QCD aspects in *W* and *Z* production with ATLAS

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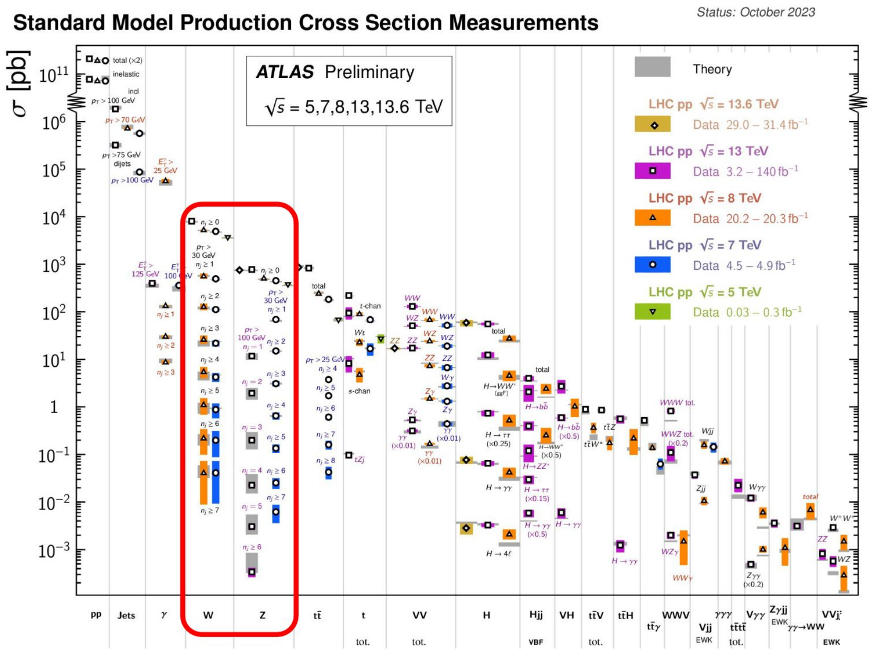
Introduction

W and Z production is abundant and is characterised by a clear experimental signature!

- Important background for many BSM and Higgs processes
- Allows for ultimate precision measurements
- Gives access to information on PDFs
- Can test state-of-the-art predictions and MCs



W and *Z* physics with ATLAS data

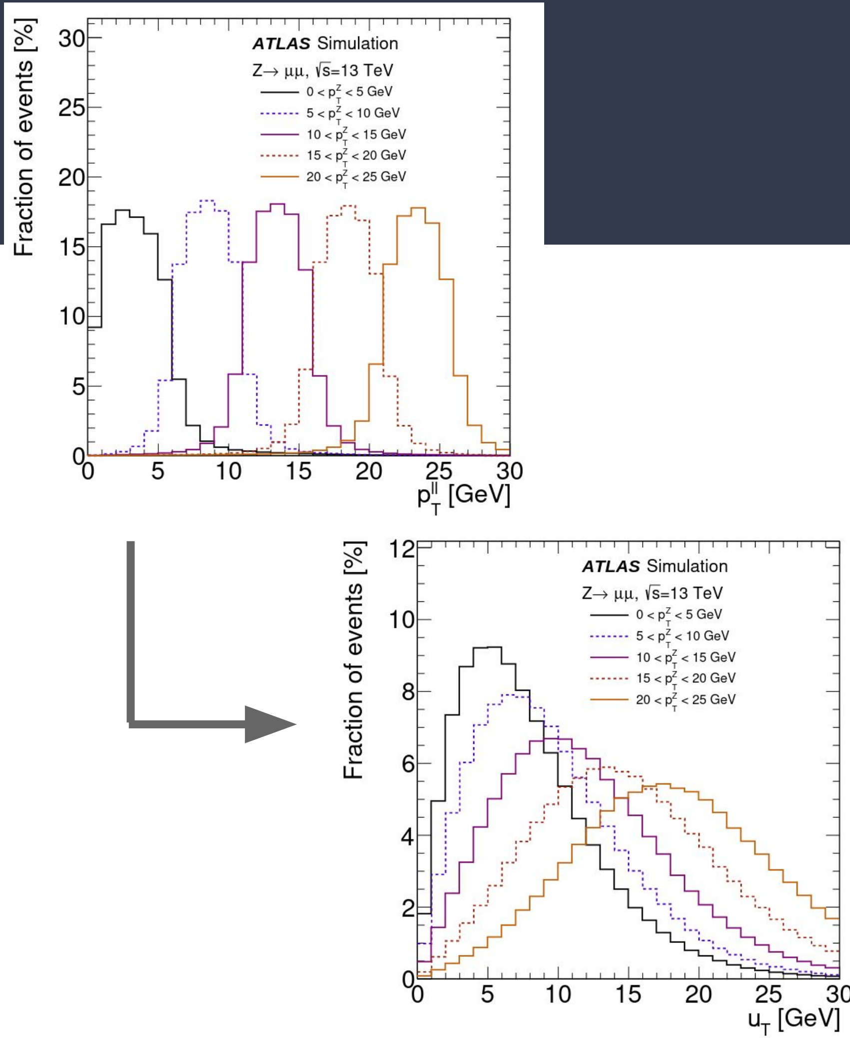
This talk will present several recent results:

- *W* and *Z* p_T spectra at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV [arXiv:2404.06204]
- *W* and *Z* production cross sections at $\sqrt{s}$ = 13.6 TeV [Phys. Lett. B 854 (2024) 138725]
- Differential cross sections for p_T^{miss} + jets [arXiv:2403.02793]
- Production of *Z* + *b*/*c* jets at $\sqrt{s}$ = 13 TeV [arXiv:2403.15093]
- *Z* + jets with unbinned unfolding [arXiv:2405.20041]

W and *Z* p_T spectra

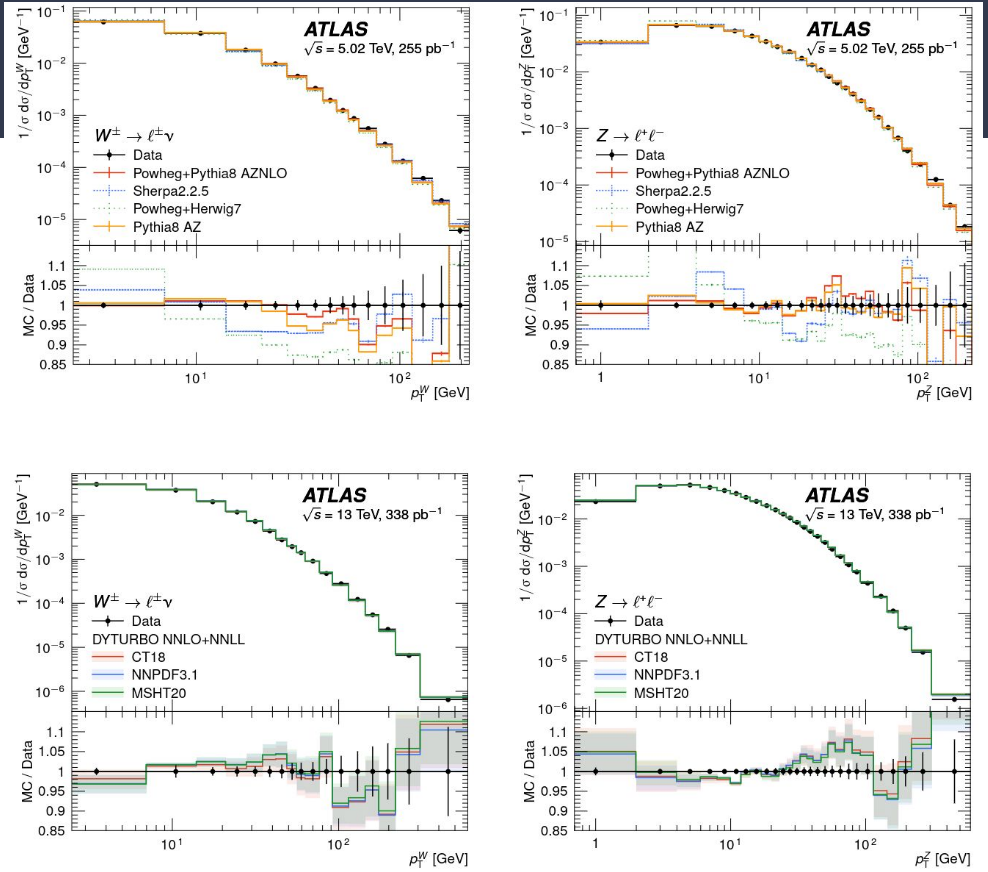
p_T^W important parameter for theoretical models needed for M_W measurement

- ➔ Low pile-up (⟨μ⟩~ 2) measurement performed at two energies √s = 5.02 TeV and √s = 13.0 TeV
- ➔ p_T^Z spectrum for $Z \rightarrow l^+l^-$ relatively straightforward to measure (l = e/μ)
- ➔ problem arises for W→lν due to missing momentum
  - ◆ measure hadronic recoil u_T to reconstruct *W* kinematics
  - ◆ u_T composed of all particles in event after identifying leptons from *V*-decay
  - ◆ Calibrate u_T reconstruction using leptonic *Z* decays

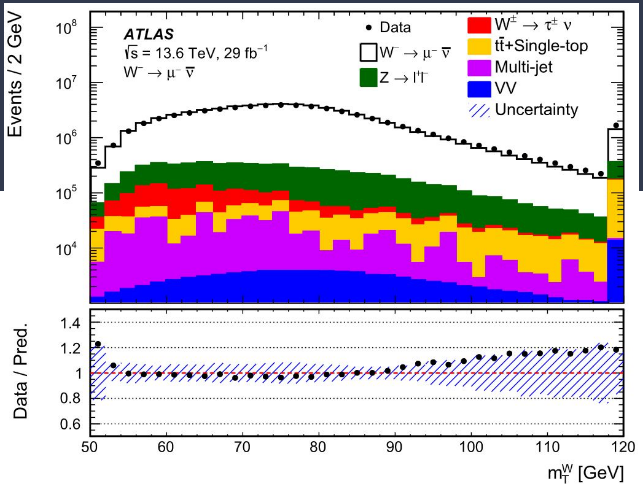


Unfolding and results

- Use Iterative Bayesian Unfolding to correct for detector effects
- Compare results to various pQCD predictions made by varying PDF set and MC
- Significant differences between various MCs, especially at high p_T^V
- Good overall agreement between MC and data at √s = 5.02 TeV due to tuning to 7 TeV dataset (AZNLO) and for DYTurbo NNLO+NNLL predictions



