Yoran Yeh
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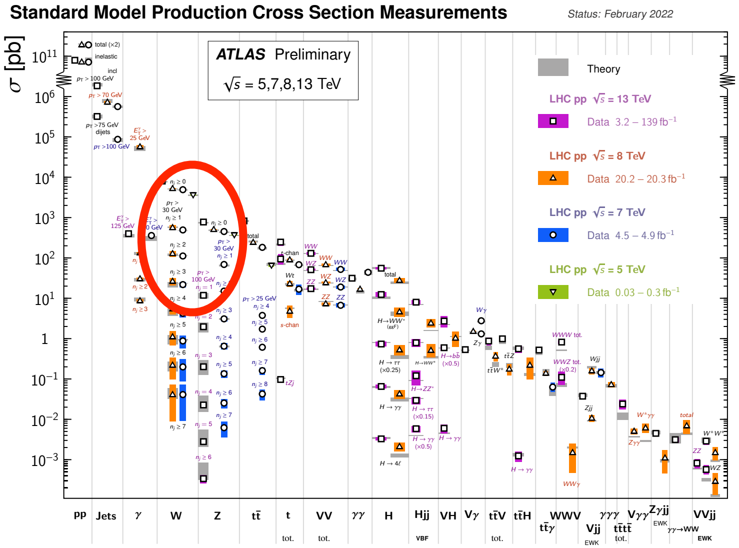
Measurements of W and Z boson production in association with jets in ATLAS

BOOST 2024, Genova

Yoran Yeh, 30 July 2024

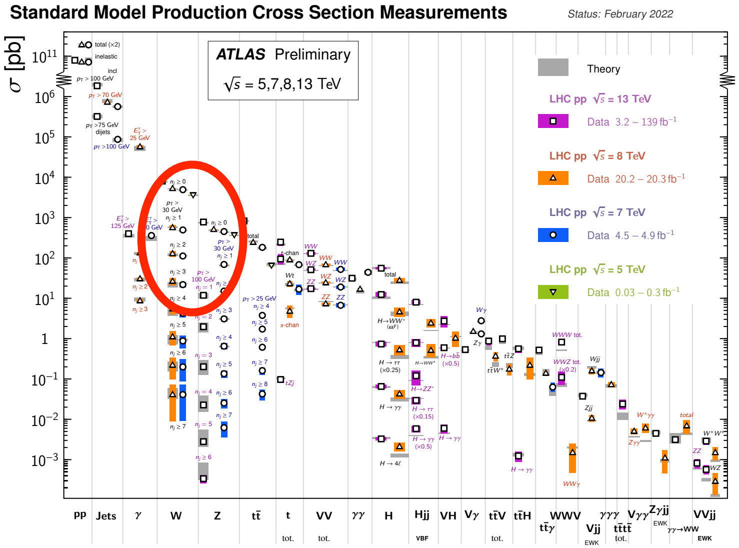
Importance of V+jets precision measurements

- In context of the SM:
  - Test state-of-the art QCD predictions
  - Sensitive to parton distribution functions (PDFs)
  - Tune and improve MC predictions

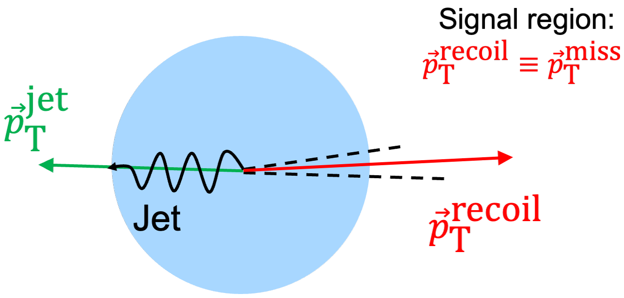


Importance of V+jets precision measurements

- In context of the SM:
  - Test state-of-the art QCD predictions
  - Sensitive to parton distribution functions (PDFs)
  - Tune and improve MC predictions
- For BSM physics:
  - Provide accurate background modelling for other processes
  - … use directly for constraining BSM parameter space!



Outline

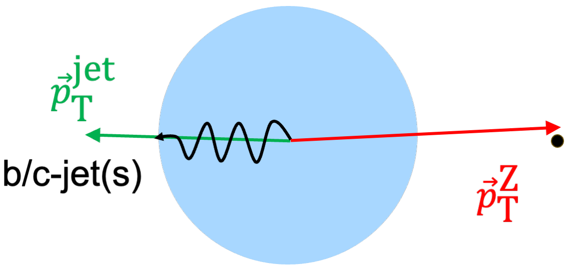


p_T^{miss} + jets

[arXiv:2403.02793](https://arxiv.org/abs/2403.02793) [hep-ex]

Submitted to JHEP

ATLAS public page



$Z + \geq 1$ b-jet

$Z + \geq 2$ b-jet

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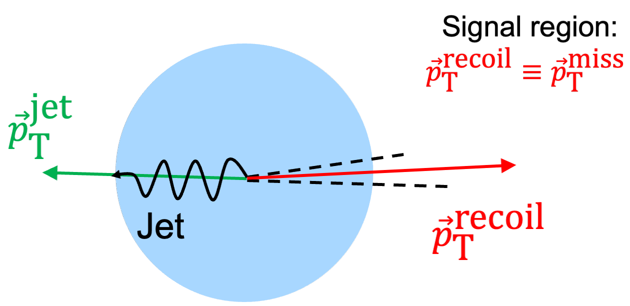

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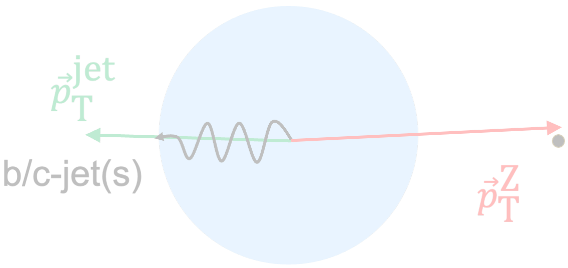

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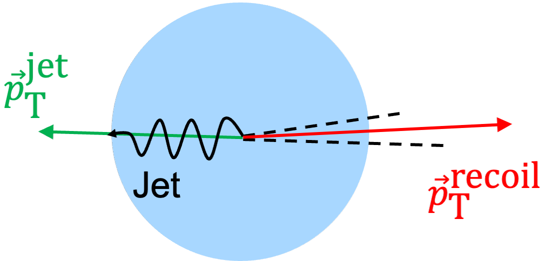


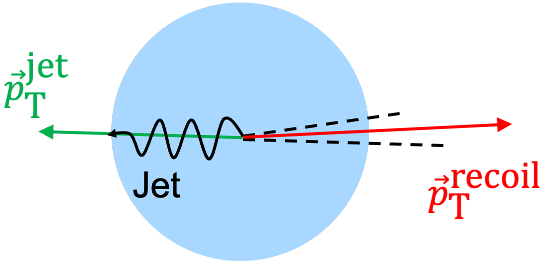
- First inclusive particle-level measurement of p_T^{miss}, using full ATLAS Run-2 dataset

Signal region (SR): $\vec{p}_T^{recoil} \equiv \vec{p}_T^{miss}$

For example: $Z \to \nu\nu$, $W \to \ell\nu$

or $Z' \to \chi\chi$

p_T^{miss} + jets



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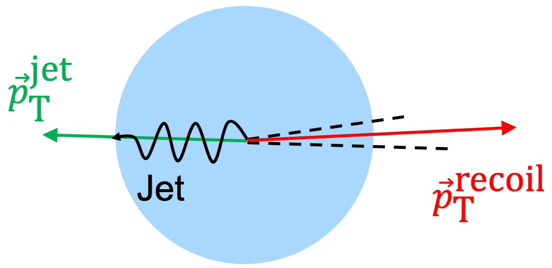
- Auxiliary regions (ARs): lepton(s)/photon + jets
  - Measure SR and ARs cross-sections individually and as ratios $R_{miss} = \sigma(p_T^{miss} + \text{jets})/\sigma(\text{AR})$

Eur.Phys.J.C 77 (2017) 11, 765

p_T^{miss} + jets



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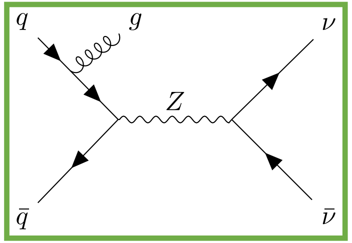
    Eur.Phys.J.C 77 (2017) 11, 765
- Designed for re-interpretation increasing **impact** and **longevity** of the analysis

p_T^{miss} + jets analysis strategy

- Measure two different jet topologies: **monojet-like** and **Vector Boson Fusion (VBF) enhanced** region
- Both topologies:
  - Kinematic cut of $p_T^{recoil} > 200$ GeV
  - Reduce fake-p_T^{miss} background with $\Delta\phi(p_T^{miss}, \text{jet})$ cut

