Measurement of multi-jets and vector boson plus jets production in ATLAS

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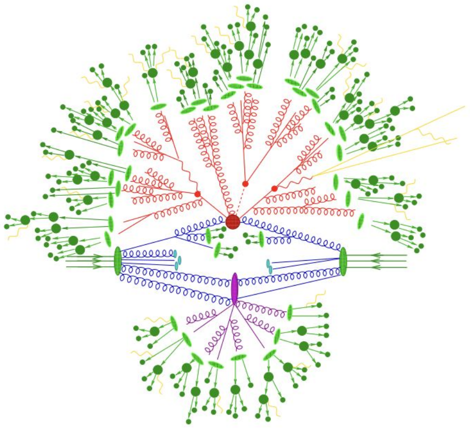
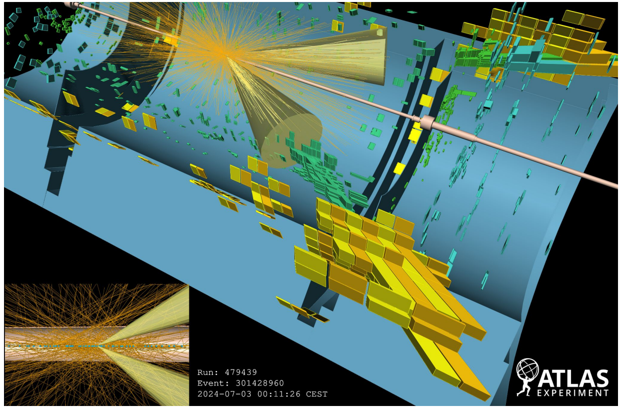
Motivation

- QCD governs strong interactions in proton–proton collisions at LHC.
- Jets result from fragmentation of high energy quarks and gluons.
  - Combination of perturbative and non-perturbative contributions.
  - Probe QCD at different regimes.
- QCD explored by:
  - Multi-jets production and measurements:
    - Jets substructures: measure correlations between multiple particles produced in the same identified jet - *Jet track functions*, *Lund Jet Plane*
  - V+jets measurements, sensitive to QCD and EW corrections. - *W+jets collinear*, *Z+HF jets.*
- This talk will focus on the most novel measurements in ATLAS.





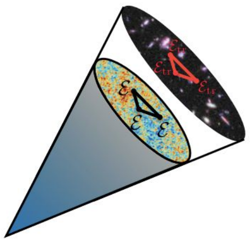
PublicATLASEventDisplayRun3

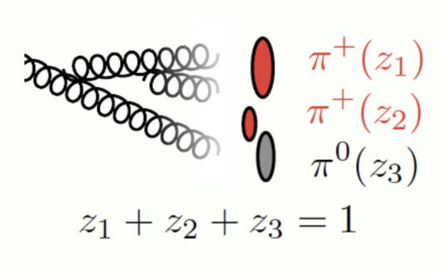
Jet track functions

- Jet substructure variable defined in theory as the fraction of a parton's energy carried by charged hadrons in the collinear limit.
- Non-linear Renormalization Group (RG) scale evolution (Beyond DGLAP paradigm).
- Universal non-perturbative functions

Experimentally, measure $r_q = p_T^{tracks}/p_T^{all}$, moments and RG evolution

$\langle r_q \rangle \sim ⅔$





$$T_g(z) \propto \underline{\delta(z_1 + z_2 - z)}$$

$$D_{g\to\pi^+}(z) \propto \underline{\delta(z_1 - z) + \delta(z_2 - z)}$$

Multi-charge-hadron observable and non-linear RG
wrt Fragmentation Functions (FFs) → single hadron and DGLAP/linear

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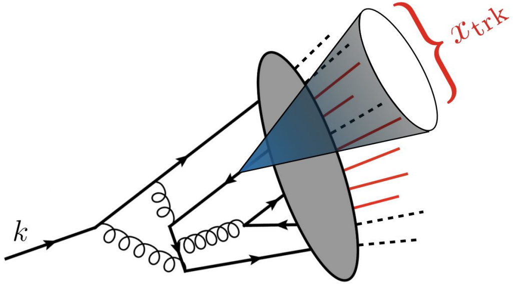
Measurement of jet track functions

arXiv:2502.02062

- Measurement of the energy distribution of tracks in identified high-p_T jets, using the full Run 2 dataset (140 fb^{-1}).
- The measurement differentially in r_q and in different regions of jet p_T and for different rapidity-ordering of a dijet system (i.e., for more-central vs. more-forward jets)
  - First measurement of cross section as a function of r_q .
  - Extract the moments of r_q as a function of jet p_T.



- Data corrected using Iterative Bayesian Unfolding (IBU) and machine learning-based method OmninFold used for moment extraction.

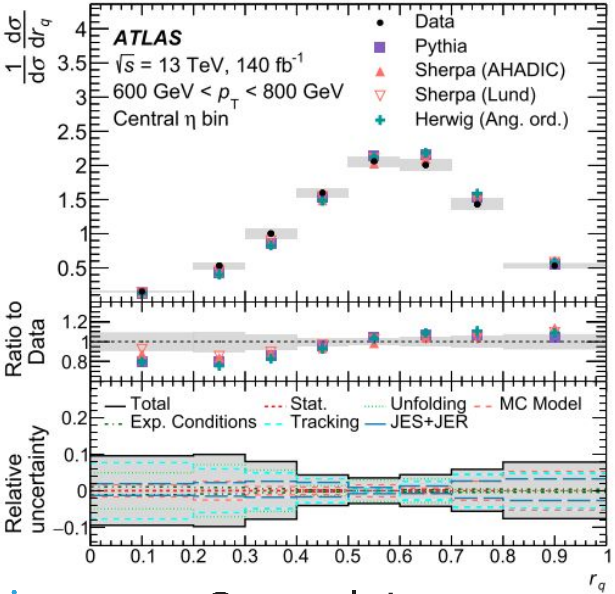
Measurement of jet track functions

arXiv:2502.02062

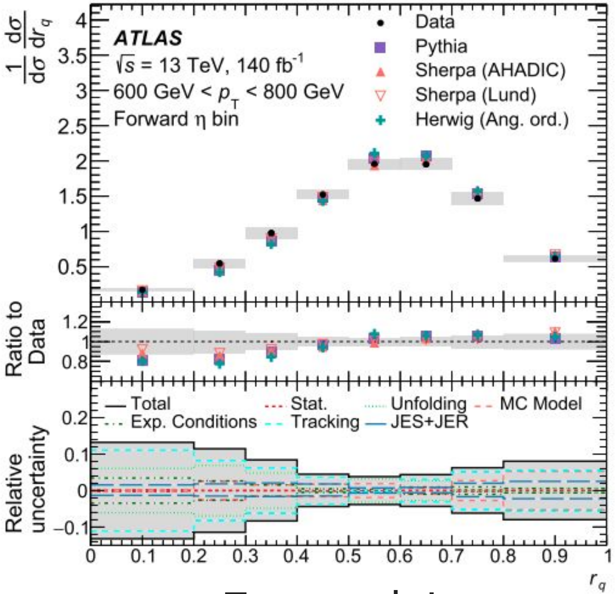
Unfolded cross sections

- Iterative bayesian Unfolding, implemented in RooUnfold.