W and *Z* production at 13.6 TeV



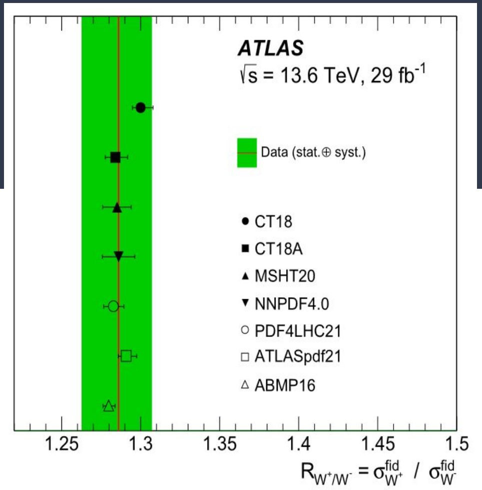
First ATLAS Run 3 measurement of W and Z production cross section and their ratios to ttbar production with 29 fb^{-1} of data

- Consider events with $Z \rightarrow l^+l^-$ and $W \rightarrow l\nu$ and measure cross section in 6 total channels and 5 ratios
  - $W^+ \rightarrow e^+\nu$, $W^- \rightarrow e^-\nu$, $W^+ \rightarrow \mu^+\nu$, $W^- \rightarrow \mu^-\nu$, $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$
  - $W^{\pm}/Z$, W^+/W^-, ttbar/$W^{\pm}$, ttbar/W^+, ttbar/W^-
- Compare to predictions calculated at NNLO+NNLL QCD + NLO EW corrections calculated with DYTurbo and ReneSANCe
- ttbar data published in [Phys. Let. B 848 (2024) 138376]

Summary of the event selection requirements.

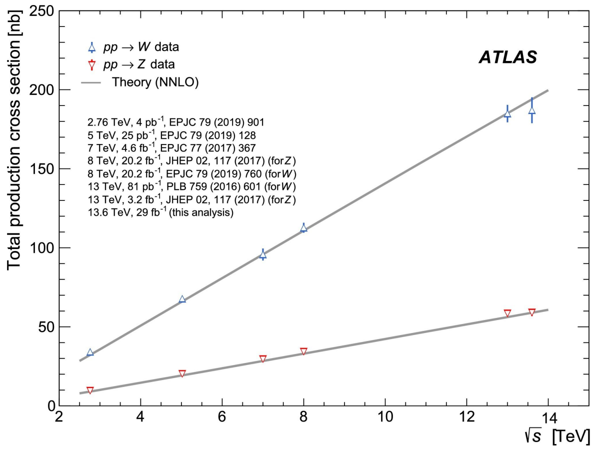
Electron selections	$p_T > 27$ GeV $\lvert\eta\rvert < 2.47$ and veto of $1.37 < \lvert\eta\rvert < 1.52$
Muon selections	$p_T > 27$ GeV $\lvert\eta\rvert < 2.5$
W-boson selections	Exactly one lepton $E_T^{miss} > 25$ GeV $m_T > 50$ GeV
Z-boson selections	Exactly two same flavour opposite charged leptons $66 < m_{\ell\ell} < 116$ GeV

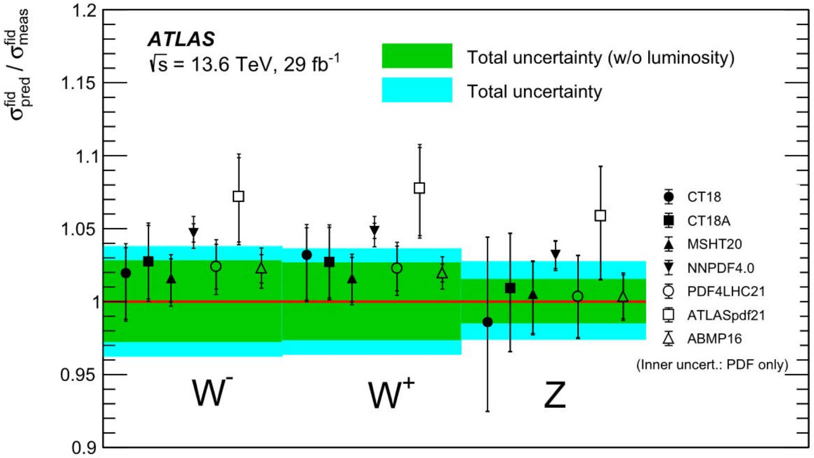
W and *Z* production at 13.6 TeV

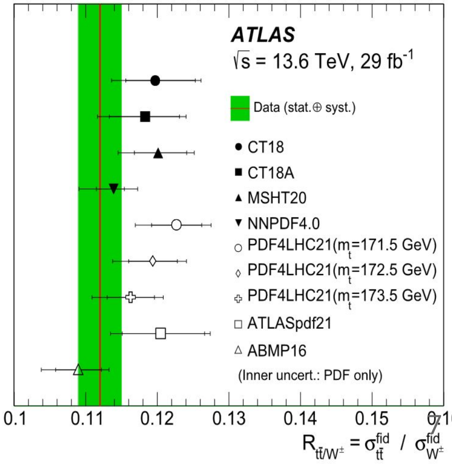


Results are in full agreement with SM predictions

ttbar/*W* ratios are overestimated — consistent with published Run 3 ttbar measurement where cross section was lower than prediction







