ATLAS measurement of m_W

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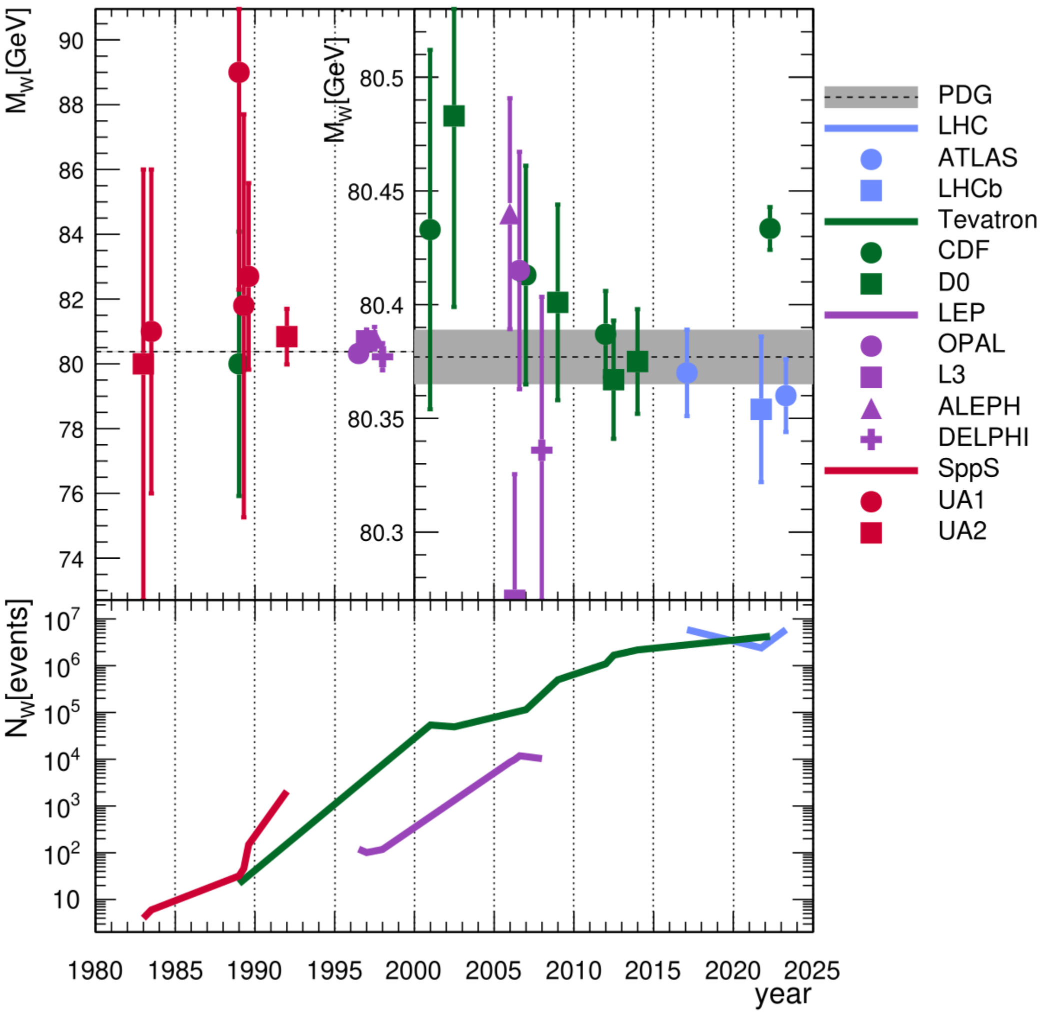
MWDays23
17th April 2023

W-boson mass history



- Only four W-boson mass measurements in the last 10 years

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

- 1983 CERN SPS – W discovery
- 1983 – UA1

  $m_W = 81 \pm 5$ 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 – ATLAS

  $m_W = 80.370 \pm 0.019$ GeV
- 2021 – LHCb

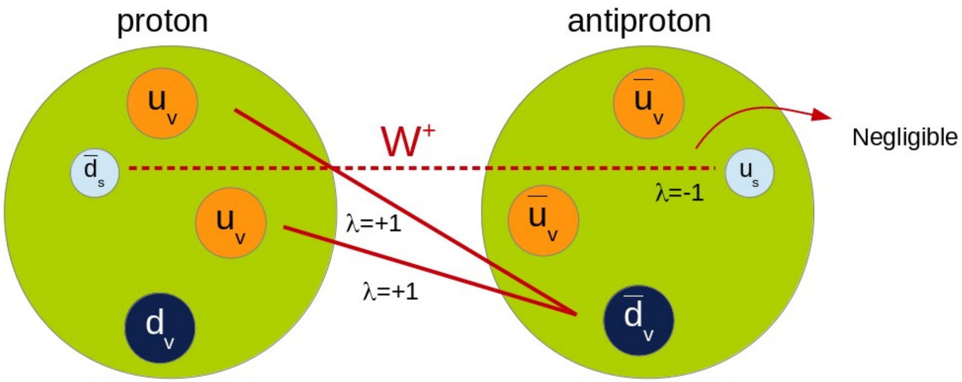
  $m_W = 80.354 \pm 0.032$ GeV
- 2022 – CDF

  $m_W = 80.434 \pm 0.009$ GeV
- 2023 – ATLAS

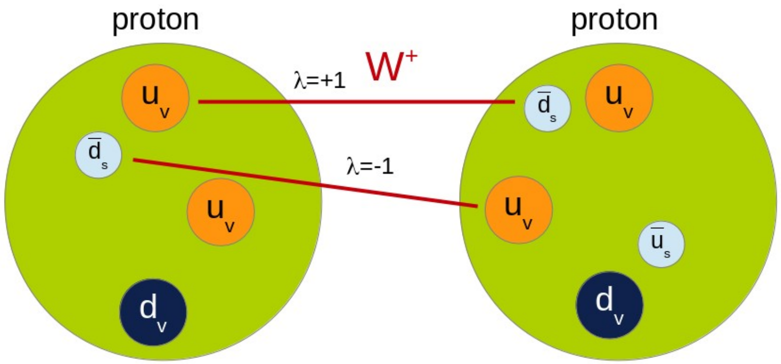
  $m_W = 80.360 \pm 0.016$ GeV

W mass at the LHC

A proton-proton collider is the most challenging environment 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

Further QCD complications

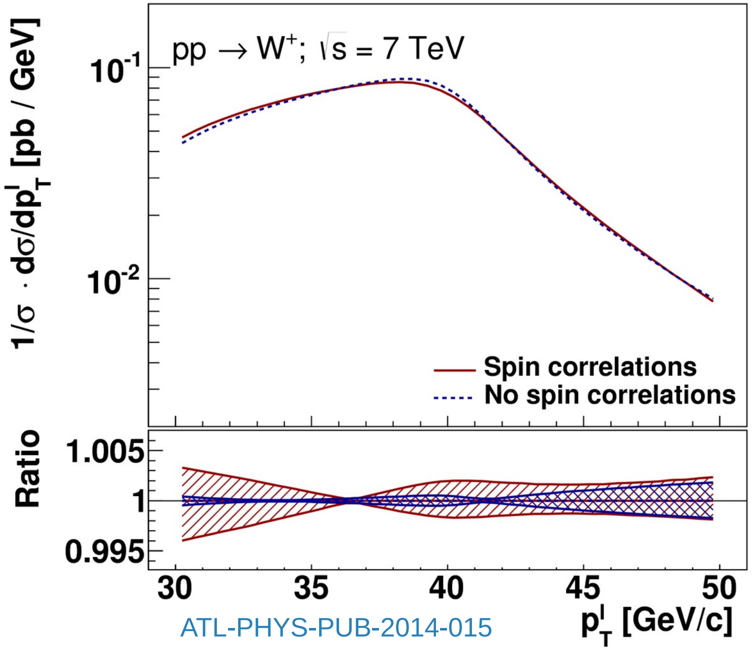
- Heavy-flavour-initiated processes
- W+, W- and Z are produced by different light flavour fractions
- Larger gluon-induced W production

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

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

LHC vs Tevatron - 1st quark generation

- W-boson production at the Tevatron is charge symmetric and dominated by interactions with at least one valence quark, whereas the sea-quark PDFs play a larger role at the LHC. The W polarisation at the LHC is more influenced by PDF uncertainties, implying larger uncertainties on the lepton p_T distribution
- The valence-sea difference, as well as the amount of sea quarks with u and d flavour, must be known with better precision than needed at the Tevatron



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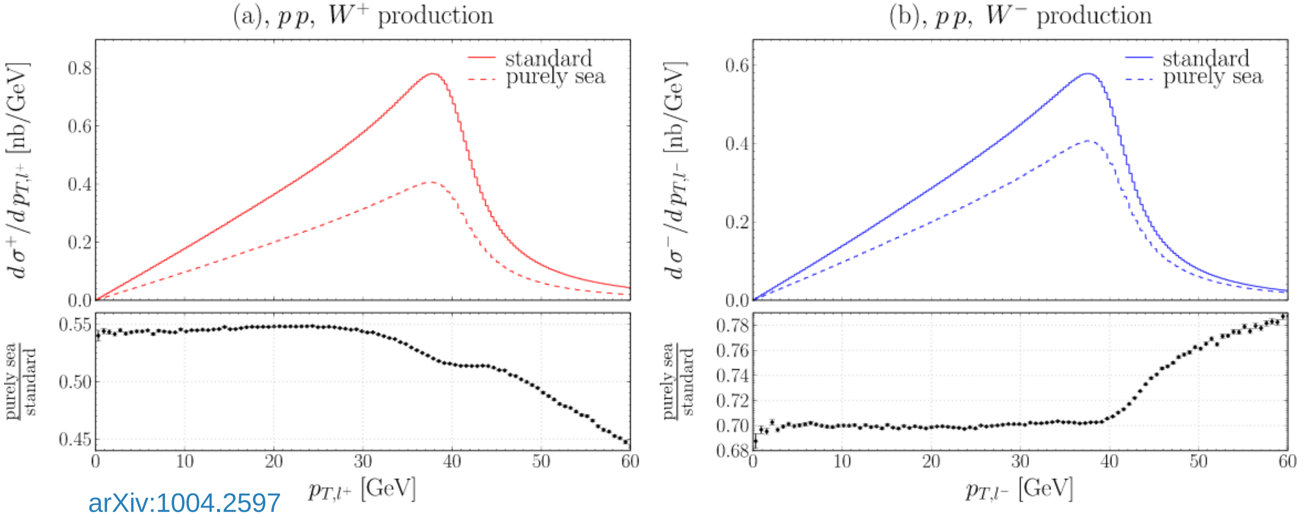
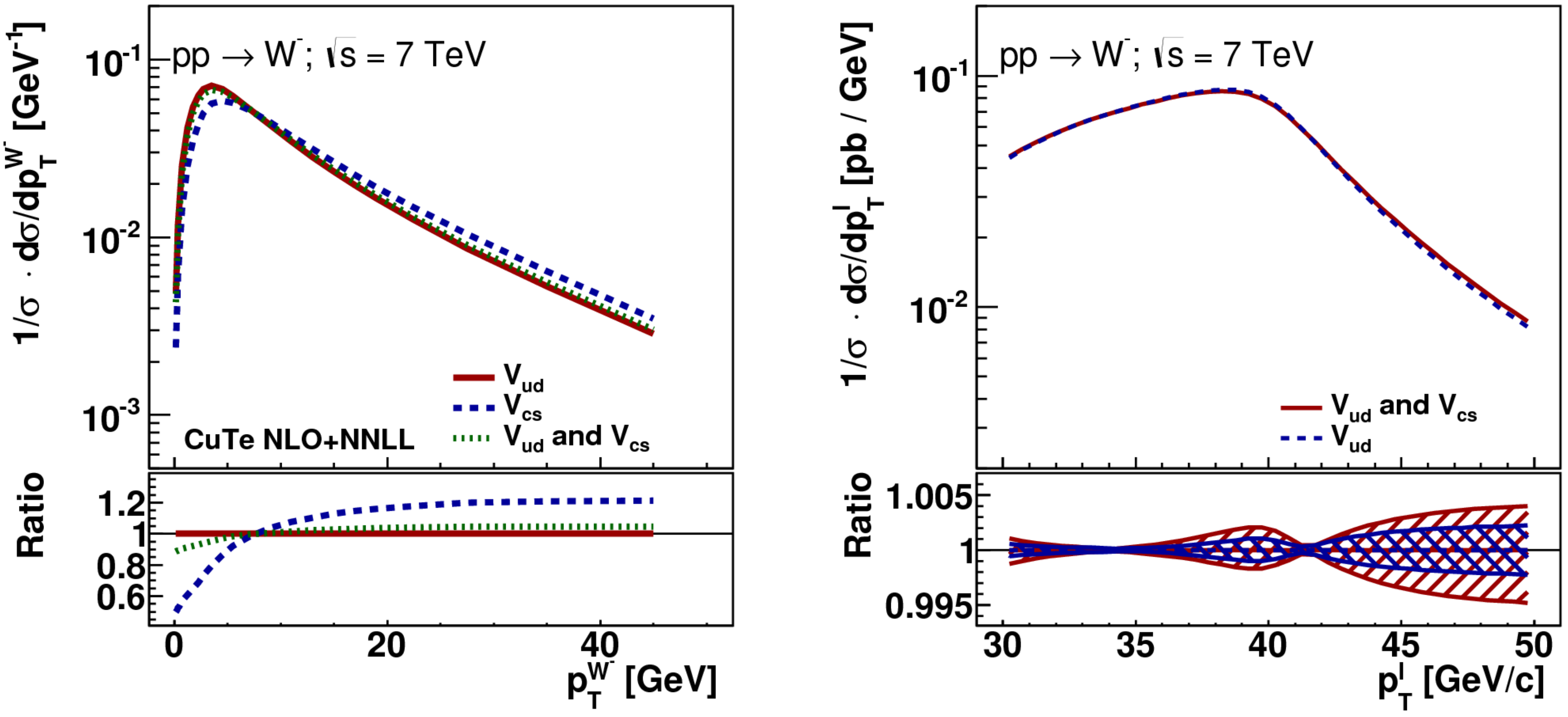


arXiv:1004.2597

LHC vs Tevatron - 2nd quark generation

- At sqrt(s) = 7 TeV, approximately 25% of the W-boson production is induced by at least one second-generation quark, s or c, in the initial state. The amount of heavy-quark-initiated production has implications for the W-boson transverse-momentum distribution and for the W polarisation



W-boson mass at the LHC

- Until the first LHC measurement in 2016, it was not obvious that the LHC could measure the W mass as precisely as the Tevatron. Theorists were wondering if 50 MeV was feasible for a first measurement
- In the years 2013-2016 there was a huge theory-experiment joint effort to understand and control these issues through theoretical understanding, ancillary measurements, and m_W physics modelling
- Measurements and studies at ATLAS,LHCb,CMS convinced the community that 15-30 MeV is possible at the LHC
- This effort continues nowadays, trying to push the measurement of m_W at the LHC towards 10 MeV and possibly below