- Simultaneous unfolding in 3 dimensions (jet p_T, η, r_q).



Central Jets



Forward Jets

- Tracking uncertainty dominant.
- Good agreement with MC predictions.
  - Ratio MC/data trend <1 lower values and >1 higher values of r_q .

Measurement of jet track functions

arXiv:2502.02062

Extracting the Moments

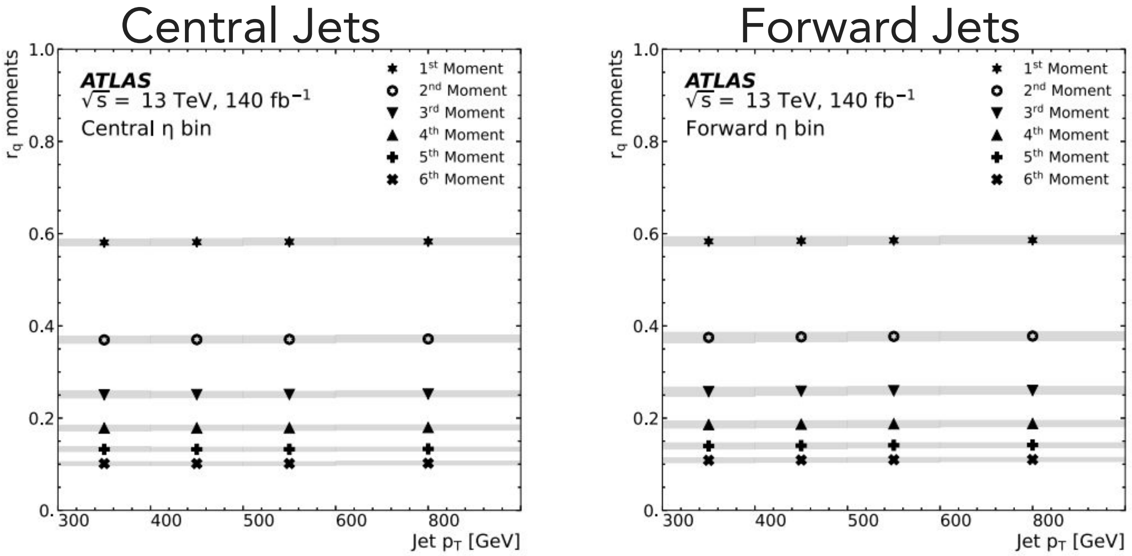
- Extract by the unfolded distributions:

$$n^{th}\ \textbf{moment:}\quad m_n = \int_0^1 dz\, z^n\, T(z)$$

where z is the fraction momentum of the charged tracks inside the jet.

Moment calculated as summed on the bin content $m_n = \sum^{i} x_i^n h_i$
→ *discretization effect*

- Data driven method with OmniFold (MultiFold) for bin correction:



$$\frac{m^{\mathrm{IBU}}}{m^{\mathrm{corrected}}} = \frac{m^{\mathrm{MultiFold}}_{\mathrm{IBU\ binning}}}{m^{\mathrm{MultiFold}}_{\mathrm{unbinned}}} \rightarrow m^{\mathrm{corrected}} = m^{\mathrm{IBU}} \times \frac{m^{\mathrm{MultiFold}}_{\mathrm{unbinned}}}{m^{\mathrm{MultiFold}}_{\mathrm{IBU\ binning}}}$$

$$m_n = \sum^{i} x_i^n h_i \times \left(\frac{m^{\mathrm{MultiFold}}_{\mathrm{unbinned}}}{m^{\mathrm{MultiFold}}_{\mathrm{IBU\ binning}}} \right)^{\mathrm{nom.}}$$

Measurement of jet track functions

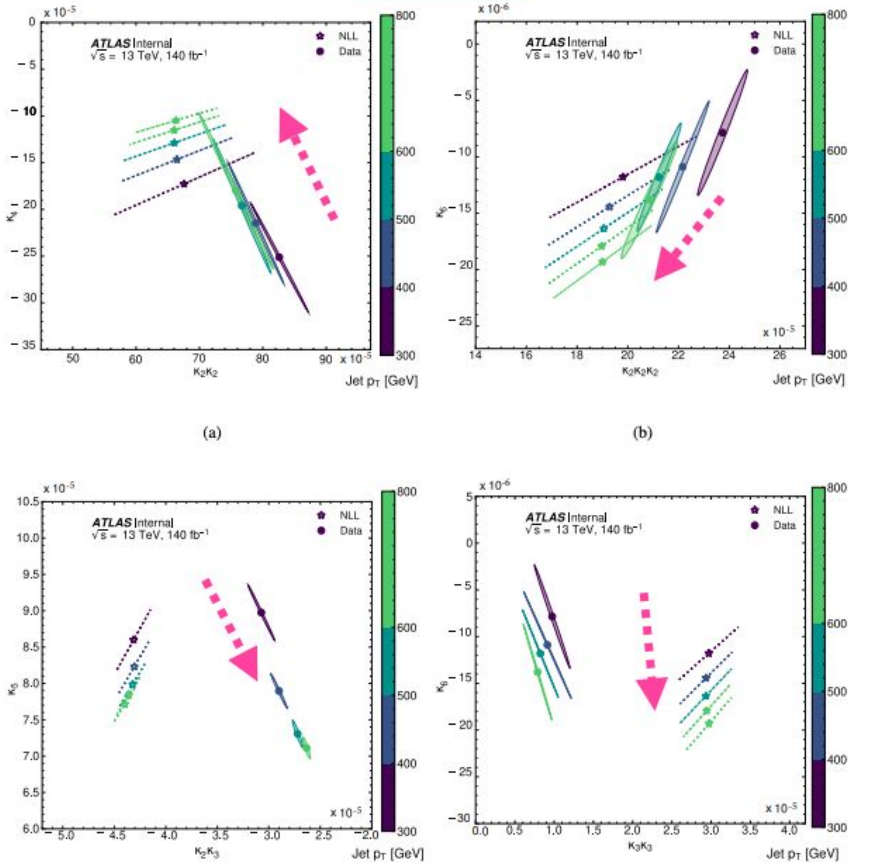
arXiv:2502.02062

Non-linear RG Evolution

- Cumulants $\boldsymbol{k}_i$ (moments' functions)

$$\kappa_1 = m_1$$
$$\kappa_2 = m_2 - m_1^2$$
$$\kappa_3 = m_3 - 3m_2m_1 + 2m_1^3$$
$$\kappa_4 = m_4 - 4m_3m_1 - 3m_2^2 + 12m_2m_1^2 - 6m_1^4$$
$$\kappa_5 = m_5 - 5m_4m_1 - 10m_3m_2 + 20m_3m_1^2 + 30m_2^2m_1 - 60m_2m_1^3 + 24m_1^5$$

- The energy dependence of cumulant pairs determined by non-linear RG group flows
  - hint on correlations in the hadronization process.
- Comparison the shape of the flows with QCD NNL prediction of RG
  - Test of the non-linear RG flows during jet formation.



