Measurement of Drell-Yan processes at ATLAS

Fabio Anulli

INFN -Sezione di Roma

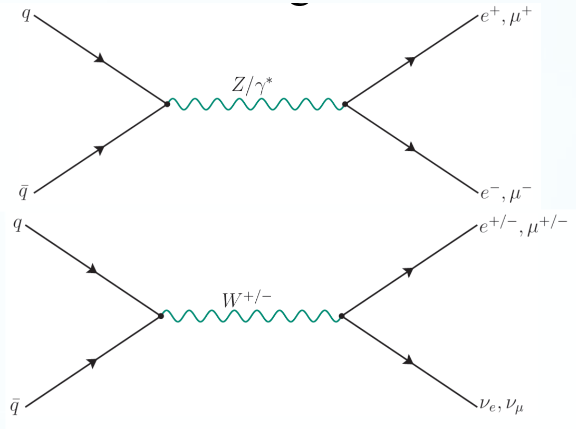
on behalf of the ATLAS Collaboration

International Workshop on QCD

QCD@Work - Trani, June 18-21, 2024

W and Z production in Drell-Yan processes

Drell-Yan di-lepton production of W and Z bosons offer clear signature, large statistics, and small background



- Benchmark for understanding of QCD processes
  - Test of state-of-the-art theory predictions: fixed-order perturbative QCD and parton shower models
  - Probe of proton structure (sensitivity to PDFs)
- High precision SM tests and extraction of SM parameters
- Background for other measurements and searches (BSM, Higgs, top,…)

Today's presentation:

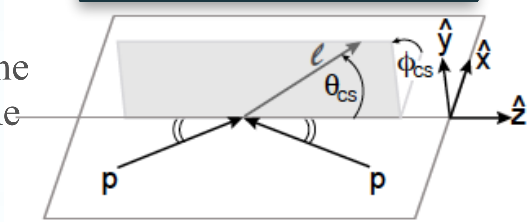
- ➢ Z double differential (p_T, $|y|$) cross section at 8 TeV — Eur. Phys. J. C 84, 315 (2024)
- ➢ p_T^Z and p_T^W at 5 and 13 TeV with low pile-up data — arXiv:2404.06204
- ➢ Reanalysis of 7 TeV data for the W mass determination — arXiv:2403.15085
- ➢ W/Z cross sections at 13.6 TeV — Phys.Lett.B854 (2024) 138725

Z double differential $(p_T, |y|)$ cross section

EPJC84 (2024) 315

5D differential cross section decomposed as a sum of harmonic polynomials $P_i(\cos\theta,\phi)$ times polarization coefficients $A_{0\text{-}7}(p_T^Z, y^Z, m^Z)$.

Angles defined in the Collins-Soper Frame



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

- 20.8 fb^{-1}, $\sqrt{s} = 8$ TeV, $\bar{\mu} \sim 20$
- Analysis derived from JHEP 08 (2016) 159
- Three $Z \to \ell^+\ell^-$ channels: ee$_{CC}$, μμ$_{CC}$, ee$_{CF}$
  - C: $|\eta^\ell| < 2.4$; F: $|\eta^\ell| > 2.4$
- $80 < m_{\ell\ell} < 100$ GeV (Z pole)

Main Backgrounds:

- Physics: $t\bar{t}$, Wt, Dibosons, $Z \to \tau\tau$ (from MC)
- Multi-jet and W+jet (CC~0.1%, CF~1.0%): estimated with data-driven methods

- Unpolarized cross sections and A_i from profile likelihood fit to truth-to-reco templates obtained in the full lepton phase space
  - Measurement of A_i consistent with 2016 publication (update in the forward region)
  - 2D differential $\frac{d^2\sigma}{dp_T d|y|}$ at the Z pole, up to |y|<3.6 thanks to forward leptons
  - Precise measurement of α_s (arXiv2309.12986, see talk by E.Conroy on Tuesday)

Z double differential $(p_T, |y|)$ cross section

EPJC84 (2024) 315

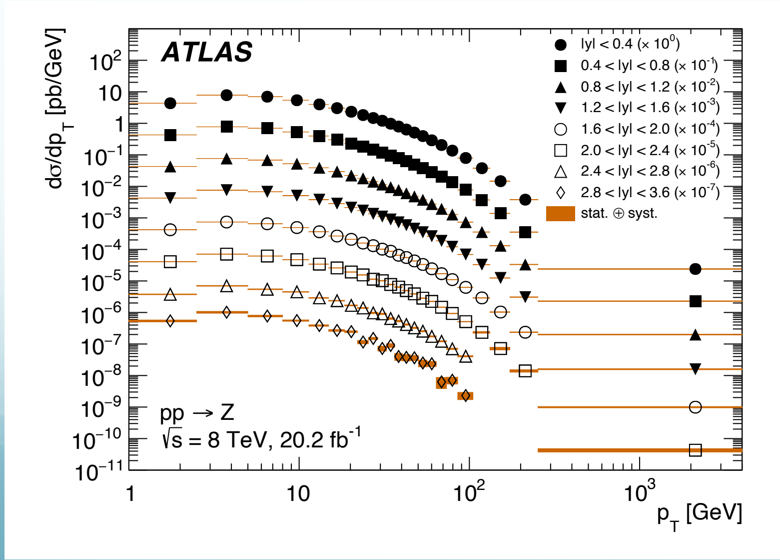
- Joint fit of the cross section and angular coefficients

$$N^n_{\text{exp}}(A, \sigma^{U+L}, \beta, \gamma) = \left\{ \sum_j \sigma_j^{U+L} \times L \times \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} \times t^n_{ij}(\beta) \right] \right\} \times \gamma^n + \sum_B^{\text{bkgs}} T^n_B(\beta)$$

- n: $(\cos\theta, \phi)$ bin; i: $(p_T, |y|)$ bin. Fitting parameters: σ_i^{U+L}, A_{ji}, and nuisance parms (β and γ)

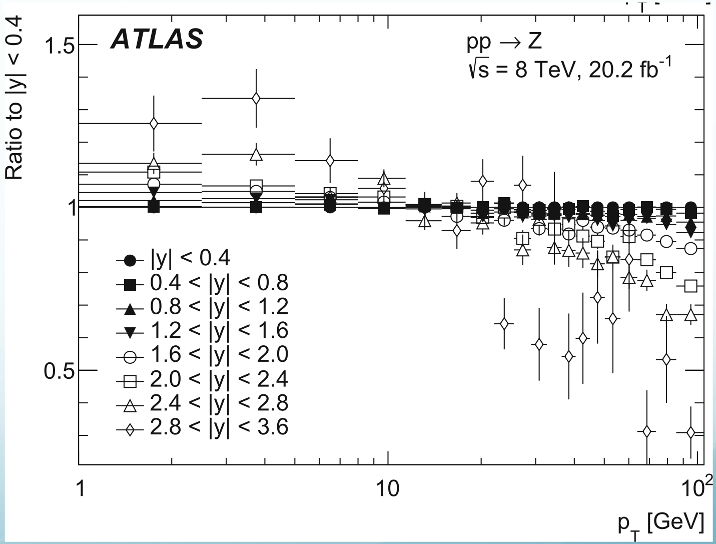
Absolute 2D differential cross section

- Statistical uncertainty dominates
- From 0.6 -> 1% for CC; 3% for CF
- Overall 1.8% uncert. from luminosity not included