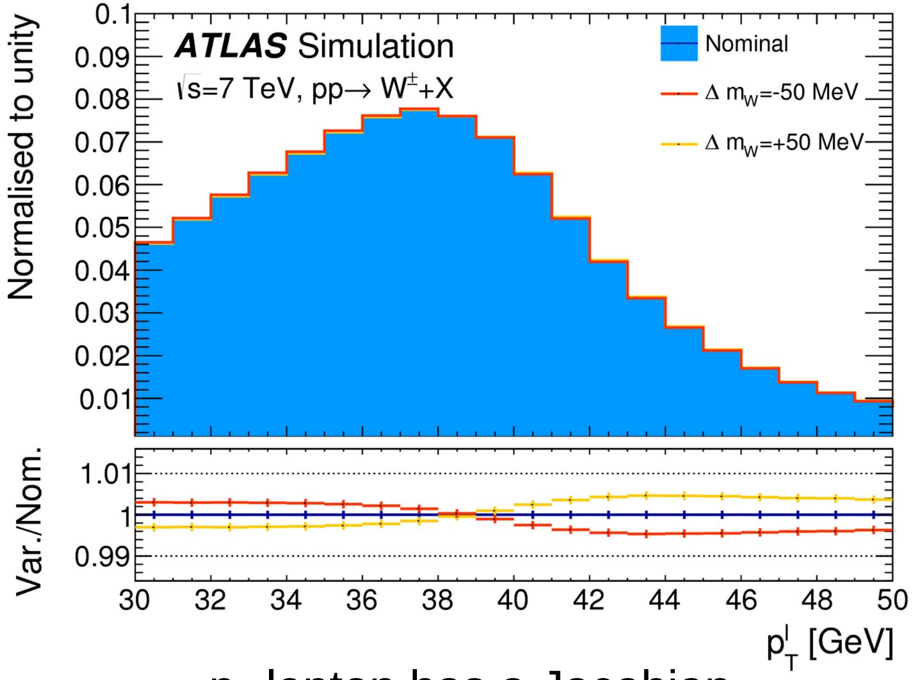
Outline

- ATLAS m_W 2023 new result
- Physics modelling
- Open issues and questions

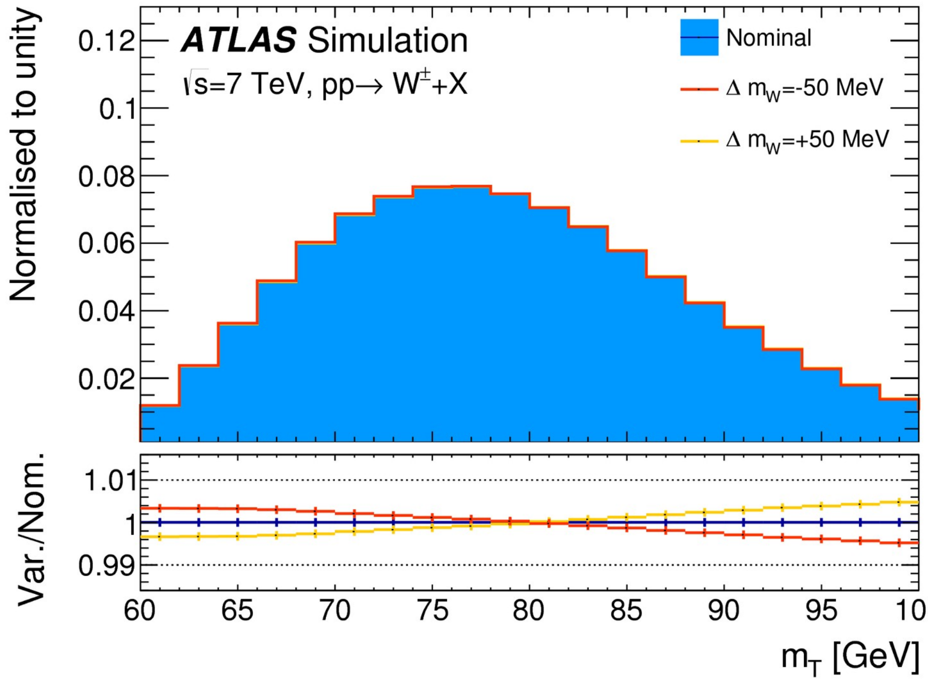
W mass – Measurement strategy

m_W extracted from the p_T lepton and transverse mass (m_T) distributions

arXiv:1701.07240



p_T lepton has a Jacobian edge at $m_W/2$



m_T has a Jacobian edge at m_W

- Vary the W-boson mass values in the theory prediction, and predict the p_T lepton and m_T distributions
- Compare to data, and determine the best fit value of the W-boson mass

Challenges:

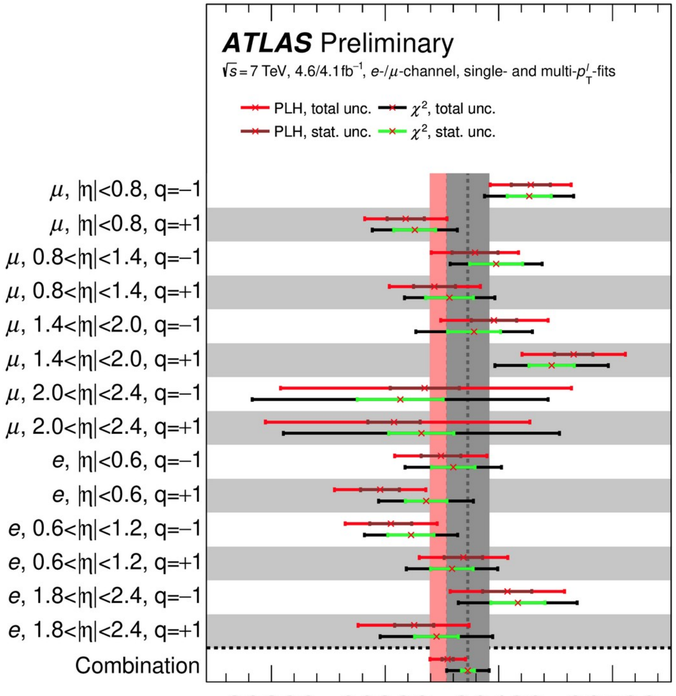
- Ultra-precise detector calibration ~ 10^{-4}
- Accurate theory predictions

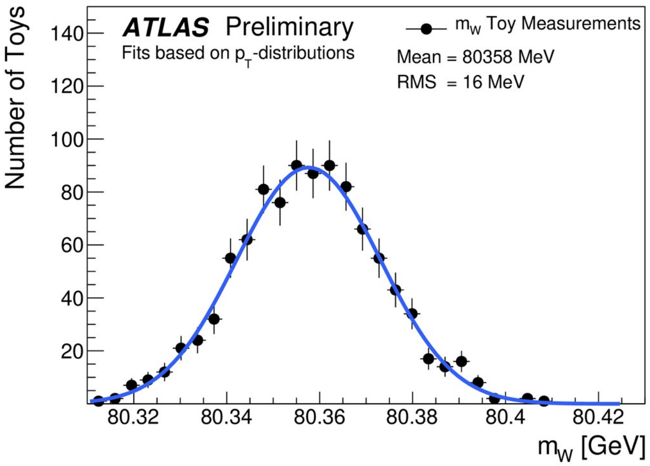
Improvements

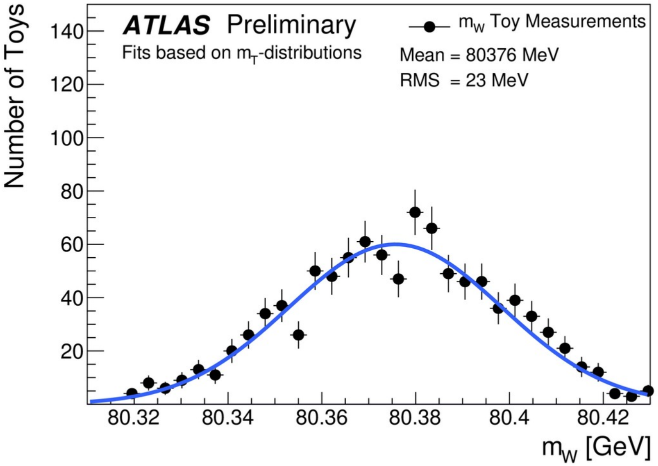
- m_W from profile likelihood of $p_T(\ell)$ and m_T distributions, instead of χ^2 minimisation with only statistical uncertainties
- CT10 → CT18 as nominal PDF set
- Multijet background estimation
- Electroweak uncertainties evaluated at detector level
- Added Γ^W as nuisance parameter
- Recovered 1.5% of data in the electron channel, random generator setup for the electron energy calibration

Profile likelihood

- Main Statistical Framework: TRExFitter
- Normalisation of the different templates is left free in the fit: a global normalisation factor is applied to all signal samples
- PLH fit results with statistical uncertainties only reproduce the legacy results

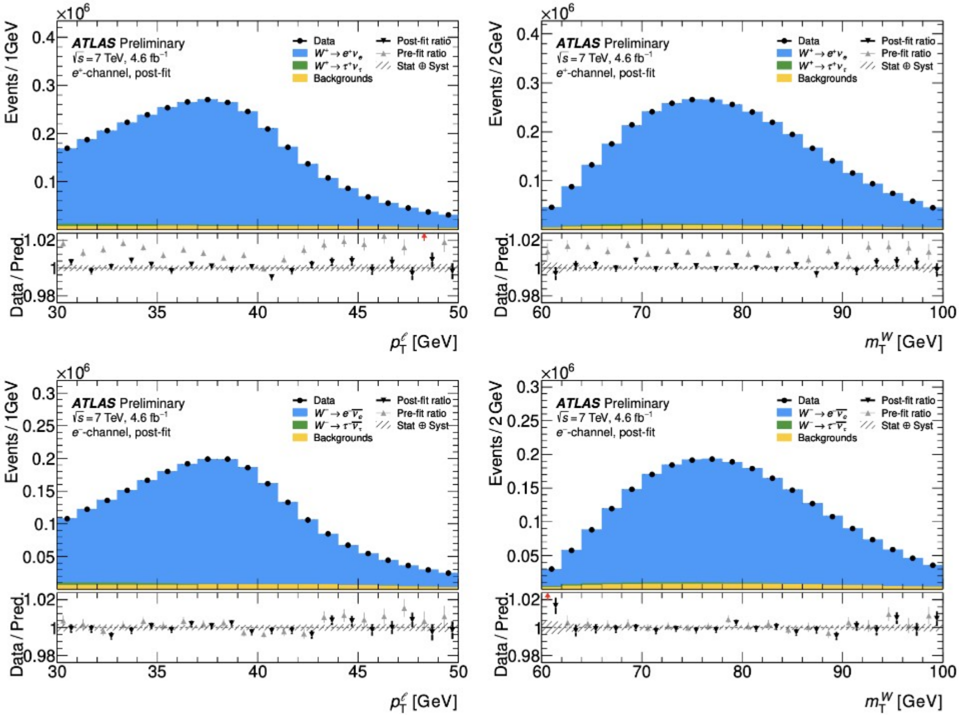


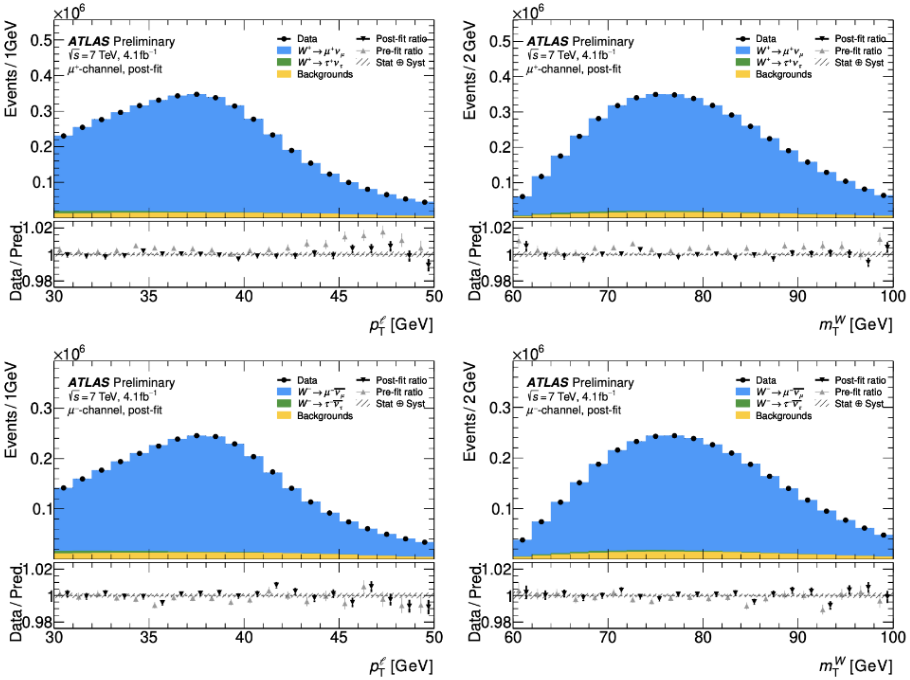




- PLH fit will move the central value by -16 MeV for $p_T(\ell)$ and -12 MeV for m_T
- Consistent with expectation from toys

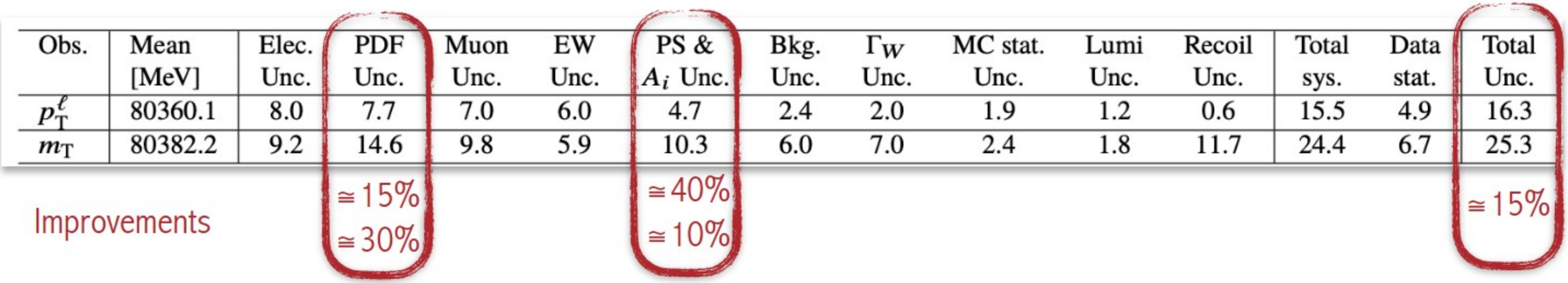
Profile likelihood





- Post-fit distributions are in very good agreement with data
- Improved agreement compared to fits with only statistical uncertainties

