Precision measurements in W and Z decays with the ATLAS Experiment

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Lake Louise Winter Institute 2024 -23/02/2024

The role of W and Z boson physics at LHC

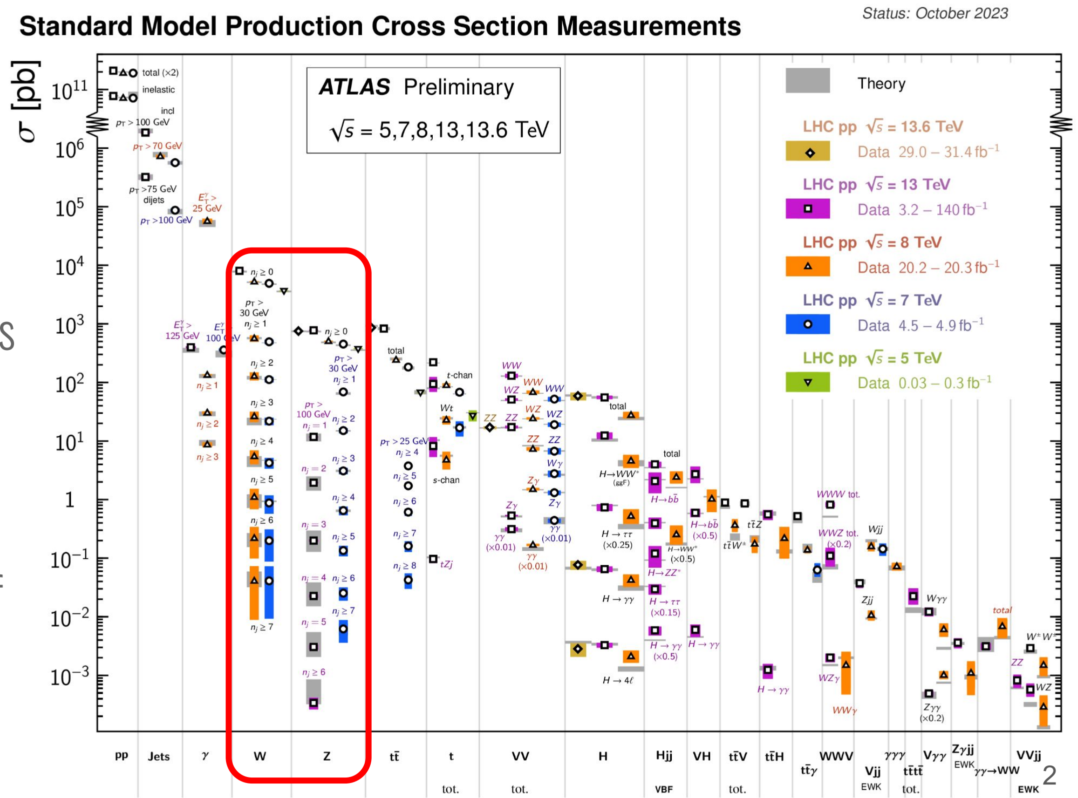
W and Z boson production is abundant and has clear experimental signature, making them a crucial probe of QCD and EWK physics!

→ Background for other measurements and searches (BSM, Higgs, top, etc.)

→ Test of state-of-the-art predictions: fixed-order perturbative QCD (pQCD) and MCs

→ Probe of proton structure, sensitivity to Parton Density Functions (PDFs)

→ Ultimate precision for the extraction of fundamental Standard Model constants

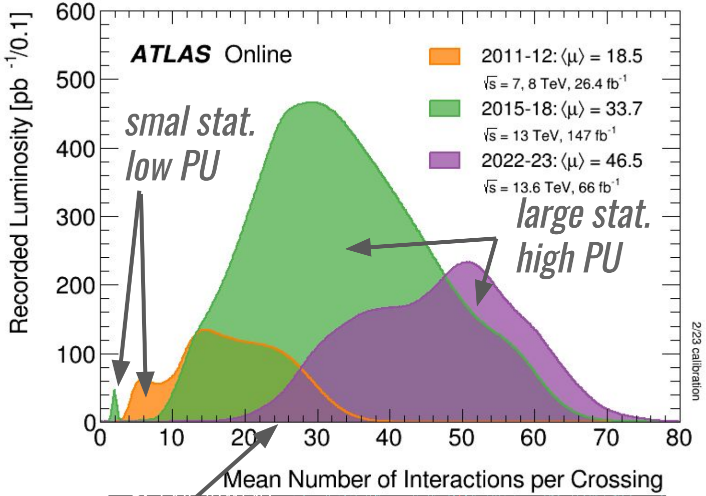


Precision W and Z physics with the ATLAS data

The ATLAS analyses presented in this talk:

- Improved W mass at 7 TeV [ATLAS-CONF-2023-004]
- W+D measurement at 13 TeV [PRD 108 (2023) 032012]
- W and Z p_T at 5.02 and 13 TeV [ATLAS-CONF-2023-028]
- Z p_T in full phase space at 8 TeV [arXiv:2309.09318]
  → measurement tightly related to α_s measurement [arXiv:2309.12986], more details about this in Jon's talk!
- Z invisible width at 13 TeV [arXiv:2312.02789]
- Search for W exclusive hadron decays [arXiv:2309.15887]

Ultimate precision may need large statistics *or* clean experimental conditions:
⇒ *different needs, different datasets!*



W mass at 7 TeV, improved analysis

[ATLAS-CONF-2023-004]

The measurement of the SM fundamental parameters is one of the goals of High Energy Physics!

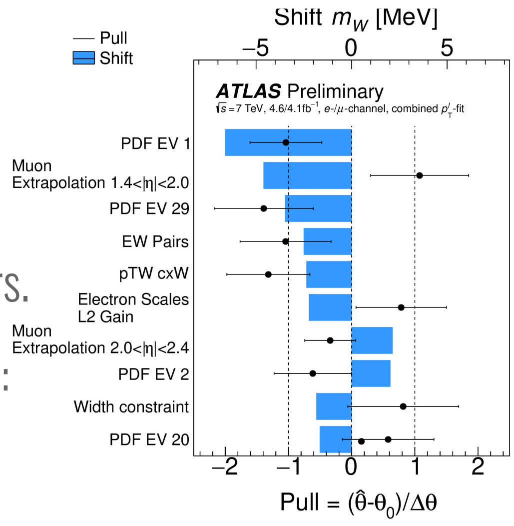
W boson mass linked to m_H and m_t ⇒ *probe SM consistency and BSM through loop corrections*