Cross section ratio to most central |y| bin

- p_T distribution softer at higher rapidities
- Expected and well reproduced by MC

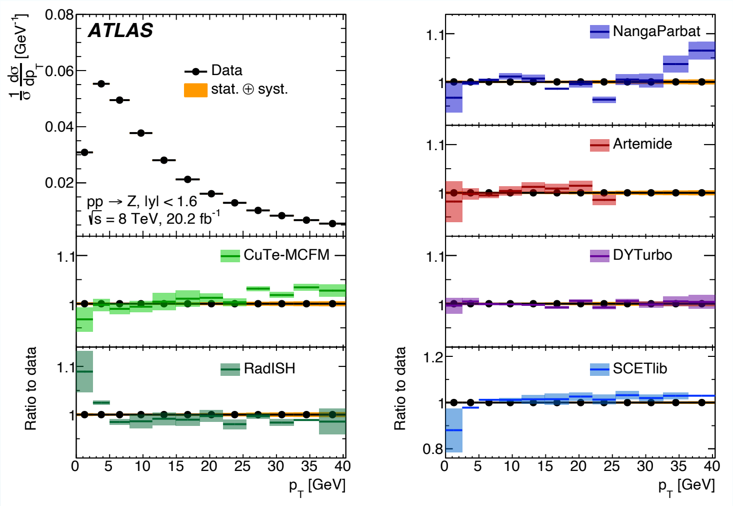


Comparison with predictions

EPJC84 (2024) 315

$\frac{1}{\sigma}\frac{d\sigma}{dp_T}$ integrated over |y|<1.6

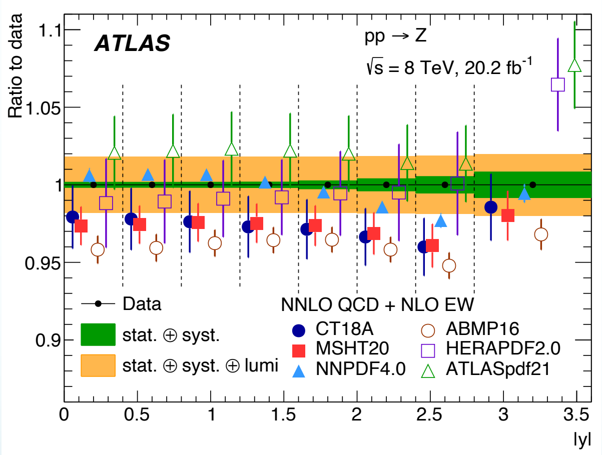
- Compared to various q_T resummation calculations at N4LL, matched with N3LO pQCD MCFM/NNLOJET



- Agreement within theory uncertainties
- 2-3% difference in the p_T peak region

$\frac{d\sigma}{d|y|}$ integrated over p_T

- Smaller experimental and theoretical uncertainties
- No dependence on q_T resummation (after p_T integration)
- Default simulation uses DYTURBO+MCFM+ aN3LO PDF set
- -0.4% correction due to ISR QED and NLO EW



- Comparison between different NNLO PDF sets
- Reasonable agreement for MSH20 and CT18A
- Some shape deviations for all sets

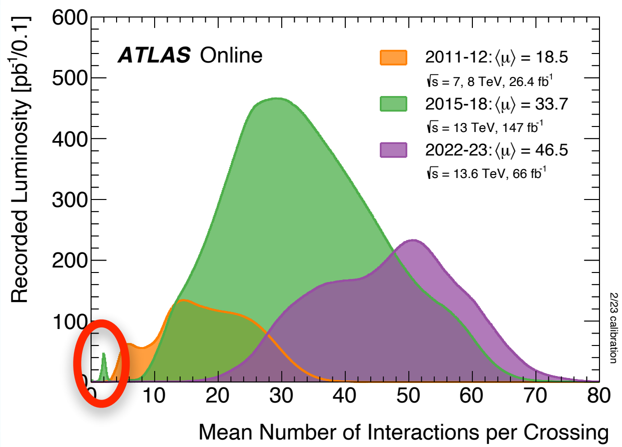
Total cross section (for |y|<3.6):

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

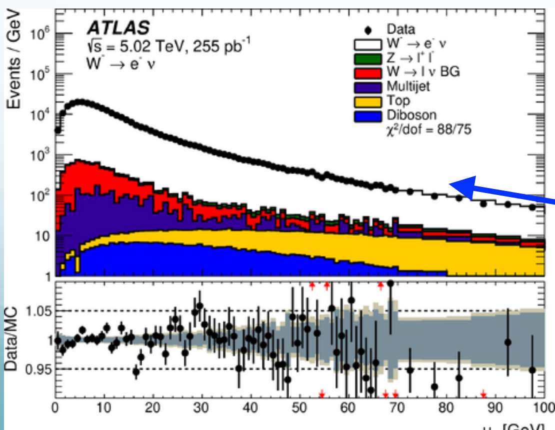
Measurement of W and Z p_T at $\sqrt{s}$ = 5.02 and 13 TeV

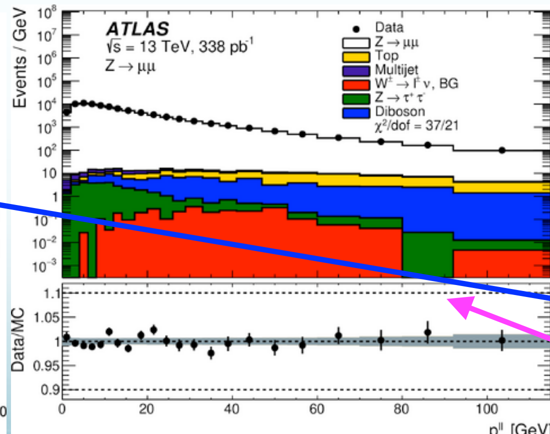
arXiv:2404.06204

- Data from 2017 and 2018 dedicated runs at low pile-up **(μ~2)**
  - 255 pb^{-1} at $\sqrt{s}$ = 5.02 TeV; 338 pb^{-1} at $\sqrt{s}$ = 13.0 TeV
  - Measured: p_T for W^+, W^-, $W^\pm$, Z and their ratios W^+/W^-, W/Z
- Event selection:
  - $p_T^\ell > 25\,\mathrm{GeV}$, $|\eta_{\ell\ell}| < 2.4$
  - W: $m_T > 50\,\mathrm{GeV}$; $E_T^{miss} > 25\,\mathrm{GeV}$; 2nd lepton vetoed
  - Z: $66 < m_T < 116\,\mathrm{GeV}$



	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
$\sqrt{s}$ = 13 TeV	2.2×10^6	2.2×10^6	1.7×10^5	2.1×10^5
$\sqrt{s}$ = 5.02 TeV	7.1×10^5	7.5×10^5	5.2×10^4	7.0×10^4





- Backgrounds:
  - EW (single-, di-bosons, top,..) from MC
  - QCD multi-jet: data driven
- Spectra unfolded using Iterative Bayesian Unfolding method
- p_T^W from hadronic recoil u_T
- p_T^Z from $p_T^{\ell\ell}$