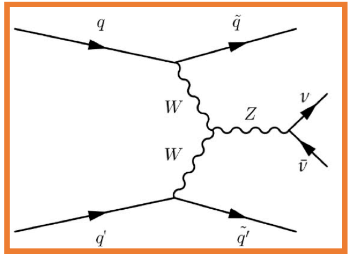
Monojet



p_T^{miss}

- ≥ 1 jet
- leading jet:
  - $p_T > 120$ GeV
  - $|\eta| < 2.4$

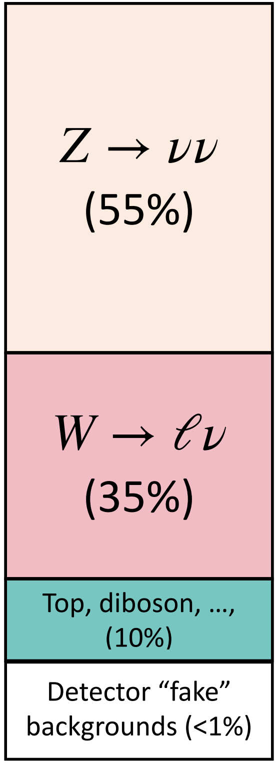
VBF



p_T^{miss}
$\Delta\phi_{jj}$
m_{jj}

- ≥ 2 jets
- leading jet: $p_T > 80$ GeV
- subleading jet: $p_T > 50$ GeV
- $|\Delta y_{jj}| > 1$, in-gap jet veto
- $m_{jj} > 200$ GeV

Two complementary measurements

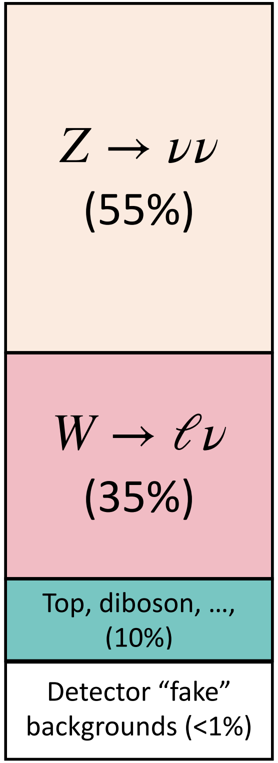


Process composition for $p_{\mathrm{T}}^{\mathrm{miss}}$ + jets signal region, monojet toplogy

Two complementary measurements

Dominant boson process

- "Traditional" measurement of final-state process e.g. $Z(\rightarrow \nu\nu) + \text{jets}$ in signal region
- Subdominant SM processes and fake detector backgrounds are subtracted before unfolding



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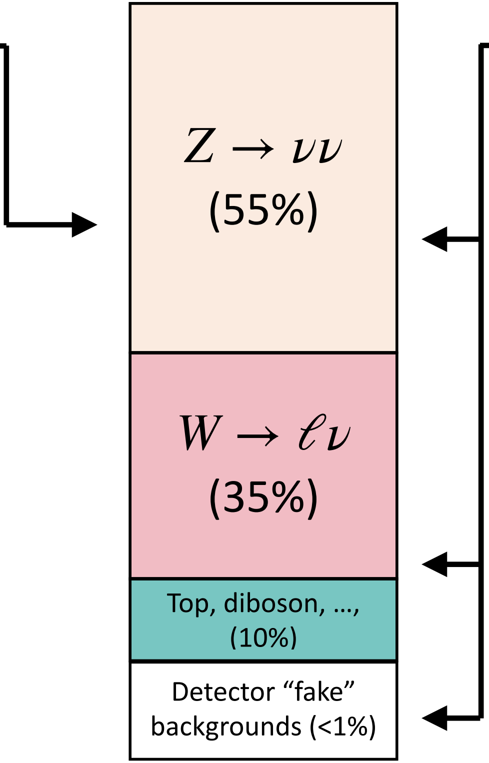


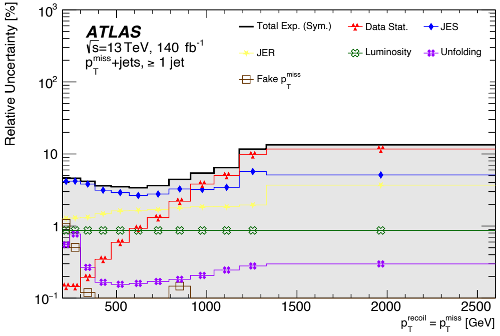
Process composition for $p_{\mathrm{T}}^{\mathrm{miss}}$ + jets signal region, monojet toplogy

Fiducial final state

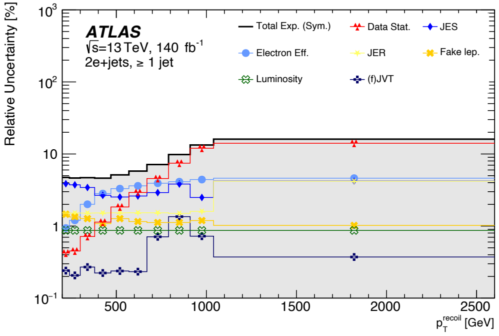
- All subdominant processes are kept as signal, only fakes subtracted from data - inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$ measurement
- Highly re-interpretable in long term, for both SM and BSM physics

Statistical and systematic uncertainties

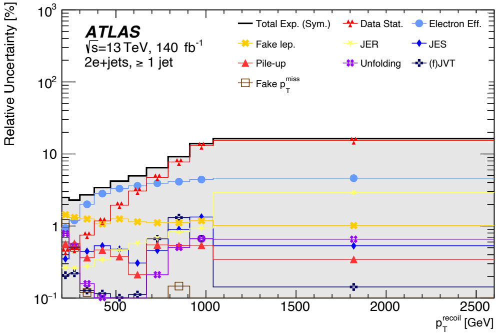
Signal region



2 electron region



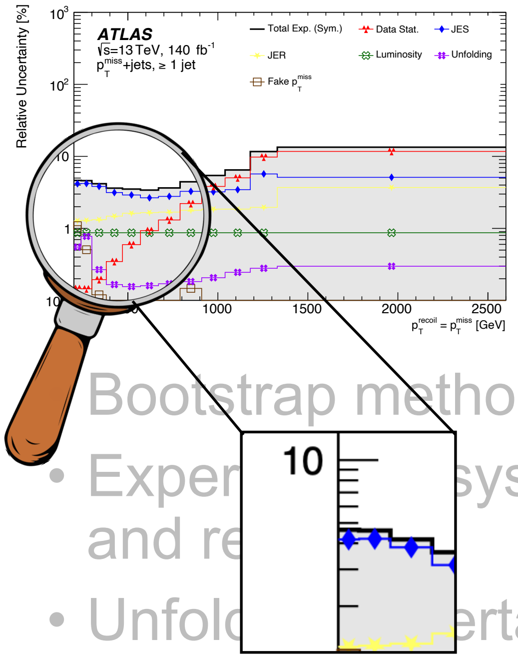
R_{miss}(SR/2e)



- Bootstrap method to track statistical correlations
- Experimental systematics from detector calibrations, identification and resolution
- Unfolding uncertainties and fake backgrounds
- Dominated by jet energy scale and resolution

Statistical and systematic uncertainties

Signal region



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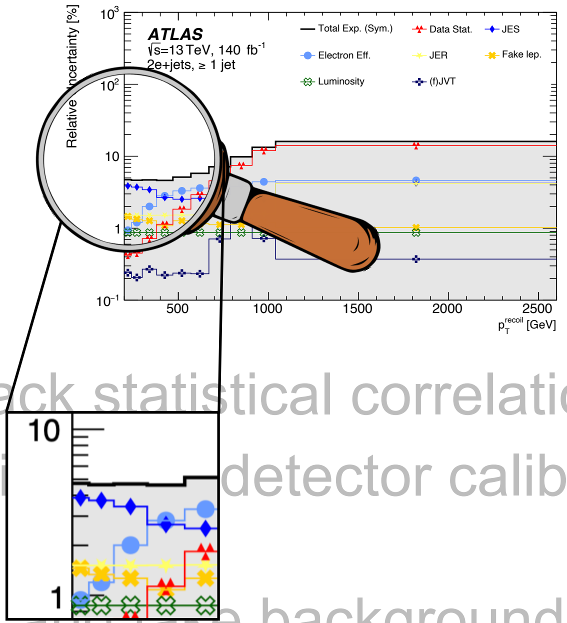