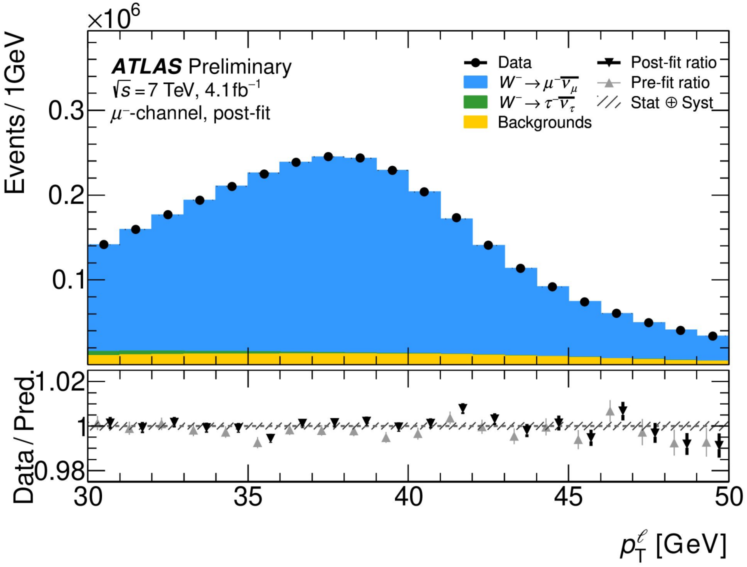
Extraction of m_W using W→lν & templates of p_T^{lep} and m_T^W

Improved re-analysis of 4.6 fb^{-1} dataset of [EPJC 78 (2018) 110]

→ Use of profile likelihood fit: 28 categories, ~500 nuisance pars.

→ Large effect of PDF set update: *moved from CT10 to newer CT18*





W mass at 7 TeV, improved analysis

[ATLAS-CONF-2023-004]

Strong reduction of uncertainties due to PDF and modelling of QCD effects w.r.t. first publication:

It was ~9 MeV! (PDF Unc.) *It was ~8 MeV!* (PS & A_i Unc.)

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

Final combined measurement using p_T^{lep} and m_T^W :

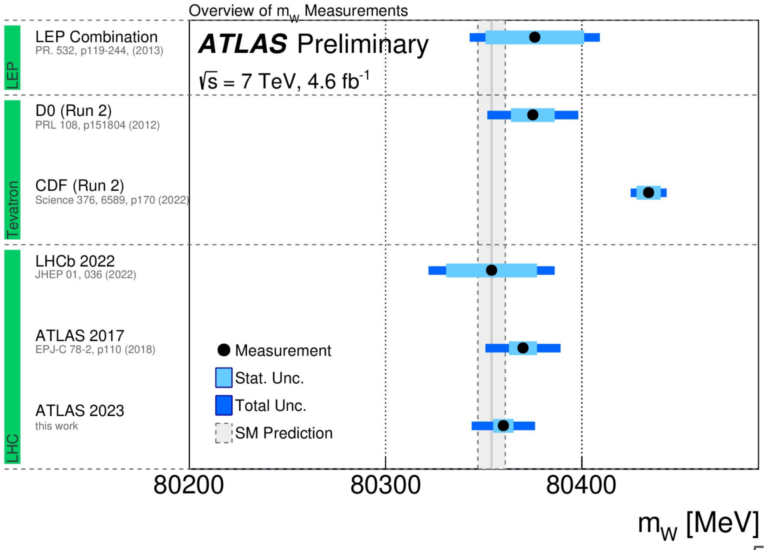
$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$

15% syst. reduction, now dominated by experimental sources

m_W central value shifted by ~10 MeV, close to SM prediction

Update CONF→paper very very close! (including Γ_W)

Could we do better on newer datasets??

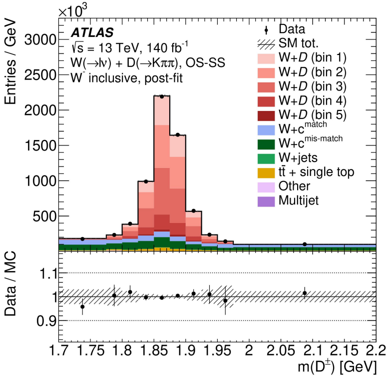


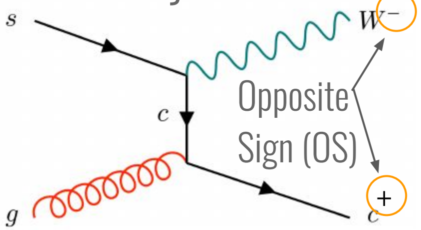
Measurement W boson plus D-mesons

[PRD 108 (2023) 032012]

Improved knowledge of proton PDF is crucial to progress further in many precision analyses

This is possible only thanks to additional dedicated precision measurements!





→ W + charmed mesons as probe s-quark PDF

→ Strong background suppression using D-meson recon. and OS-SS charge correlation

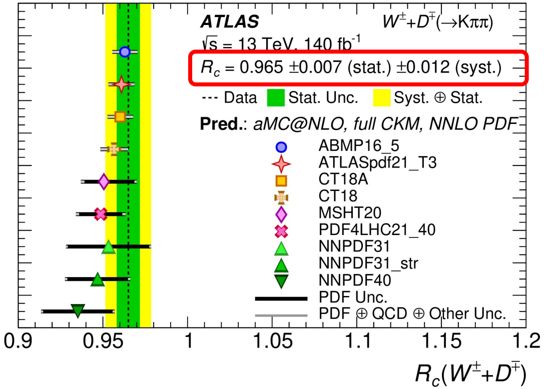
→ Differential measurement in p_T^{lep} and η^{lep}

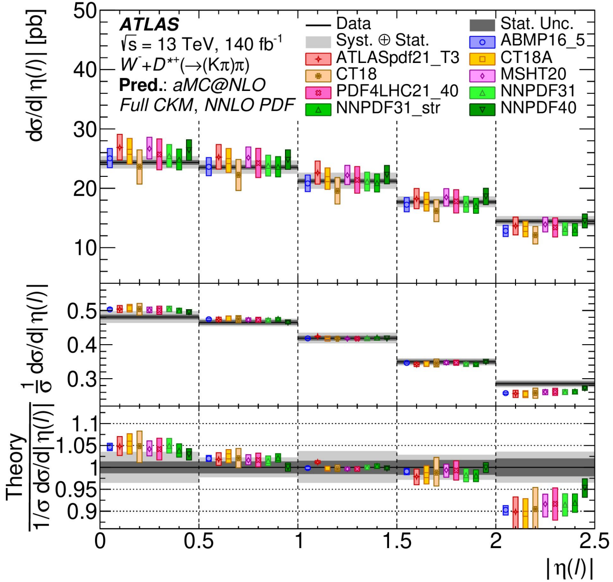
→ Comparison with different PDFs

→ Constraints for future global fits

→ R_c sensitive to s-sbar symmetry:

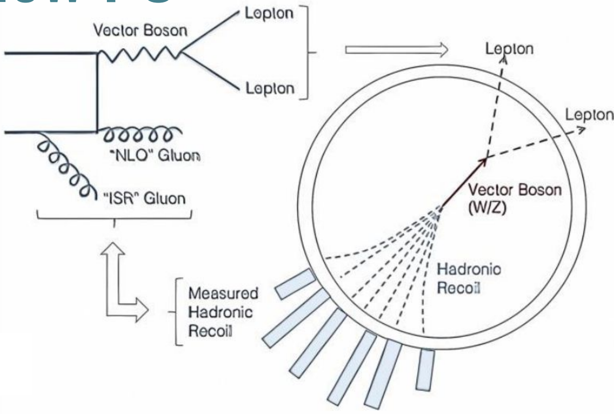
$$R_c^{\pm} = \frac{\sigma_{fid}^{OS-SS}(W^+D^{(*)-})}{\sigma_{fid}^{OS-SS}(W^-D^{(*)+})}$$





[ATLAS-CONF-2023-028]

W and Z p_T measurement at 5.02 and 13 TeV, low PU



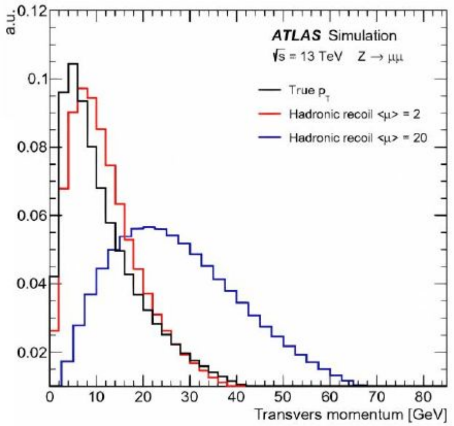
Precision measurements also crucial to test and better understand QCD

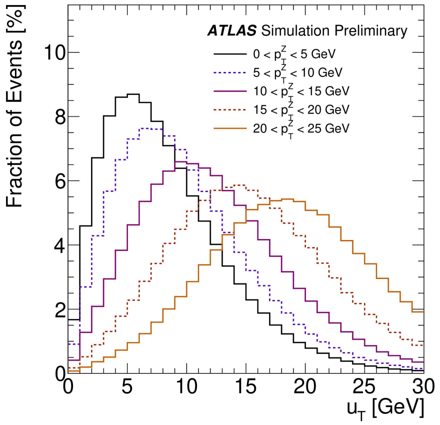
→ W and Z p_T spectra sensitive to pQCD and non-perturbative effects, p_T^V description below ~30 GeV also important for m_W

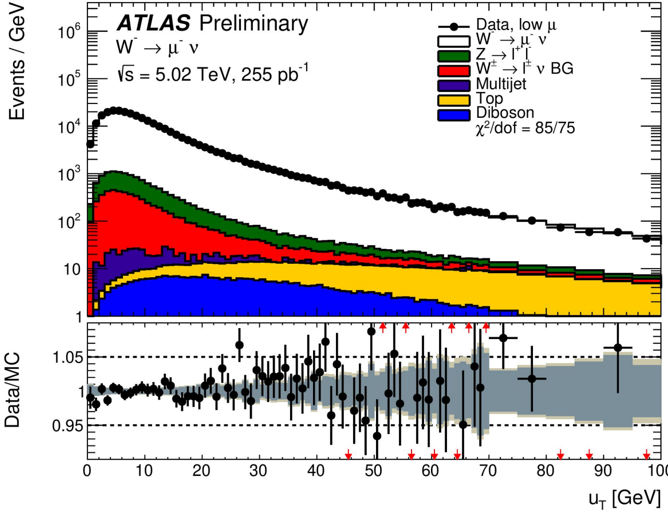
→ Hadronic recoil, u_T, of the event for p_T^W measurement

→ Low pile-up for good u_T resolution, use Z→ll for calibration

→ Use of dedicated low-μ 5.02 and 13 TeV datasets!







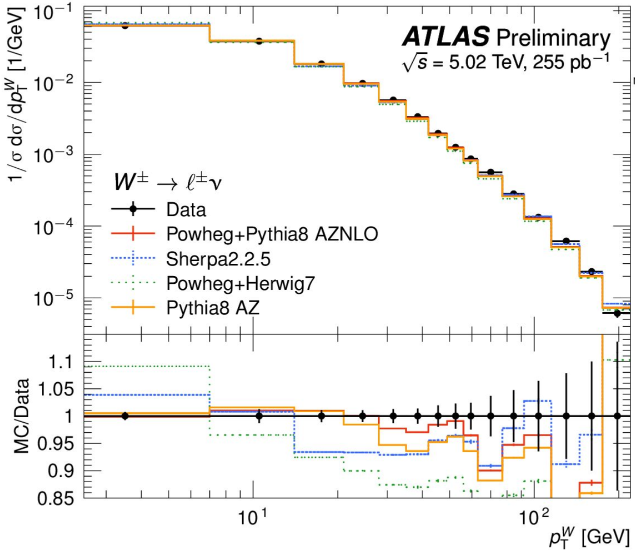
W and Z p_T measurement at 5.02 and 13 TeV, low PU

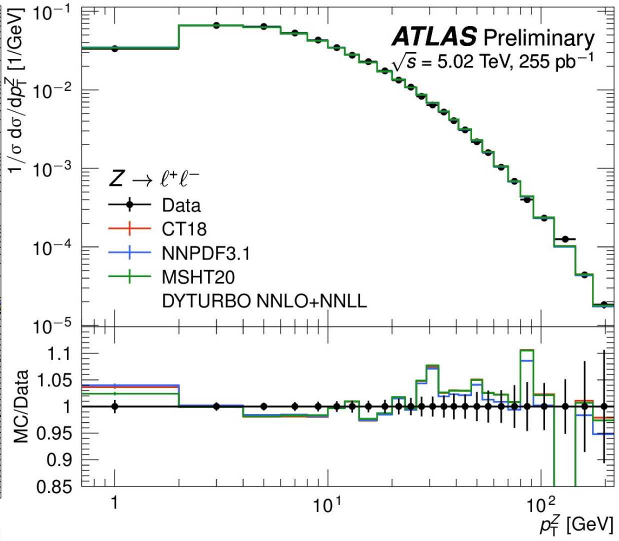
[ATLAS-CONF-2023-028]

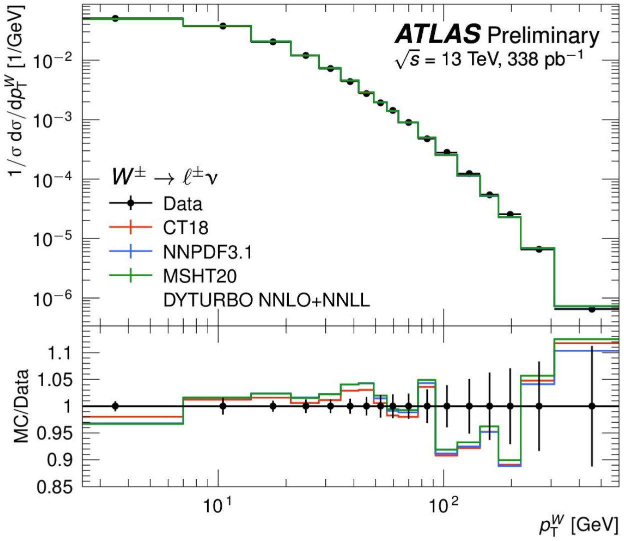
Iterative Bayesian Unfolding to correct for detector effects → good resolution crucial at low p_T^V

Measurement of differential cross section and ratios compared to many MC and pQCD predictions

Large differences between MCs, good description from resummed predictions (NNLO+NNLL)







Data also used for further validation of AZNLO tune, used for m_W measurement!