(a)

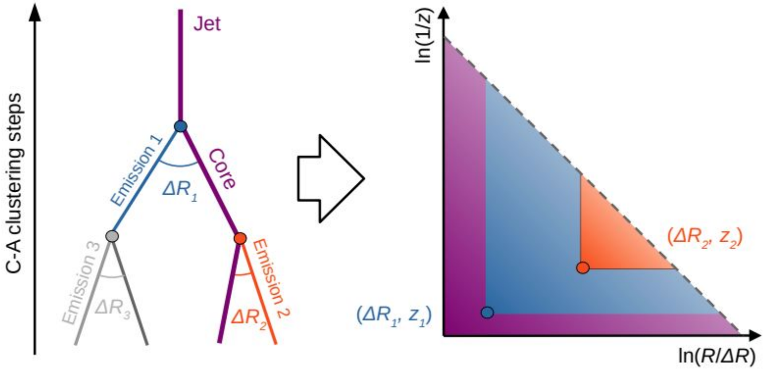
(b)

Lund Jet Plane (LJP) measurement

arXiv:2407.10879

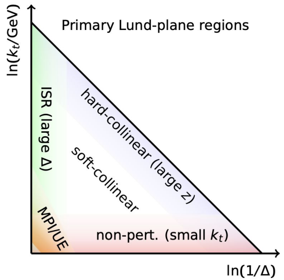
- Jet substructure observable.
- Reconstruct the hierarchy of QCD emissions within jets.

- 2D representation of the jet substructure:
  - Displays momentum fraction and opening angle of emissions inside a jet.
  - Use for kinematics of parton showers and hadronization, factorise QCD effects.
  - Built by reclustering emissions with Cambridge-Aachen algorithm.



$$\Delta R^2 = (y_{core} - y_{em})^2 + (\phi_{core} - \phi_{em})^2$$

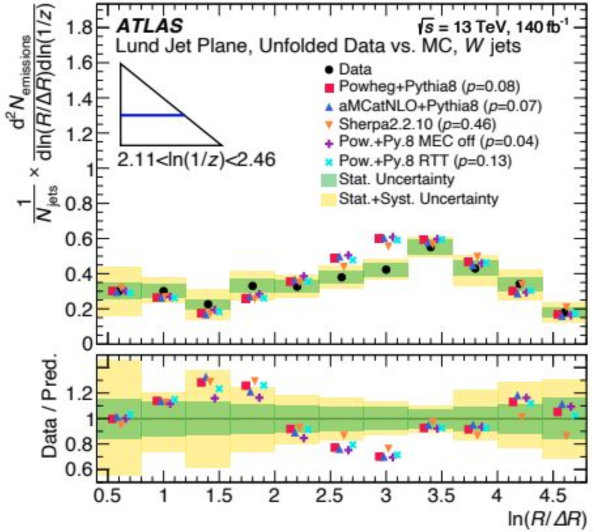
$$z = \frac{p_T^{em}}{p_T^{core} + p_T^{em}}$$

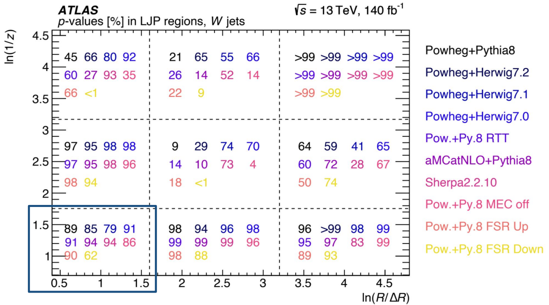


Lund Jet Plane (LJP) measurement

arXiv:2407.10879

- **First measurement of the LJP** for jets initiated by W bosons and top-quarks, with the Run-2 dataset (140 fb^{-1})
  - W boson: large mass and colour singlet.
  - using *tt* events, selections on jet mass and distance from b jet.
- Systematic uncertainty of 10-40% (signal modelling).
- Comparison with MC event generator: different matrix element, parton-shower and hadronization models.
  - None generators agrees across the whole LJP for W jets, better agreements in subregions.
- Useful for improving and tuning of MC *tt* event generators in parameters controlling the source radiation, poorly modelled in LJP.

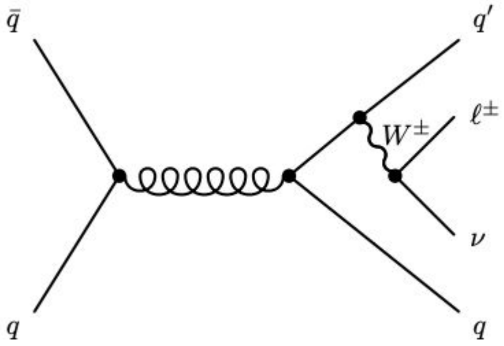




W+jets collinear

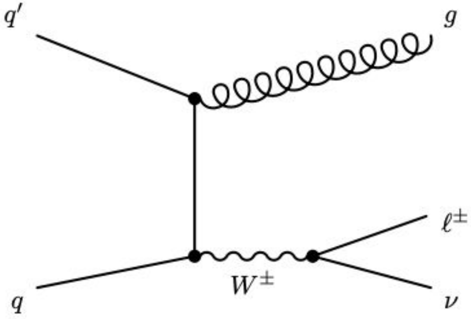
arXiv:2412.11644

- Measurement of **collinear** W boson emission from high energy jets at $\sqrt{s}$ = 13 TeV with the full Run-2 ATLAS dataset (140 fb^{-1})
- Inclusive and differential cross-section of ***W*-boson** decay in electron and muon produced in association with at least one **high-p_T jet** of pT>500 GeV.
- Clear signature for testing EW and QCD.
- Differential cross section in $\Delta R_{min}(l,jet^{100}_{i})$, $p_T^{l\nu}/p_T^{\text{closest jet}}$ sensitive to the collinear/back-to-back regions.
  - Collinear enhancement in the total rate.
- Unfolded data comparison with NLO-merged W+jet MC, with and without EW corrections (Sherpa, Madgraph) and fixed order W+1jet NNLO predictions (MCFM).