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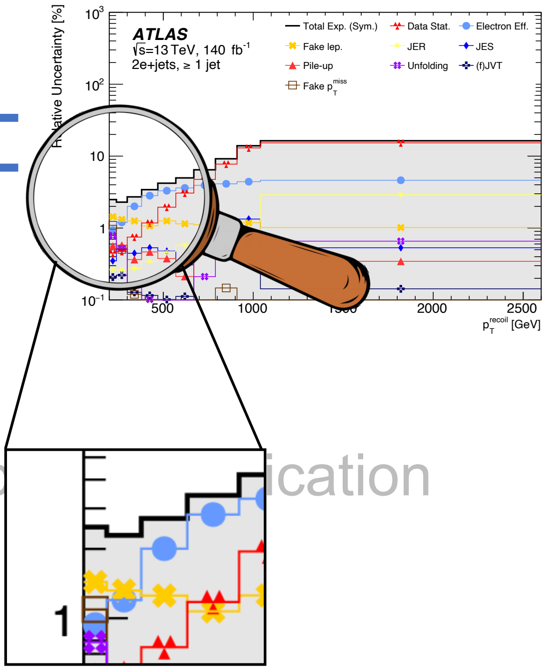
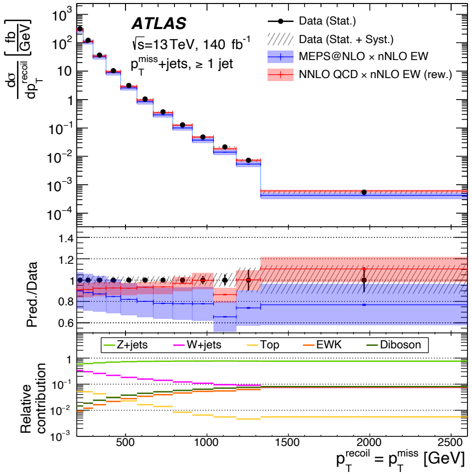
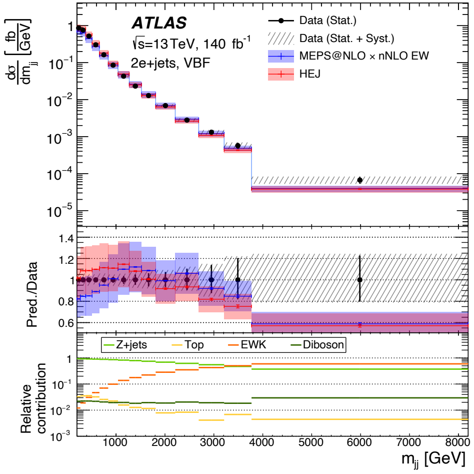


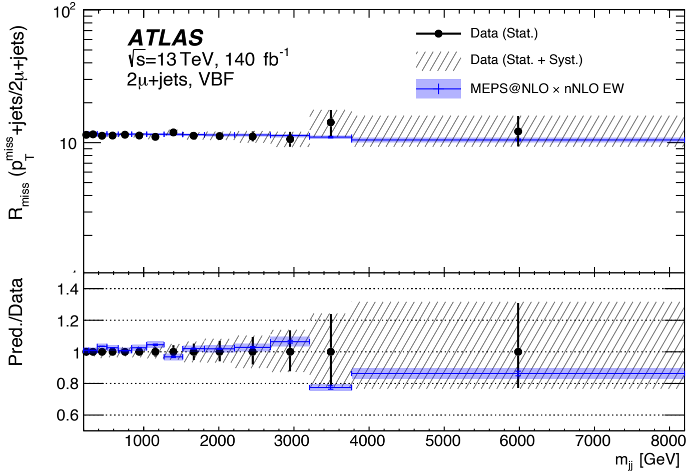
- Bootstrap method to track statistical correlations
- Exper… systemati… detector calibratio… ication and re…
- Unfold… ertainties and fake backgrounds
- Dominated by jet energy scale and resolution: **cancellation in ratios**

4-5% to 2% in R_{miss}

p_T^{miss} + jets results







- Reasonable agreement with state-of-the-art SM predictions
  - Constant 10-20% offset in NLO prediction improves with NNLO reweighting
  - Shape mismodelling of m_{jj}, slight improvement with High Energy Jet (HEJ) package
- R_{miss} benefits from cancellation of discrepancies in modelling
- Preserved on HEPData and RIVET with re-submission to journal

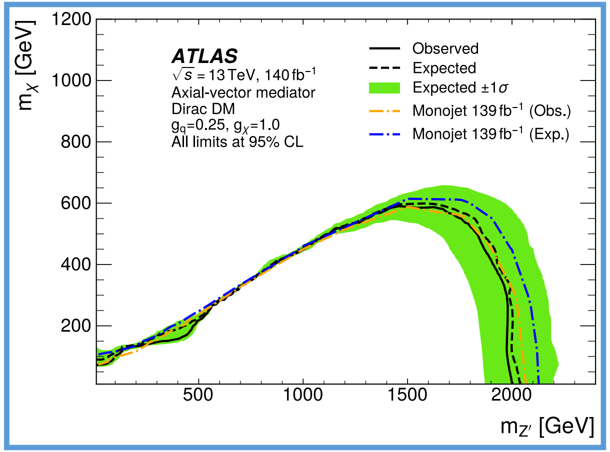
J. M. Lindert et al., Eur. Phys. J. C 77 (2017) 829

J. R. Andersen et al., arXiv: 2303.15778 [hep-ph]

p_T^{miss} + jets interpretation

- Use R_{miss} for interpretation in two models
- Axial-vector DM: benchmarked to dedicated DM search

Phys. Rev. D 103, 112006 (2021)



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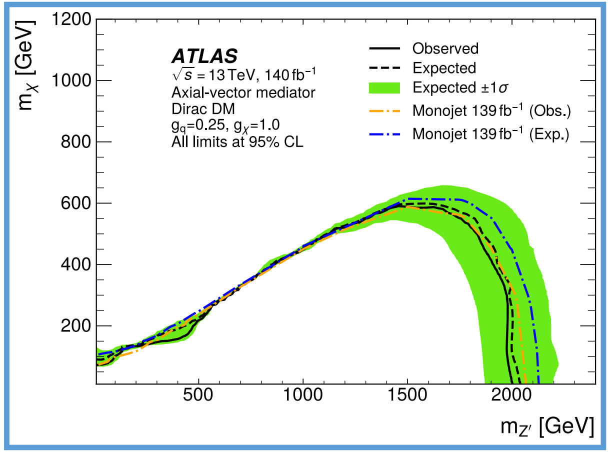
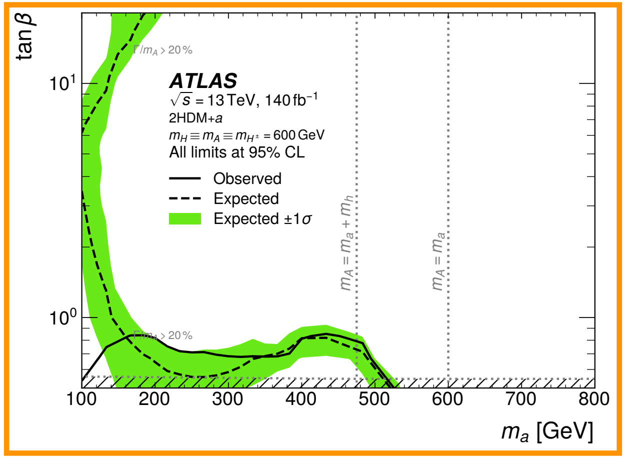
- 2HDM+a model: Higgs doublet and scalar couple to DM





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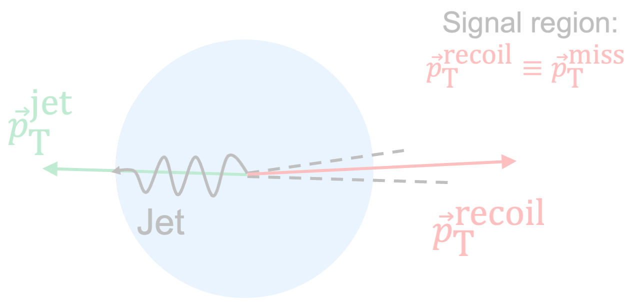
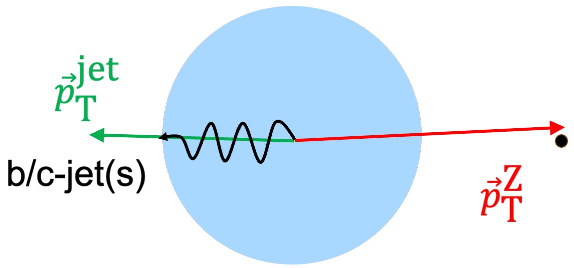


$p_{\mathrm{T}}^{\mathrm{miss}}$ + jets



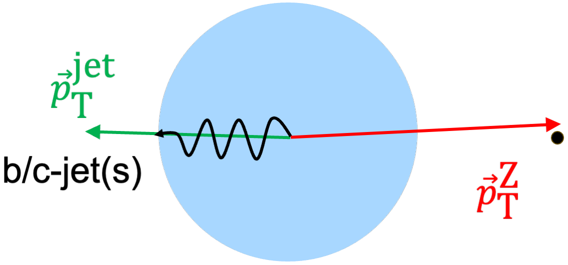
$Z + \geq 1$ b-jet

$Z + \geq 2$ b-jet

$Z + \geq 1$ c-jet

Z + HF-jets measurements

- Inclusive and differential cross-sections of Z + heavy flavour (HF)



