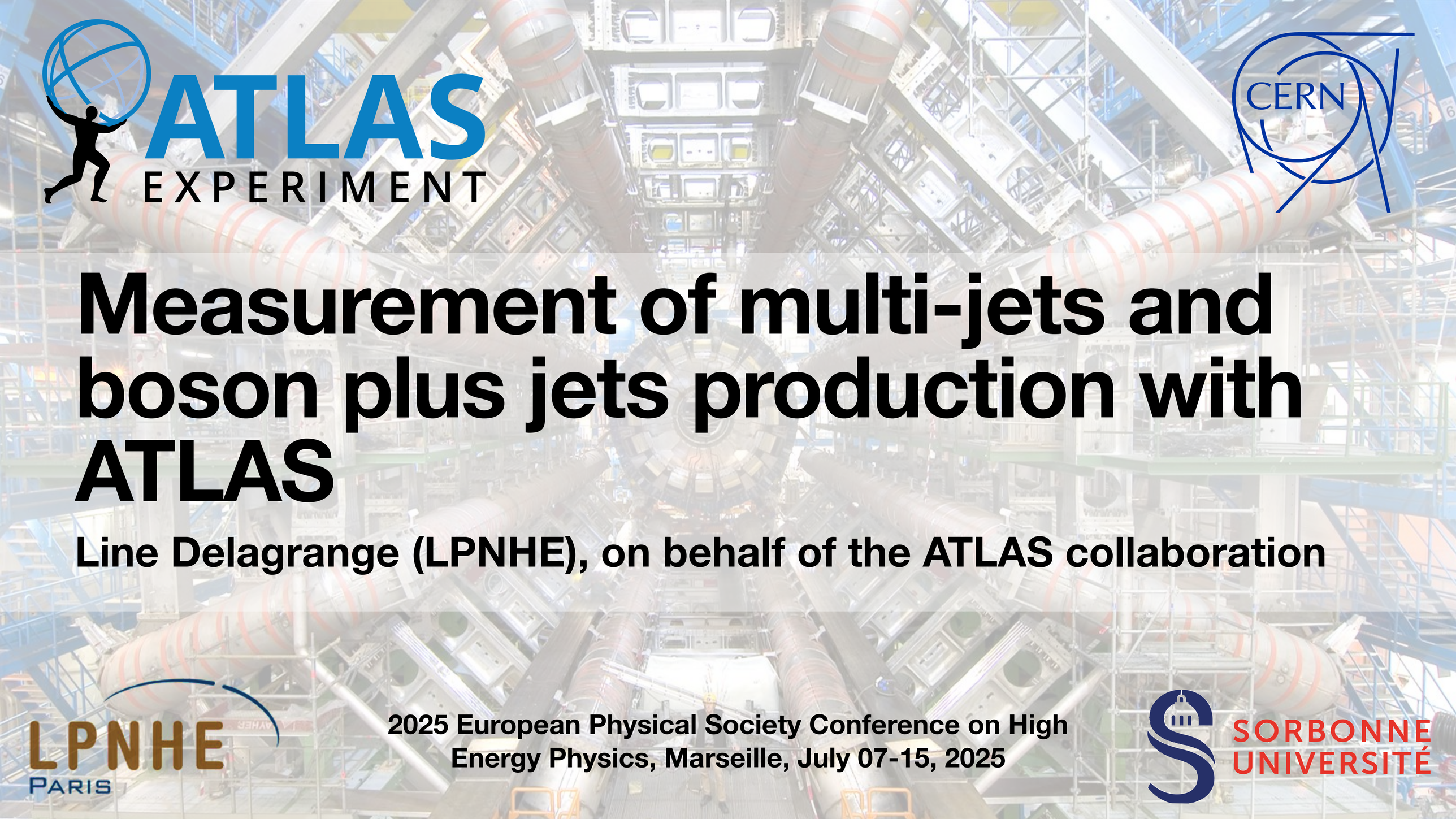


Measurement of multi-jets and boson plus jets production with ATLAS

Line Delagrange (LPNHE), on behalf of the ATLAS collaboration

2025 European Physical Society Conference on High Energy Physics, Marseille, July 07-15, 2025

Motivation

- **QCD** governs strong interactions in proton–proton collisions at LHC
- **Jets** stem from the **emission of a quark or gluon** + **parton shower** (quark/gluon radiation) + **hadronisation**