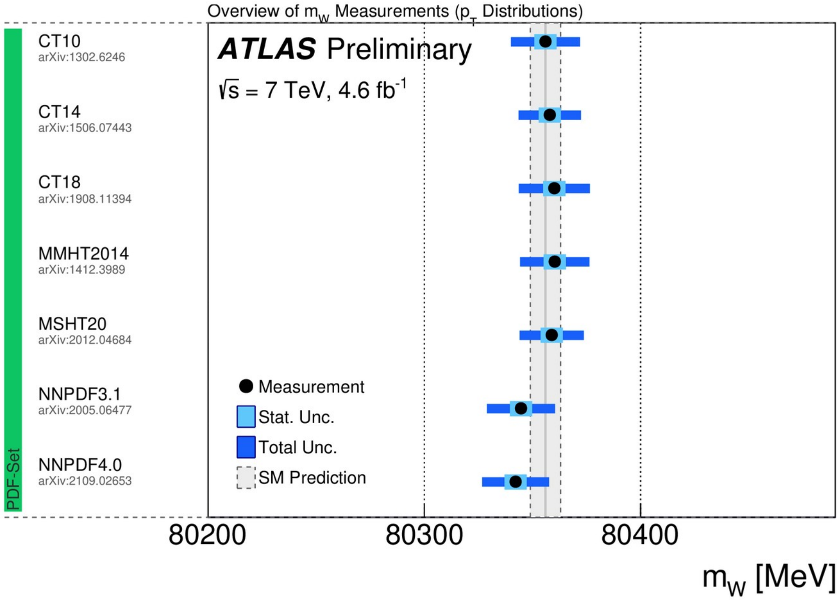
Improvements

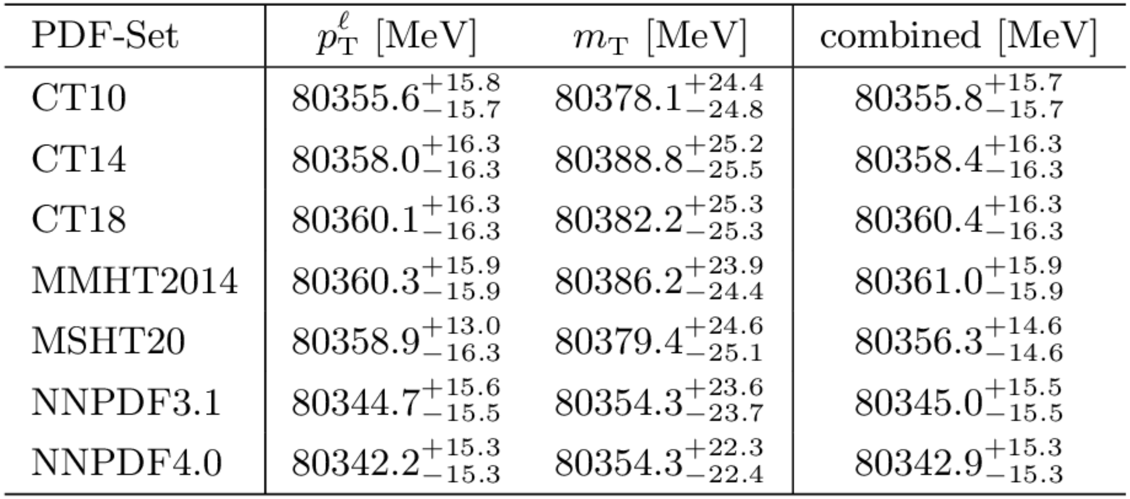


Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3
Improvements			≅15% ≅30%			≅40% ≅10%								≅15%

- Profiling helps to reduce mostly the physics modelling systematic uncertainties
- Overall uncertainties improvement of 15%

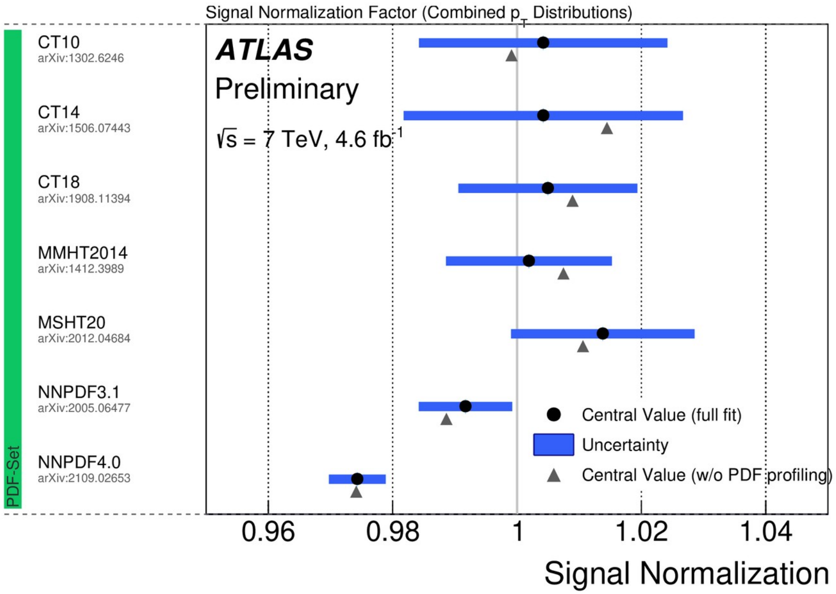
PDFs



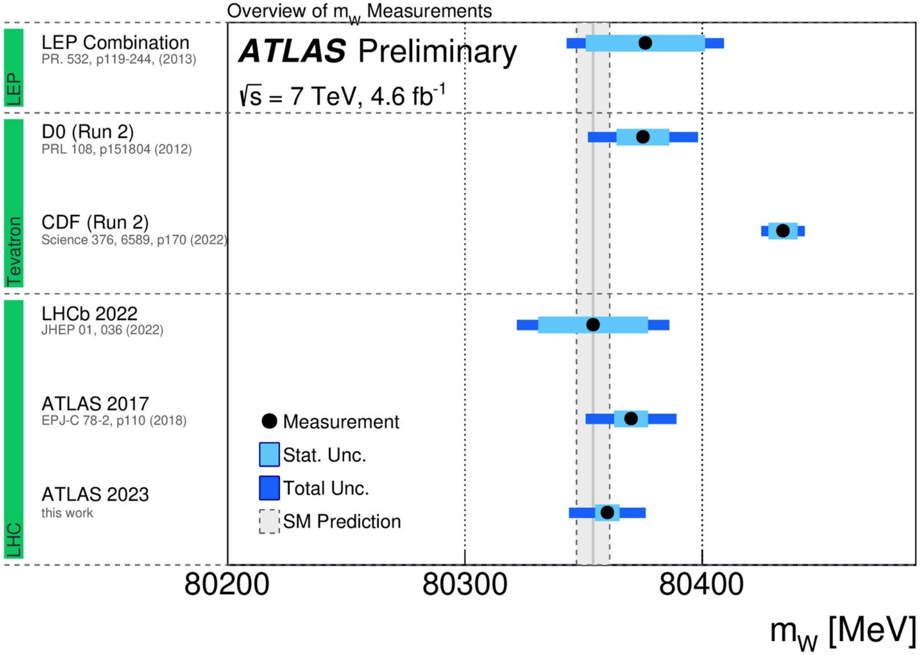


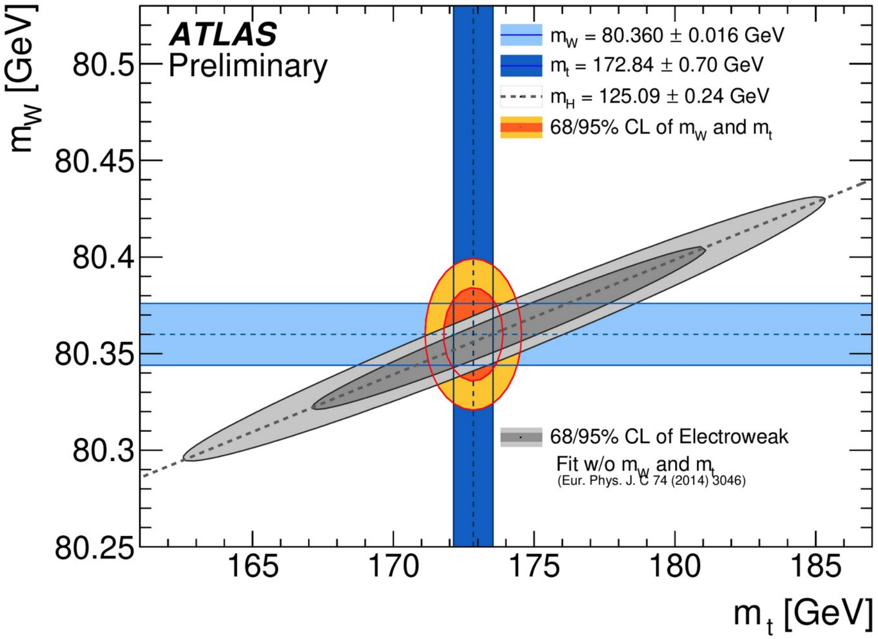
PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

- Profiling reduces the spread of PDFs from 28 to 18 MeV
- CT18 PDF Set chosen as new baseline: yields most conservative uncertainties
- CT18 PDF uncertainties of 7.7 MeV cover the central values of CT10, CT14, MMHT2014 and MSHT20, but not of NNPDF3.1 and NNPDF4.0
- Normalization of NNPDF4.0 not consistent with 1
- Important PDF issue that should be understood and addressed



Results



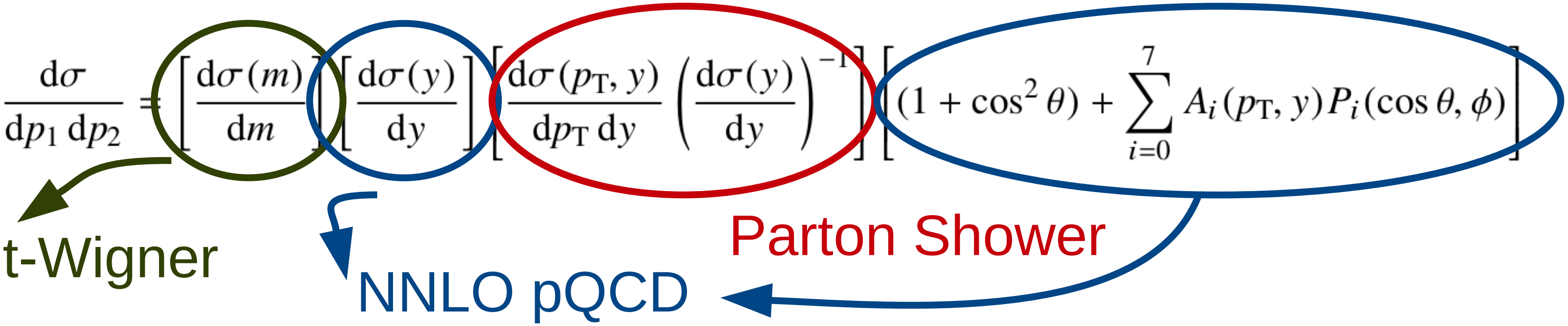


- New ATLAS m_W 2023 measurements yields a value of

  m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV
- Result even more consistent with the Standard Model than before
- Legacy ATLAS m_W 2017 measurement