Collinear region

NLO α_s



Back-to-back region

LO α_s

W+ jets collinear

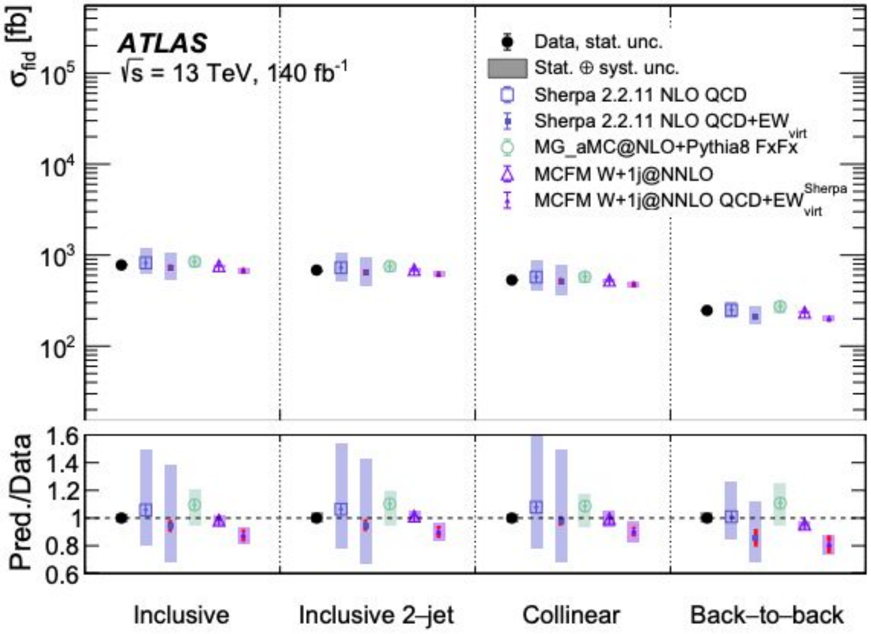
[arXiv:2412.11644](https://arxiv.org/abs/2412.11644)

*see backup

Fiducial total cross section

- High uncertainties from Sherpa and Madgraph (QCD scale uncertainty variations).
- Good agreement data-MCFM in all the regions.
- NLO EW correction improve Sherpa agreement in collinear region, but 10% underestimation for MCFM.
- Total systematic uncertainty of 3-4%, dominated by background modelling and JES/JER.

Signal regions	
Inclusive	All requirements above*
Inclusive 2-jet	Inclusive plus $n_{\text{jet}} \geq 2$
Collinear	Inclusive plus $\Delta R_{\min}(\ell, \text{jet}_i^{100}) < 2.6$
Back-to-back	Inclusive plus $\Delta R_{\min}(\ell, \text{jet}_i^{100}) > 2.6$

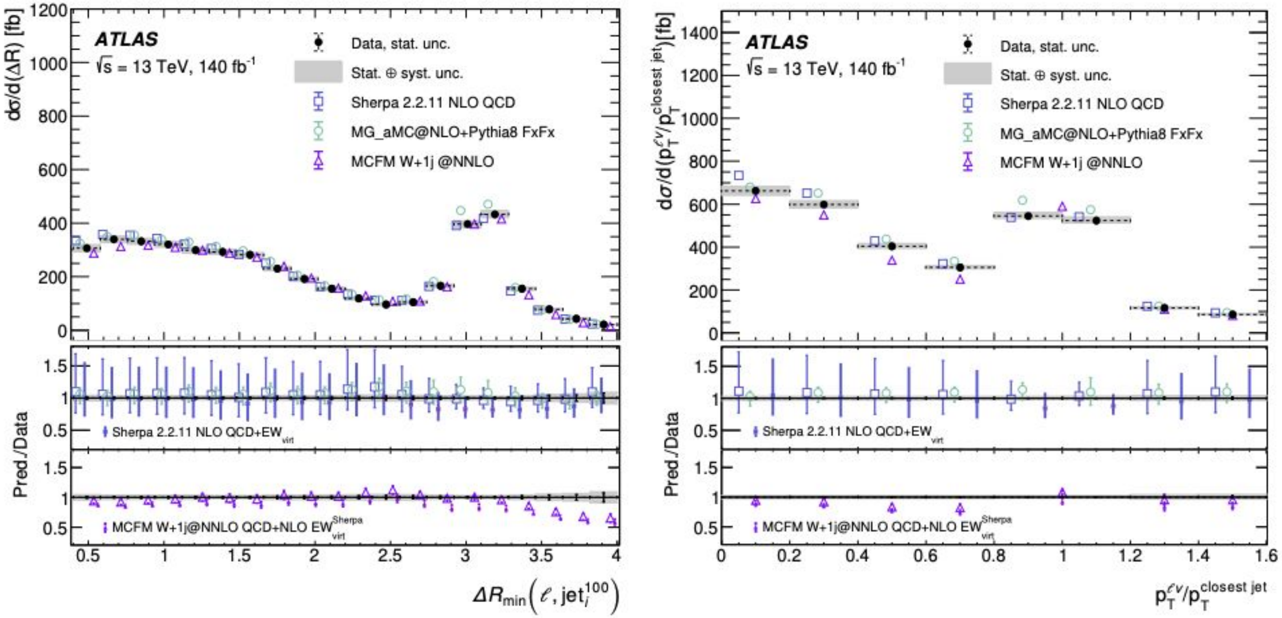


W+ jets collinear

arXiv:2412.11644

Differential cross section:

- $\Delta R_{min}(l, jet^{100}_i)$, $p_T^{l\nu}/p_T^{closest\ jet}$:
  - $\Delta R_{min}(l, jet^{100}_i)<2.6$ and $p_T^{l\nu}/p_T^{closest\ jet} \neq 1$ collinear region
- Madgraph+Pythia8 FxFx good agreement both variables
- $\Delta R_{min}(l, jet^{100}_i)>\pi$ MCFM disagreement

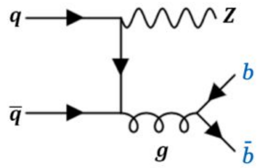


- Inclusion of NLO EW in Sherpa improves the agreement in the collinear regions but underestimate in back-to-back regions.

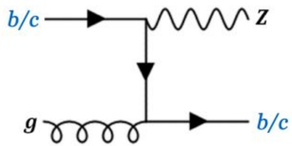
Z+Heavy Flavours jets

[arXiv:2403.15093](https://arxiv.org/abs/2403.15093)

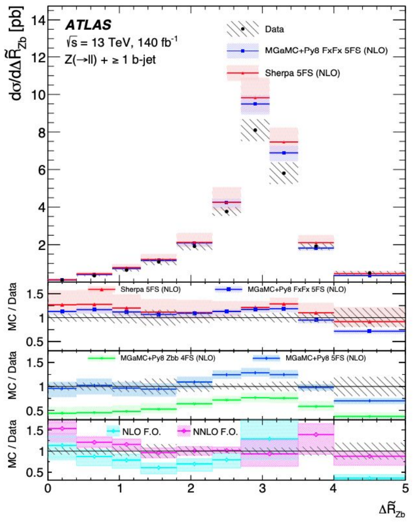
- Measurements of production rate of a Z+c-jets (first time in ATLAS) and Z+bjets
  - Input for the improvement of theoretical predictions and MC generators of Z+c/b and QCD.
  - Sensitive to flavour number schemes (4FS and 5FS) in PDF and intrinsic charm in PDF.
- Differential cross section (angular separation, leading jet p_T).
- In general: 5FS Madgraph and Sherpa well described Z+b.
- All generators underestimate the Z+c.