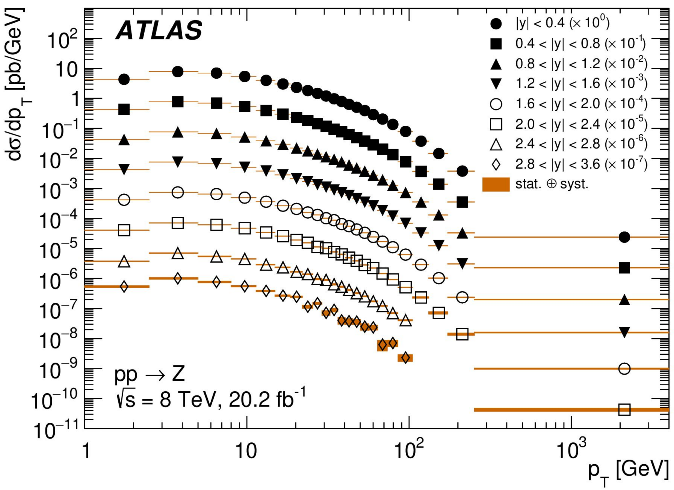
Z double differential in full phase space at 8 TeV

[arXiv:2309.09318]

Also another recent precision measurement focusing on Z boson p_T, and also |y|

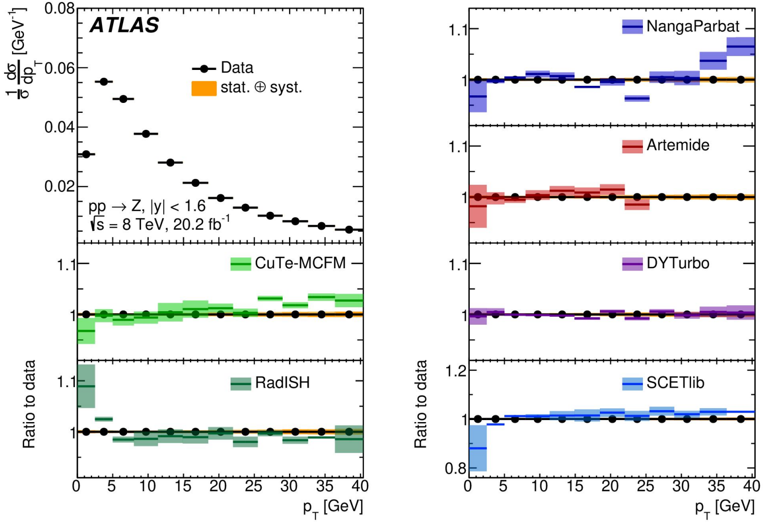
→ Analysis derived from [JHEP08 (2016) 159], 20.2 fb^{-1} dataset, 15.3 M Z→ll events, using profile likelihood fit of truth-to-reco templates obtained in full lepton phase space

→ First time double differential measurement at Z pole of $\frac{d^2\sigma}{dp_T dy}$, with |y| < 3.6 thanks forward lep.



→ Comparing to most accurate predictions: **N^{4}LLa+N^{3}LO pQCD**

→ Very stringent test: Agreement at ~% level



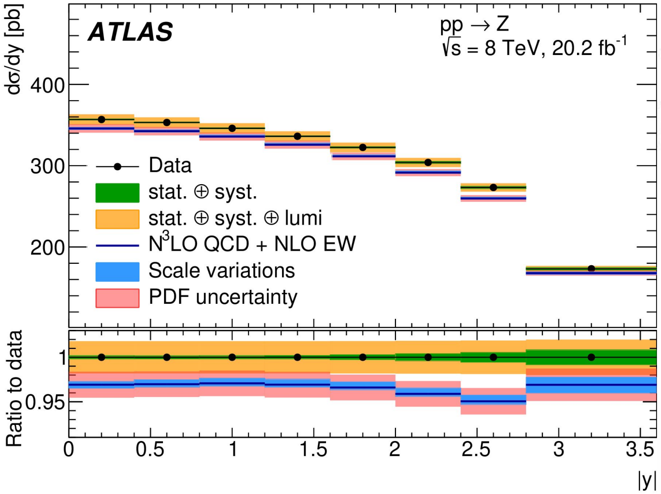
Z double differential in full phase space at 8 TeV

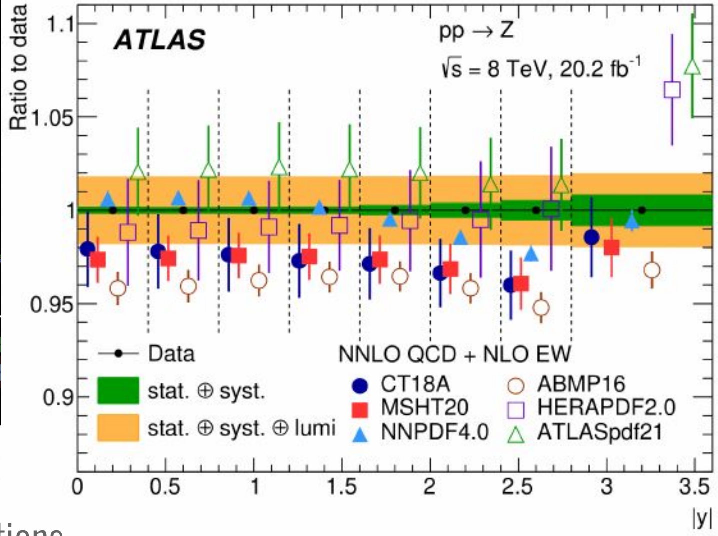
[arXiv:2309.09318]

Impressive precision: level of 0.2-0.5%, plus global normalization uncertainty of 1.8% from lumi:

$$\sigma_Z = 1055.3 \pm 0.7\,(\text{stat.}) \pm 2.2\,(\text{syst.}) \pm 19.0\,(\text{lumi.})\ \text{pb}$$

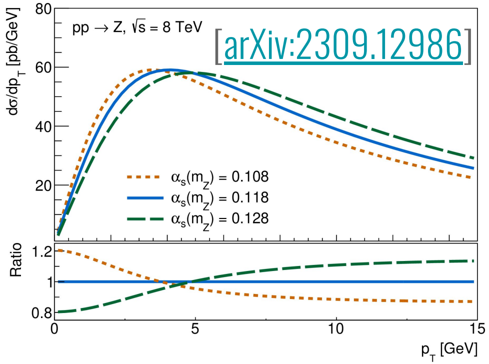
Use of N^{3}LO predictions allows comparison with variety of PDF sets with tiny scale uncertainties





NB: −0.8% flat vs |y| from NLO EW corrections

Z p_T spectrum sensitive to α_s!