  m_W = 80370 ± 19 MeV

Physics modeling

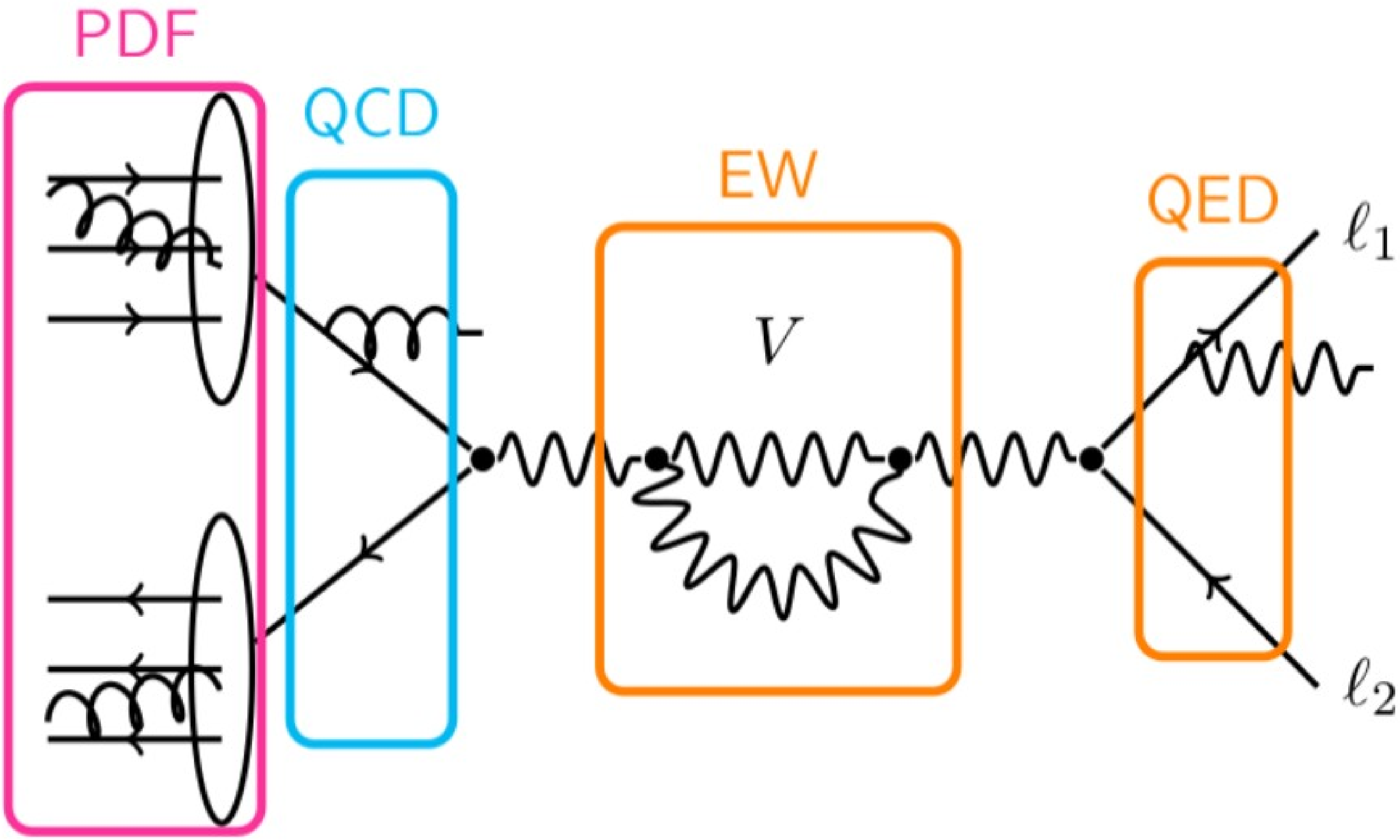


$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right]$$

Breit-Wigner

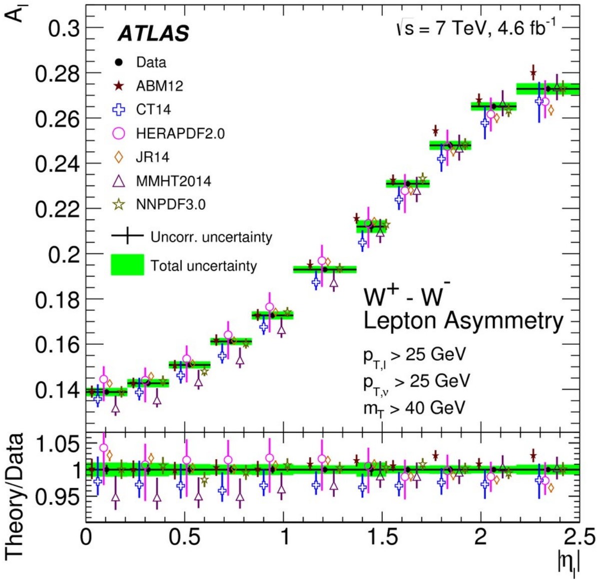
NNLO pQCD

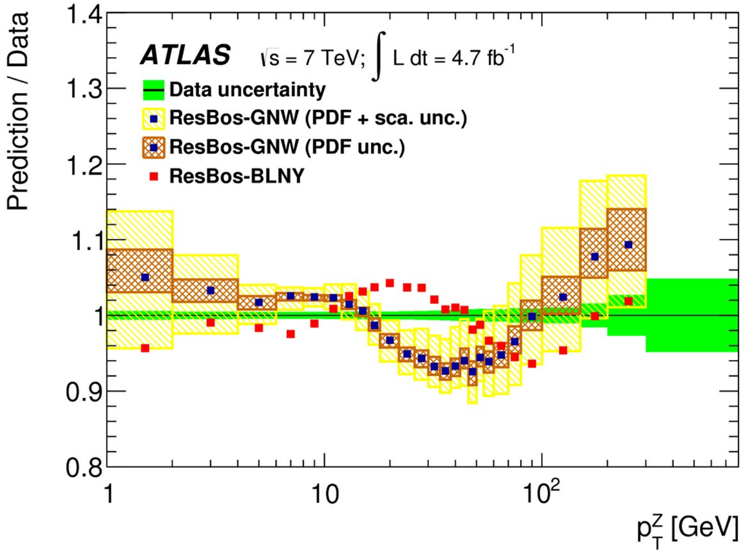
Parton Shower

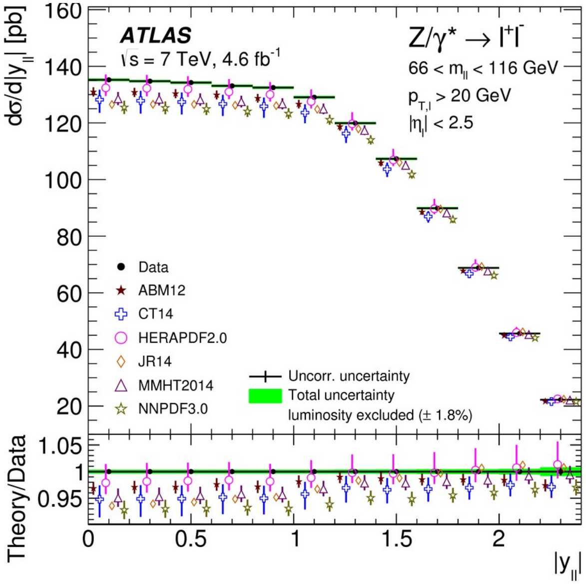


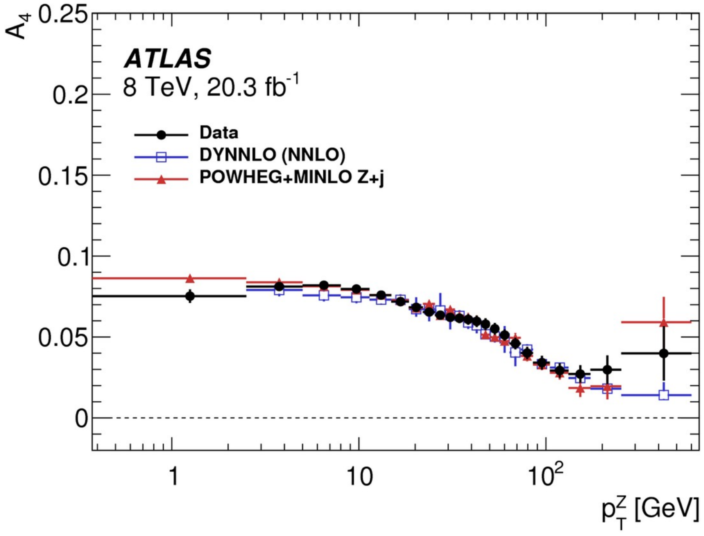
Physics modelling – DY ancillary measurements

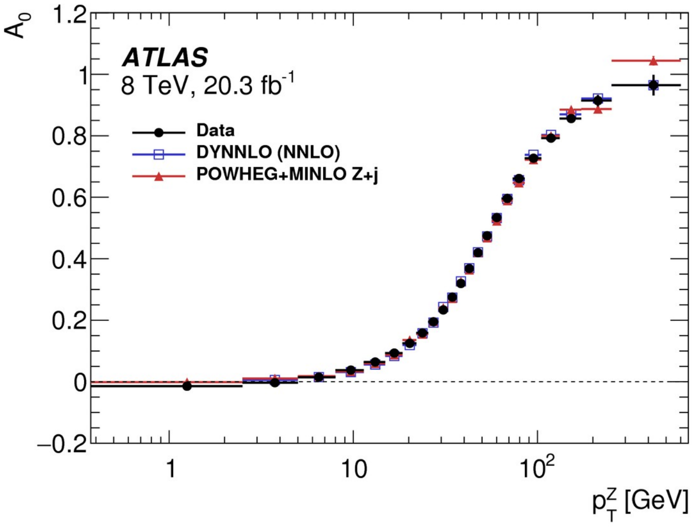
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right]$$





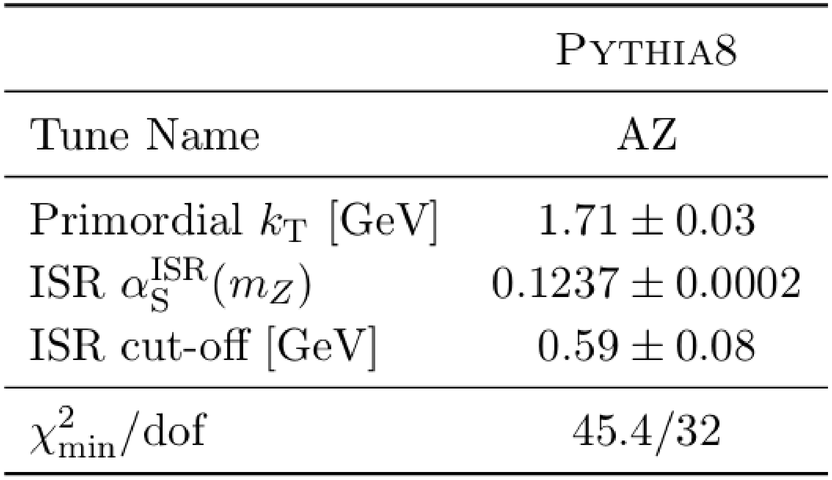






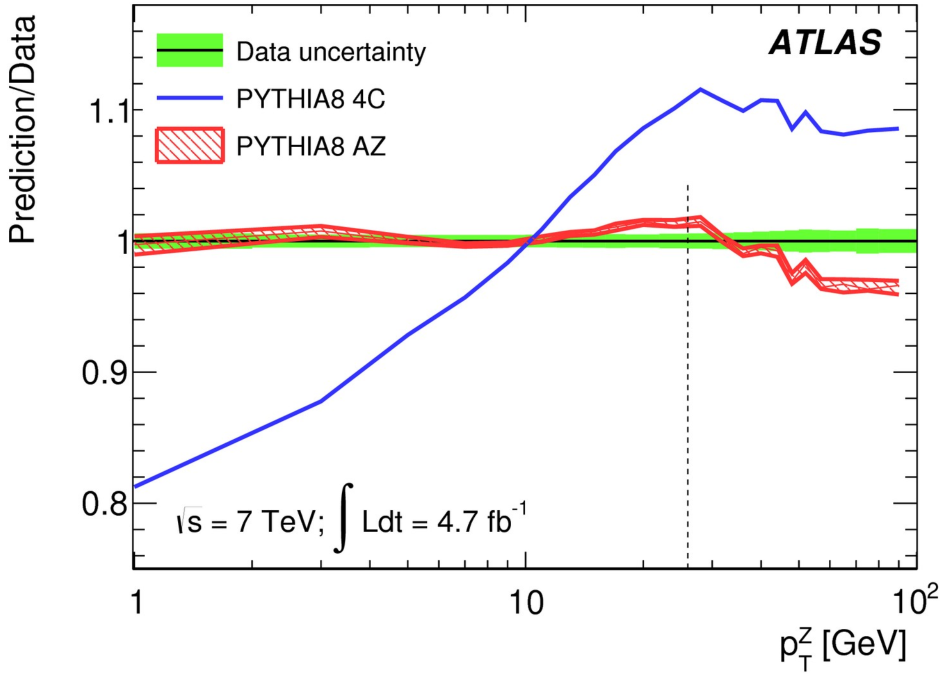
Physics modeling – p_T W

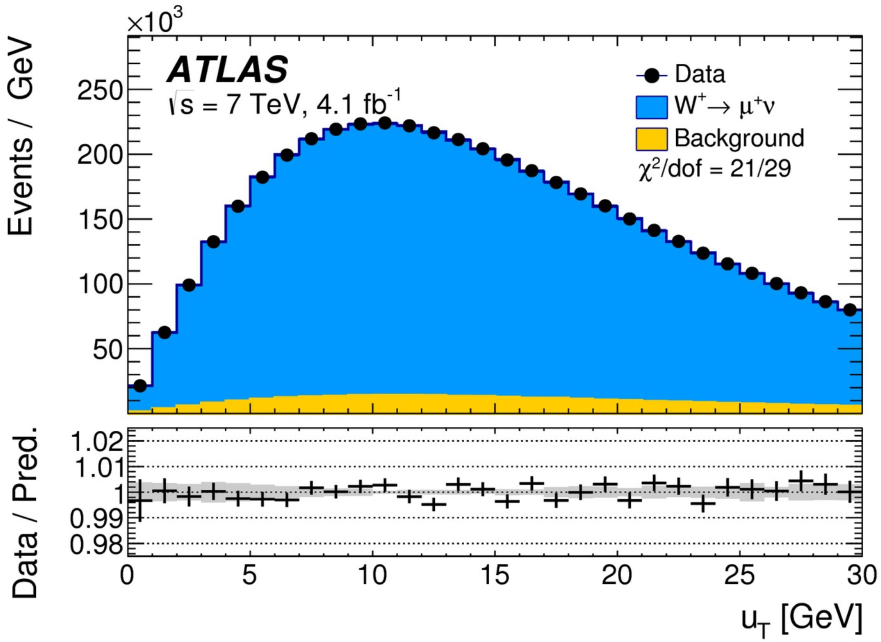
- The Pythia8 p_T-ordered parton shower is used as model for the p_T W
- The parameters of the model are fit to the p_T Z measurement at 7 TeV (AZ tune)



	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

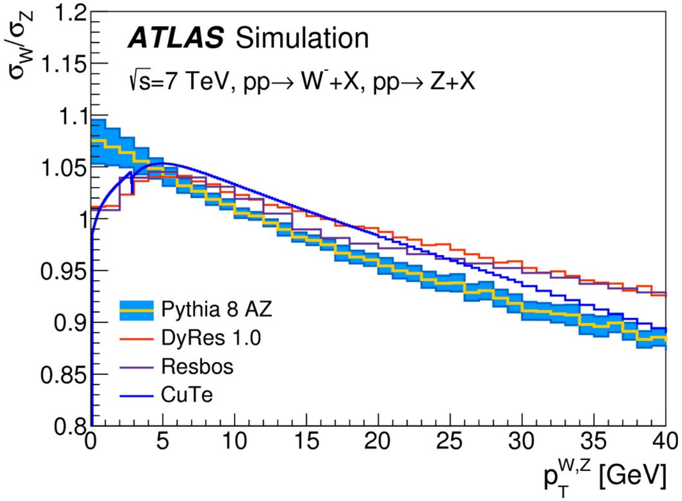
- The Pythia8 AZ tune describe the p_T Z data within 2% inclusively and in rapidity bins
- Pythia8 is used to transfer from the p_T Z to the p_T W distribution and to evaluate theory uncertainties on the W/Z p_T ratio

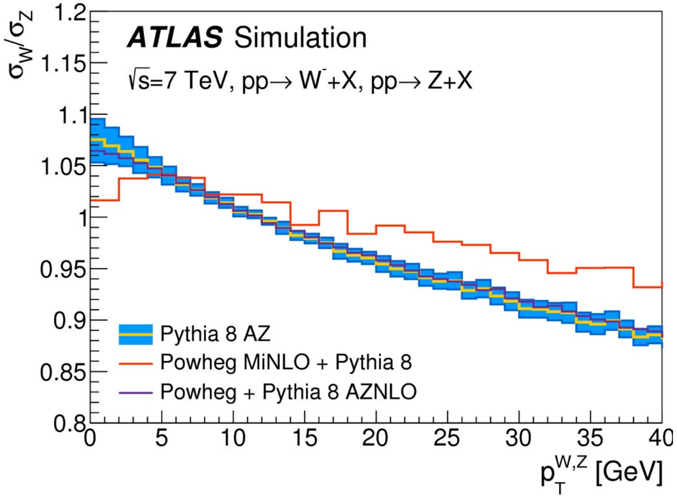


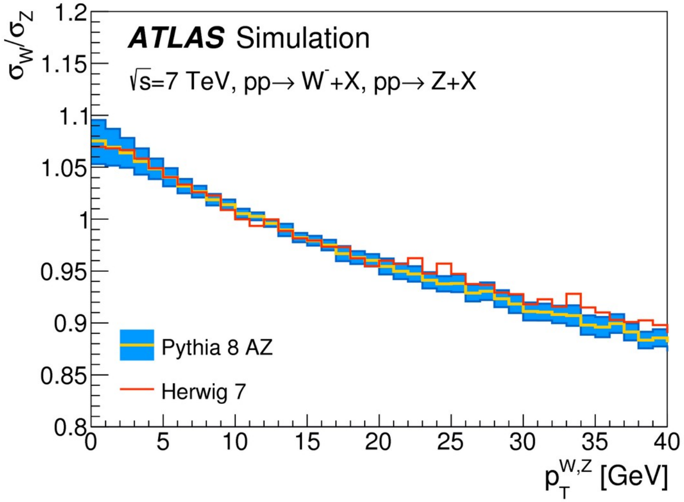


Alternative higher order models for p_T W

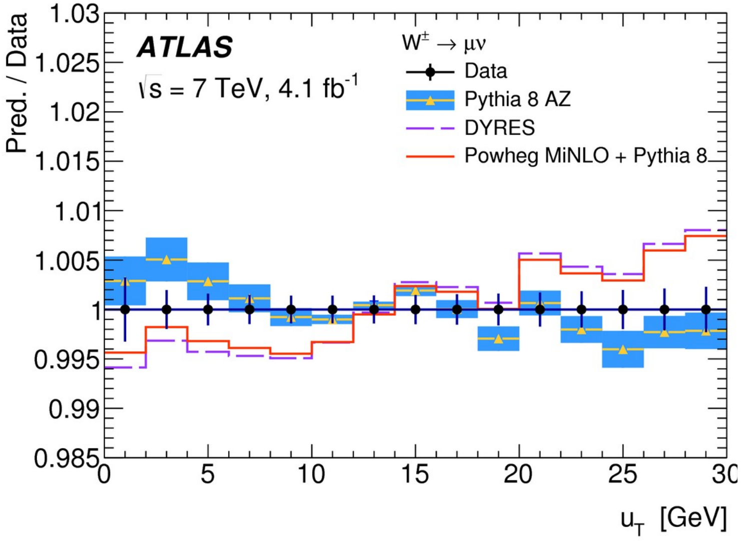
Since the p_T Z distribution is very well measured, the relevant theoretical uncertainties are those which affect the W/Z p_T distribution