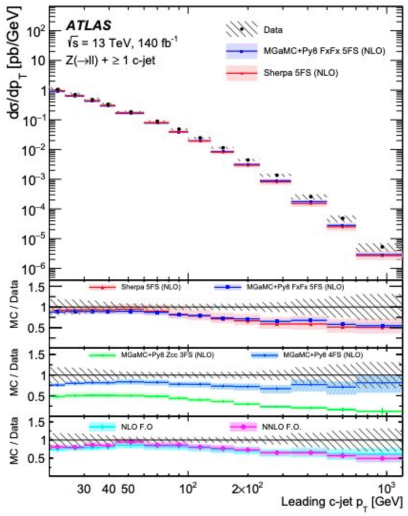


4FS



5FS





Conclusion

- An overview of recent ATLAS measurement of multijet and vector boson plus jets production are presented here
  - Enabling precise QCD and EW studies.
- Recent studies:
  - Measurement of the energy distribution of tracks in identified high-pT jets as jet substructure investigation (arXiv:2502.02062)
  - First measurement of Lund Jet Plane for jets by W boson, sensitive to tt modelling (arXiv:2407.10879v2)
  - Measurement of collinear W boson emission from high energy jets, sensitive to EW and pQCD (arXiv:2412.11644)
  - Measurements of Z+c for the first time in ATLAS and Z+b jets, sensitive to flavour schemes and intrinsic charm in PDF. (arXiv:2403.15093)

Backup

Measurement of jet track functions

arXiv:2502.02062

Selections:

- Jets reconstruction : anti-k_t algo with R=0.4 PFlow.
- The two most leading jets (separated into central/forward jet).
- Fiducial selection:
  - $p_T^{leading} > 240$ GeV,
  - $\eta_{jet} < 2.1$,
  - $p_T^{leading} / p_T^{subleading} < 1.5$.

Main uncertainties:

- Track reconstruction (8-12%)
- MC Modeling (2-5%)
- JES+JER (R21 jet energy scale & jet energy resolution)
- Exp. Condition (pile-up reweighting & disabled Tile modules) (2-3%)
- Unfolding (data-driven non-closure) (up to 12%)
- Statistical uncertainty

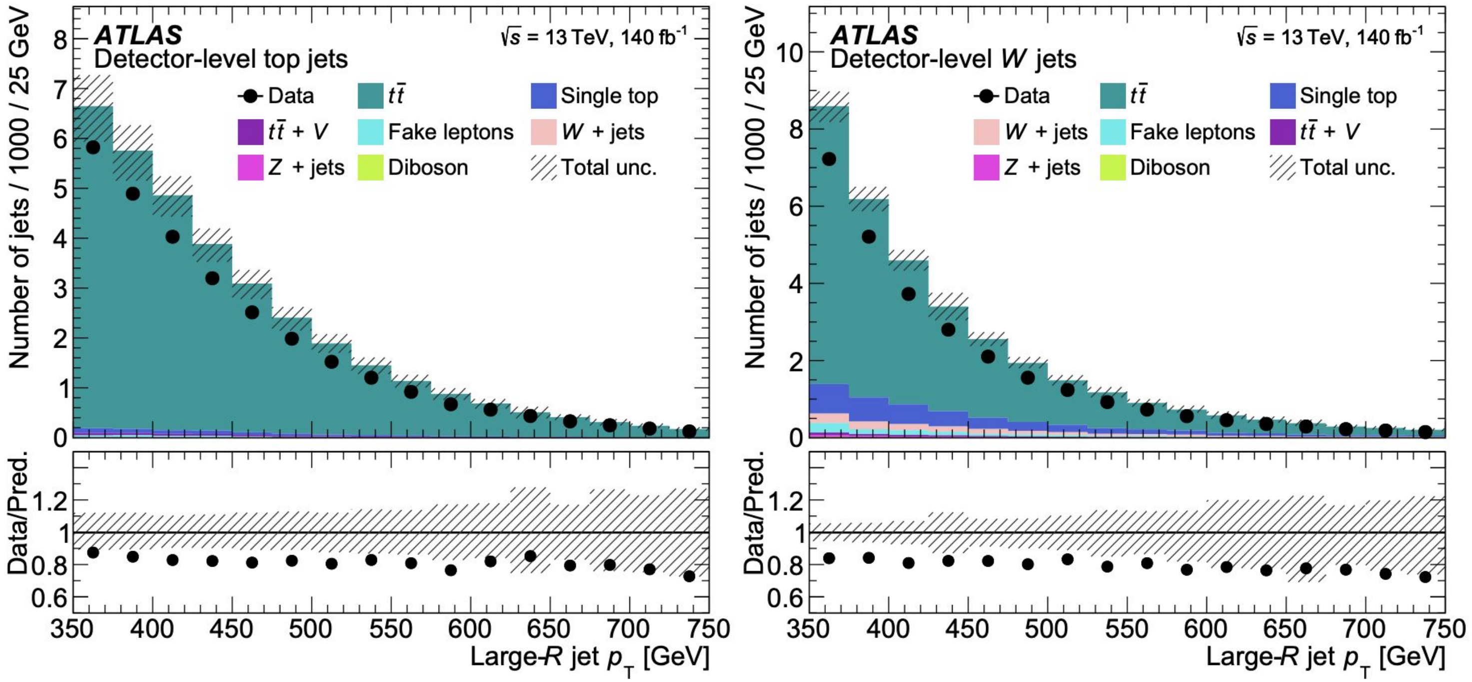
Lund Jet Plane (LJP) measurement

MC Signal generators:

- Powheg+Pythia 8: Nominal (hdamp=1.5 mt). Variants:
  - $h$damp var: hdamp=3.0 mt
  - ISR Up/Down, FSR Up/Down: change of scale parameters for ISR and FSR.
  - MEC Off: Matrix Element Corrections off (use tree-level ME emissions for improve accuracy of the prediction and approximate the emission at NLO precision)
  - RTT: Recoil to Top (different strategy for the treatment of recoil against gluon emissions from b-quarks originating in top quark decays)
  - pT(hard): Set to 1. This parameter changes the scale used to veto emissions in the PS to avoid overlaps between the phase spaces of the outgoing partons and the initial emissions of the Pythia shower.