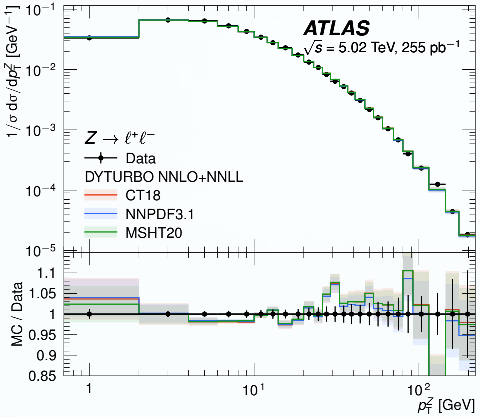
Results: p_T distributions

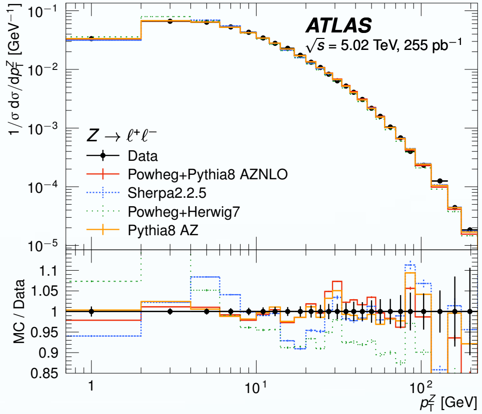
arXiv:2404.06204

DY Turbo + PDFs | Parton showers

p_T^Z

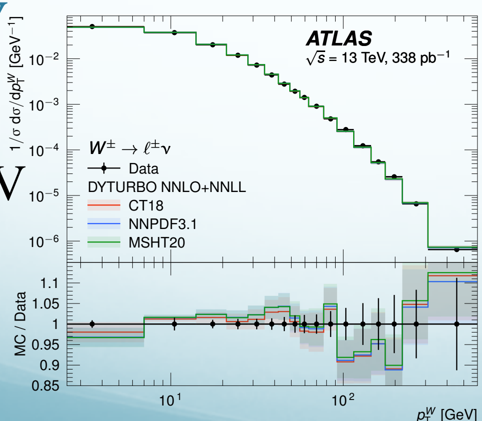
5 TeV

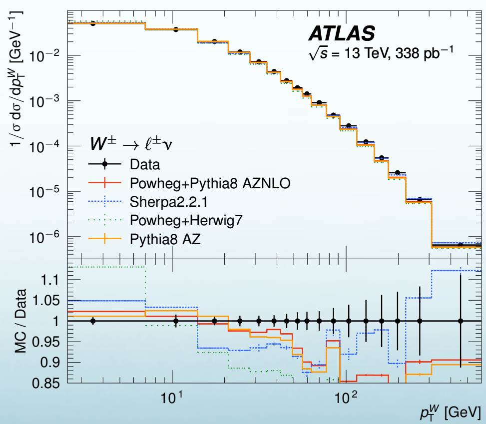




p_T^W

13 TeV





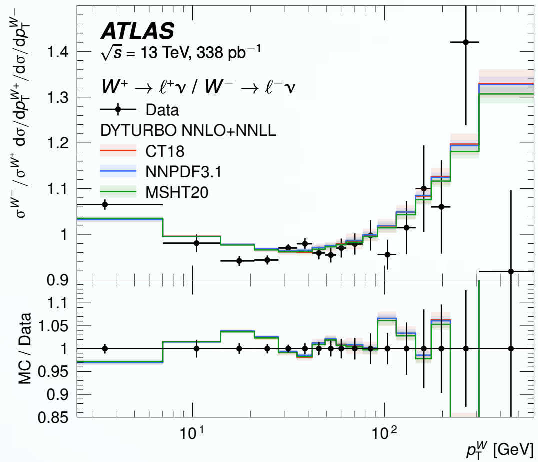
Distributions compared to predictions:

- Resummation calculation: DYTurbo + different PDFs
  - state-of-the-art calculations (NNLO+NNLL)
  - best overall agreement across the spectra
- Parton shower approach: PYTHIA, HERWIG7 and SHERPA
  - Significant differences among MCs
  - Generally good agreement at low p_T
  - SHERPA matches data best at high p_T
- AZNLO tune [JHEP **09** (2014) 145] further validated by these measurements (developed for the W-mass measurement)

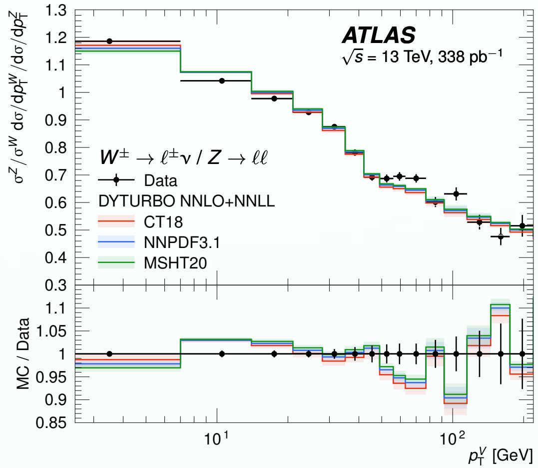
Results: p_T ratios

arXiv:2404.06204

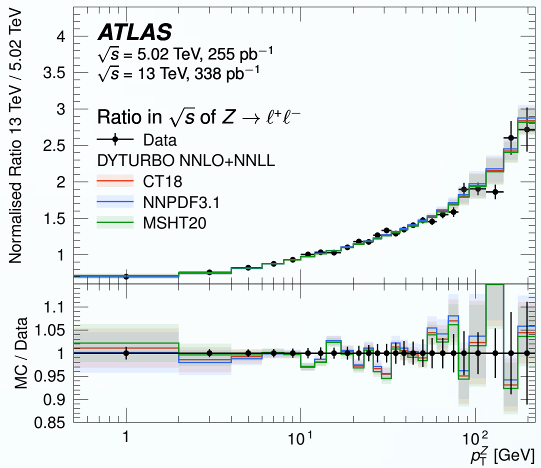
W^+/W^- ratio at 13 TeV



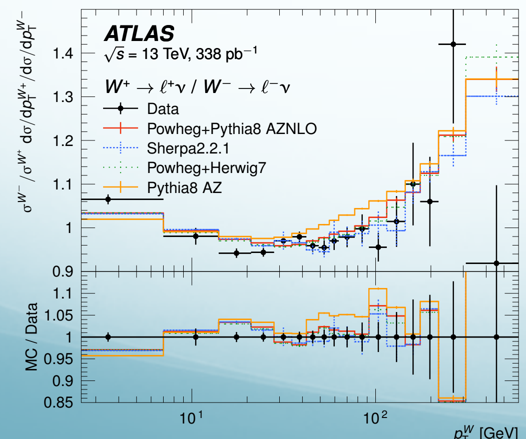
W^+/Z ratio at 13 TeV



Z ratio "13/5" TeV



W^+/W^- ratio at 13 TeV



- Ratios take advantage of systematic uncertainties cancellation
  - More stringent tests of model predictions
- All models agree with data within ~5%
- Good agreement with AZNLO tune also for ratios