Z + jets with unbinned unfolding

Measurement of 24 observables unfolded using Omnifold [Phys. Rev. Lett. 124, 182001 (2020)]

- Full Run 2 measurement using 139 fb^{-1} of data at $\sqrt{s} = 13.0$ TeV
- Measurement performed on $Z \to \mu^+\mu^-$ events containing with $p_T^{\mu\mu} > 200$ GeV
- Anti-k_t R = 0.4 jets built from charged particles with $p_T > 500$ MeV and $|\eta| < 2.5$
- Predictions obtained with MadGraph_aMC@NLO v2.6.5 interfaced to Pythia8 v8.240

Sample composition:

- 95% Drell-Yan
- 3% diboson
- 2% EW Zjj

Observables measured:

- **$p_T^{\mu\mu}$ and $y_{\mu\mu}$**
- **p_T^{μ}, η_{μ}, φ_{μ} for both muons**
- **p_T^{j}, η_{j}, φ_{j} for the two leading jets**
- **Jet substructure quantities such as:**
  - **Mass, charged particle multiplicity N-subjettiness**

Omnifold

Idea: Learn weights to be applied to a generated sample until it resembles an unfolded version of data

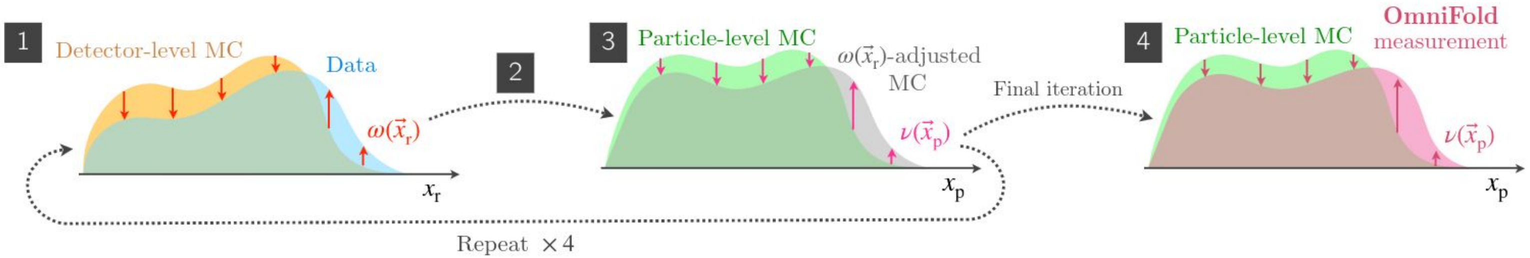
Principal advantage: can re-analyse event-level dataset and construct new observables from those measured

Iterative algorithm: Take a list of truth samples, the corresponding reco samples and data samples

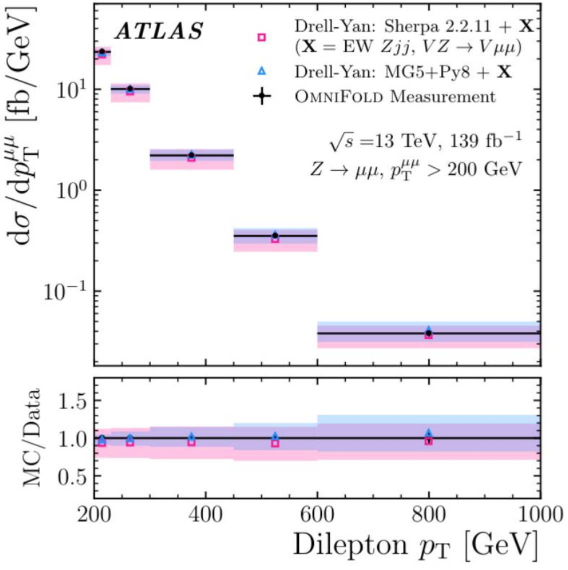
Two weights ω^i_n ν^i_n per sample i. Start with ω^i_0 ν^i_0 = (1, 1, …, 1). Update weights iteratively until event yields and kinematics match data

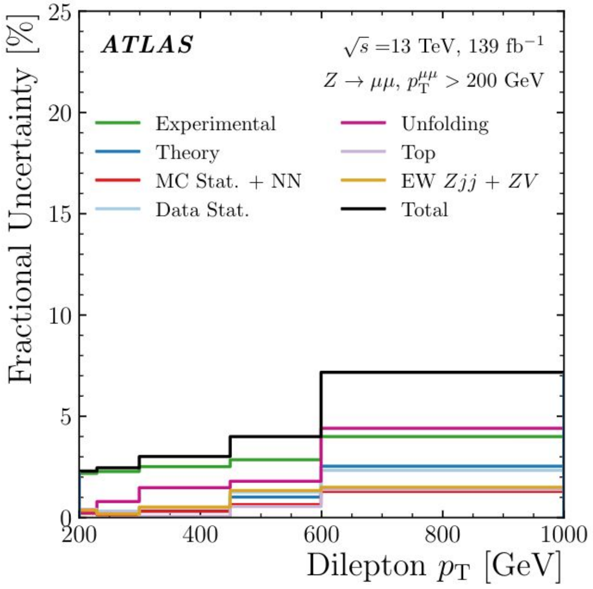
$$\omega^i_{n+1} = \omega^i_n \cdot L[(1, \text{data}), (\nu_\text{n}, \text{reco.})](\text{i})$$
$$\nu^i_{n+1} = \nu^i_n \cdot L[(\omega_{n+1}, \text{truth}), (\nu_\text{n}, \text{truth})](\text{i})$$