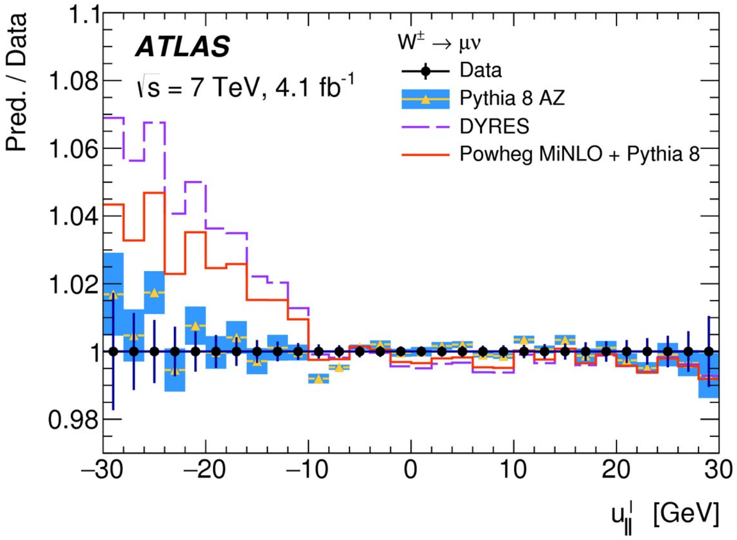






At that time, only Herwig, Pythia, and Powheg predicted a W/Z p_T ratio in agreement with data





MINLO and NNLL analytic resummed predictions as Resbos, Cute, and DyRes were strongly disfavoured by the recoil distribution in data

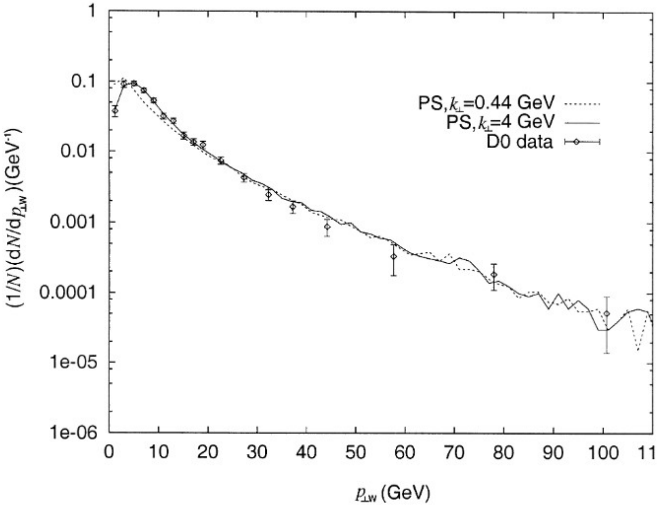
Which is the formal accuracy of Pythia 8 p_T W?

- Pythia8 implements the so-called “matrix-element” reweighting of the first emission, which make the p_T distribution accurate at $O(\alpha_s)$ at medium/high p_T

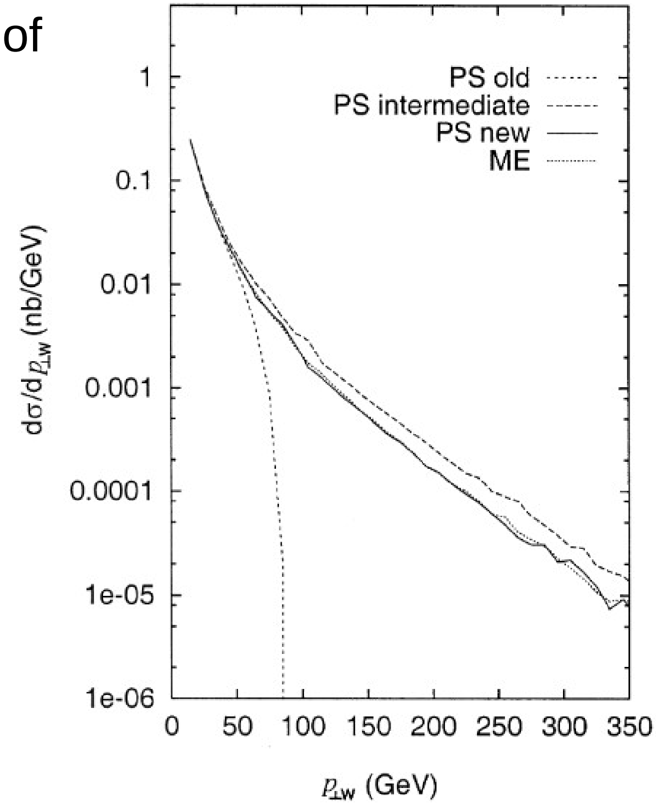
Nucl. Phys. B 349 (1991) 635-654

$$P(\alpha_s, z) = \frac{\alpha_s}{2\pi} C_F \frac{1+z^2}{1-z} + \left(\frac{\alpha_s}{\pi}\right)^2 \frac{A^{(2)}}{1-z}$$

$$\alpha_s^{(MC)} = \alpha_s^{(\overline{MS})}\left(1 + K\frac{\alpha_s^{(\overline{MS})}}{2\pi}\right)$$



arXiv:hep-ph/9812455



- Resummation arguments show that a set of universal QCD corrections can be absorbed in coherent parton showers by applying the Catani-Marchesini-Webber (CMW) rescaling of the $\overline{\text{MS}}$ value of Λ_{QCD}

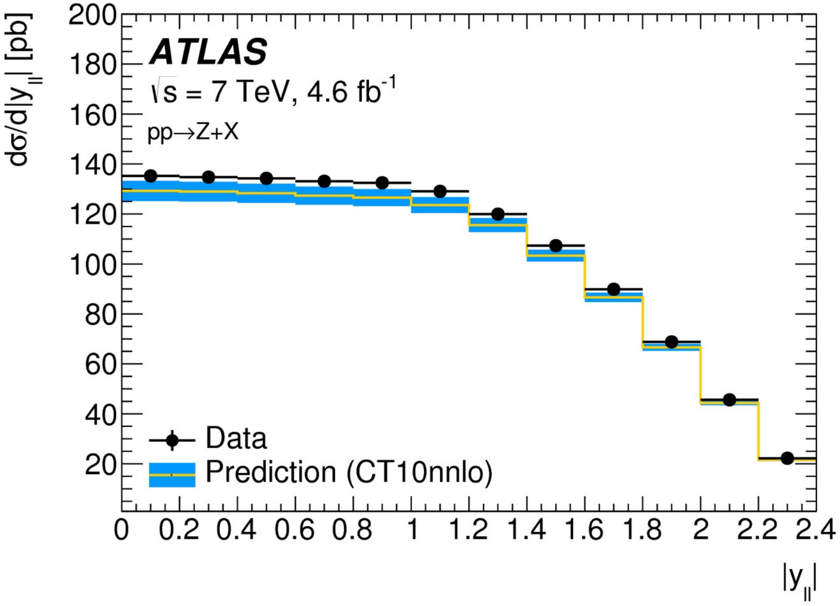
$$\alpha_s = 0.118 \rightarrow \alpha_s^{CMW} = 0.126$$

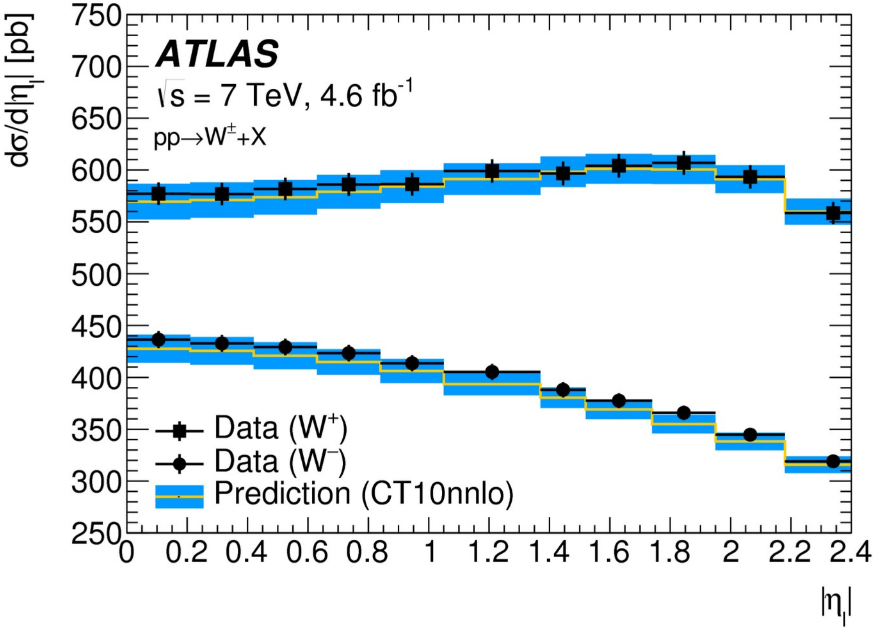
Close to the value α_s= 0.124 of the AZ tune

The W and Z p_T normalised distribution of tuned Pythia 8 are formally NLO+NLL accurate

Rapidity distributions

- Rapidity distributions are modeled with NNLO predictions
- m_W physics modelling predictions compared to rapidity measurements



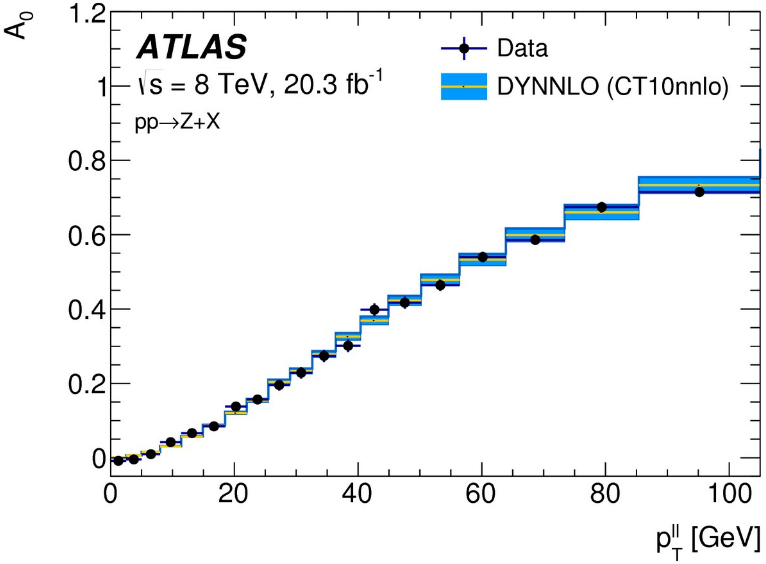


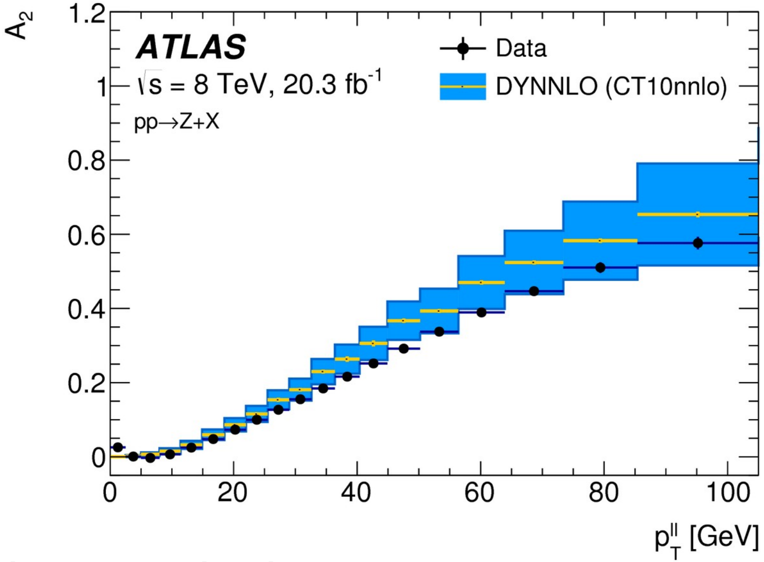
Physics modelling – angular coefficients A_i

- The DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the boson decay

$$\frac{d\sigma}{dp\,dq} = \frac{d^3\sigma}{dp_T\,dy\,dm} \sum_i A_i(y, p_T, m) P_i(\cos\theta, \phi)$$

- P_i (cos θ, φ) are spherical harmonics. In the assumption of spin 1 of the boson and spin ½ of the fermions, the 9 harmonics of order 0, 1, and 2 provide a complete decomposition

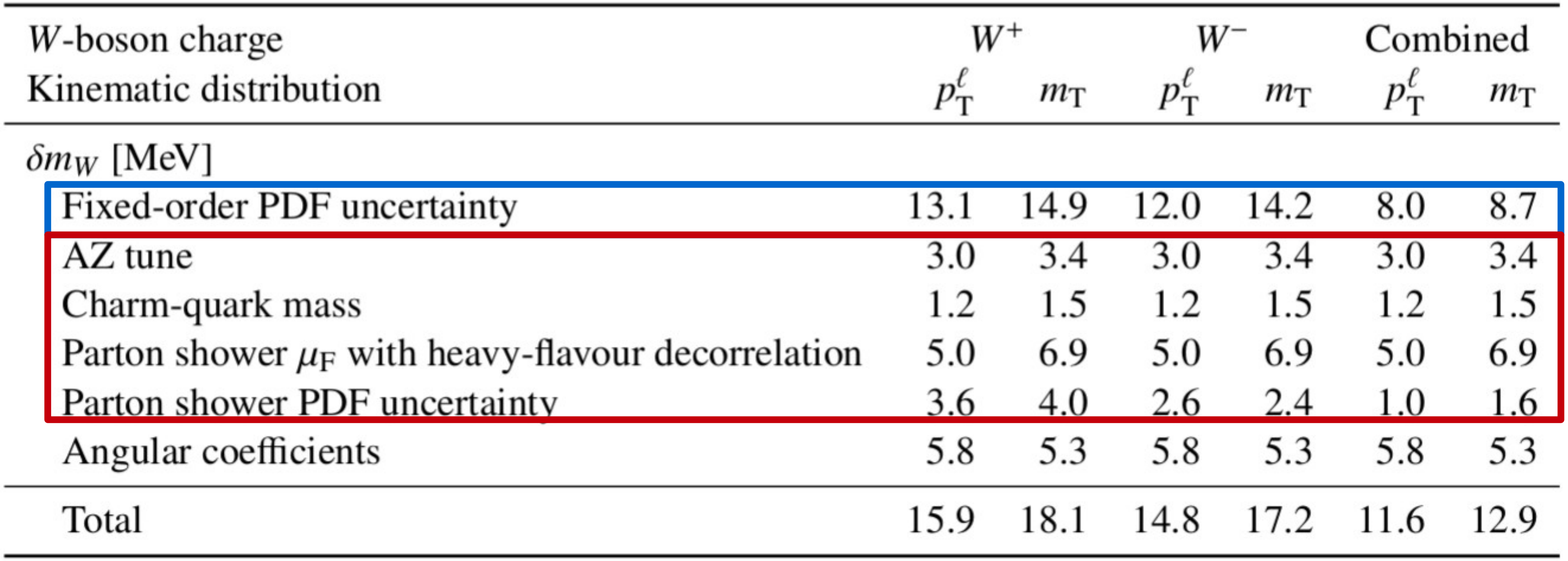




- Angular coefficients are modelled with fixed order perturbative QCD at NNLO

- A_i predictions are validated by comparisons to the Z measurement at 8 TeV

Physics modelling – Summary of QCD uncertainties

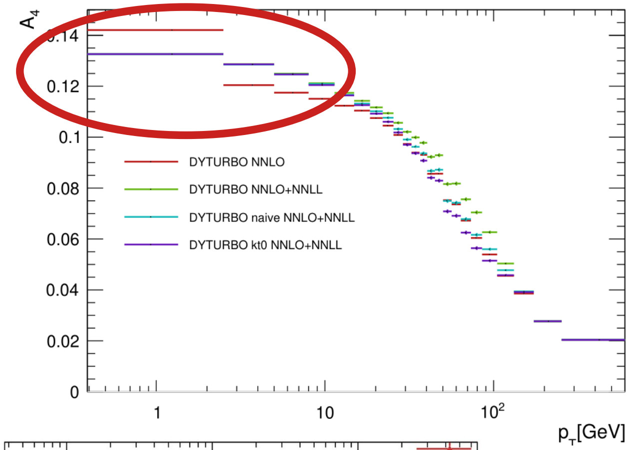


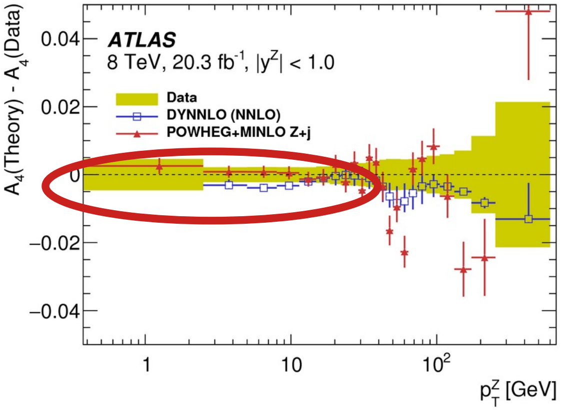
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9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