[arXiv:2309.12986]

More about this in Jon’s talk!

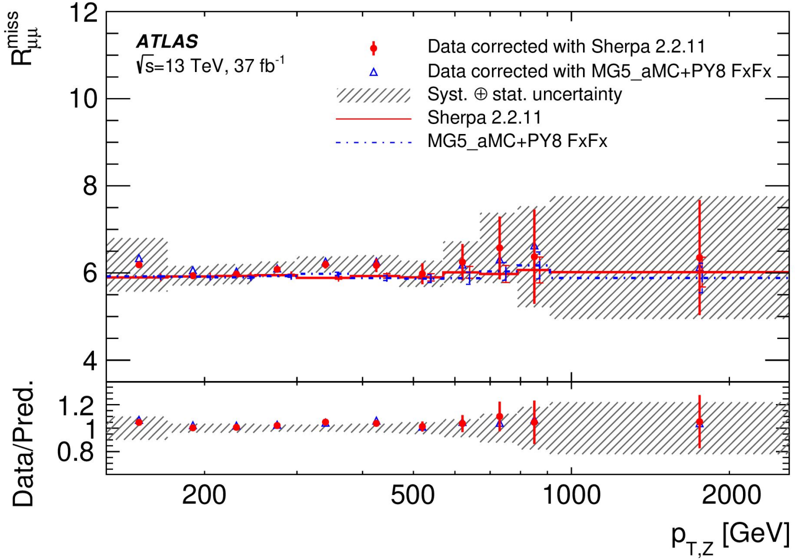
Z invisible width at 13 TeV

Submitted to PLB in December!
[arXiv:2312.02789]

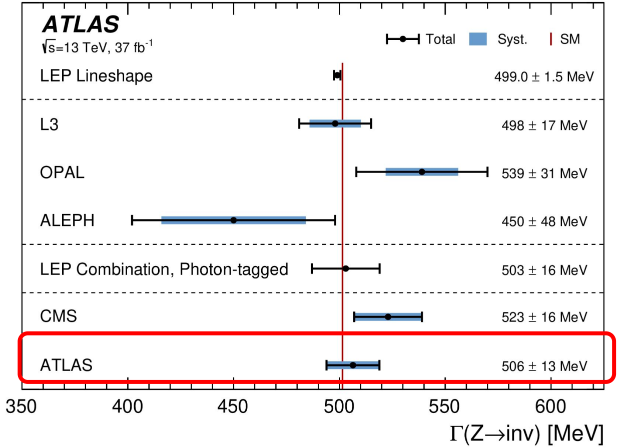
Very recent measurement, *also using Z p_T*, and testing 3 ν generation in SM

Differential Z p_T ratio of Z+jets cross section using 37 fb^{-1}:
→ recoil based final state, i.e. E_T^{miss} from $Z \to \nu\nu$
→ lepton final state from $Z \to ee$ or $Z \to \nu\nu$

$$R^{miss}_{p_{T,Z}} = \frac{\frac{d\sigma(Z \to inv + j)}{dp_{T,Z}}}{\frac{d\sigma(Z \to ll + j)}{dp_{T,Z}}} = \frac{\Gamma(Z \to inv)}{\Gamma(Z \to ll)}$$



Most precise recoil-based result!



May improve further with better lepton calibration & full Run 2!

Search for exclusive W hadronic decays

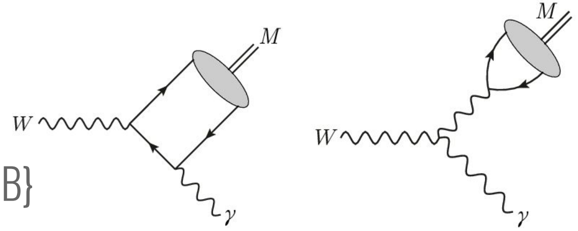
Submitted to PRL in September! [arXiv:2309.15887]

Closing with also a recent precision analysis that is actually a search!

SM forbids LO

$W \to M\gamma$

M={π, K, ρ, D, D_s , B}



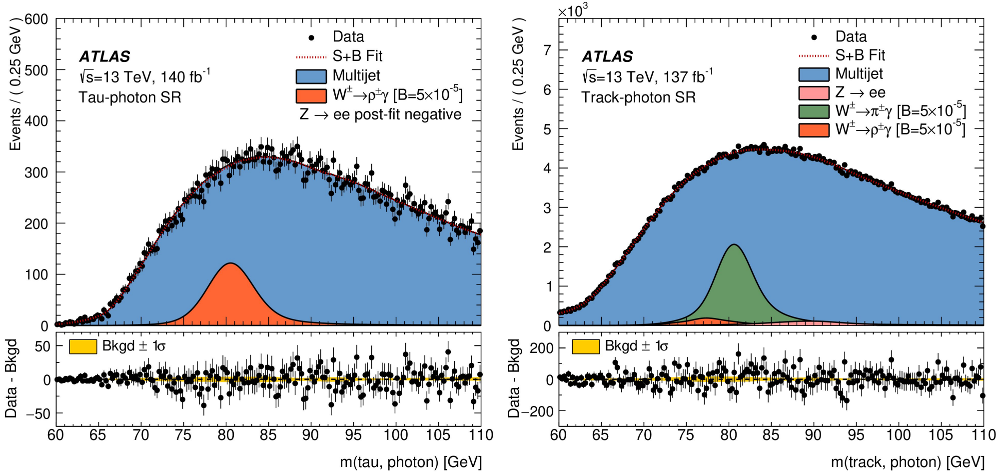
Radiative decays are extremely rare, with BR predictions between 10^{-7} and 10^{-9}:

→ probe W coupling to quark generations

→ test QCD factorization, possible BSM window

→ may allow new W-mass measurement method

Special trigger for $W\to\pi/K\gamma$, use τ recon. for $W\to\rho\gamma$



Most stringent limits to date!