  → Involves **perturbative** *(calculable from first principles)* and **non-perturbative** *(from phenomenological models)* regimes

  → Jet studies (cross-section, substructure) probe **QCD** across **both regimes**
- **V + jets** measurements sensitive to **QCD** and **EW** corrections

→ Provide valuable input for **refining theoretical predictions**

Outline

- Measurement of **collinear W boson emission from high energy jets** at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset (arxiv:2412.11644)

- **First measurement** of the **LJP for jets initiated by W bosons and** top-quarks, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset (Eur. Phys. J. C 85 (2025) 416)

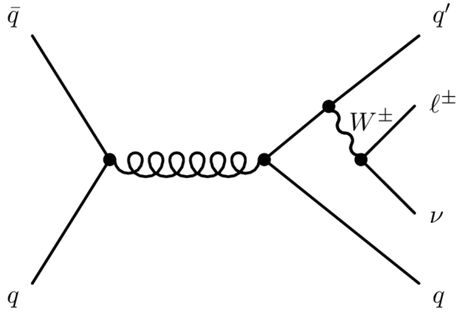
- Measurement of **cross section ratios of inclusive jet multiplicity bins**, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset (Phys. Rev. D110, 072019 (2024))

- Differential cross-section measurement of **Z+b**, **Z+2b** and **Z+c processes**, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset (Eur. Phys. J. C 84 (2024) 984)

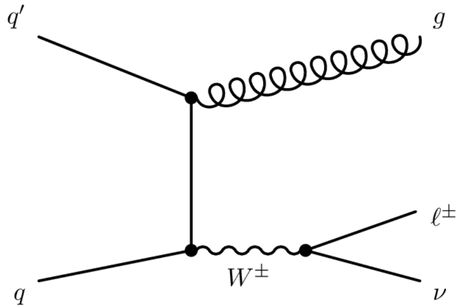
Collinear W+Jets

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 ($140\,\text{fb}^{-1}$)
- Goal: test **EW** and **pQCD** in advantageous final state (clean signature, large cross-section)
- Inclusive and differentially in $\Delta R_{\text{min}}(\ell, \text{jet}_i^{100})$ (sensitive to collinear enhancement in the production rate), $p_T^{\ell\nu}$
- Comparing the results with **NLO-merged W+jets** MC, with and without NLO EW corrections (**Sherpa**, **Madgraph**) and **fixed order W+1jet** **NNLO** predictions (**MCFM**)