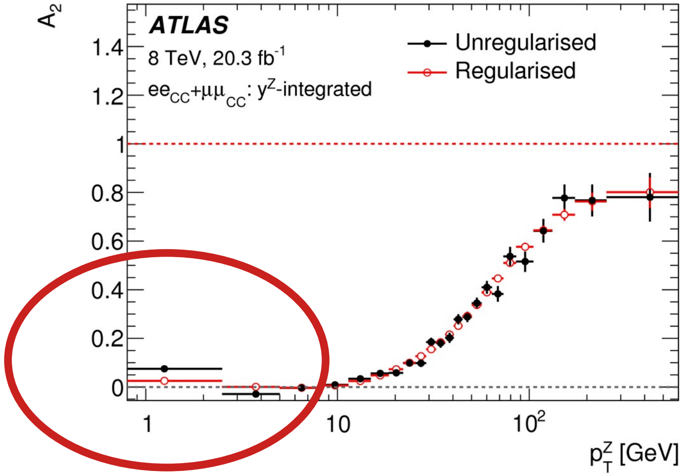
- PDFs are the dominant uncertainty, followed by p_T W uncertainty due to heavy-flavour-initiated production
- PDF uncertainties are partially anti-correlated between W+ and W-, and significantly reduced by the combination of these two categories.
- p_T W uncertainties are similar for m_W extracted from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

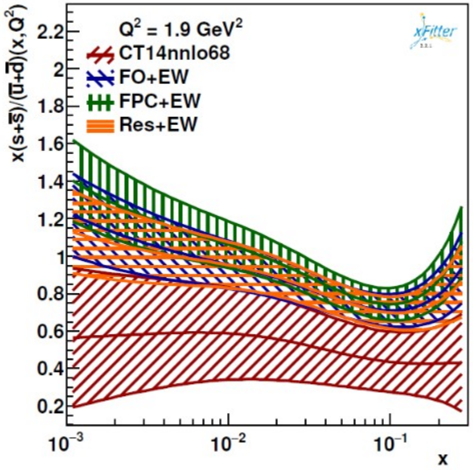
Physics modelling potential weak points

- $p_T W$ modelling based on (N)LL parton shower
- Potential issues with modelling of A4 at very low p_T with fixed order
- Evidence for non perturbative A2 in the Z data, not accounted for in any available prediction
- PDF fits to W,Z rapidity data could be biased due to symmetric fiducial cuts
- Diffractive W?



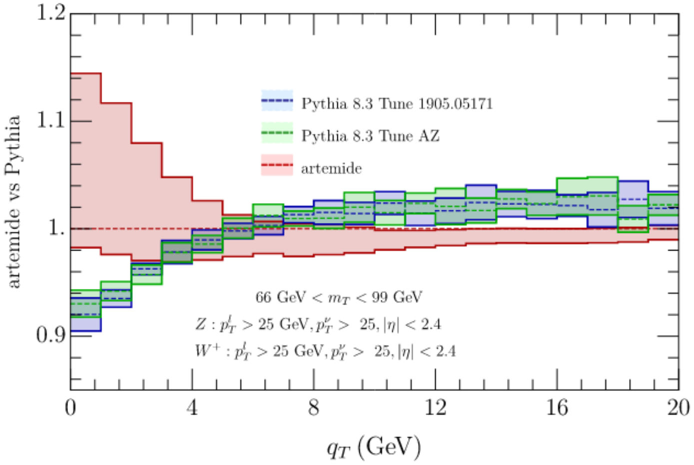


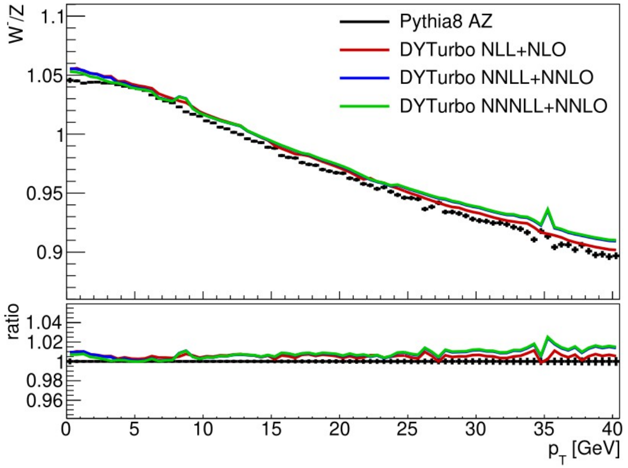


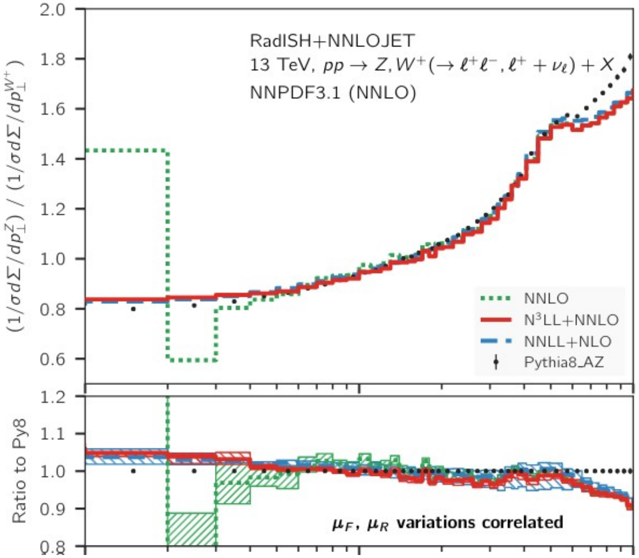


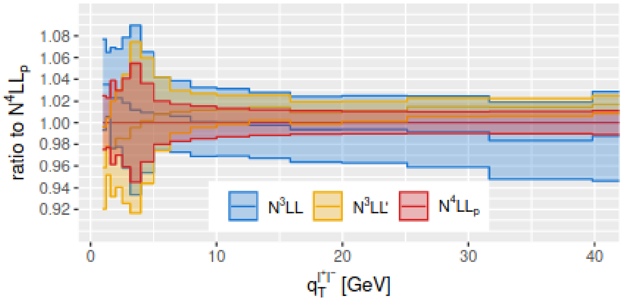
p_TW modelling

- p_TW modelling based on (N)LL parton shower
- In 2016, only few resummation codes were fully public (CuTe, Dyres), and they had issues for the W/Z pT ratio
- Many more qt-resummation public codes are available now, and they are in reasonable agreement with Pythia for the W/Z p_T ratio
- State-of-the-art moved from NNLL to N3LL/N4LL
- Huge progress also thanks to the LPCC W/Z pT benchmark group



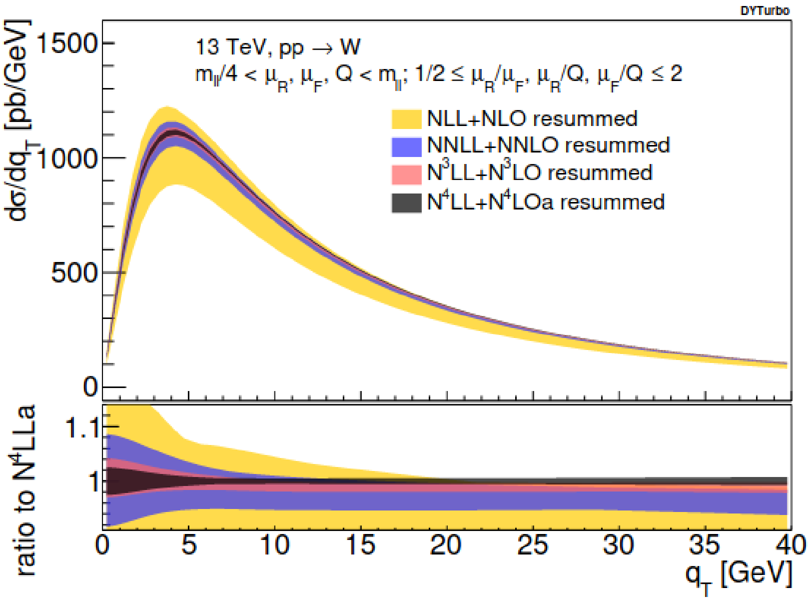


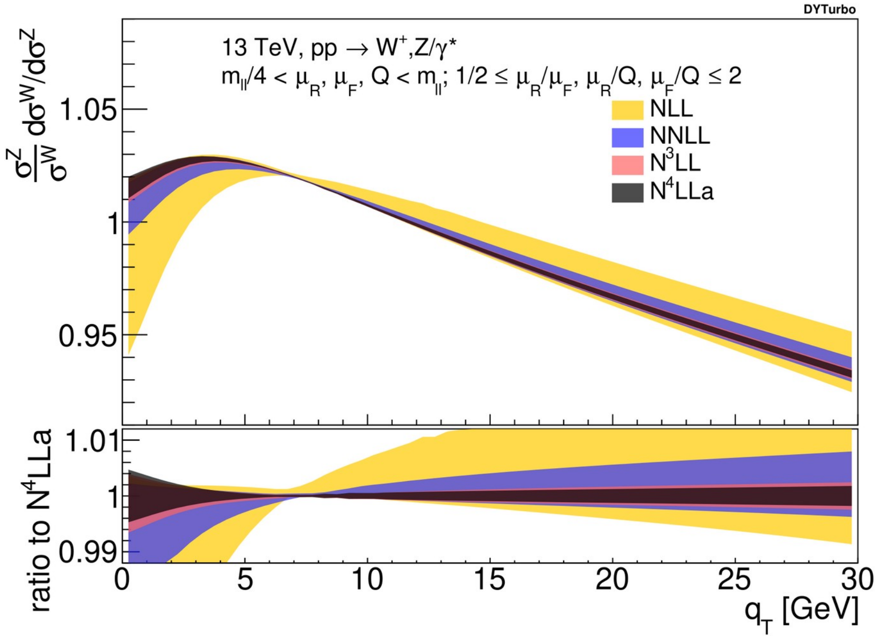




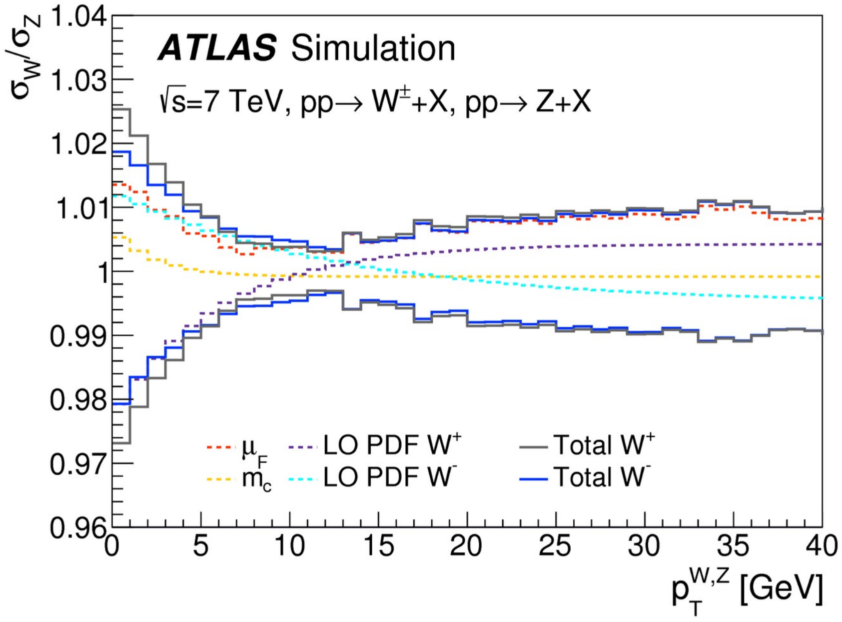
p_TW modelling

- Do we need highest perturbative accuracy for the p_TW modelling?