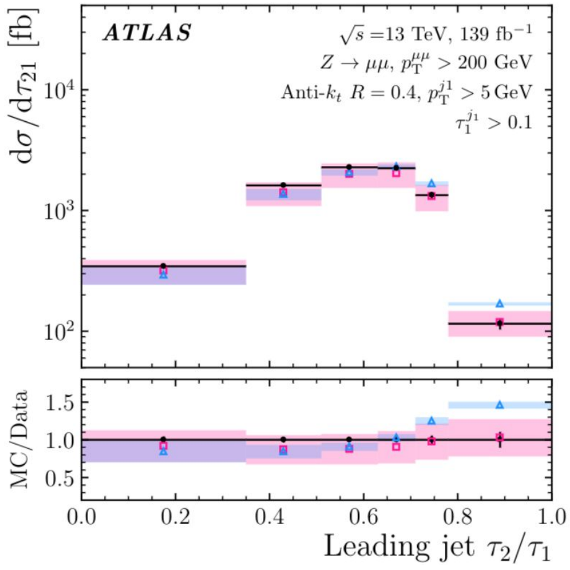
L = likelihood ratio usually approximated by a neural network classifier



Z+jet unbinned unfolding







Results are compatible with predictions

Omnifold uncertainties similar, but slightly larger than those found with Bayesian comparison (3.0% average bin uncertainty vs. 3.9% for Omnifold)

p_T^{miss} and jets

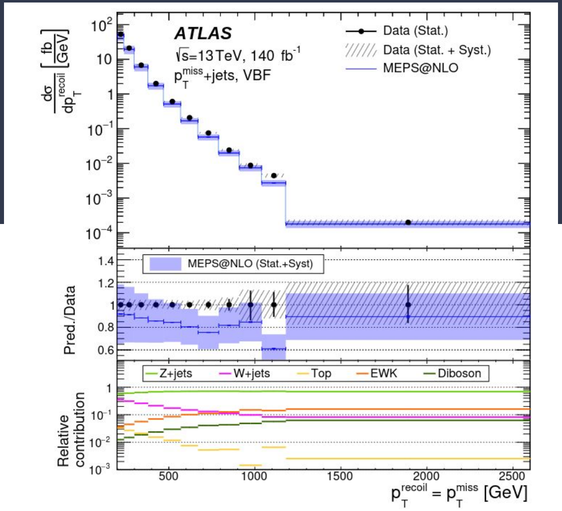
Measurement of differential cross section of $Z \to \nu\nu$ + jets

- First such measurement with Full Run 2 dataset
  - 139 fb^{-1} of data at $\sqrt{s}$ = 13.0 TeV
- Aim to be as inclusive and model-independent as possible
- Important background for BSM processes
  - Simplified DM models
  - 2HDM+a models
- Measurement made in 6 phase-space regions and their ratios
  - p_T^{miss} + jets, e+jets, 2e+jets, μ + jets, 2μ + jets, γ + jets
  - 2 subregions per region: ≥1 jets & VBF

Attribute	p_T^{miss}+jets	e+jets	$2e$+jets	μ+jets	2μ+jets	γ+jets
Lepton or photon rapidity	–	$\lvert y\rvert \leq 1.37$ or $1.52 \leq \lvert y\rvert \leq 2.47$		$\lvert y\rvert \leq 2.5$		$\lvert y\rvert \leq 1.37$ or $1.52 \leq \lvert y\rvert \leq 2.47$
Leading lepton or photon p_T [GeV]	–	> 30	> 80	> 7	> 80	> 160
Sub-leading lepton p_T [GeV]	–	–	> 7	–	> 7	–
Dilepton mass, $m_{\ell\ell}$ [GeV]	–	–	$m_{\ell\ell} \in (66, 116)$	–	$m_{\ell\ell} \in (66, 116)$	–
(Additional) muons	None with p_T > 7 GeV, $\lvert\eta\rvert < 2.5$					
(Additional) electrons	None with p_T > 7 GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$					
m_T [GeV]	–	$m_T \in (30, 100)$	–	–	–	–
p_T^{miss} [GeV]	> 200	> 60	–	–	–	–
p_T^{recoil} [GeV]	> 200	> 200	> 200	> 200	> 200	> 200

Attribute	≥ 1 jet	VBF
$\Delta\phi$ (jet, p_T^{miss})	> 0.4 for four leading p_T jets	
Hadronic τ-lepton	None with p_T > 20 GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Leading jet p_T [GeV]	> 120	> 80
Sub-leading jet p_T [GeV]	–	> 50
Leading jet $\lvert y\rvert$	< 2.4	< 4.4
Sub-leading jet $\lvert y\rvert$	–	< 4.4
Dijet invariant mass m_{jj} [GeV]	–	> 200
$\lvert\Delta y_{jj}\rvert$	–	> 1
In-gap jets	–	None with p_T > 30 GeV