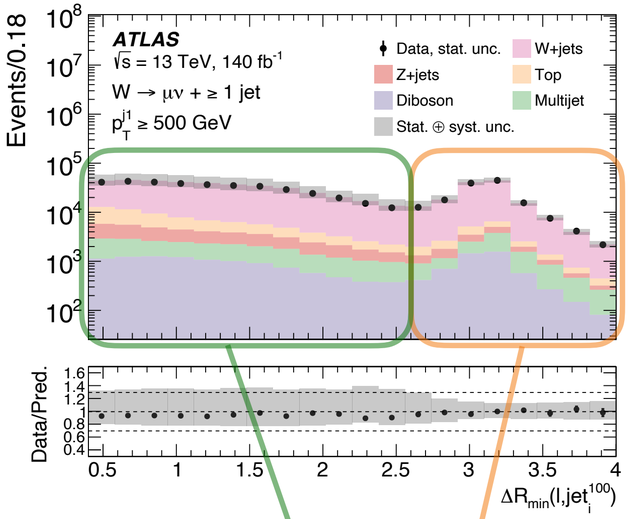
Typically **collinear** topologies

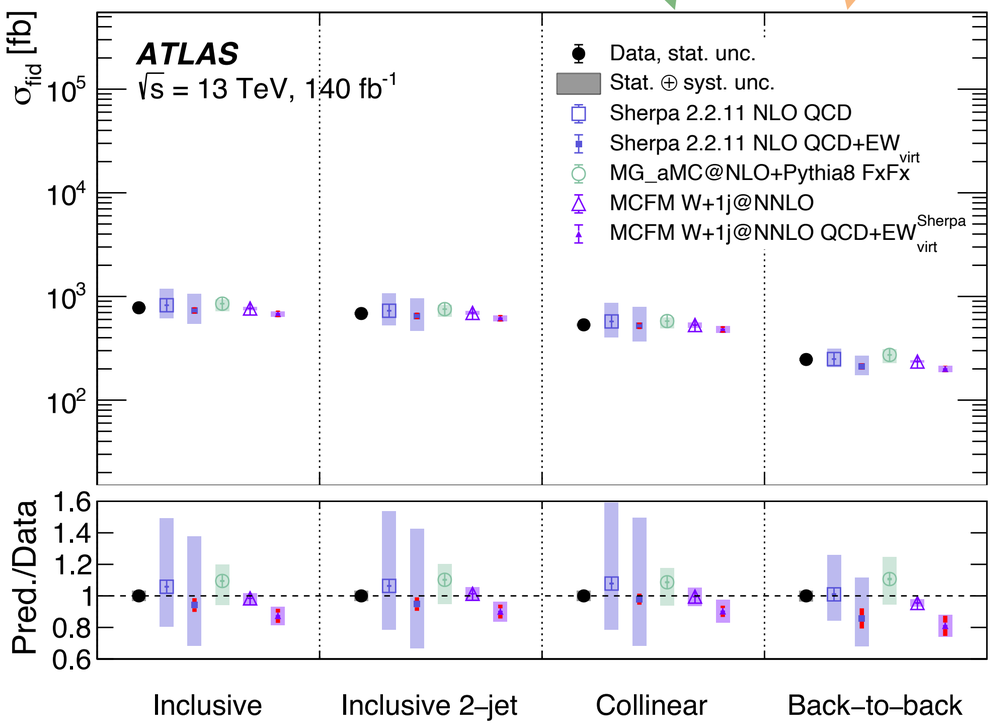


Typically **back-to-back** topologies

Collinear W+Jets

- **Collinear**/**back-to-back** region defined wrt $\Delta R_{\text{min}}(\ell, \text{jet}_i^{100})$
- Total cross-section for each region:
  - **Experimental uncertainties ~3-4%**, dominated by JES, JER, b-tagging, background modelling
  - **Sherpa, MG** uncertainties larger, dominated by QCD scale uncertainties, **MCFM** uncertainties of same order of magnitude as exp unc
  - **Good data/theory agreement** for all regions
  - **NLO EW corrections** improve agreement for **Sherpa** but leads to underestimation of data by **MCFM**