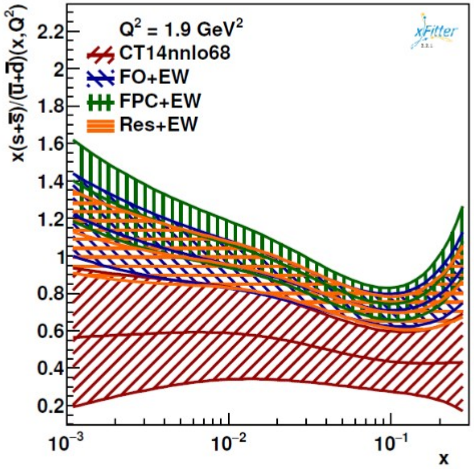




- Yes if we are trying to predict p_TW from first principles, but not necessarily if we measure p_TZ and predict the W/Z p_T ratio
- Perturbative accuracy is a subdominant uncertainty in the W/Z p_T ratio already at NNLL other effects are more important (PDFs, HF, QED)
- However, only with high order qt-resummation we can coherently use high order PDFs



Rapidity cross sections and PDF fits



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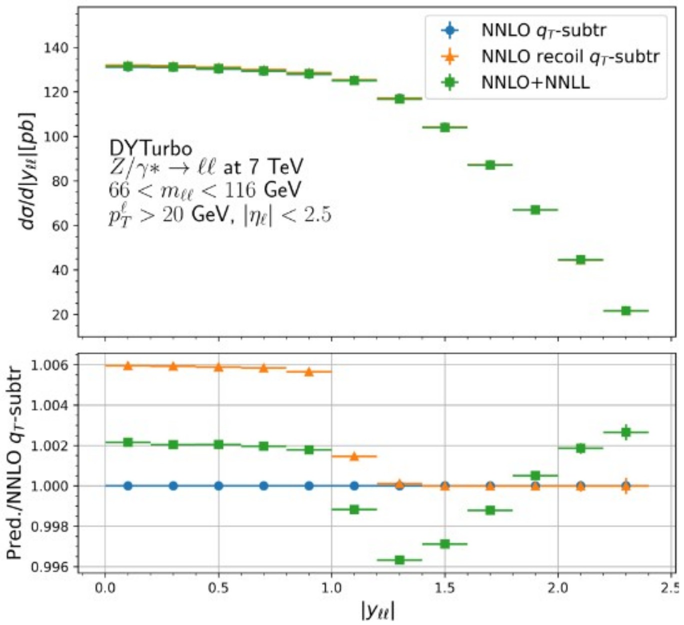
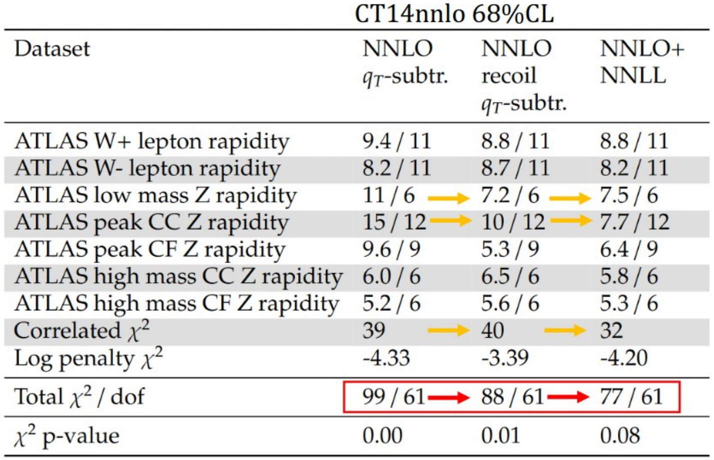
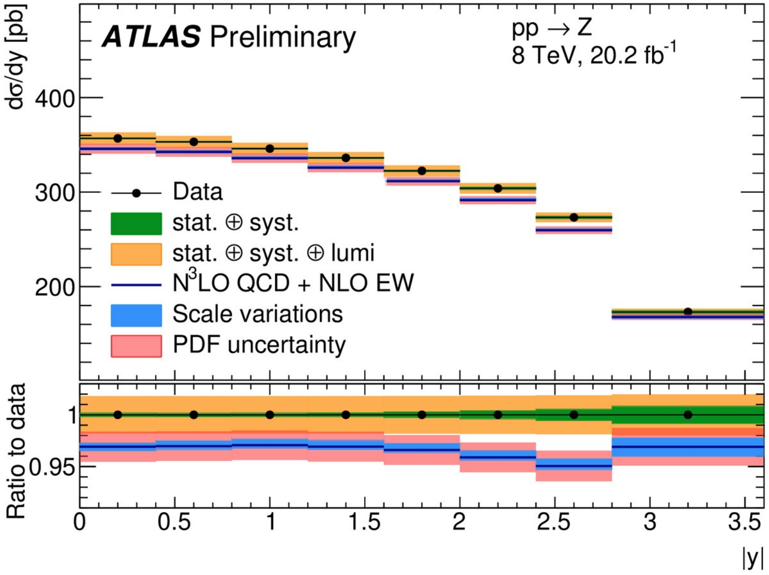


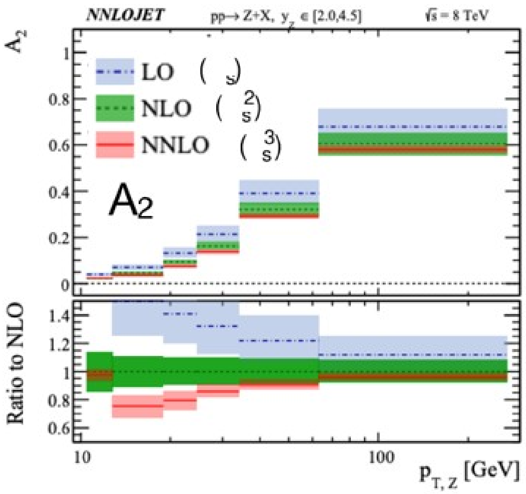


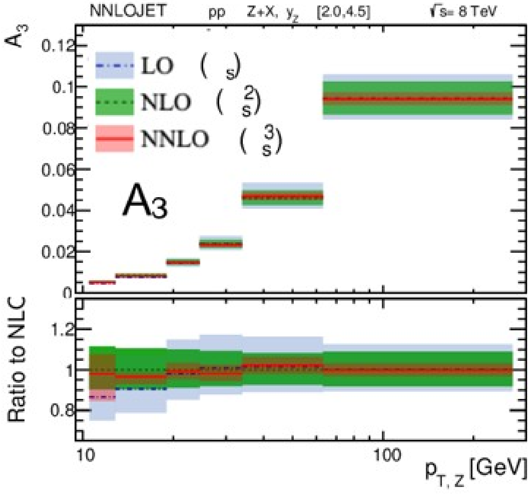
	CT14nnlo 68%CL		
Dataset	NNLO q_T-subtr.	NNLO recoil q_T-subtr.	NNLO+ NNLL
ATLAS W+ lepton rapidity	9.4 / 11	8.8 / 11	8.8 / 11
ATLAS W- lepton rapidity	8.2 / 11	8.7 / 11	8.2 / 11
ATLAS low mass Z rapidity	11 / 6	7.2 / 6	7.5 / 6
ATLAS peak CC Z rapidity	15 / 12	10 / 12	7.7 / 12
ATLAS peak CF Z rapidity	9.6 / 9	5.3 / 9	6.4 / 9
ATLAS high mass CC Z rapidity	6.0 / 6	6.5 / 6	5.8 / 6
ATLAS high mass CF Z rapidity	5.2 / 6	5.6 / 6	5.3 / 6
Correlated χ^2	39	40	32
Log penalty χ^2	-4.33	-3.39	-4.20
Total χ^2 / dof	99 / 61	88 / 61	77 / 61
χ^2 p-value	0.00	0.01	0.08

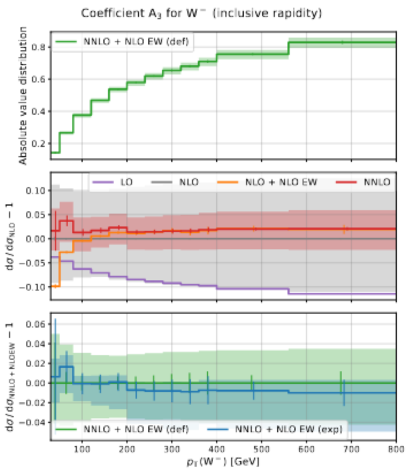
- PDF fits to W,Z rapidity data could be biased due to symmetric fiducial cuts
- Now possible to include resummation effects in the PDF fits
- We also have measurements without cuts
- It is very important for the precision of m_W measurements that PDF fits study and address this issue

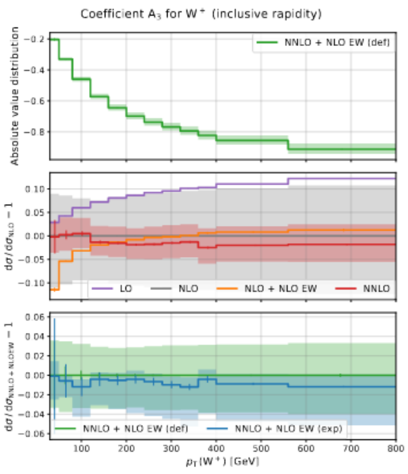


Ai at O(α_s^3)







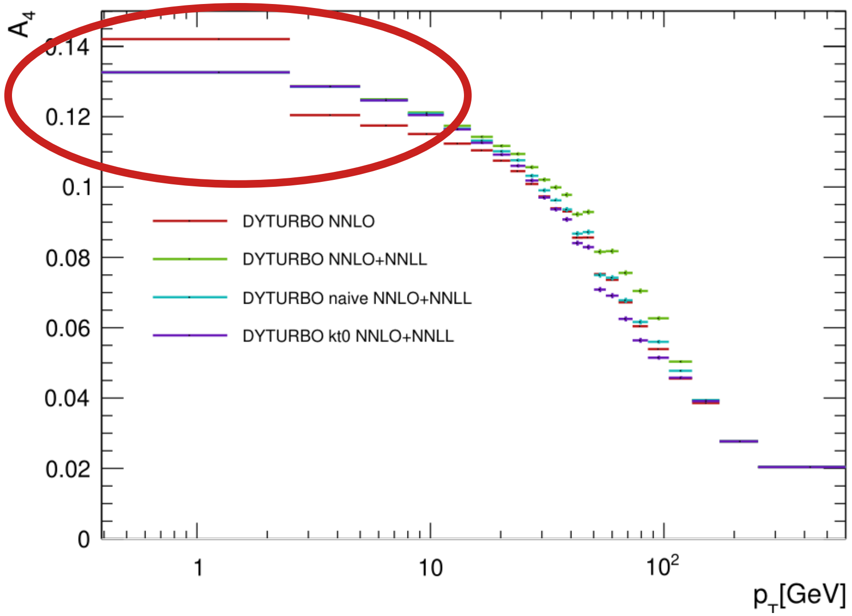


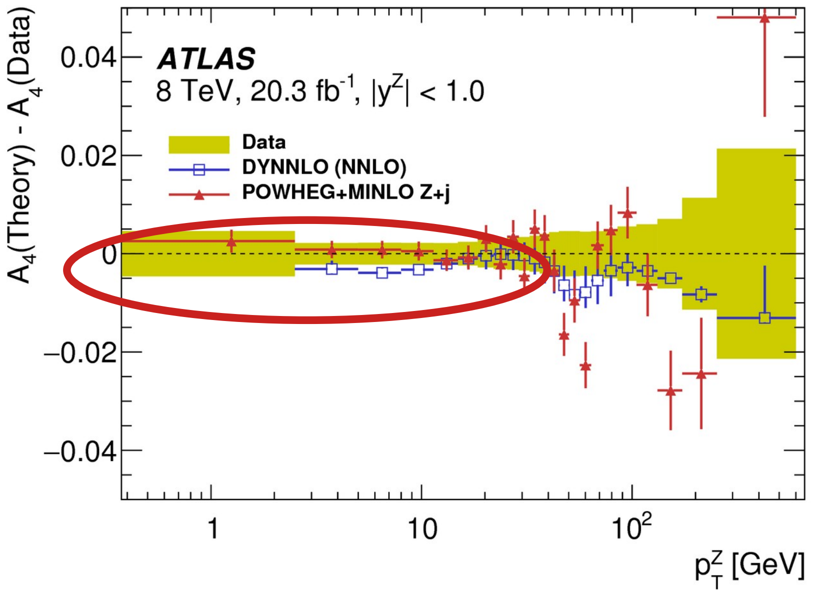
- Accurate modelling of W Ai is very important for the W mass measurement
- Recently achieved α_s^3 accuracy with
  - NNLOJET
  - STRIPPER
  - MCFM/NJETTI
- However no public code yet available for W
- Computing Ai coefficients for the W mass is very expensive ATLAS measurement used O(α_s^2) predictions, and took about 500K CPU hours

- Is it possible to have these predictions available for the next round of W mass measurements?
- What is the preferred and more efficient way of providing these calculations to the experiments?
- Is HighTea an option?
- Analytic calculations a-la Mirkes [Nucl.Phys.B 387 (1992) 3-85], if feasible, would be extremely useful

Resummation effects on Ai

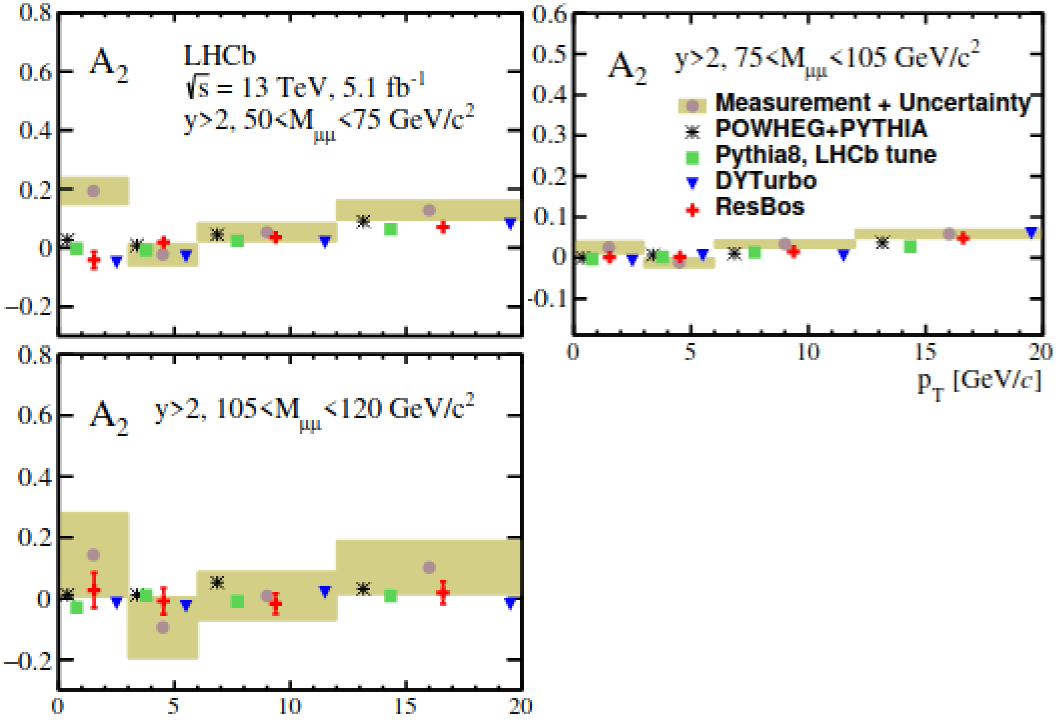
- Is it appropriate to model all angular coefficients at fixed order?
- Are there potential issues with modelling of A4 at very low p_T with fixed order?
- Validation of A4 in Z production may not be sufficient for W, where A4 is much larger