Results



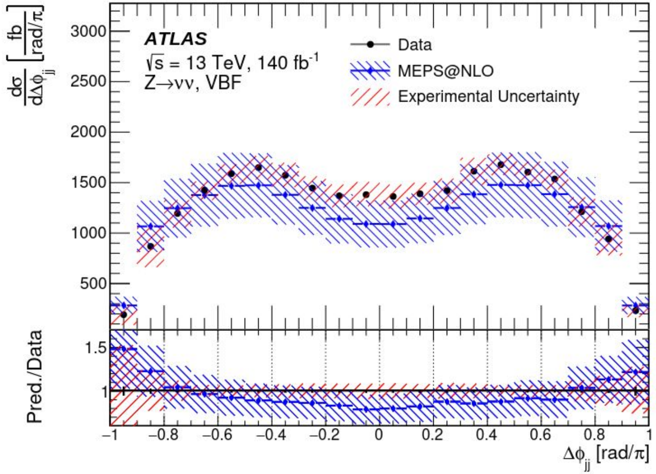
Observables measured
All regions: p_T^{recoil}
VBF: m_{jj}, $\Delta\varphi_{jj}$

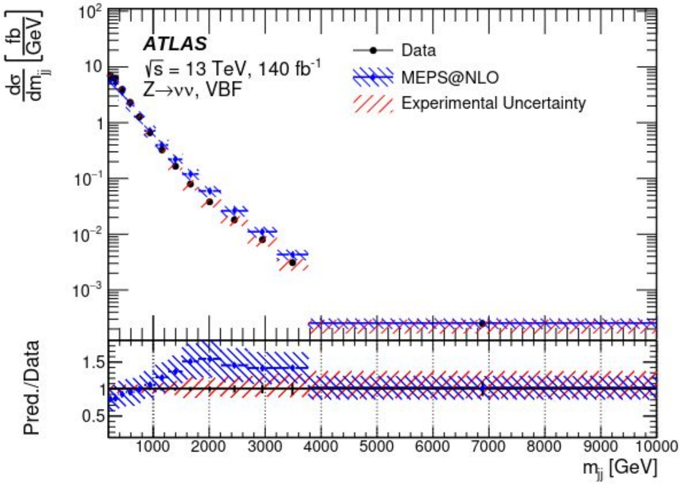
Results well-described by SM predictions except for m_{jj} distribution

Signal samples simulated with Sherpa v2.2.1

Matching to Sherpa parton shower with MEPS@NLO prescription

NLO QCD corrections for up to 2 jets, LO matrix elements accurate for up to 4 jets





BSM interpretation

Measurement compatible with SM

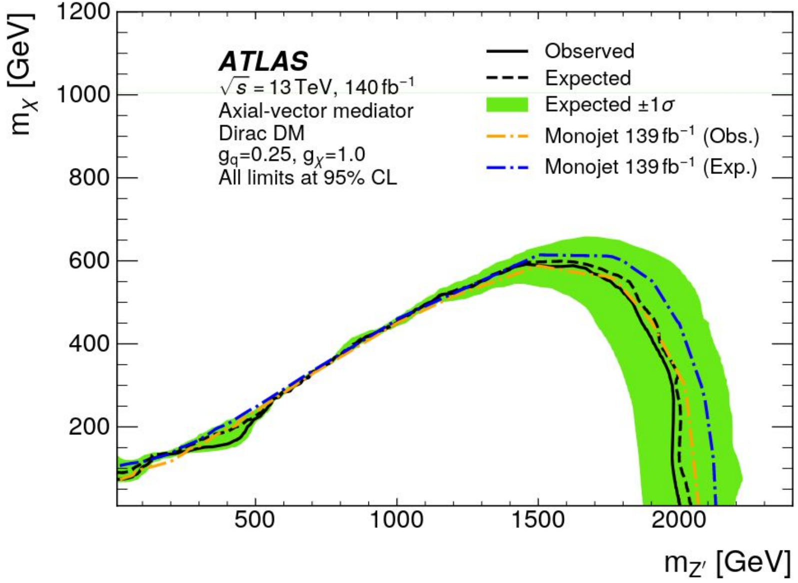
- Use to set limits on contribution from BSM particles

Two models:

- Simplified DM (additional scalar X with additional U(1) gauge symmetry)
- 2HDM+a (introduction of additional Higgs doublet h with pseudoscalar mediator a)

Sensitivity is similar to that of dedicated ATLAS searches [Phys. Rev. D 103, 112006], [arXiv:2306.00641]

Inclusive, particle-level measurements can be sensitive to BSM physics!