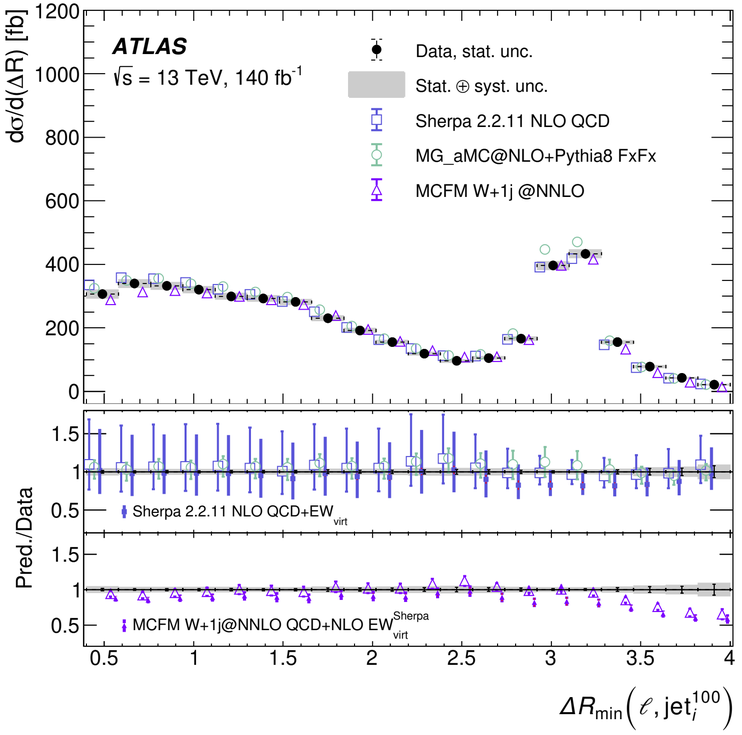




Collinear W+Jets

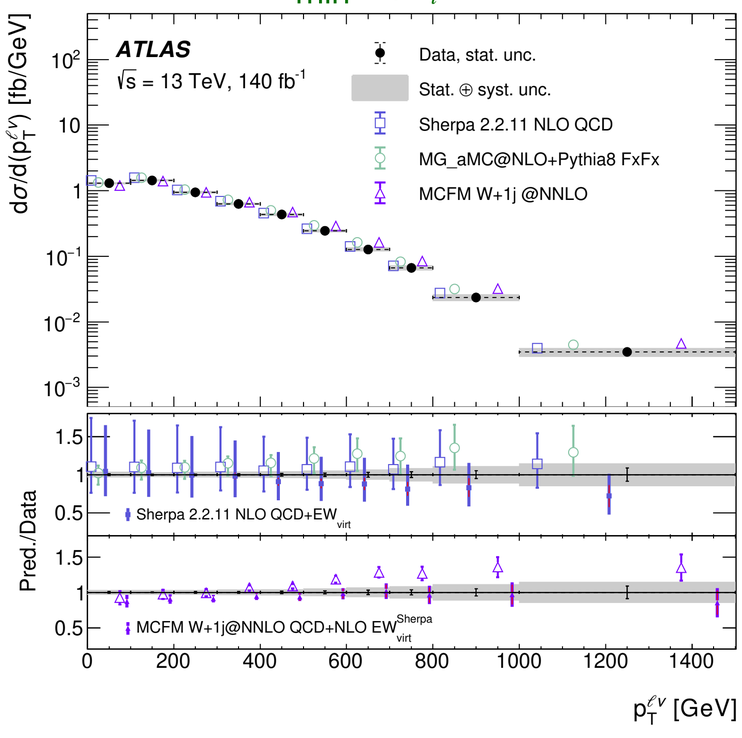
- Differential cross-sections
  - ~5-15% experimental unc
  - Inclusion of **NLO EW** corrections **in Sherpa improve agreement with data** in the **collinear region**
  - **MCFM** underestimates data for $\Delta R_{\text{min}} > \pi$

Collinear **Back-to-back**



Collinear phase-space only

$(\Delta R_{\text{min}}(\ell, \text{jet}_i^{100}) < 2.6)$

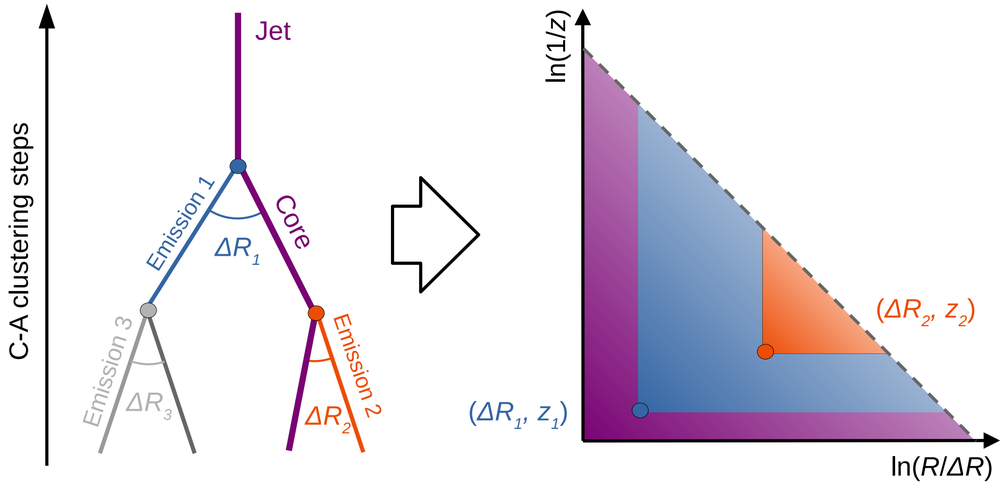


- Inclusion of **NLO EW** corrections in **MCFM** significantly improve agreement with data for large values of $p_T^{\ell\nu}$

→ Provide insights for **improving QCD modelling & MC generator tuning**

Lund jet plane

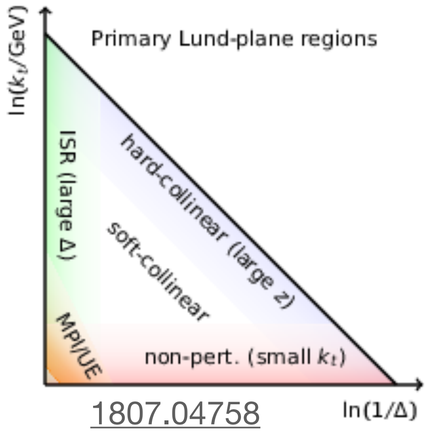
Eur. Phys. J. C 85 (2025) 416



- **First measurement** of the **LJP for jets initiated by W bosons and** top-quarks, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset ($140\,\text{fb}^{-1}$)
- 2D representation of the **jet substructure**
  - Displays **momentum fraction** z and **opening angle** ΔR of emissions inside a jet
  - Proxy for kinematics of **parton showers** and **hadronisation, factorise QCD effects**
  - Built by reclustering emissions with **Cambridge-Aachen algorithm** (angular ordered) following the core branch, fill the LJP at each step
- W boson: **large mass, colour-singlet**