$Z + \geq 1$ b-jet
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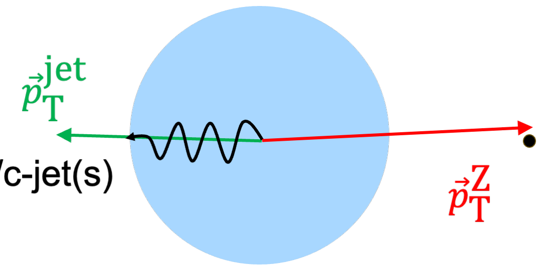
} **Update to 36 fb^{-1} result**

$Z + \geq 1$ c-jet → **Premiere in ATLAS!**

Z + HF-jets measurements

- Inclusive and differential cross-sections of Z + heavy flavour (HF)
- Precise test of pQCD
  - Reliability of state-of-the-art ME+PS at the LHC? (→ Different mass/flavour schemes)
  - Explore sensitivity to proton intrinsic charm component
  - Inputs for MC modelling (→ for VHbb and BSM searches)



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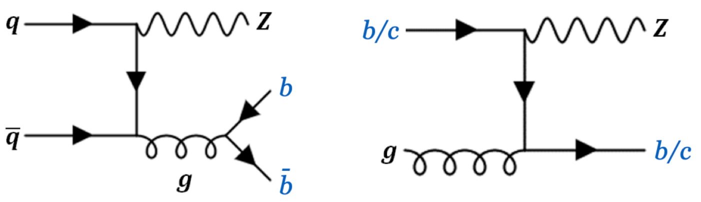
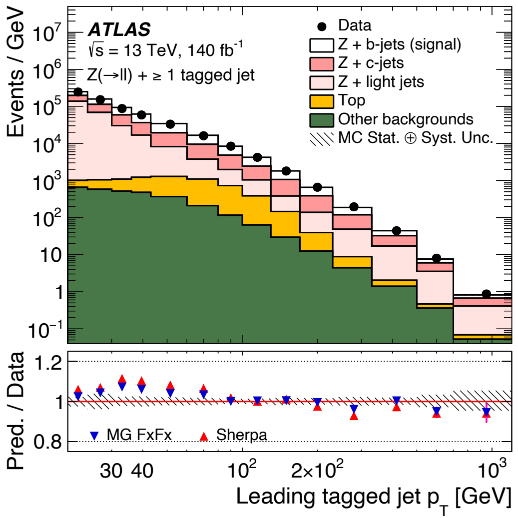


Z + HF-jets strategy

- Select same flavour, opposite sign lepton pair ($Z \rightarrow ee, \mu\mu$) and 1 or 2 flavoured jets, with 85% DL1r score (30% c-jet efficiency)
- Two major background processes:
  - **Top**: data-driven approach, dedicated control region
  - **Z+jets**: flavour fit
- Iterative unfolding after background-subtraction

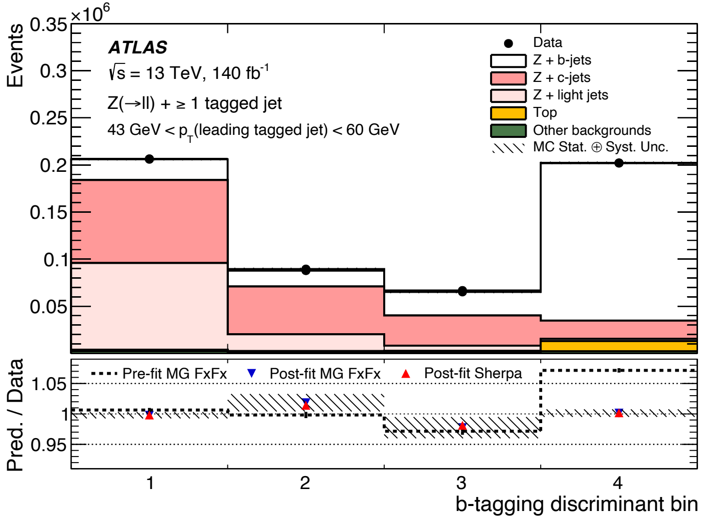
Z + ≥ 1 b-jet

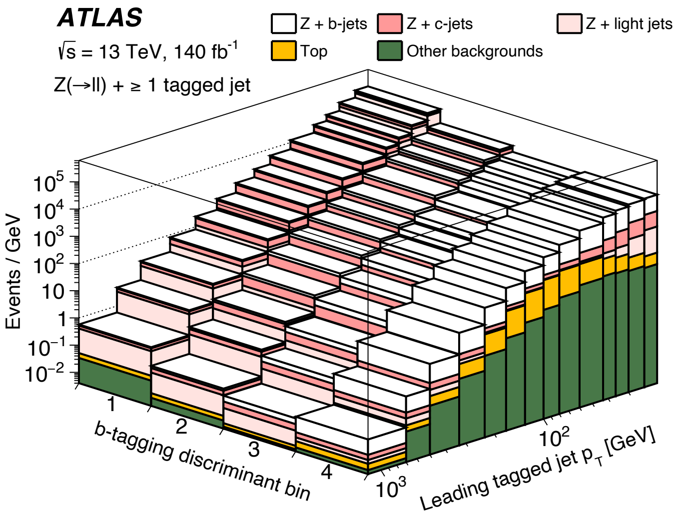


Region	1-tag		2-tag
Signal	Z+≥1 b-jet	Z+≥1 c-jet	Z+≥2 b-jets
Background	Z+c, Z+l	Z+b, Z+l	Z+1b, Z+c, Z+l

Z + HF-jets flavour fit

- Maximum-likelihood fit to data in bins of each measured observable
  - Fit of flavour-tagging score (DL1r)
  - Three free parameters, Z+b-jets, Z+c-jets and Z+light jets normalisation





Results

Final state	Observable
$Z + \geq 1\ b$-jet	$p^0_{\mathrm{T},b}$ $p_{\mathrm{T}}(Z)$ $\Delta\tilde{R}_{Zb}$
$Z + \geq 1\ c$-jet	$p^0_{\mathrm{T},c}$ $p_{\mathrm{T}}(Z)$ $x_F(c)$ $\mathrm{R}(p_{\mathrm{T}}(Z))$
$Z + \geq 2\ b$-jets	m_{bb} $\Delta\phi_{bb}$

Measured observables

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Measured observables

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Main MC samples			
MGAMC+PY8 FXFX	5FS	NNPDF3.1 (NNLO) LuxQED	325100
SHERPA 2.2.11	5FS	NNPDF3.0 (NNLO)	303200
Predictions to test various flavour schemes			
MGAMC+PY8	5FS	NNPDF2.3 (NLO)	229800
MGAMC+PY8 Zbb	4FS	NNPDF3.1 (NLO) PCH	321500
MGAMC+PY8 Zcc	3FS	NNPDF3.1 (NLO) PCH	321300
Intrinsic charm (IC) predictions			
MGAMC+PY8 FXFX	5FS	NNPDF4.0 (NNLO) PCH (no IC)	332100
		NNPDF4.0 (NNLO)	331100
		NNPDF4.0 (NNLO) EMC+LHCbZc	– [24]
		CT18 (NNLO) (no IC)	14000
		CT18FC – CT18 BHPS3	14087
		CT18FC – CT18 MCM-E	14093
		CT14 (NNLO) (no IC)	13000
		CT14 (NNLO)IC – BHPS1	13082
		CT14 (NNLO)IC – BHPS2	13083
Fixed-order predictions [3]			
NLO	5FS	PDF4LHC21	93000
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Test multiple theoretical predictions

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Measured observables

FS in matrix-element calculation

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Measured observables

FS in matrix-element calculation

IC-component in proton PDFs

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Measured observables

FS in matrix-element calculation

IC-component in proton PDFs

Higher order terms in QCD

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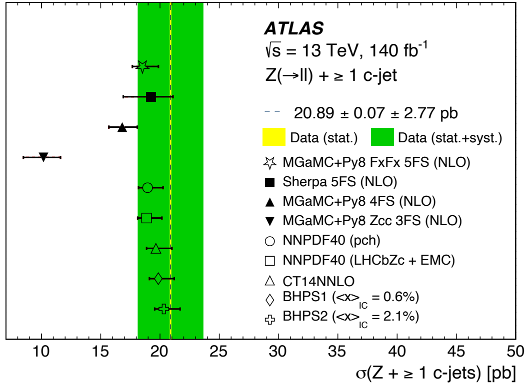
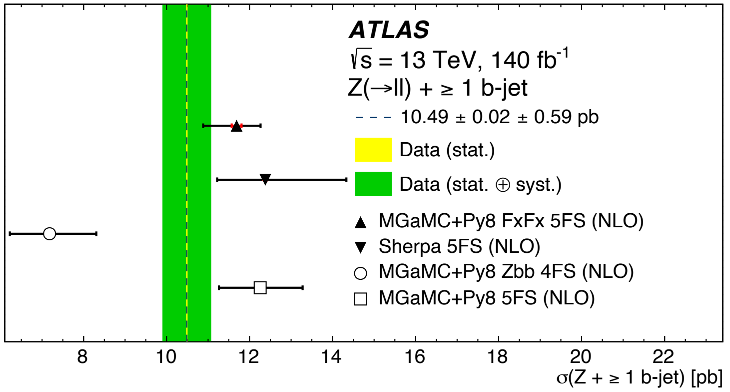
		CT18FC – CT18 BHPS3	14087
		CT18FC – CT18 MCM-E	14093
		CT14 (NNLO) (no IC)	13000
		CT14 (NNLO)IC – BHPS1	13082
		CT14 (NNLO)IC – BHPS2	13083
Fixed-order predictions [3]			
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