Production cross section of $Z + b/c$ jets

Measurement of $Z(l^+l^-)$+ ≥1 b/c-jets or ≥2 b-jets, first ATLAS measurement of Z + ≥1 c-jets

Full Run 2 measurement with 140 fb^{-1} of data at √s = 13.0 TeV

NLO ME+PS state-of-the art generators with high parton-multiplicity in ME

- MadGraph_aMC@NLO + PY8 with FXFX merging and SHERPA 2.2.11
- Consider 4/5 Flavour Scheme for b-jet signal regions and 3/4/5 Flavour Scheme fo c-jet signal region

Consider anti-k_t R = 0.4 jets with p_T > 20 GeV and |y| < 2.5 *b*-tagged (*c*-tagged) with 85% (30%) efficiency

Dedicated Flavour fit to correct normalisation/shape of observables

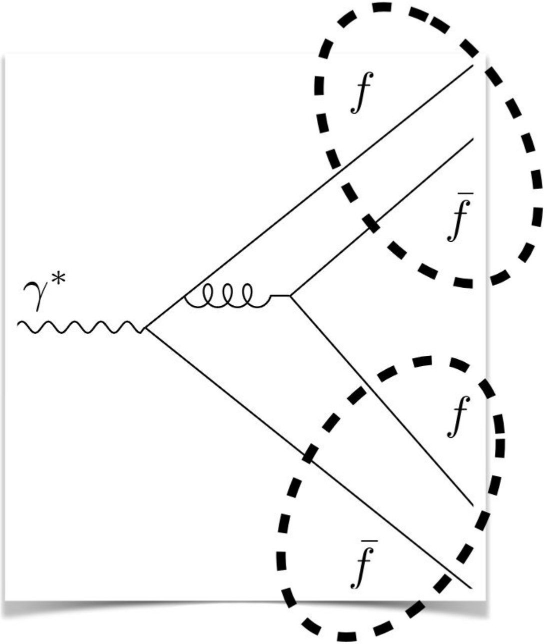
Comparison of results to novel IRC safe flavour-aware algorithms

Comparison of *Z* + ≥1 *c*-jets results to benchmark intrinsic charm models

Final state	Observable
$Z + \geq 1$ b-jet	p_T of the leading b-jet
	p_T of the Z boson
	$\Delta\tilde{R} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$ between the Z boson and leading b-jet, where $\Delta\phi$ (Δy) is the azimuthal angle (rapidity) difference
$Z + \geq 1$ c-jet	p_T of the leading c-jet
	p_T of the Z boson
	Feynman-x variable $x_F = 2\|p_z(c)\|/\sqrt{s}$ [25]
	Cross-section ratio of $p_T(Z)$ in $\|y(Z)\| < 1.2$ and $\|y(Z)\| > 1.2$
$Z + \geq 2$ b-jets	Invariant mass of the two leading b-jets
	Azimuthal angle difference between the two leading b-jets

Flavour-dressing algorithm

- One of several new algorithms designed to assign flavour to jets in an IRC safe manner
- Main idea is to identify *b*-quarks originating from soft gluon splittings and to ensure that they don't lead to the assignment of a jet's flavour
- Start from flavour-agnostic (anti-k_t) jets
- Dress flavoured particles in event with surrounding radiation. Build flavour-cluster by accumulating flavour information from surrounding particles
- Associate flavour clusters to jets. Assign flavour to jet based on accumulation criterion

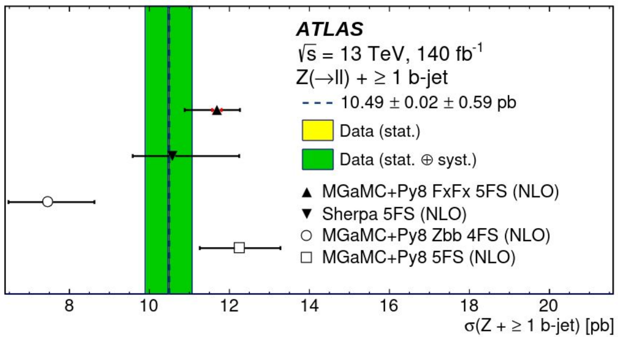


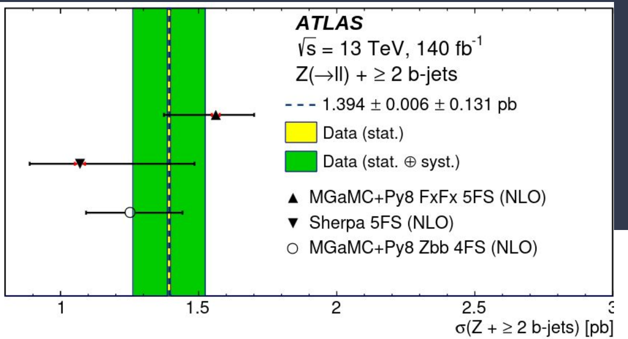
"Bad" event where jets are misidentified as flavourless due to gluon splitting.

[G. Stagnitto "Flavor dressing algorithm (GHS)"](#)

[PRL 130 (2023) 16, 161901](#) + erratum [[2208.11138v2]](#)

