modern NNLO PDFs provide the best description, no set gives a χ^2/ndf~1
- Decision on the final PDF will consider χ^2 and uncertainty of the combination itself

Combination – status

- Analysis completed :
  - Generator corrections and PDF extrapolations finalized for all experiments
  - Results available for a variety of PDF sets : ABMP16, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1 and NNPDF4.0
    - Important messages on the PDF dependence of the measurement
  - Compatibility quantified for the full combination, and for relevant subsets of measurements : LHC only; Tevatron only; “All – 1”
  - Final recommendation : ?

→ currently under review by all collaborations

Conclusions

- The W boson mass is arguably the most difficult measurement in HEP
  - Partial event reconstruction, incomplete kinematics
  - Calibrations
  - Physics modelling
  - Precision goal
- First measurement ~2017, with 2011 data. Being updated
- Next measurement will use low-pile-up data collected in 2017,2018.
- Combination
  - At present, it is difficult to quote a conclusive “world average”. The most precise measurement is also discrepant.
  - Still important work : comparing LEP, Tevatron, LHC measurement results forces to look deep into the modelling aspects, to “translate” the measurements into eachother, allowing quantitative comparisons and better studies of model dependence