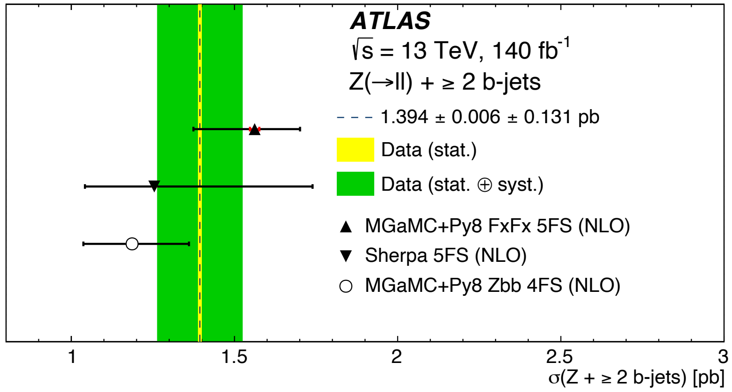
Test multiple theoretical predictions

Inclusive fiducial cross-section

- 5FS most accurate modelling of data
- Underestimation from:
  - 4FS for Z + ≥ 1 b-jet
  - 3FS for Z + ≥ 1 c-jet
    lack of log-resummation $\ln(Q^2/m_c^2)$



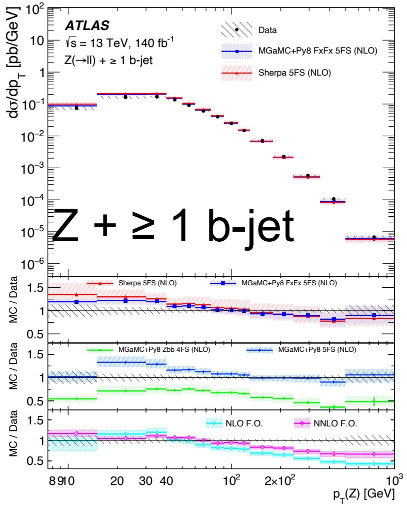


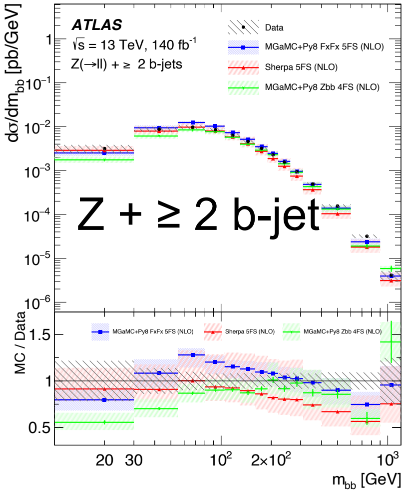


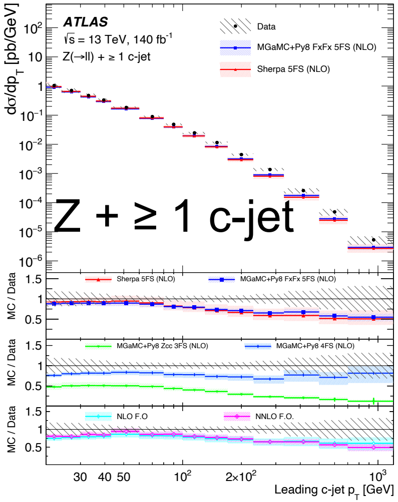
Differential cross-sections

- MGAMC+PY8 FXFX and SHERPA 2.2.11 in 5FS ✅
- 4FS 📉
- m_{bb} shape not in agreement with data across the spectrum
- MGAMC+PY8 FXFX and SHERPA 2.2.11 at low p_T ✅
- 3FS 📉

* IC in backup







- Fixed-order: bin-by-bin corrections applied to predictions to enable direct comparison with data
  Some of the NLO discrepancies improve with NNLO

Conclusion

- LHC is proving to be a great laboratory for precision EW physics
- Experimental measurements of V+jets help us to push advancements in understanding of QCD, PDFs and more!
  - Recent LHC analyses benefit from larger datasets, new analysis techniques and improved calibrations/flavour-tagging

Backup slides

p_T^{miss} + jets analysis selections

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

p_T^{miss} + jets jet topology selections

Attribute	≥ 1 jet	VBF
$\Delta\phi\left(\text{jet}, p_T^{miss}\right)$	> 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

p_T^{miss} + jets background estimations

Signal region	Lepton regions	Photon region
1. Fake p_T^{miss} 2. Non-collision background	Fake leptons - non-prompt leptons - misidentified objects	Fake photons - multijet background

Estimated with:

1. Jet smearing method 2. Data-driven method	Fake factor and matrix method	ABCD method

Subdominant SM processes	Subdominant SM processes	-

Estimated with:

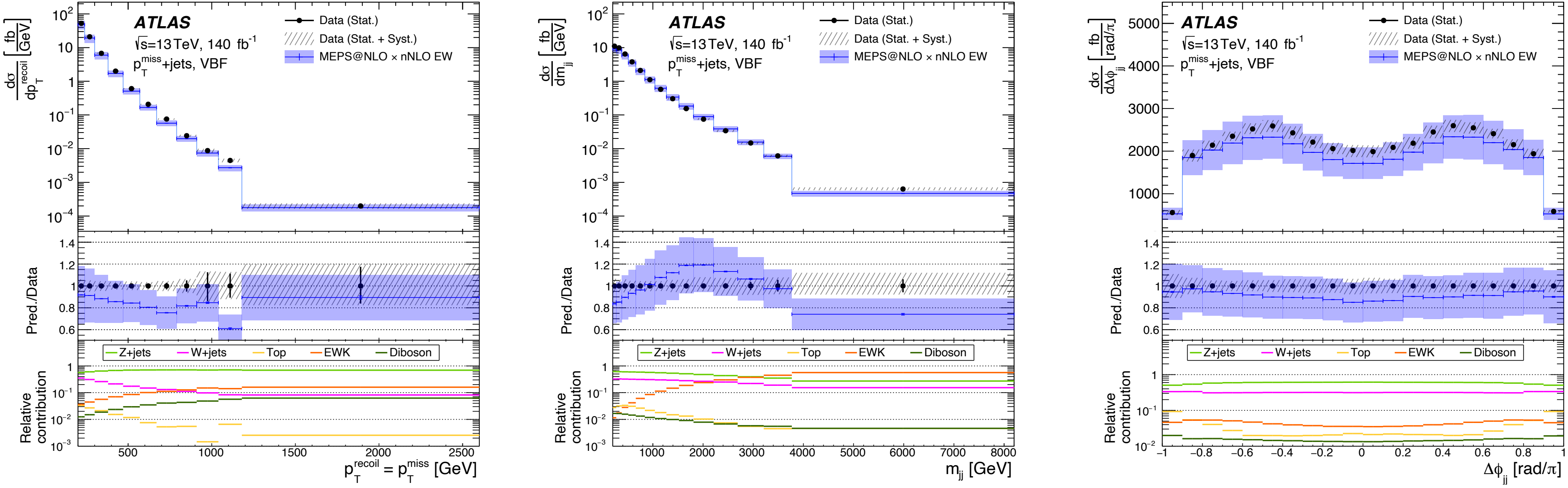
Shape validation in background control regions (BCR), normalisation factor via data-driven method

p_T^{miss} + jets process contributions

Monojet topology

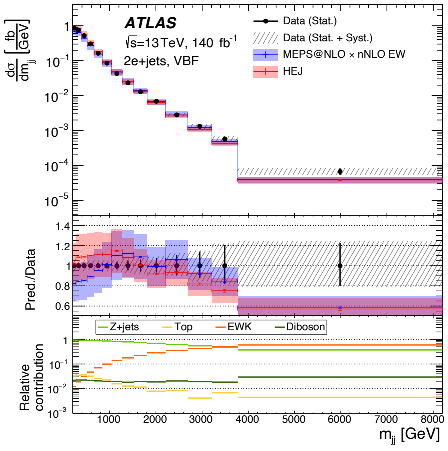
Production process	Final-state event selection					
	p_T^{miss}+jets	$2e$+jets	2μ+jets	e+jets	μ+jets	γ+jets
$Z \to \nu\nu$ + jets	55%	–	–	–	–	–
$Z \to ee$ + jets	–	94%	–	–	–	–
$Z \to \mu\mu$ + jets	–	–	95%	–	2%	–
$W \to e\nu$ + jets	6%	–	–	68%	–	–
$W \to \mu\nu$ + jets	9%	–	–	–	67%	–
$W \to \tau\nu$ + jets	20%	–	–	5%	7%	–
γ + jets	–	–	–	–	–	>99%
Top	7%	3%	2%	25%	21%	–
Multi-boson	3%	3%	3%	2%	3%	<1%