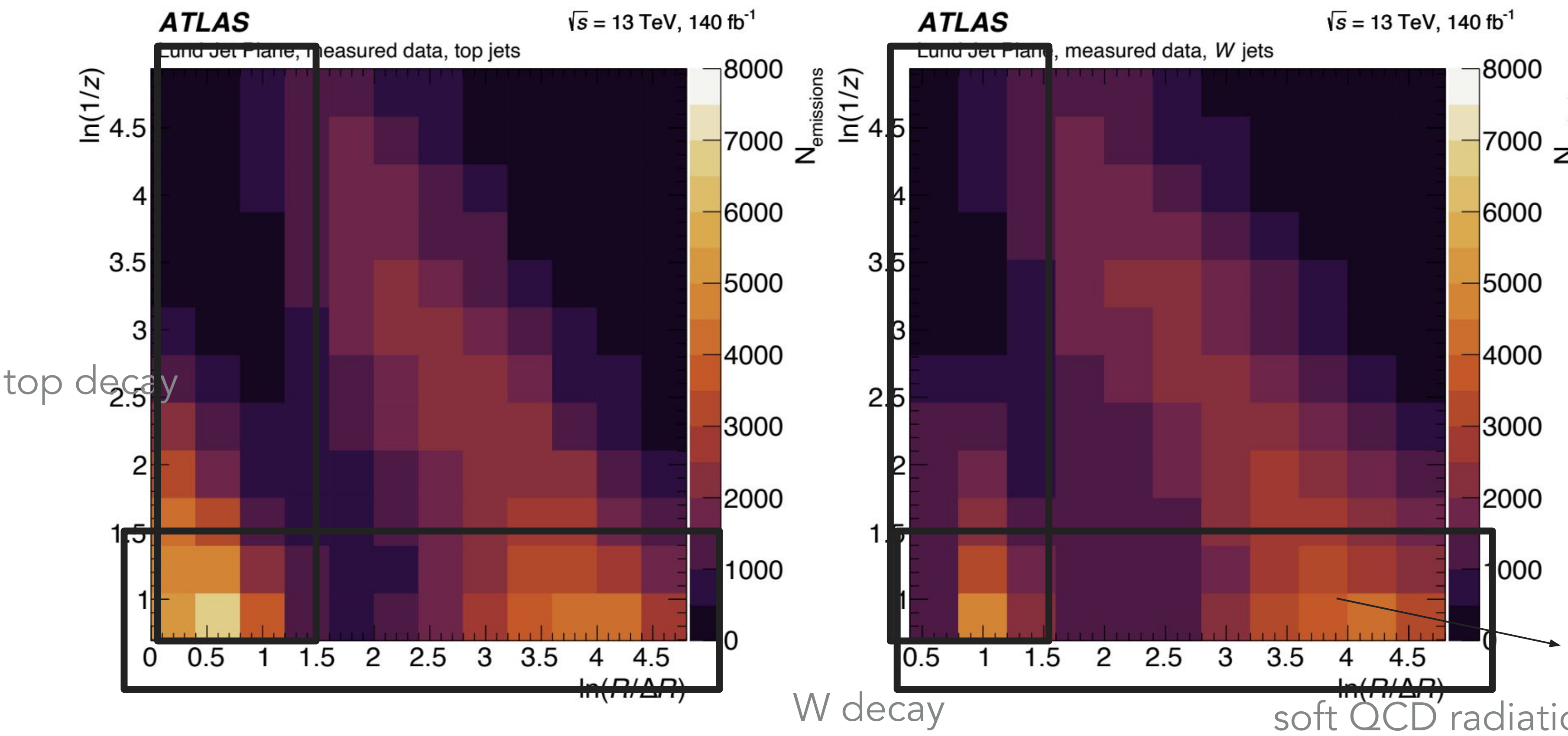
- Powheg+Herwig (7.0, 7.1, 7.2): The various Herwig 7 generator versions differ in terms of tunes of the hadronisation parameters, simulation of multiple-parton interactions and choice of evolution variable in the parton shower.
- MadGraph5_aMC@NLO+Pythia 8: Samples from additional $t\bar{t}$ matrix-element generator. MEC off here.
- Sherpa 2.2.10: The sample uses NLO-accurate matrix elements for processes with up to one additional parton, and LO-accurate matrix elements for up to four additional partons.