	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^\pm \to \pi^\pm\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^\pm \to K^\pm\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^\pm \to \rho^\pm\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

Conclusions and prospects

Have shown the power and the variety of precision physics measurements using W & Z

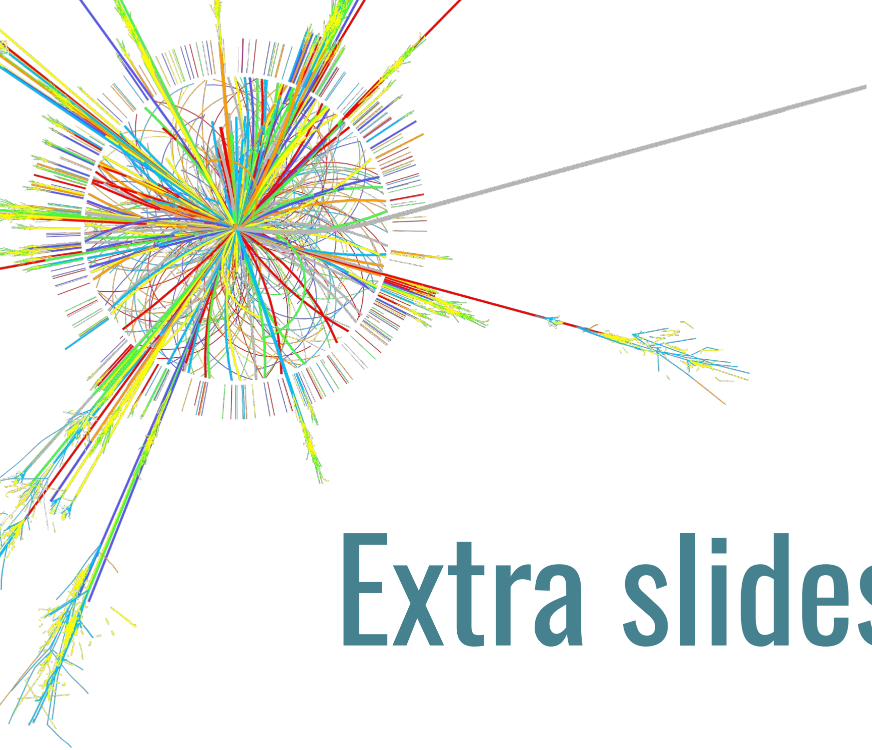
Multiple datasets allowed the ATLAS experiment to deliver a variety of results

Current measurement are foundation for improvement of future results

Crucial aspect of fundamental physics rely on them: test state-of-the-art predictions, understand the proton structure, knowledge of SM constants and mechanics, test BSM

Expect even more updates in the coming weeks ⇒ *stay tuned!*
[Standard Model Physics ATLAS]

Thank you for your attention!



Extra slides & Backup Material

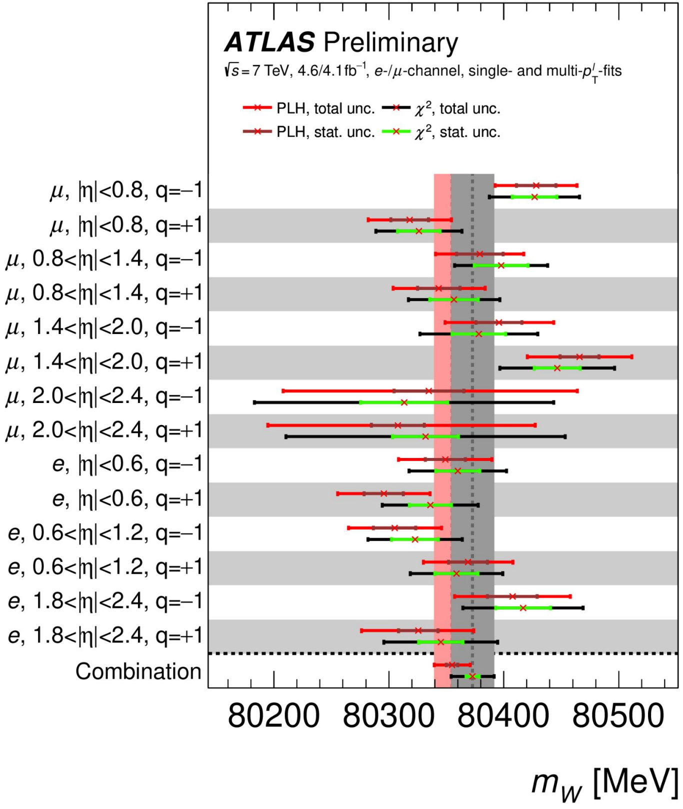
W-mass reanalysis

$$L\left(\mu,\vec{\theta}|\vec{n}\right) = \prod_{j}\prod_{i} \text{Poisson}\left(n_{ji}|\nu_{ji}(\mu,\vec{\theta})\right)\cdot \text{Gauss}\left(\vec{\theta}\right)$$

$$\nu_{\text{ji}}(\mu,\vec{\theta}) = \Phi\times\left[S_{\text{ji}}^{\text{nom}} + \mu\times\left(S_{\text{ji}}^{\mu} - S_{\text{ji}}^{\text{nom}}\right)\right] + \sum_{s}\theta_s\times\left(S_{\text{ji}}^{p} - S_{\text{ji}}^{\text{nom}}\right)$$

$$+ B_{\text{ji}}^{\text{nom}} + \sum_{b}\theta_b\times\left(B_{\text{ji}}^{p'} - B_{\text{ji}}^{\text{nom}}\right),$$

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	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$



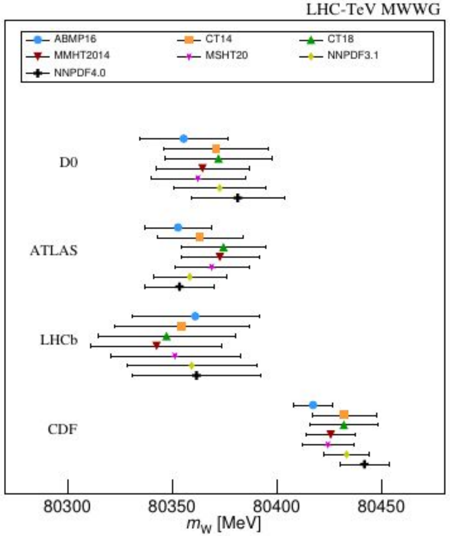
W-mass combination and take-over considerations

But... W-mass measurements combination: [arXiv:2308.09417]

Very low uncertainty CDF measurement: [Science 376 (6589)(2022)170]

Source	Uncertainty
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Abstract. The compatibility of W-boson mass measurements performed by the ATLAS, LHCb, CDF, and D0 experiments is studied using a coherent framework with theory uncertainty correlations. The measurements are combined using a number of recent sets of parton distribution functions (PDF), and are further combined with the average value of measurements from the Large Electron-Positron collider. The considered PDF sets generally have a low compatibility with a suite of global rapidity-sensitive Drell-Yan measurements. The most compatible set is CT18 due to its larger uncertainties. A combination of all m_W measurements yields a value of $m_W = 80394.6 \pm 11.5$ MeV with the CT18 set, but has a probability of compatibility of 0.5% and is therefore disfavoured. Combinations are performed removing each measurement individually, and a 91% probability of compatibility is obtained when the CDF measurement is removed. The corresponding value of the W boson mass is 80369.2 ± 13.3 MeV, which differs by 3.6σ from the CDF value determined using the same PDF set.