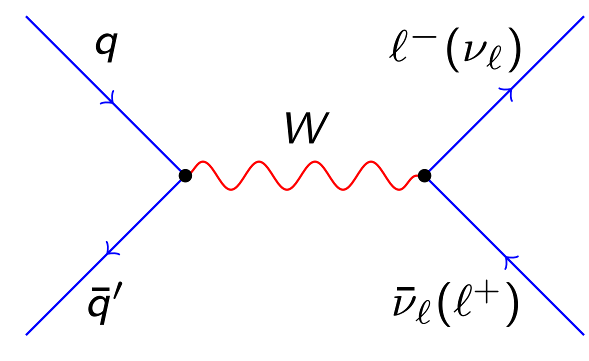
Measurement of the W-boson mass and width

arXiv:2403.15085

- m_W value precisely predicted by global EW fit of the SM parameters, with an uncertainty $\Delta m_W^{EW} \sim 6$ MeV
- A precise measurement ($\Delta m_W^{exp} \lesssim 10$ MeV) would allow to probe SM consistency and seek for New Physics effects
- Measurement performed by fitting p_T^{ℓ} and $m_T^{\ell\nu}$.
  - Then combine the two results (combine also e and μ samples)
  - p_T^{ℓ}: more precise for m_W but more sensitive to p_T^W and PDF details
  - $m_T^{\ell\nu}$: better for measuring Γ_W

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

NP would hide here



<u>This analysis:</u>

- ~4.5fb^{-1} at 7 TeV (same as previous analysis [EPJC 78 (2018) 10])
- Use of profile likelihood fits
  - Include uncertainties as nuisance parameters
- Systematics uncert. on PDF, PS, and A_i significantly improved

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^{ℓ}	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Measurement of the W-boson mass and width

arXiv:2403.15085

- A dependence on PDF choice is seen
- CT18 chosen as the baseline
- Combined result:

$m_W = 80366.5 \pm 9.8(\text{stat.}) \pm 12.5(\text{syst.})$ MeV

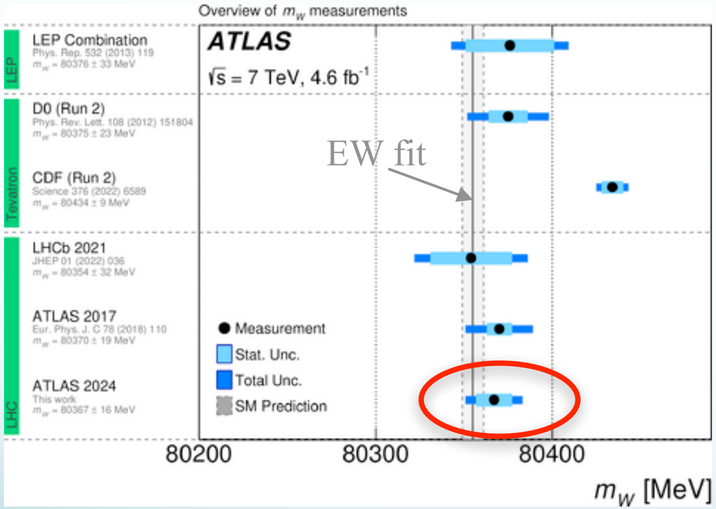
- Consistent with superseded measurement.
- Total uncertainty reduced by ~3 MeV.

PDF set	Combined m_W [MeV]
CT14	80363.6 ± 15.9
CT18	80366.5 ± 15.9
CT18A	80357.2 ± 15.6
MMHT2014	80366.2 ± 15.8
MSHT20	80359.3 ± 14.6
ATLASpdf21	80367.6 ± 16.6
NNPDF31	80349.6 ± 15.3
NNPDF40	80345.6 ± 14.9

10 MeV (CT14 to ATLASpdf21)

22 MeV (all PDF sets)

Largest deviations from NNPDFxx

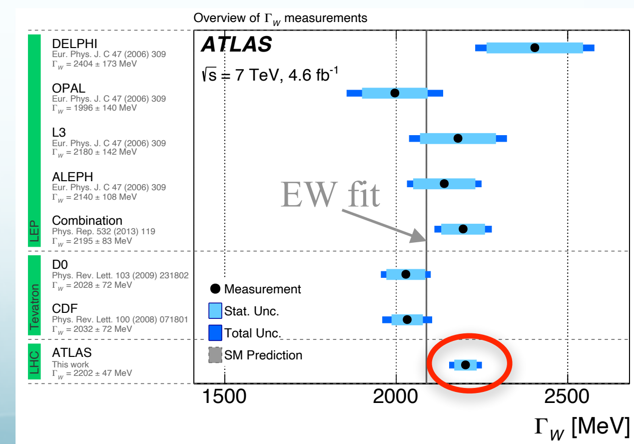


- Consistent with previous measurements, with the exception of CDF result
- No deviation from SM fit seen

First measurement of Γ_W in ATLAS

- Same strategy as for m_W: profile LH fits to p_T^ℓ and $m_T^{\ell\nu}$.
  - m_W nuisance parameter (fixed value from EW global fit)
  - Strong dependence on m_W value: $\Delta\Gamma_W = -1.25\Delta m_W$

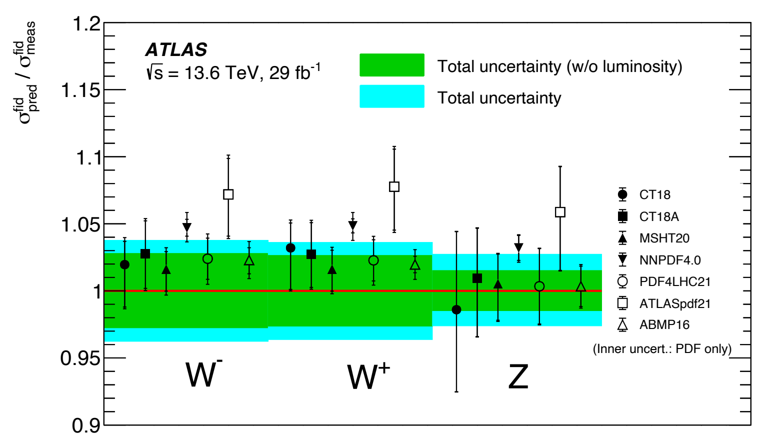
$\Gamma_W = 2202 \pm 32(\text{stat.}) \pm 34(\text{syst.})$ MeV



Vector boson production at 13.6 TeV

PLB854 (2024) 138725

- 29.1 fb^{-1}, $\sqrt{s}$ = 13.6 TeV, collected in 2022 (initial RUN 3 data set)
- Test theory predictions at a new center-of-mass energy
- **Early validation of detector performances and software**
- Measurements:
  - Inclusive fiducial&total cross sections: σ^{W^+}, σ^{W^-} and σ^{Z}
  - Ratios: $\sigma^{W^+}/\sigma^{W^-}$, $\sigma^{W^\pm}/\sigma^{Z}$, and $\sigma^{t\bar{t}}/\sigma^{W^\pm}$
  - $\sigma^{t\bar{t}}$ from ATLAS PLB 848.138376 (test the proton's parton content)
- Comparison to theory (NNLO + NNLL QCD and NLO EW accuracy), with different PDF sets



Fiducial cross section extracted with a **binned profile likelihood fit**

- Total cross section: $\sigma^{tot} = \sigma^{fid}/A$, where A is the acceptance
- Dominant source of uncertainties:
  - $W^{\pm}$: luminosity, multijet background
  - Z: luminosity, lepton efficiency