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

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

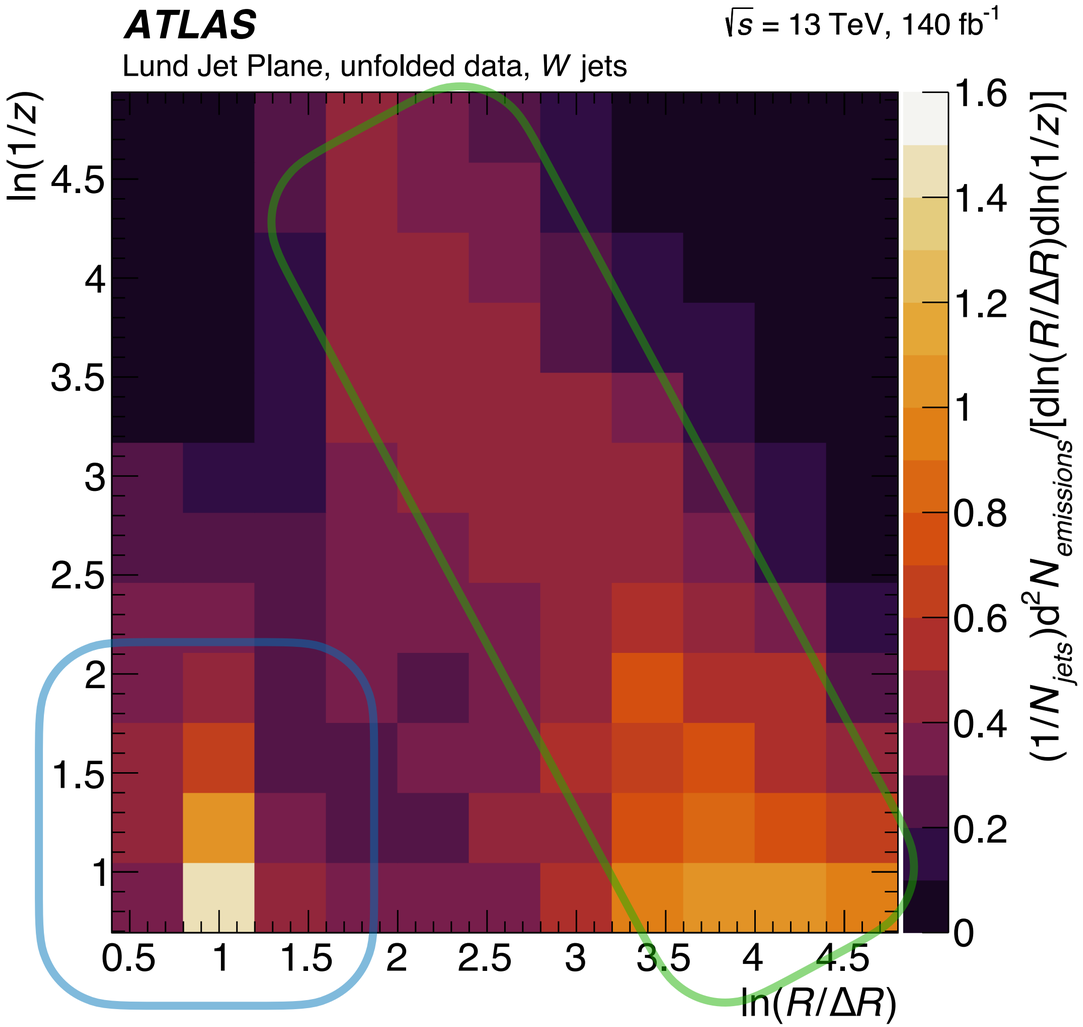


1807.04758

Lund jet plane

- Using $t\bar{t}$ events, selecting W-initiated jets from t decay with selection on the **jet mass** and **closeness to b-tagged jet**
- **Experimental uncertainties ~10-40%** dominated by signal modelling uncertainties
- Sensitivity to W decay into highly boosted quarks in the **hard and wide-angle emission region** (Decay products have $\Delta R \propto m/p_T$)
- Other densely populated region corresponds to **subsequent emissions of softer QCD radiations**