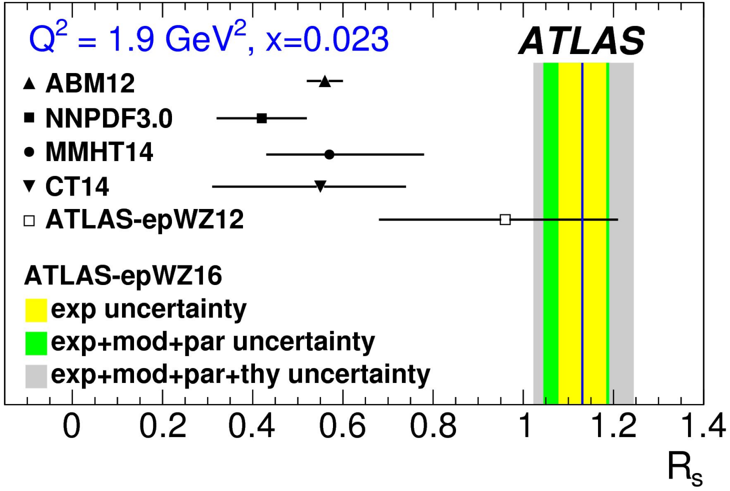
W+c comparison and proton strangeness

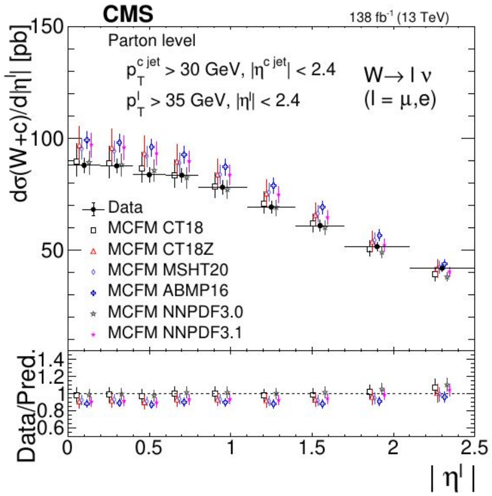
CMS

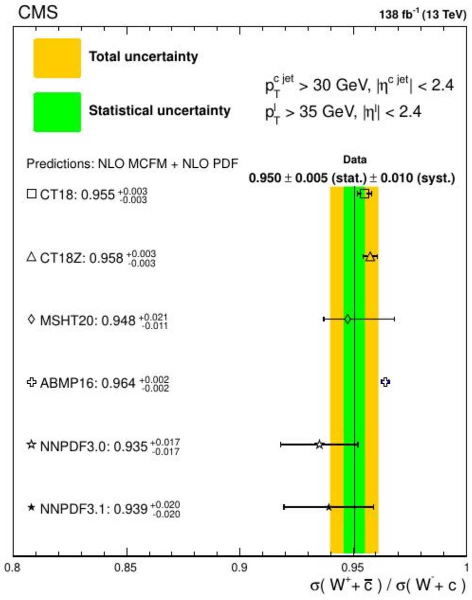
Measurement of the inclusive W and Z cross sections in the electron and muon decay channels in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector [PRD 85 (2012) 072004]

Measurement of the production cross section for a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV

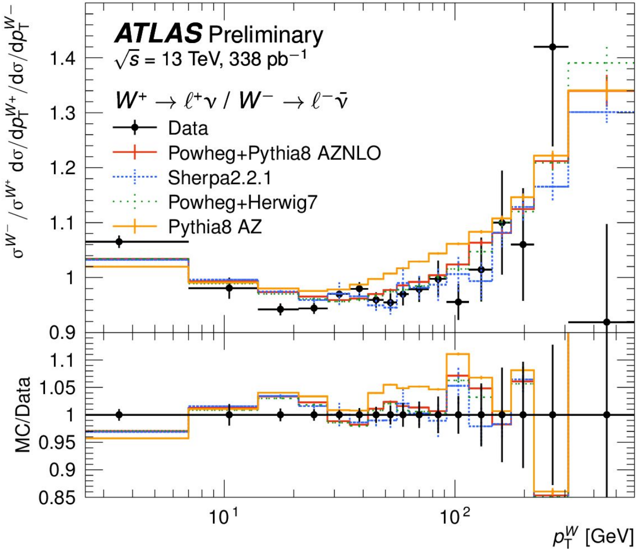
[arXiv:2308.02285]