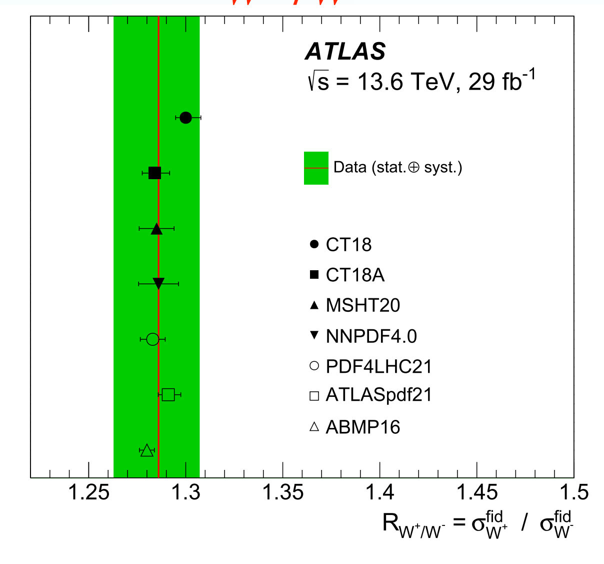
Good agreement with predictions, though ATLASpdf21 and NNPDF4.0 tend to give higher cross sections in all cases

Vector boson production at 13.6 TeV

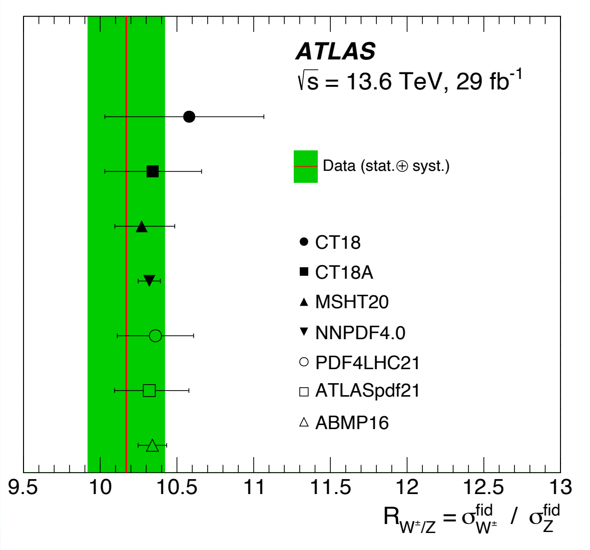
PLB854 (2024) 138725

Cross-section ratios

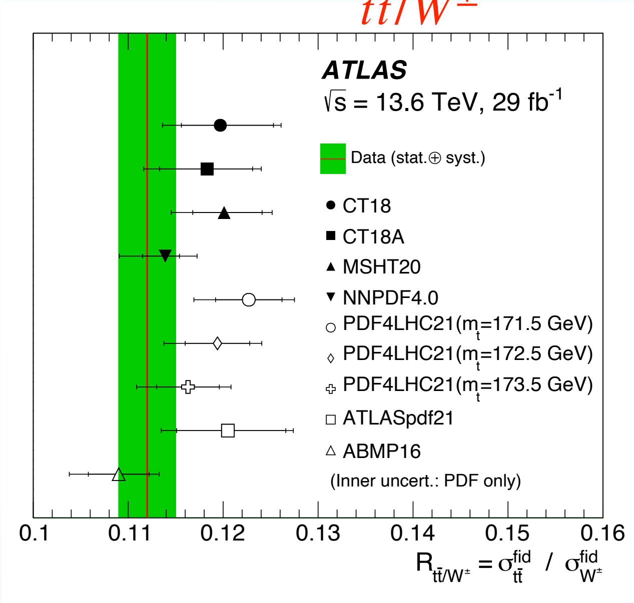
W^+/W^-



$W^\pm/Z$



$t\bar{t}/W^\pm$



- Ratios benefits from cancellations of some systematic uncertainties
- Good agreement with SM predictions for the W/Z ratios
- Slightly lower than predictions for $t\bar{t}/W$ ratios
  - important uncertainties from $t\bar{t}$ modelling

Summary

- The high quality of collected data allows for precise measurements of SM processes

- Drell-Yan processes are a powerful tools to:
  - test state-of-the-art theory predictions
  - study the proton structure
  - measure precisely SM constants to probe the consistency of global EW fits and of different BSM scenarios

- We've presented a variety of measurements with different data sets
  - Revised W-mass measurement with 7-TeV data
  - 2D differential cross sections with the Run2 at 8 TeV (also A_i, $\sin\theta_W$, and α_s, not shown here)
  - Dedicated low-pileup Runs at 5 and 13 TeV, for p_T^V measurements
  - Study of vector boson production in association to HF jets at 13 TeV
  - First studies with RUN3 data at 13.6 TeV
- Many more results from ATLAS on the way!

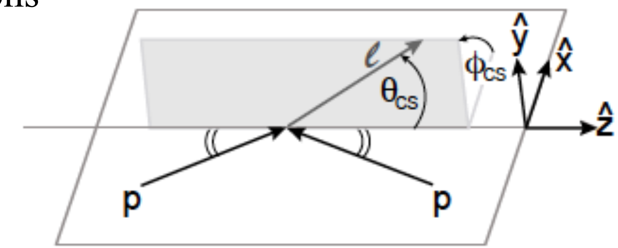
BACKUP SLIDES

Angular coefficients in Z-boson production

Motivations:

- Spin correlation between initial quarks and decay leptons
- Probe fixed-order QCD predictions
- Probe parton-shower approach
- Ingredient for future precision EW measurements

Angles defined in the Collins-Soper Frame



- 5-dimension differential cross section decomposed as a sum of harmonic polynomials $P_i(\cos\theta,\phi)$ times polarization coefficients $A_{0\text{-}7}(p_T^Z, y^Z, m^Z)$.

Unpolarized cross section

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}$$

- A_0 Transverse polarization
- A_2 Longitudinal polarization
- A_1 interference between T and L polarizations
- A_3 and A_4 sensitive to the Weinberg angle

- LO: only A_4 different from zero
- NLO: A_0--A_4 non zero,
  - $A_0 = A_2$ (Lam-Tung relation)
- NNLO: also A_5, A_6, A_7 slightly different from zero at large p_T^Z
  - $A_0 \neq A_2$

Measurement of the W-boson mass

arXiv:2403.15085

- A dependence on PDF choice is seen
- CT18 chosen as the baseline
- Final result:

$m_W = 80366.5 \pm 9.8(\text{stat.}) \pm 12.5(\text{syst.})$ MeV

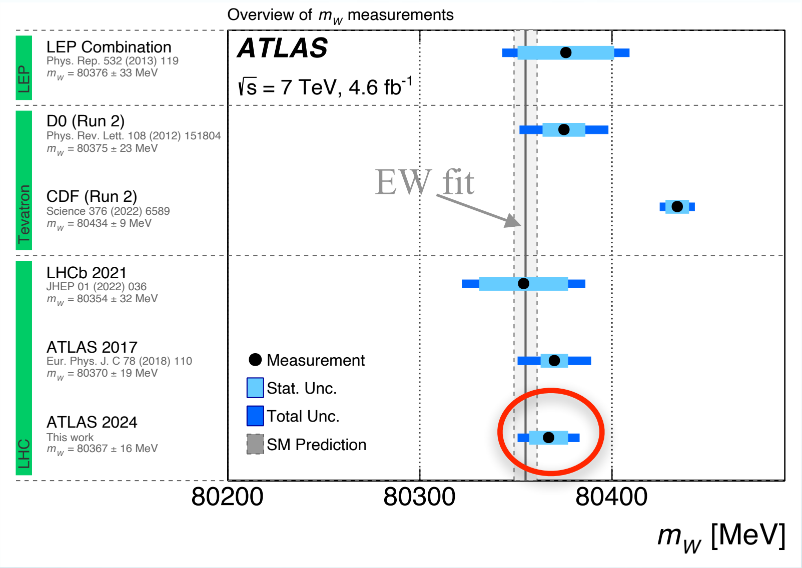
- Consistent with superseded measurement. Total uncertainty reduced by ~3 MeV.