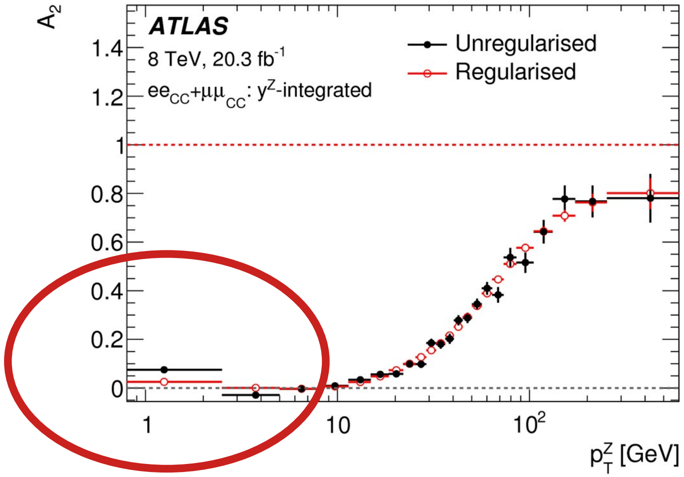




Non perturbative contributions to Ai

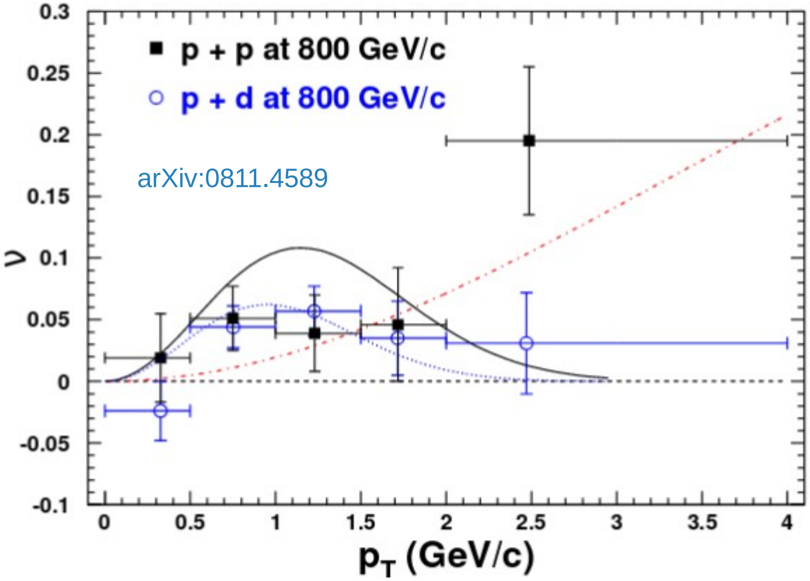
- Evidence for non perturbative A2 in the Z data, not accounted for in any available prediction





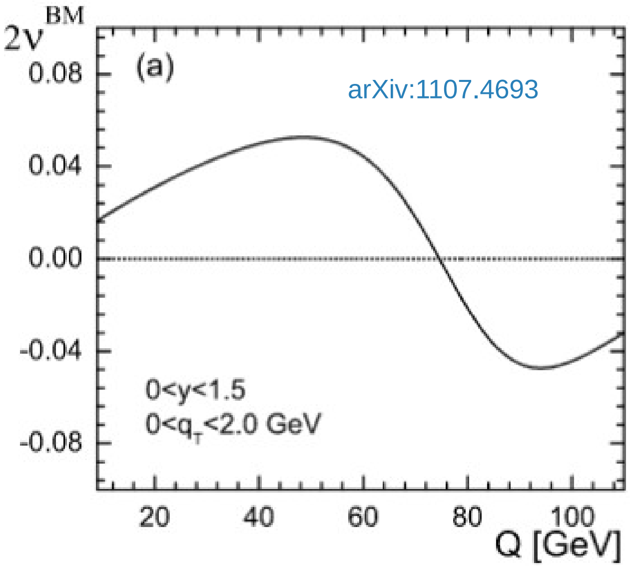
Non perturbative A2

- Beyond the current precision, the measurement of m_W could be sensitive also to asymmetries from non-perturbative QCD effects



arXiv:0811.4589

- $\cos(2\phi)$ (A2) asymmetries in the non perturbative regime were observed in fixed target Drell-Yan experiments (NA10, E866)
- They are well described by Boer-Mulder TMD functions



arXiv:1107.4693

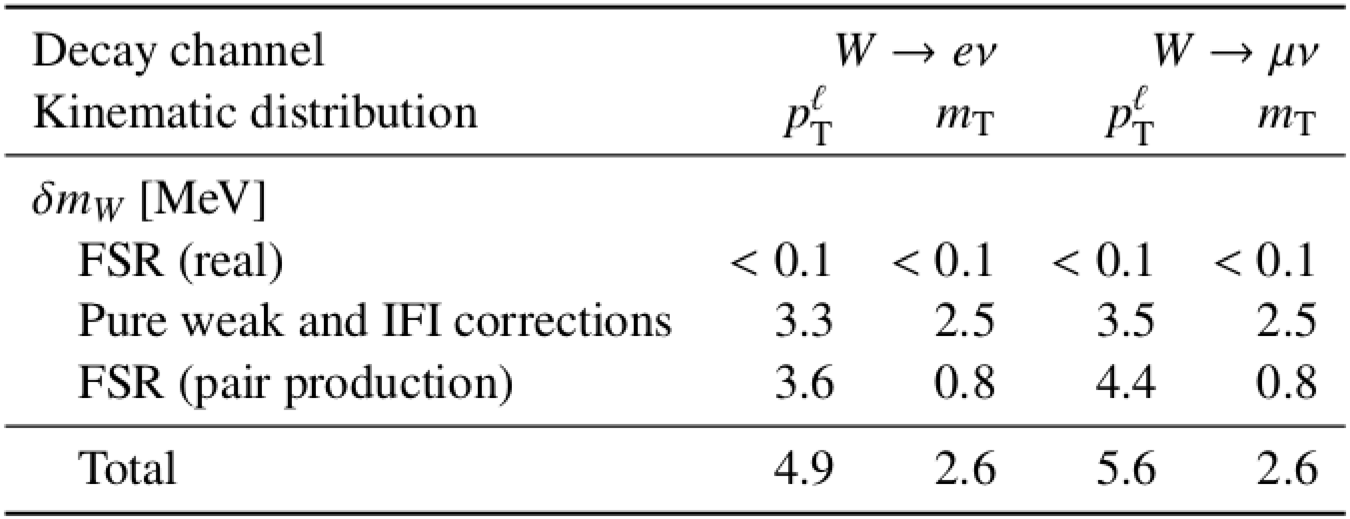
- The non-perturbative contribution to A2 at small q_T is expected to change sign between γ^* and Z exchange
- Is such an asymmetry expected also in W?
- The effect on m_W is expected to be small, but it may be necessary to quantify it precisely for future measurements

Summary

- Long tradition of theory-experiment meetings for m_W have strongly contributed to the measurements at the LHC, in particular to the shape of the physics modelling used for m_W
- New reanalysis of ATLAS m_W at 7 TeV confirms previous result and reduce uncertainties from 19 to 16 MeV. The most important improvement is the usage of a profile likelihood
- The new reanalysis is still based on the physics modelling of the legacy measurement. Outlined a few potential weak points of our own ATLAS physics modelling
- Much progress was made in the understanding of vector boson production, in particular p_TW. A few open issues still remain, for which feedback from theorists would be very useful

Electroweak corrections

- QED FSR: dominant correction, included in the simulation with PHOTOS or others MC
- Other NLO electroweak corrections are usually estimated independently from QCD corrections, and applied as uncertainty

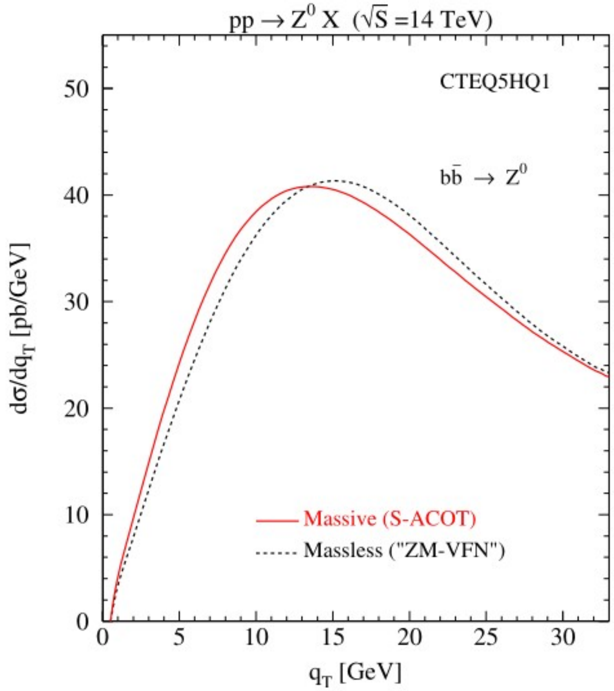


Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

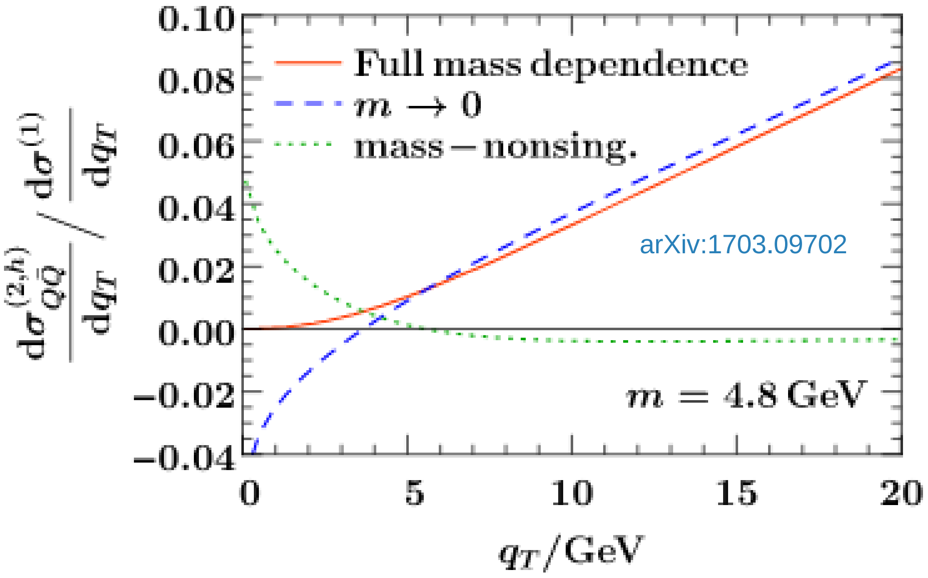
- Many recent developments in higher order corrections, mixed EW-QCD, and benchmarking between different codes presented in the LPCC EW working group
- Main challenge for the m_W analyses: include electroweak corrections in the analyses, coherently combined with QCD corrections. Available tools are Powheg-EW, DIZET form factors, WINHAC, KKMC, but they do not include state-of-the-art QCD corrections
- EW corrections are now determined at detector level, increasing their impact on m_W by typically 20%.

Modelling of p_T W, HF initiated production

hep-ph/0509023

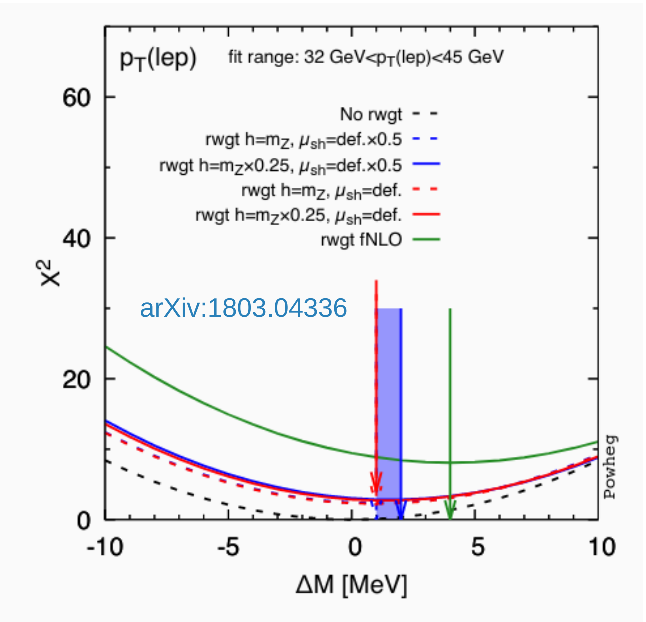


- Heavy flavours initiated production with ACOT VFN scheme for Drell-Yan



arXiv:1703.09702

- SCET-based approach for q_T-resummation with massive quark effects

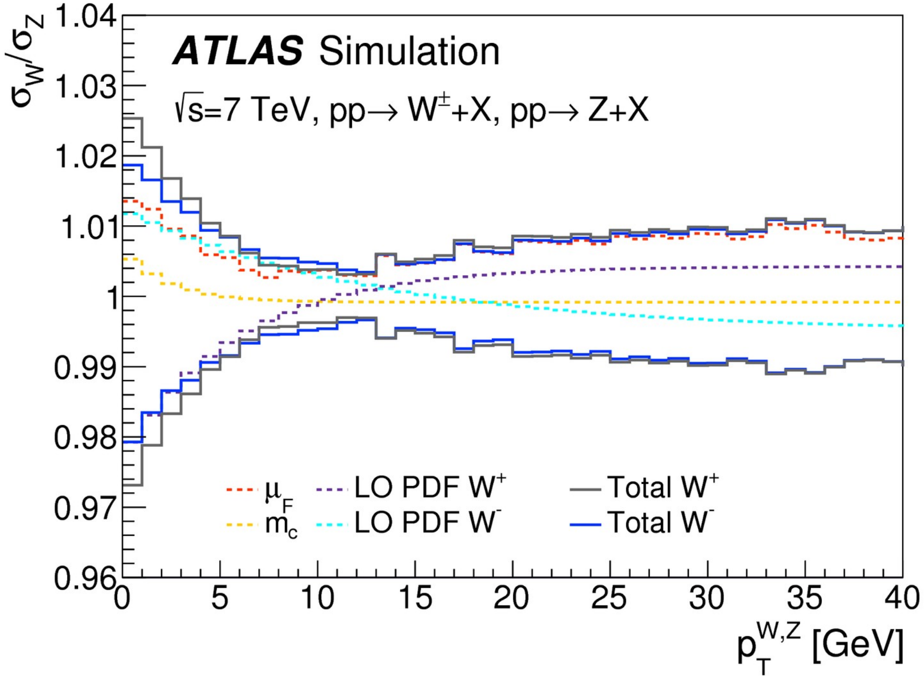


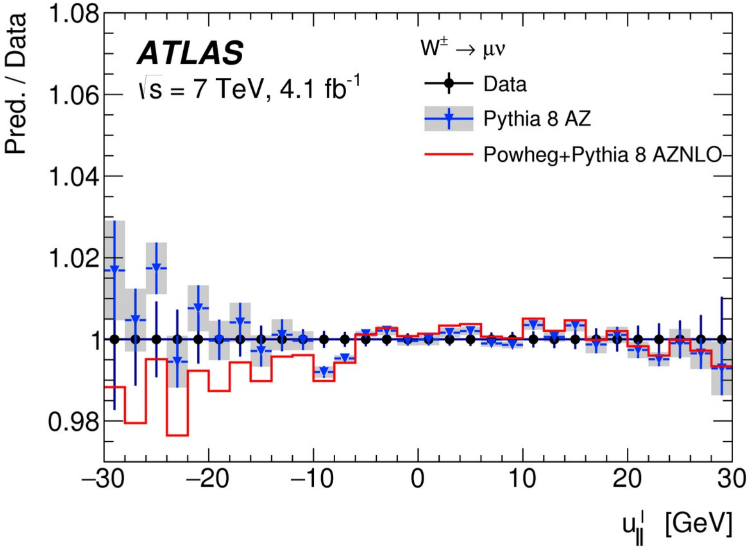
arXiv:1803.04336

Uncertainties in the p_T W modeling

- Heavy-flavour-initiated (HFI) production introduce differences between Z and W production
- HFI production determines a harder boson p_T spectrum, $cc \rightarrow Z$ and $bb \rightarrow Z$ are 6% and 3% of Z production, $cs \rightarrow W$ is ~20% of W production
- HFI addressed with charm-quark mass variations, and by decorrelating the PS μ_F between light and HFI processes

p_T W theory uncertainties are evaluated as the sum of experimental Z p_T unc. and theory unc. on the W/Z p_T ratio





Central prediction and uncertainty validated with the recoil distribution → when using the data to constrain the model we end up with compatible central value and similar uncertainties