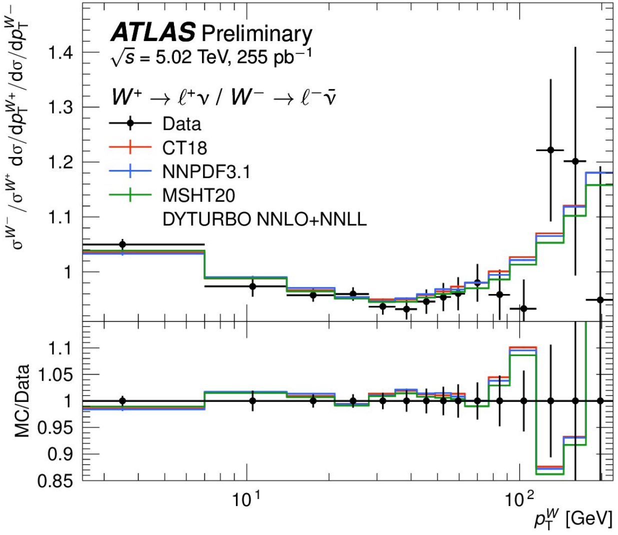


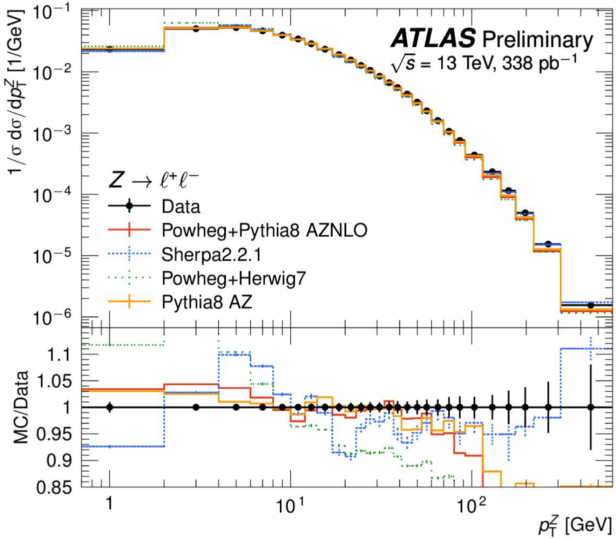




W and Z p_T at 5.02 and 13 TeV, low PU

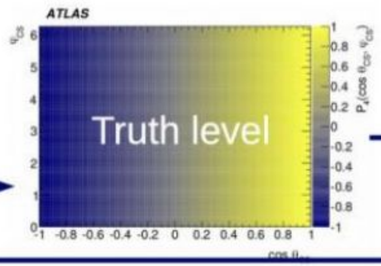


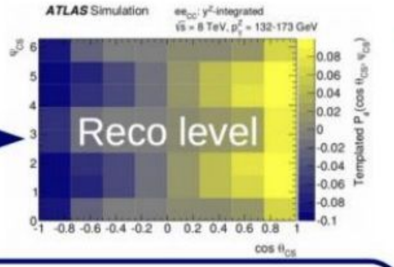




Z p_T at 8 TeV, angular coefficients, full phase space

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





Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{bins}} \mathcal{L}\sigma_j \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{\mathrm{bkgs}} T^n_B(\beta)$$

Truth (p_T^Z, y^Z, m^Z) bin

Angular coefficient

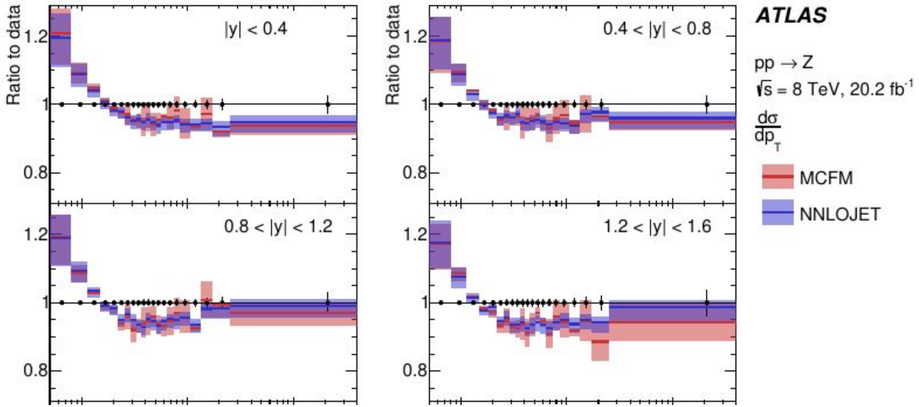
Templated polynomial

Likelihood

$$\mathcal{L}(A,\sigma,\theta|N_{\mathrm{obs}}) = \prod_{n}^{N_{bins}} \{P(N^n_{\mathrm{obs}}|N^n_{\mathrm{exp}}(A,\sigma,\theta))P(N^n_{\mathrm{eff}}|\gamma^n N^n_{\mathrm{eff}})\}\prod_{m}^{M} G(0|\beta^m,1)$$

2

Z double differential, full phase space, 8 TeV: more predictions



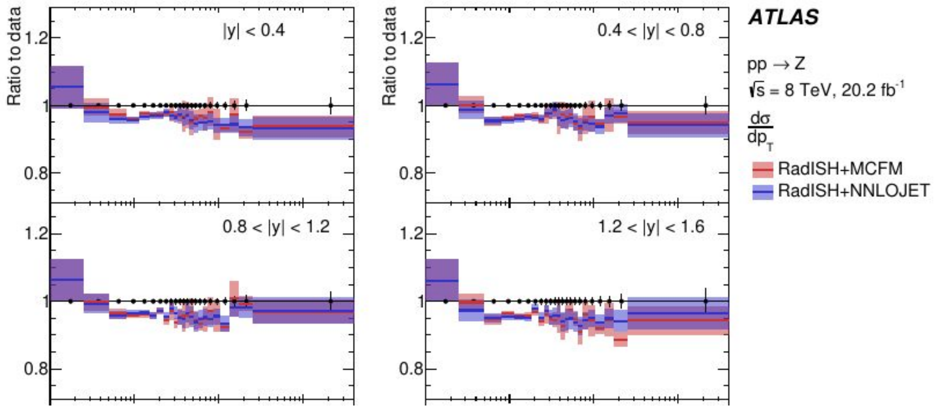


Table 4: Compatibility test between $\frac{d\sigma}{dy}$ measurements and predictions obtained from DYTurbo using different PDF sets. Based on the total uncertainties in the measurements and on the PDF uncertainties in the predictions shown in Figs. 19 and 20, the χ^2 per degree of freedom (d.o.f.) and corresponding p-values are shown for each PDF set (the uncertainties from CT18A have been rescaled from 95% to 68% confidence level). Also shown is the pull on the integrated luminosity in units of its total uncertainty of 1.8%.

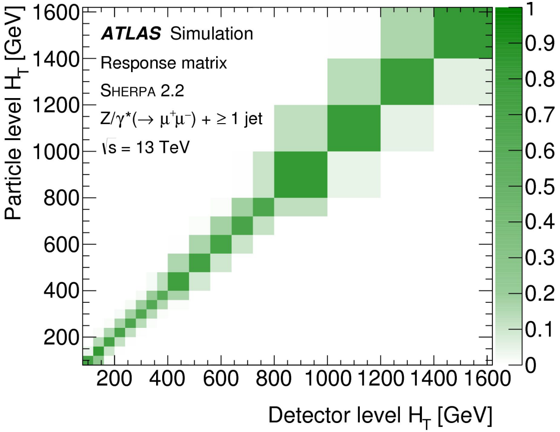
PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [58]	13/8	0.11	1.2 ± 0.6
CT18A [59]	12/8	0.17	0.9 ± 0.7
MSHT20 [60]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [61]	30/8	0.0002	0.0 ± 0.2
ABMP16 [62, 63]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [64]	22/8	0.005	−1.3 ± 0.8
ATLASpdf21 [65]	20/8	0.01	−1.1 ± 0.8

Iterative Unfolding with Bayesian method

Response matrix accounts for migrations using MC simulation:

$$M_{ij}=M(R_i|T_j)$$

Conditional probability that the effect R_i is produced by the cause T_j



How to extract *"prediction-unbiased"* probability using iterative Bayesian unfolding:

- Bayes theorem:

$$M(T_i|R_j) = M(R_i|T_j)\, P_0(T_j) \,/\, \mathrm{Sum}_l\ M(R_i|T_l)\, P_0(T_l)$$

- Particle level MC used as initial prior, $P_0(T_j)$, to determine a first estimate of the unfolded data distribution:

$$T_j = \mathrm{Sum}_i\ M(T_j \mid R_i)R_i$$

- In each further iteration the estimator of the unfolded distribution from previous iteration is used as a new prior