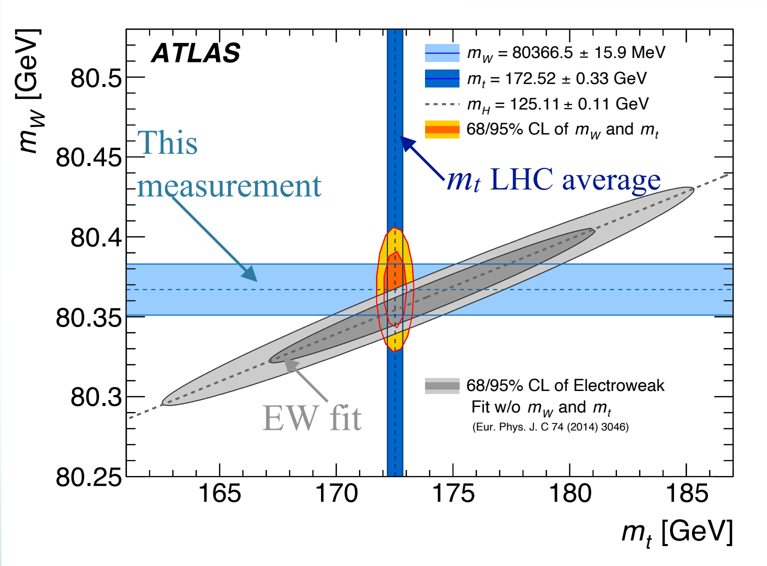
PDF set	Combined m_W [MeV]
CT14	80363.6 ± 15.9
CT18	80366.5 ± 15.9
CT18A	80357.2 ± 15.6
MMHT2014	80366.2 ± 15.8
MSHT20	80359.3 ± 14.6
ATLASpdf21	80367.6 ± 16.6
NNPDF31	80349.6 ± 15.3
NNPDF40	80345.6 ± 14.9

10 MeV

22 MeV

Largest deviations from NNPDFxx





- Consistent with previous measurements, with the exception of CDF result
- No deviation from SM fit seen

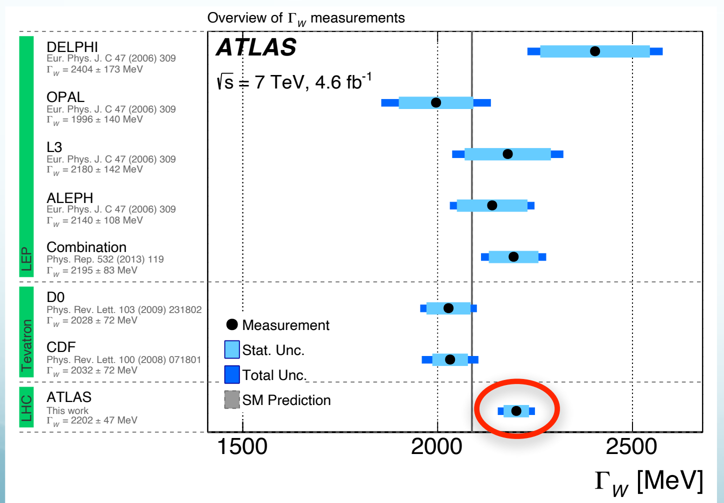
Measurement of the W-boson width

arXiv:2403.15085

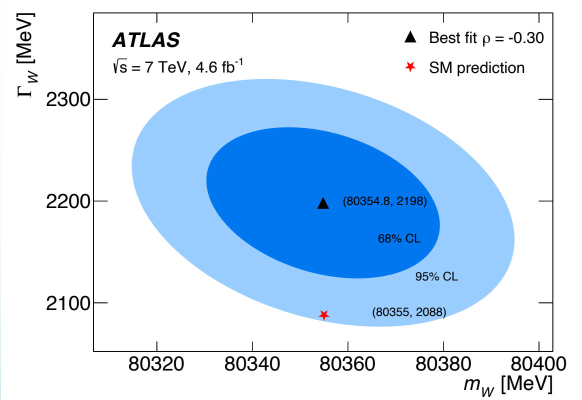
- First measurement of Γ_W in ATLAS
- Same strategy as m_W:
  - profile LH fits to p_T^{ℓ} and $m_T^{\ell\nu}$. Then, the two results are combined.
  - m_W nuisance parameter, set to its value from the EW global fit
  - Strong dependence on m_W value: $\Delta\Gamma_W = -1.25\Delta m_W$
  - Several PDF sets tested. A 10% maximum variation observed
  - As for m_W, the baseline is provided by CT18

PDF set	Combined Γ_W [MeV]
CT14	2204 ± 47
CT18	2202 ± 47
CT18A	2184 ± 47
MMHT2014	2182 ± 47
MSHT20	2181 ± 47
ATLASpdf21	2193 ± 46
NNPDF31	2182 ± 46
NNPDF40	2184 ± 46

$$\Gamma_W = 2202 \pm 32(\text{stat.}) \pm 34(\text{syst.})\ \text{MeV}$$



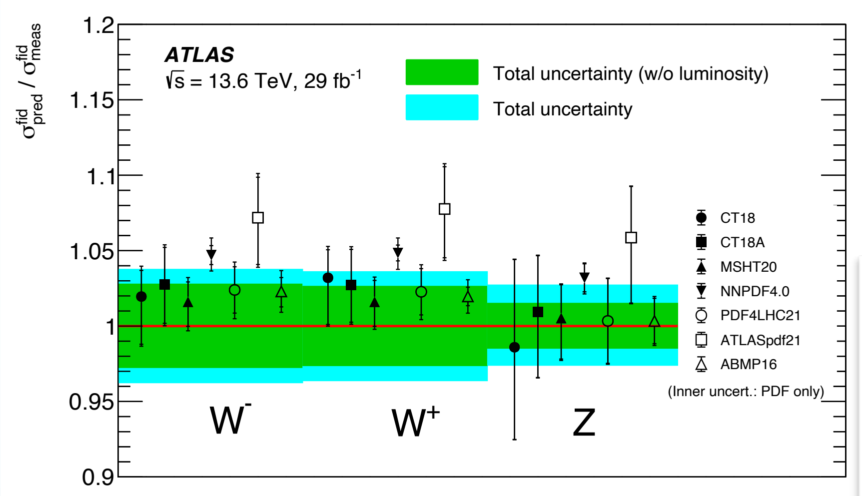
- Simultaneous determination of m_W and Γ_W
- $\Gamma_W = 2198 \pm 49$ MeV; $m_W = 80354.8 \pm 16.1$ MeV
- -30% correlation