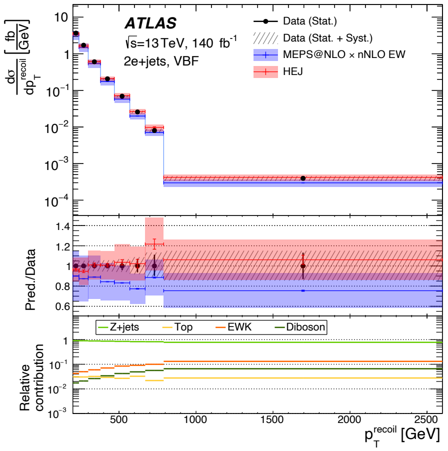
p_T^{miss} + jets final state VBF SR

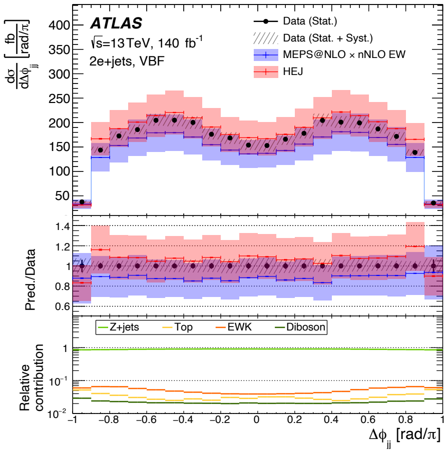


p_T^{miss} + jets final state VBF lepton regions

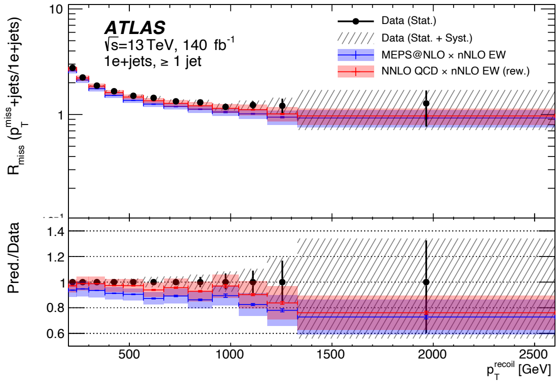
- Additional High Energy Jets (HEJ) V+jets predictions
  - Corrections phase space where jets span a large range of rapidity or where pairs of jets have a large invariant mass.
  - J. R. Andersen et al., HEJ 2.2: W boson pairs and Higgs boson plus jet production at high energies, (2023), arXiv: 2303.15778 [hep-ph]
- Improves shape modelling of m_{jj}

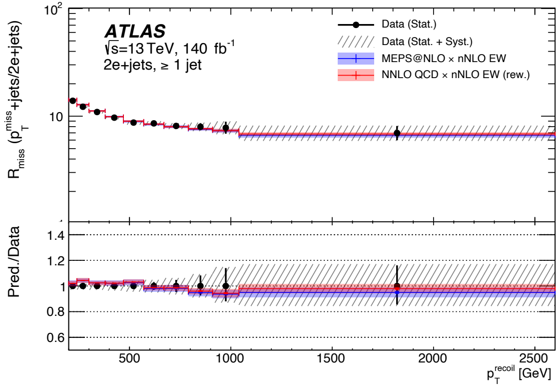


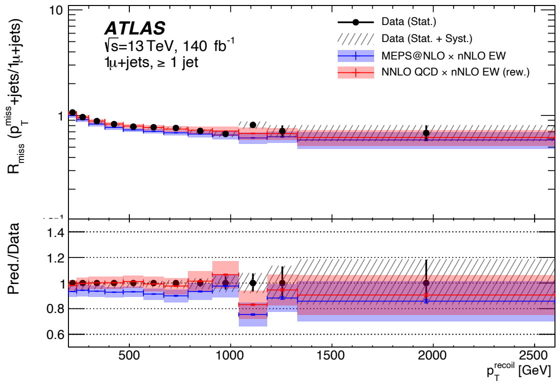


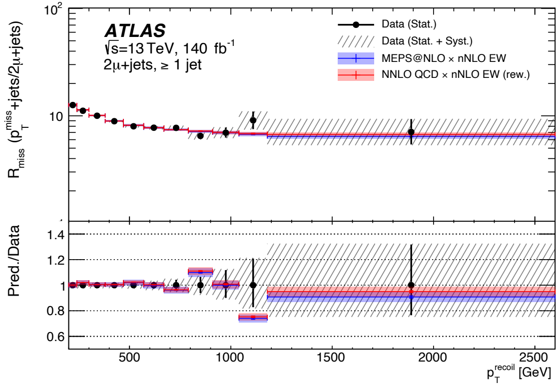


p_T^{miss} + jets final state Rmiss

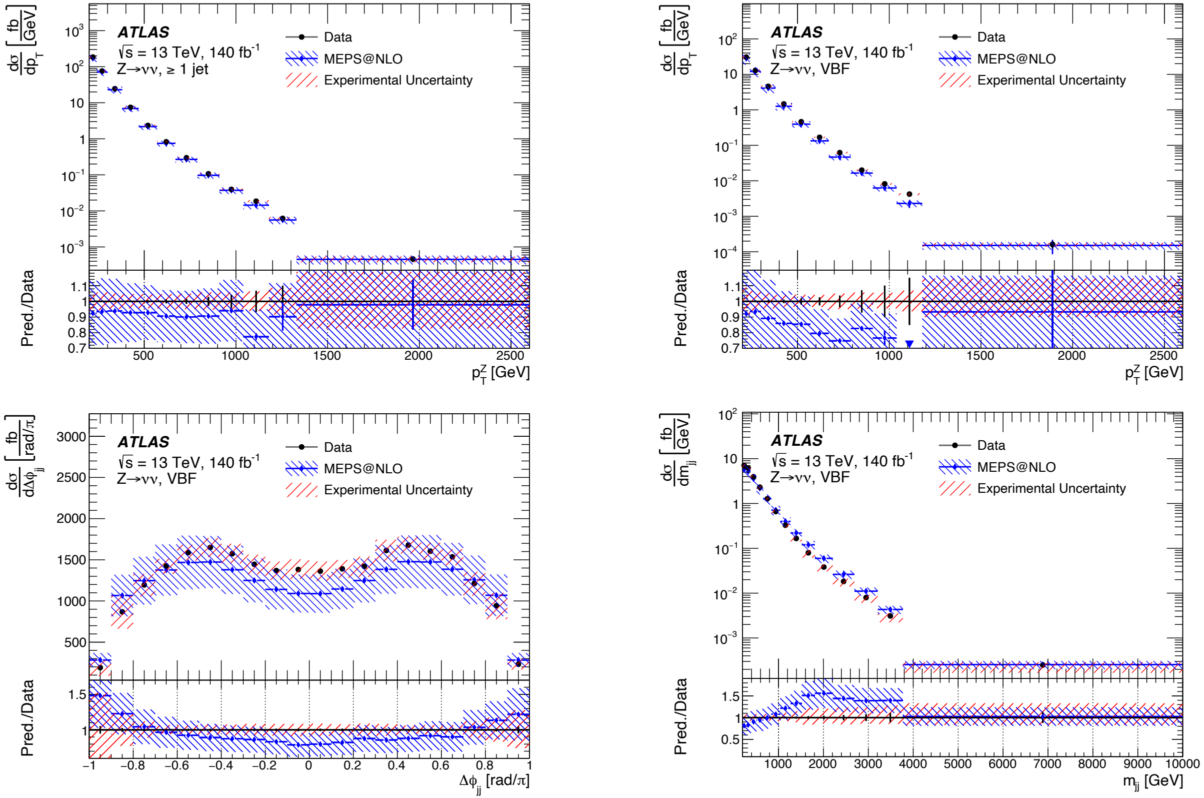








p_T^{miss} + jets dominant process results



Z+HF Flavour-schemes

- V+HF characterised by hard scale Q and quark mass m_q
- pQCD calcuations contain terms of m_q^2/Q^2 and $\ln(Q^2/m_q^2)$ for q/g collinear splittings
  - 3FS: massive c-quarks → c-quark appears only via gluon splitting
  - 4FS: massive b-quarks → b-quark appears only via gluon splitting
    - Suitable for $Q \sim m_q$
  - 5FS: massless b-quarks → b-quark allowed via intrinsic PDF
    - For $Q^2 \gg m_b^2$

Slide borrowed from Yi Yu's talk !