Results



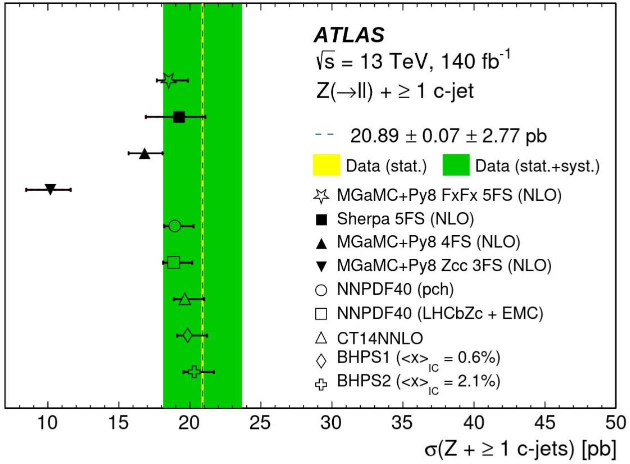


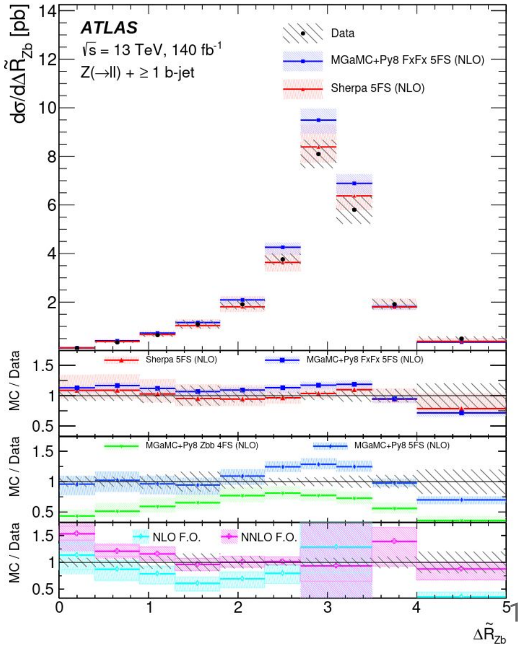
5FS predictions describe *Z* +*b*-jets data within uncertainties

4FS predictions underestimate *Z*+ ≥1 *b*-jets data

All generators do not describe *Z*+ ≥1 *c*-jets data

Predictions with flavour-dressing algorithm show similar results for *Z*+ ≥1 *b*-jets but predict softer p_T spectrum



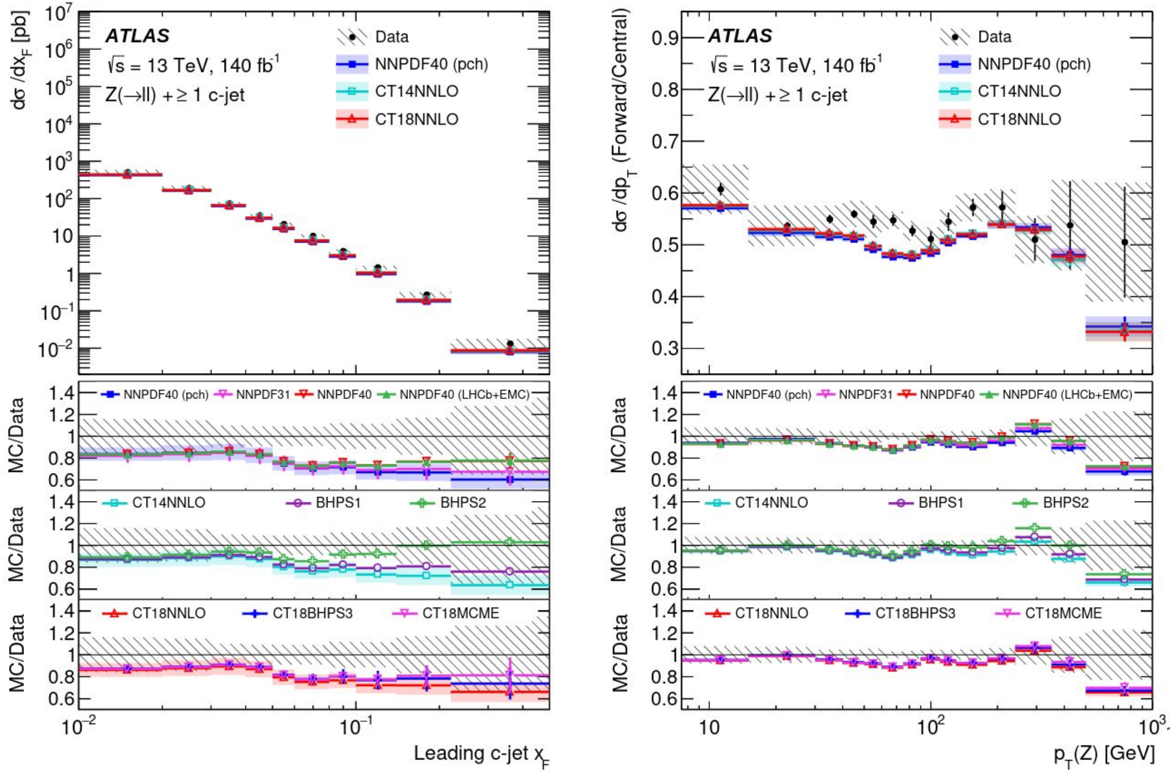


Intrinsic charm

Compare IC-sensitive observables x_F and $p_T(Z)$ distributions to various models including IC

- NNPDF40 w/ and w/o perturbative charm (pch)
- CT14NNLO with no IC, 0.6% IC (BHPS1) and 2.1% IC(BHPS2)
- CT18NNLO with BHPS3 model and meson-baryon model based on effective mass (MBME)

No significant improvement in agreement to data



Conclusions

- V + jets processes are abundant and allow for precision tests of SM predictions
- Latest ATLAS results highlight variety of tests that are possible
- Novel unfolding techniques will allow for easier re-utilisation of data for future tests
- Run 3 will provide many more opportunities for exciting results!

Thank you for your attention!