Vector boson production at 13.6 TeV: Results

PLB854 (2024) 138725

Fiducial cross sections



Good agreement with predictions, though ATLASpdf21 and NNPDF4.0 tend to give higher cross sections in all cases

Channel	$\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat}\oplus\text{syst}}$ [pb]	Acceptance A	$\sigma^{\text{tot}} \pm \delta\sigma_{\text{stat}\oplus\text{syst}}$ [pb]
$Z \to e^+e^-$	740 ± 22	0.374 ± 0.011	1981 ± 82
$Z \to \mu^+\mu^-$	747 ± 23	0.374 ± 0.011	1997 ± 82
$Z \to \ell^+\ell^-$	744 ± 20	0.374 ± 0.011	1989 ± 77
$W^- \to e^-\bar{\nu}$	3380 ± 170	0.381 ± 0.009	8880 ± 490
$W^- \to \mu^-\bar{\nu}$	3310 ± 130	0.381 ± 0.009	8680 ± 390
$W^- \to \ell^-\bar{\nu}$	3310 ± 120	0.381 ± 0.009	8690 ± 390
$W^+ \to e^+\nu$	4350 ± 200	0.366 ± 0.009	11880 ± 620
$W^+ \to \mu^+\nu$	4240 ± 160	0.365 ± 0.010	11620 ± 530
$W^+ \to \ell^+\nu$	4250 ± 150	0.366 ± 0.009	11620 ± 520
$W^\pm \to \ell^\pm\nu$	7560 ± 270	0.372 ± 0.009	20310 ± 890

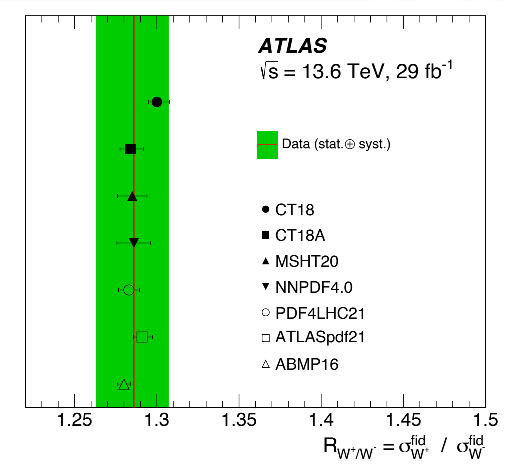
Dominant source of uncertainties:

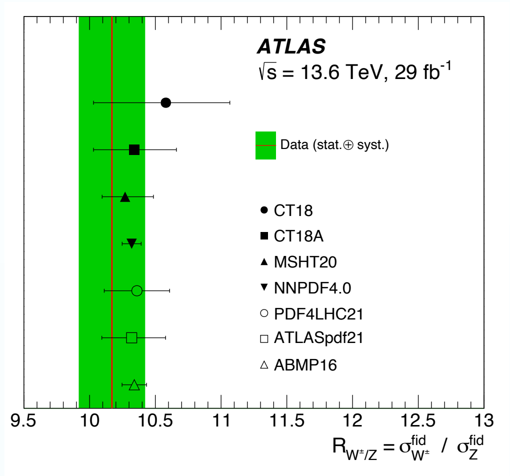
- $W^\pm$: luminosity, multijet background
- Z: luminosity, lepton efficiency

Vector boson production at 13.6 TeV

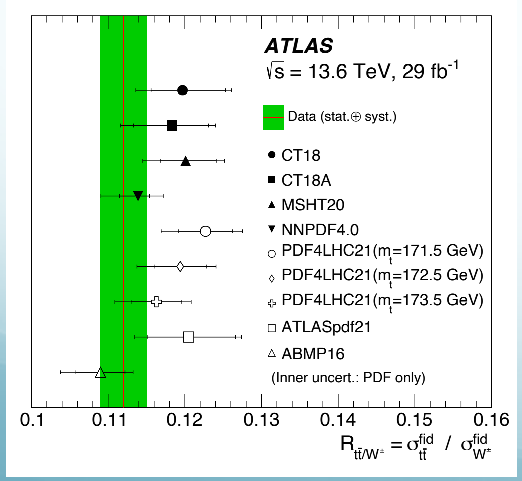
PLB854 (2024) 138725

Cross-section ratios





- Ratios benefits from cancellations of some systematic uncertainties
- Good agreement with SM predictions for the W/Z ratios
- Slightly lower than predictions for $t\bar{t}/W$ ratios



Ratio	$R \pm \delta R_{\text{stat} \oplus \text{syst}}$
W^+/W^-	1.286 ± 0.022
$W^\pm/Z$	10.17 ± 0.25
$t\bar{t}/W^-$	0.256 ± 0.008
$t\bar{t}/W^+$	0.199 ± 0.006
$t\bar{t}/W^\pm$	0.112 ± 0.003

Dominant source of uncertainties:

- W^+/W^-: multi-jet bkgd
- $W^\pm/Z$: jet-related uncertainties
- $t\bar{t}/W$: $t\bar{t}$ modelling, jet and multi-jet bkg.

Z + Heavy Flavor jets

arXiv:2403.15093

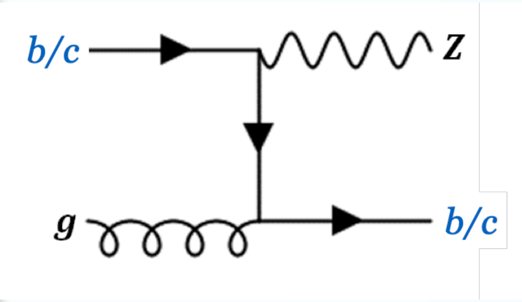
- Inclusive and differential $Z+\geq 1$ b-jet, $Z+\geq 2$ b-jets, $Z+\geq 1$ c-jet

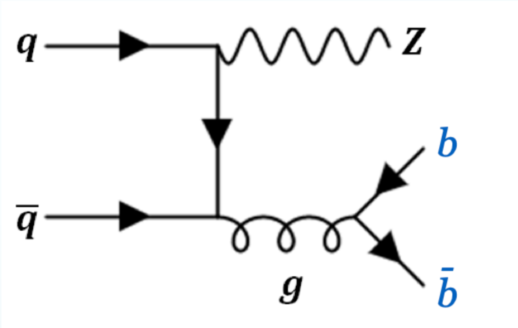
- Access to *b-quark*, *c-quark* and *gluon* PDFs
  - Potentially sensitive to the proton *Intrinsic Charm* (IC) component

- Precise test of pQCD predictions and MC modelling
  - Z+HF bkgd for VHbb analyses and various BSM searches

- Test predictions of different Flavor number Schemes (5/4/3 FS)

- This analysis: $\sqrt{s} = 13$ TeV, 140 fb^{-1} (full RUN2)
  - supersedes [JHEP 07 (2020) 044] $Z+\geq 1$ b-jet and $Z+\geq 2$ b-jets based on 36 fb^{-1}
  - $Z+\geq 1$ c-jet first time in ATLAS
  - Selected samples: ≳4M, ~0.3M, and ≳4M for 1b-, 2b- and 1c-jet





Z + HF jets: Inclusive cross sections

[arXiv:2403.15093]