Lund Jet Plane (LJP) measurement

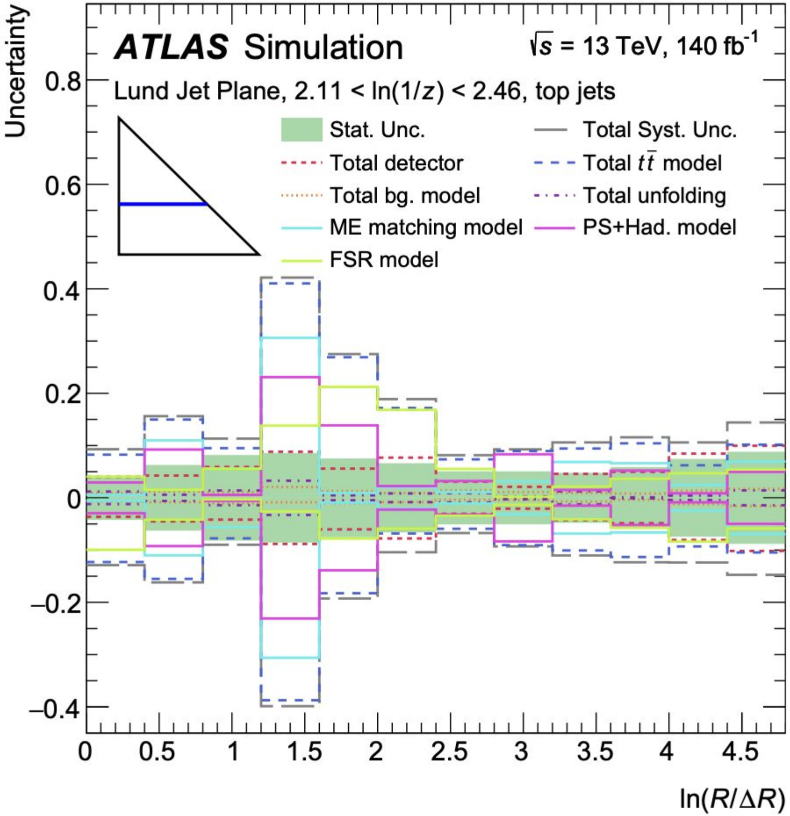


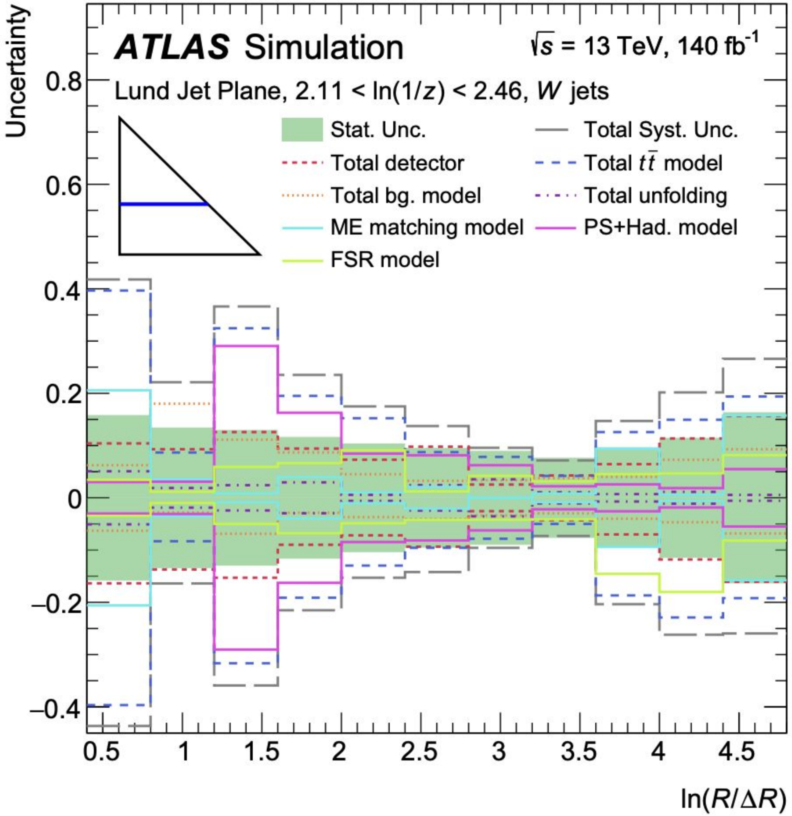
Mis-modelling of 30% in the tails and 15-20% in the head.
Due to tt cross-section in tt at high pt. (missing NLO ME predictions)

Lund Jet Plane (LJP) measurement



Lund Jet Plane (LJP) measurement





W+ jets collinear

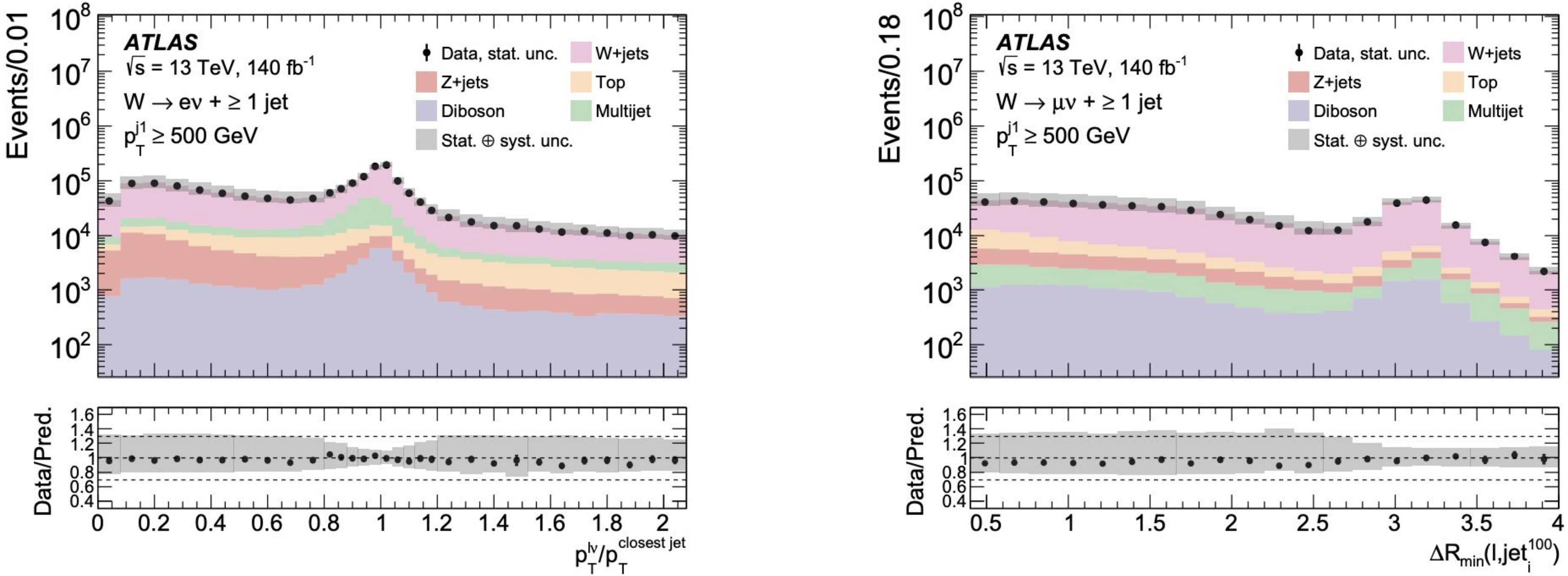
Simulated MC samples used to model signal and background processes.
The perturbative accuracy of the QCD calculation in the matrix element is given in the last column.

Process	Matrix element / Parton shower	Ref.	PDF set / Tune	Ref.	pQCD
W+jets	SHERPA 2.2.11	[40, 42, 68] [44, 69]	NNPDF30NNLO / SHERPA default	[43]	0-2j@NLO+3-5j@LO
W+jets	MADGRAPH v2.6.5 / PYTHIA 8.240	[47] [48]	NNPDF3.1luxQED / A14+FxFx	[51]	0-3j@NLO
Z/γ^* + jets	SHERPA 2.2.11	[40, 42, 68] [44, 69]	NNPDF30NNLO / SHERPA default	[43]	0-2j@NLO+3-5j@LO
Diboson	POWHEG v2 / PYTHIA 8.210	[55–57, 70] [48]	NLO CT10 / AZNLO	[64] [63]	0j@NLO
$t\bar{t}$+jets	SHERPA 2.2.12	[40, 42, 68] [44, 69]	NNPDF30NNLO / SHERPA default	[43]	0-1j@NLO+2-3j@LO
t (s-channel)	POWHEG v2 / PYTHIA 8.230	[55–57, 70] [48]	NLO CT10 / PERUGIA2012	[64] [71]	0j@NLO
t (t-channel)	POWHEG v2 / PYTHIA 8.230	[55–57, 70] [48]	NLO CT10f4 / PERUGIA2012	[64] [71]	0j@NLO
$t + W$	POWHEG v2 / PYTHIA 8.230	[55–57, 70] [48]	NLO CT10 / PERUGIA2012	[64] [71]	0j@NLO
EW W+jj	SHERPA 2.2.11	[40, 42, 68] [44, 69]	NNPDF30NNLO / SHERPA default	[43]	2j@LO
Multijet	PYTHIA 8.230	[48]	NNPDF2.3LO / A14	[36]	2j@LO