Z+HF fixed-order predictions

- Difficult to have a definition of a flavoured jet that is infrared and collinear (IRC) safe
  - e.g. consider a soft $g \to bb$ splitting, with one b-quark clustered in a hard jet and the other forms another jet
  - Fixed-order predictions in this measurement use flavour dressing algorithm
    [Gauld, Huss, Stagnitto] Phys. Rev. Lett. 130 (2023) 161901
- Corrections are applied to fixed-order predictions for direct comparison to data, because former are made at parton level and use different jet-flavour algorithm
  - Ratio of hadron-level sample with multi-parton interaction (MPI) to parton-level sample without MPI (using LO Sherpa 8.3831 samples)
  - Ratio of hadron-level distributions using cone-based vs. flavour-dressing algorithm, MGaMC+Py8 FxFx. Same ratio with Sherpa 2.2.11 sample used as its uncertainty
  - Both corrections are applied to the fixed-order predictions as bin-by-bin multiplicative factors.

Z+HF detector-level selections

Object definition		
	Electron channel	Muon channel
Leptons	Single electron trigger Tight Isolated $d_0/\sigma_{d_0} < 5$, $\|z_0 \sin(\theta)\| < 0.5$ mm $p_T > 27$ GeV $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	Single muon trigger Medium Isolated $d_0/\sigma_{d_0} < 3$, $\|z_0 \sin(\theta)\| < 0.5$ mm $p_T > 27$ GeV $\|\eta\| < 2.5$
Jets	$p_T > 20$ GeV and $\|y\| < 2.5$ $\Delta R(\text{jet}, \ell) > 0.4$	
Flavour-tagged jets	$p_T > 20$ GeV and $\|y\| < 2.5$ DL1r@85%	

Event selection	
Leptons	Exactly 2, same-flavour, opposite-charge
$m_{\ell\ell}$	76 GeV $< m_{\ell\ell} <$ 106 GeV
E_T^{miss}	$E_T^{miss} < 60$ GeV if $p_T^{\ell\ell} < 150$ GeV
Flavour-tagged jets	≥ 1 or ≥ 2 jets, DL1r@85%
Signal regions	
1-tag	≥ 1 flavour-tagged jets
2-tag	≥ 2 flavour-tagged jets
Rapidity regions	
Central rapidity	Z boson rapidity $\|y(Z)\| < 1.2$
Forward rapidity	Z boson rapidity $\|y(Z)\| \geq 1.2$

Z+HF observables

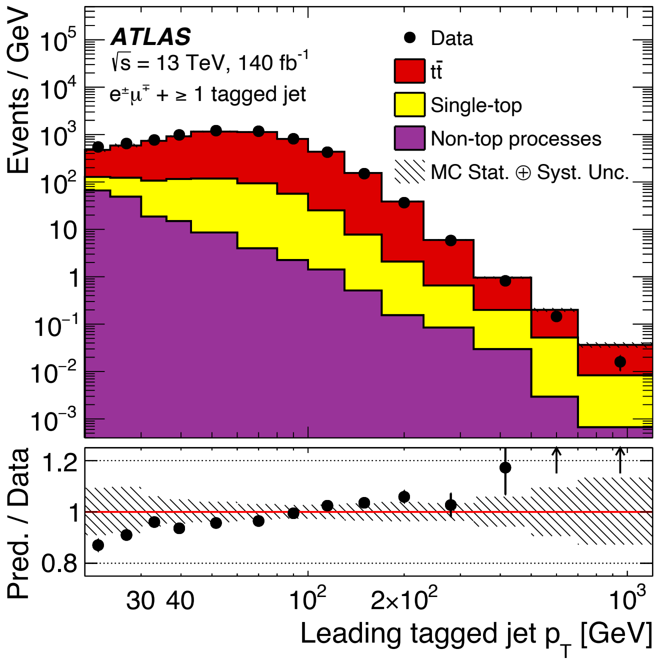
Table 1: List of observables used to perform differential cross-section measurements.

Final state	Observable	Notation
$Z + \geq 1$ b-jet	p_{T} of the leading b-jet	$p^{0}_{\mathrm{T},b}$
	p_{T} of the Z boson	$p_{\mathrm{T}}(Z)$
	$\Delta\tilde{R} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$ between the Z boson and leading b-jet, where $\Delta\phi$ (Δy) is the azimuthal angle (rapidity) difference	$\Delta\tilde{R}_{Zb}$
$Z + \geq 1$ c-jet	p_{T} of the leading c-jet	$p^{0}_{\mathrm{T},c}$
	p_{T} of the Z boson	$p_{\mathrm{T}}(Z)$
	Feynman-x variable $x_F = 2\lvert p_z(c)\rvert/\sqrt{s}$ [25]	$x_F(c)$
	Cross-section ratio of $p_{\mathrm{T}}(Z)$ in $\lvert y(Z)\rvert < 1.2$ and $\lvert y(Z)\rvert > 1.2$	$\mathrm{R}(p_{\mathrm{T}}(Z))$
$Z + \geq 2$ b-jets	Invariant mass of the two leading b-jets	m_{bb}
	Azimuthal angle difference between the two leading b-jets	$\Delta\phi_{bb}$

Z+HF top background estimate

- Dileptonic $t\bar{t}$ constitute a large background
- Estimated in data-driven approach to mitigate large modelling uncertainties
- Dedicated CR with $e^{\pm}\mu^{\mp}$ in 71 GeV $< m_{\ell\ell} < 111$ GeV
- $\text{ttbar}^{\text{SR}}_{\text{Data}} = \text{ttbar}^{\text{SC}}_{\text{Data}} * TF^{\text{CR}\to\text{SR}}$

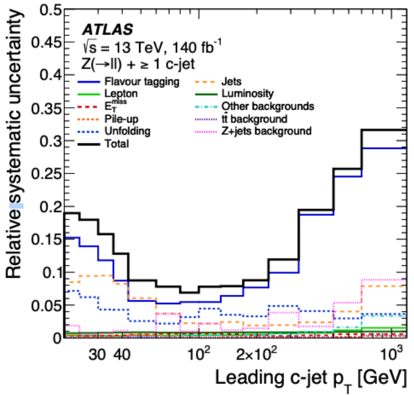
$$TF^{\text{CR}\to\text{SR}} = \text{ttbar}^{\text{SR}(ee/\mu\mu)}_{\text{MC}} / \text{ttbar}^{\text{CR}(e\mu)}_{\text{MC}}$$