Source of uncertainty	$Z(\to \ell\ell) + \geq 1$ b-jet [%]	$Z(\to \ell\ell) + \geq 2$ b-jets [%]	$Z(\to \ell\ell) + \geq 1$ c-jet
Flavour tagging	3.6	5.7	10.3
Jet	2.4	4.3	6.5
Lepton	0.3	0.3	0.4
E_T^{miss}	0.4	0.5	0.3
Z+jets background	0.6	1.5	1.6
Top background	0.1	0.3	<0.1
Other backgrounds	<0.1	0.2	0.1
Pile-up	0.6	0.6	0.2
Unfolding	3.3	5.8	5.0
Luminosity	0.8	0.9	0.7
Total [%]	5.6	9.4	13.2

- Large production rate:
  - results dominated by systematic uncertainties
- X2 improved precision w.r.t. JHEP 07, 044 (2020)
- Dominant uncertainties:
  - flavor tagging
  - unfolding
  - jet energy scale and resolution
- Statistical uncertainties very small

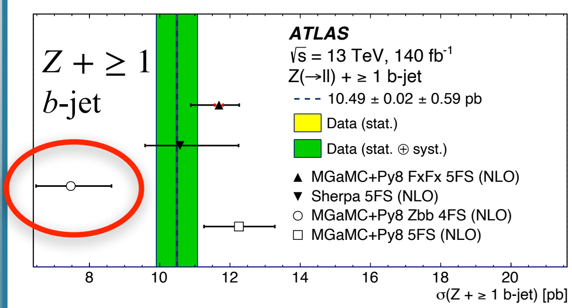
Inclusive cross sections:

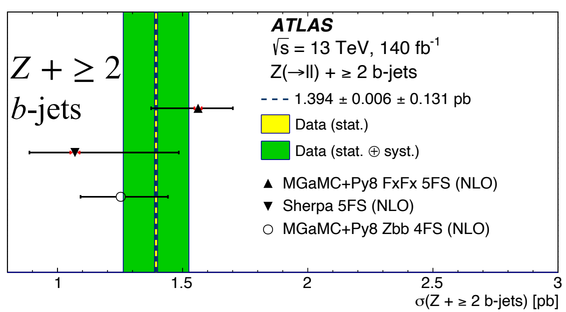
- 5FS describe data well both with MGaMC+Py8 and Sherpa
- 4FS underestimate data in 1 b-jet case (OK for 2b-jet)
- 3FS ~3σ below data for $Z + \geq 1$ c-jet

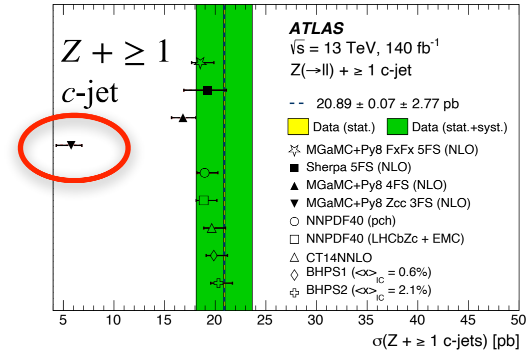
- lack of log-resummation term $ln(Q^2/m_c^2)$

$Z + \geq 1$ c-jet: comparison with various PDF sets to test IC component

- all PDFs provide rates consistent with data





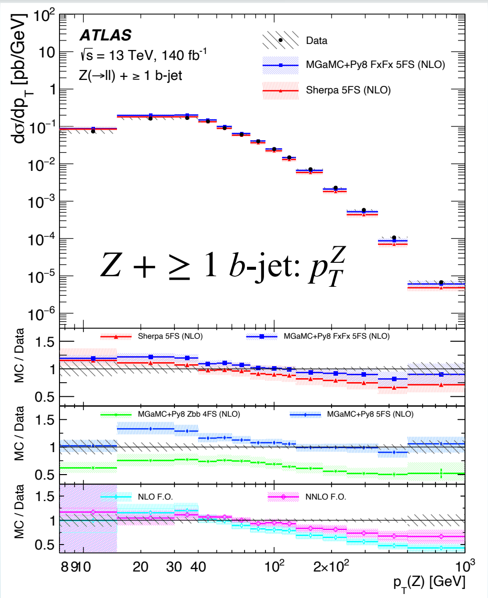


Z + HF jets: Differential cross sections

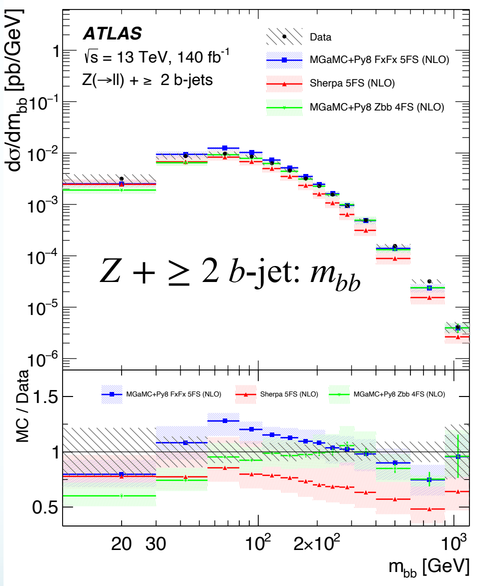
arXiv:2403.15093

1D differential cross section vs
- $(Z + \geq 1\ b\text{-jet})$: p_T^Z, $\Delta R_{Z,jet}$, p_T of leading b-jet
- $(Z + \geq 2\ b\text{-jet})$: p_T^Z, $\Delta R_{Z,jet}$, p_T of leading b-jet, m_{bb}, $\Delta\phi_{bb}$
- $(Z + \geq 1\ c\text{-jet})$: p_T^Z, $\Delta R_{Z,jet}$, p_T and x_F of leading c-jet

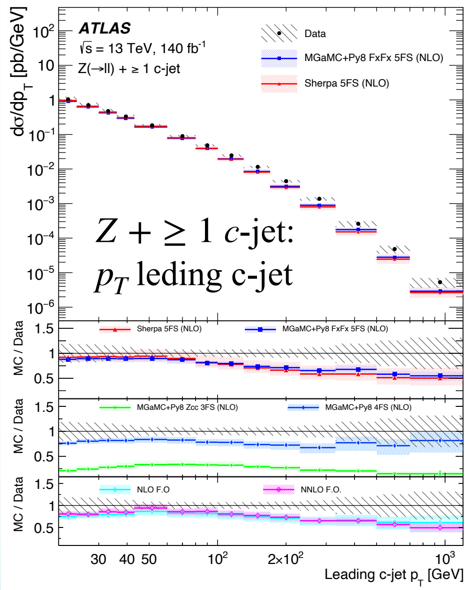
Comparison with:
- 5/4 FS MGaMG+ Py8 and Sherpa
- 5FS fixed-order NLO and NNLO
- various PDF sets (*charm*-jet sample)



Best description by 5FS MGaMC+Py8 FxFx
F.O. underestimate data at high p_T^Z
F.O: large uncertainties at low p_T^Z



m_{bb} shape not well reproduced by any simulation
$\Delta\phi_{bb}$ (not shown) instead generally well reproduced



5FS predictions starts to deviate from data above ~50 GeV
Worst agreement F.O. predictions
Shape looks better for MGaMG+ Py8 4FS