W+ jets collinear

Object selection	
Lepton momentum	$p_{\mathrm{T}}^{\ell} > 10$ GeV
Electron pseudorapidity	$\|\eta\| < 1.37,\ 1.52 < \|\eta\| < 2.47$
Muon pseudorapidity	$\|\eta\| < 2.4$
Jet transverse momentum	$p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV
Jet rapidity	$\|y\| < 2.5$
Event selection	
Leading lepton	$p_{\mathrm{T}}^{\ell} > 30$ GeV, trigger matched
Number of leptons	$n_{\ell} = 1$
Angular separation of leptons and jets	$\Delta R(\ell, \mathrm{jet}) > 0.4$
Number of jets	$n_{\mathrm{jet}} \geq 1$
Leading jet transverse momentum	$p_{\mathrm{T}}^{\mathrm{jet}} > 500$ GeV
b-jet veto	$n_{b\text{-jet}} = 0$
Signal regions	
Inclusive	All requirements above
Inclusive 2-jet	Inclusive plus $n_{\mathrm{jet}} \geq 2$
Collinear	Inclusive plus $\Delta R_{\min}(\ell, \mathrm{jet}_i^{100}) < 2.6$
Back-to-back	Inclusive plus $\Delta R_{\min}(\ell, \mathrm{jet}_i^{100}) > 2.6$

W+ jets collinear



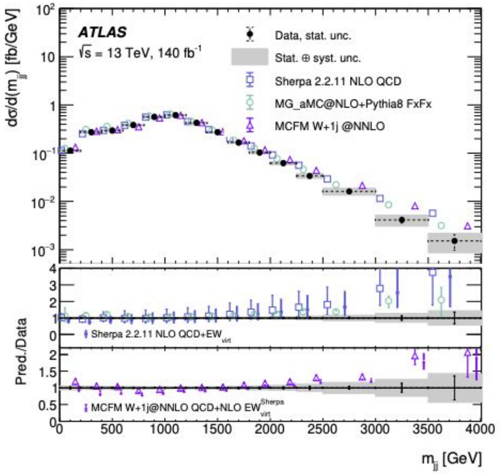
W+ jets collinear

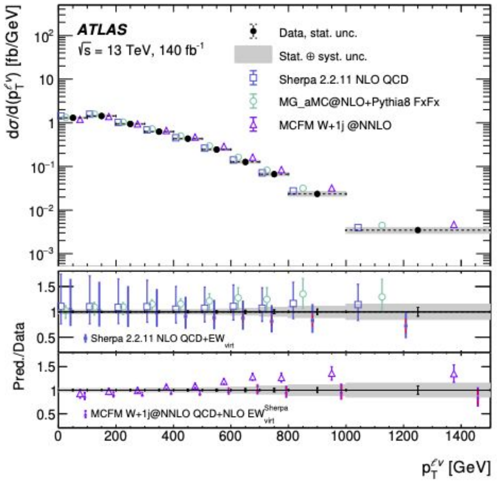
Relative uncertainties (in %) in the measured integrated cross-sections.

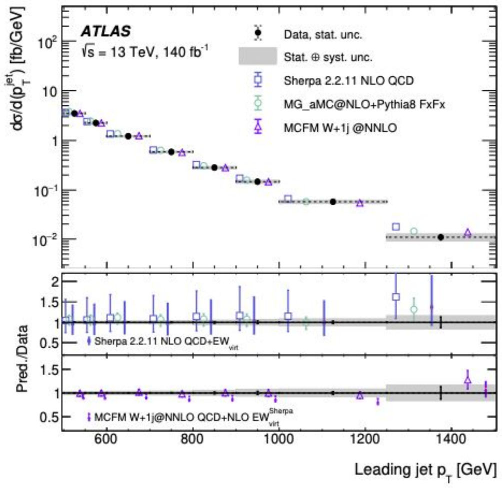
	Regions			
Uncertainty source	Inclusive	Inclusive 2-jet	Collinear	Back-to-back
Background modelling	2.0	2.1	2.0	2.3
JES/JER	1.3	1.2	1.1	1.6
b-tagging	1.2	1.4	1.5	0.7
Lepton	0.8	0.8	0.7	1.2
Unfolding	0.34	0.4	0.6	0.05
Luminosity	0.8	0.8	0.8	0.8
Pile-up	0.19	0.15	0.22	0.18
Others	0.14	0.19	0.20	0.03
Data statistical	0.4	0.5	0.5	0.8
Total uncertainty	3.3	3.4	3.4	4

W+ jets collinear

arXiv:2412.11644







- Important for BSM searches.
- Historically difficult to model.

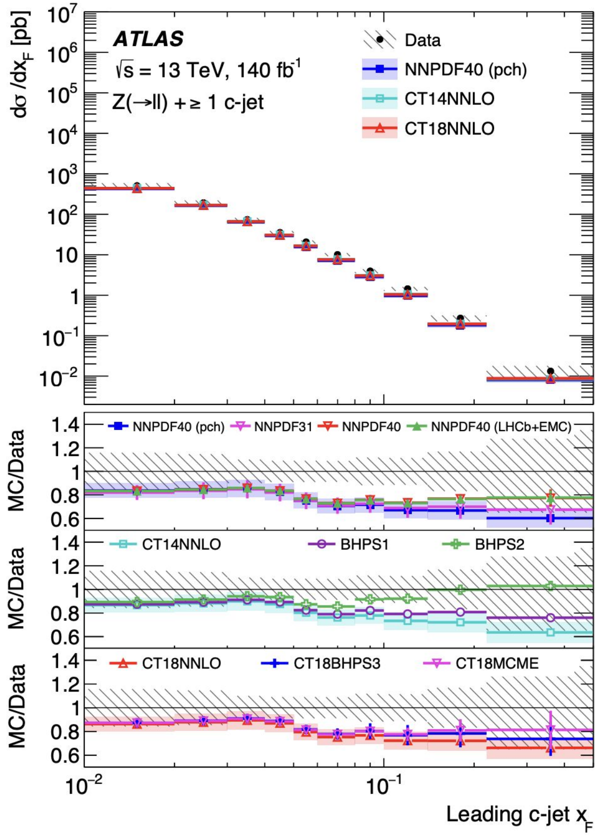
- MCFM NLO EW correction improve agreement at high values.

- Fixed order MCFM good agreement.
- Application of NLO EW leads a 10% of underestimation.

Z+Heavy Flavours jets

Cross section as a function of the Feynman-x variable, high values sensitive to IC.

- Test of NNLO predictions with various amount of IC
- Similar trend with respect to data by all IC model from NNPDF, CT14, and CT18 families
- BHPS2 improves agreement, but large measurement and modelling unc. → non conclusive yet
- Marginal improvement for more realistic scenario (BHPS1, NNPDF and CT18 families)



Z+Heavy Flavours jets

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