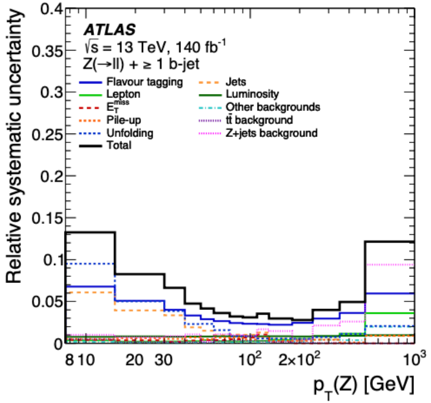


Z+HF uncertainty breakdown

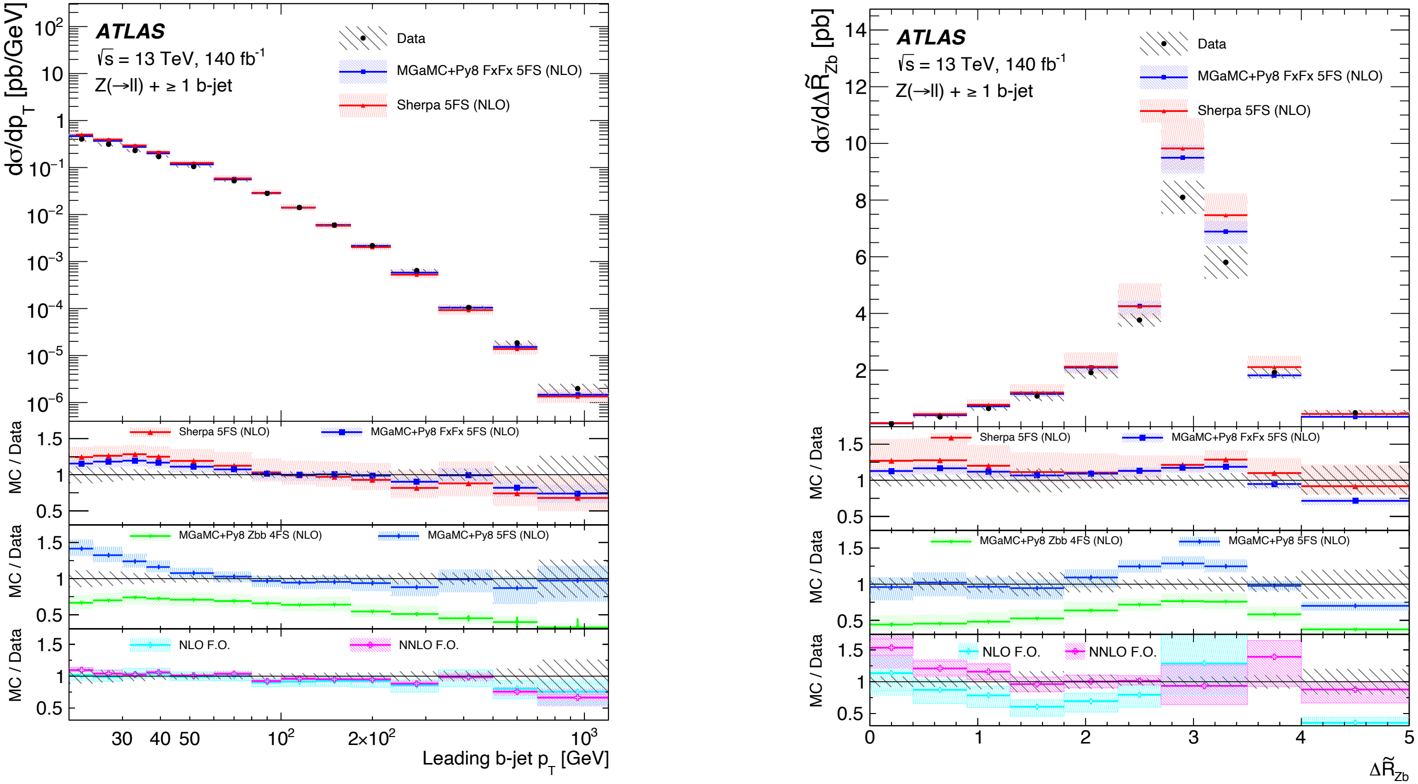
Source of uncertainty	$Z(\to \ell\ell) + \geq 1$ b-jet [%]	$Z(\to \ell\ell) + \geq 2$ b-jets [%]	$Z(\to \ell\ell) + \geq 1$ c-jet
Flavour tagging	3.6	5.7	10.3
Jet	2.4	4.3	6.5
Lepton	0.3	0.3	0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	0.5	0.3
Z+jets background	0.6	1.5	1.6
Top background	0.1	0.3	<0.1
Other 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

- Jet: energy scale, resolution, jet-vertex-tagging
- Z+jets: (i) post-fit MGAMC+PY8 FXFX vs SHERPA 2.2.11 difference and (ii) MGAMC+PY8 FXFX QCD scale
- Top: extrapolation from CR to SR
- Statistical uncertainty from bootstraps ($< 1\,\%$)
- Unfolding: (i) MGAMC+PY8 FXFX statistics, (ii) data-driven unfolding-bias and (iii) modelling from comparison with SHERPA

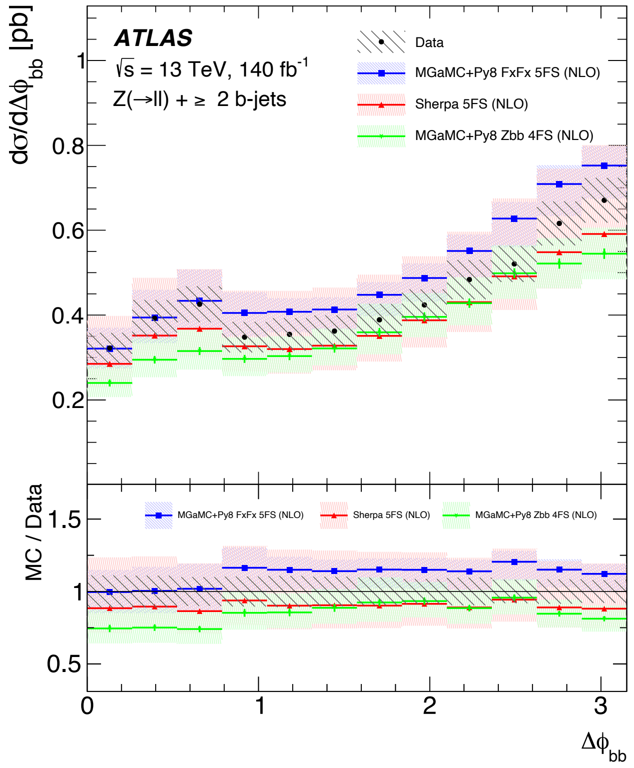




Z+HF (Z+≥ 1 b-jet)

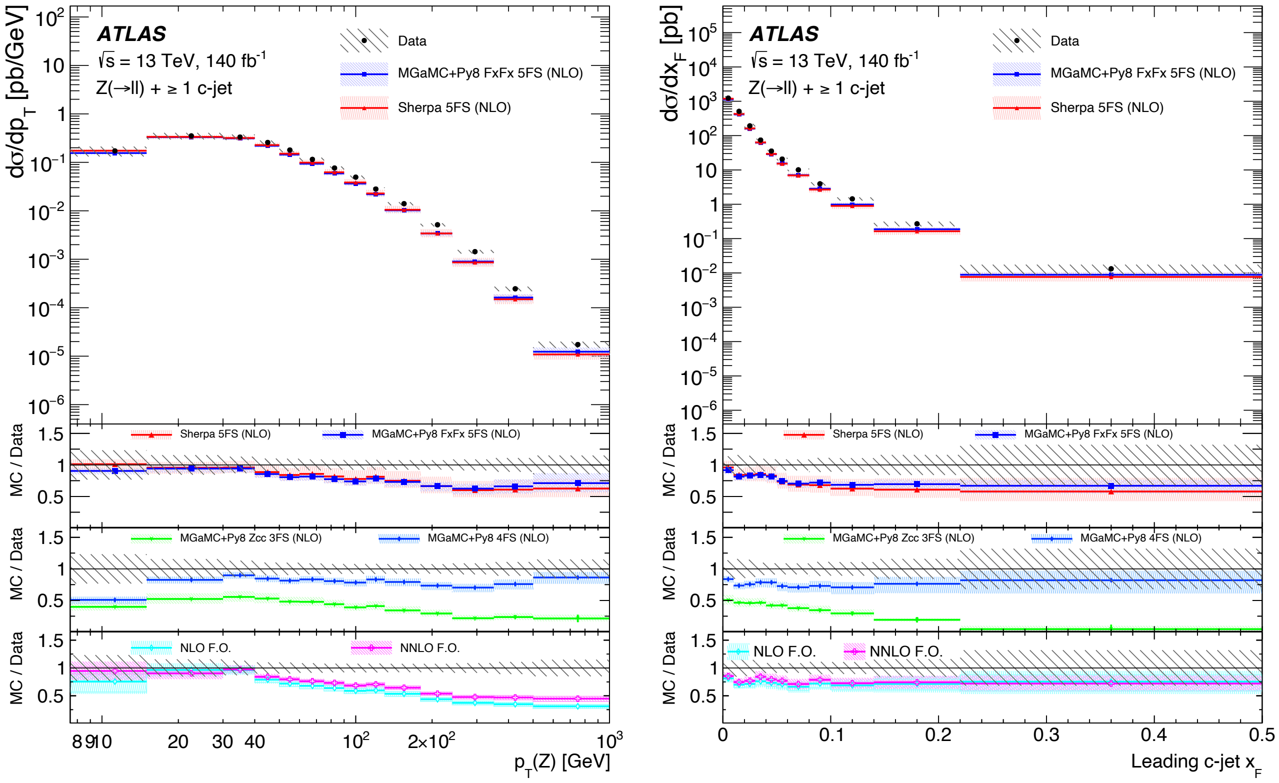

ATLAS
√s = 13 TeV, 140 fb-1
Z(→ll) + ≥ 1 b-jet
Data
MGaMC+Py8 FxFx 5FS (NLO)
Sherpa 5FS (NLO)
dσ/dp_T [pb/GeV]
MC / Data
MGaMC+Py8 Zbb 4FS (NLO)
MGaMC+Py8 5FS (NLO)
NLO F.O.
NNLO F.O.
Leading b-jet p_T [GeV]
dσ/dΔR̃_Zb [pb]
ΔR̃_Zb

Z+HF (Z+≥ 2 b-jet)



ATLAS
√s = 13 TeV, 140 fb-1
Z(→ll) + ≥ 2 b-jets
Data
MGaMC+Py8 FxFx 5FS (NLO)
Sherpa 5FS (NLO)
MGaMC+Py8 Zbb 4FS (NLO)
dσ/dΔφbb [pb]
MC / Data
Δφbb

Z+HF (Z+≥ 1 c-jet)



ATLAS
√s = 13 TeV, 140 fb-1
Z(→ll) + ≥ 1 c-jet
Data
MGaMC+Py8 FxFx 5FS (NLO)
Sherpa 5FS (NLO)
dσ/dp_T [pb/GeV]
MC / Data
MGaMC+Py8 Zcc 3FS (NLO)
MGaMC+Py8 4FS (NLO)
NLO F.O.
NNLO F.O.
p_T(Z) [GeV]
dσ/dx_F [pb]
Leading c-jet x_F

Z+HF (Z+≥ 1 c-jet) for different IC models