Similar to light-quark LJP



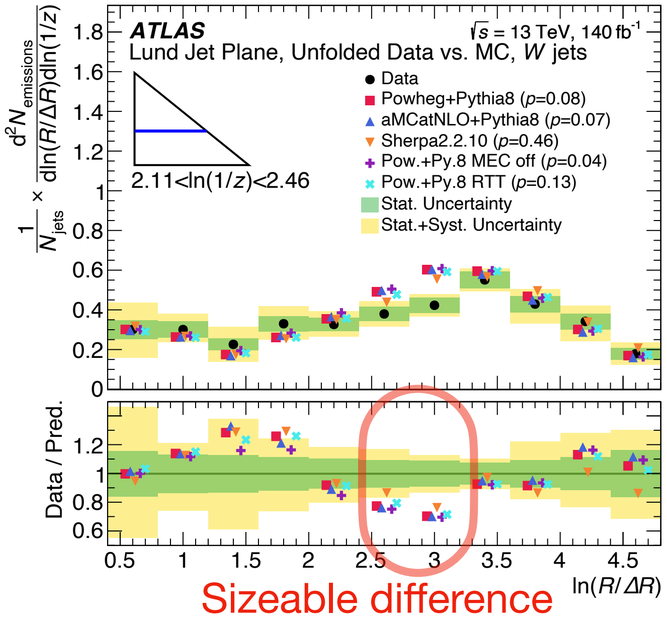
Gives rise to 2/3-pronged distribution in (η, φ)

Lund jet plane

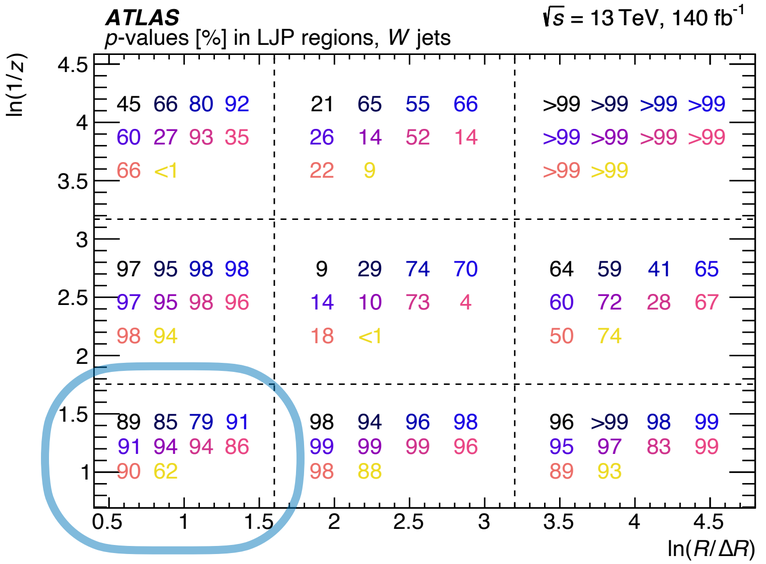
- Comparison with various MC event generator setup using different **matrix-element**, **parton-shower and hadronisation models**, quantified with χ^2 test

- **No generator agrees** with the measurement across the whole LJP (p-values < 1%), **better agreement in the subregions** (consistent with other LJP measurements)

→ **Useful for improving the tuning of MC $t\bar{t}$ event generators** by targeting the parameters controlling sources of radiation that are poorly modelled in the LJPs



Sizeable difference



Good agreement

Jet cross section ratios

$$R_{3/2} = \frac{\sigma_{\geq 3j}}{\sigma_{\geq 2j}}$$

[Phys. Rev. D110, 072019 (2024)]

- Measurement of **cross section ratios of inclusive jet multiplicity bins**, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset ($140\,\text{fb}^{-1}$), and **comparison with NNLO predictions**
- Direct sensitivity to α_S , **cancellation of NP and PDF effects**
- Differentialy in variables sensitive to the **energy scale of hard-scattering process** or **angular distribution of hadronic energy flow** in the final state

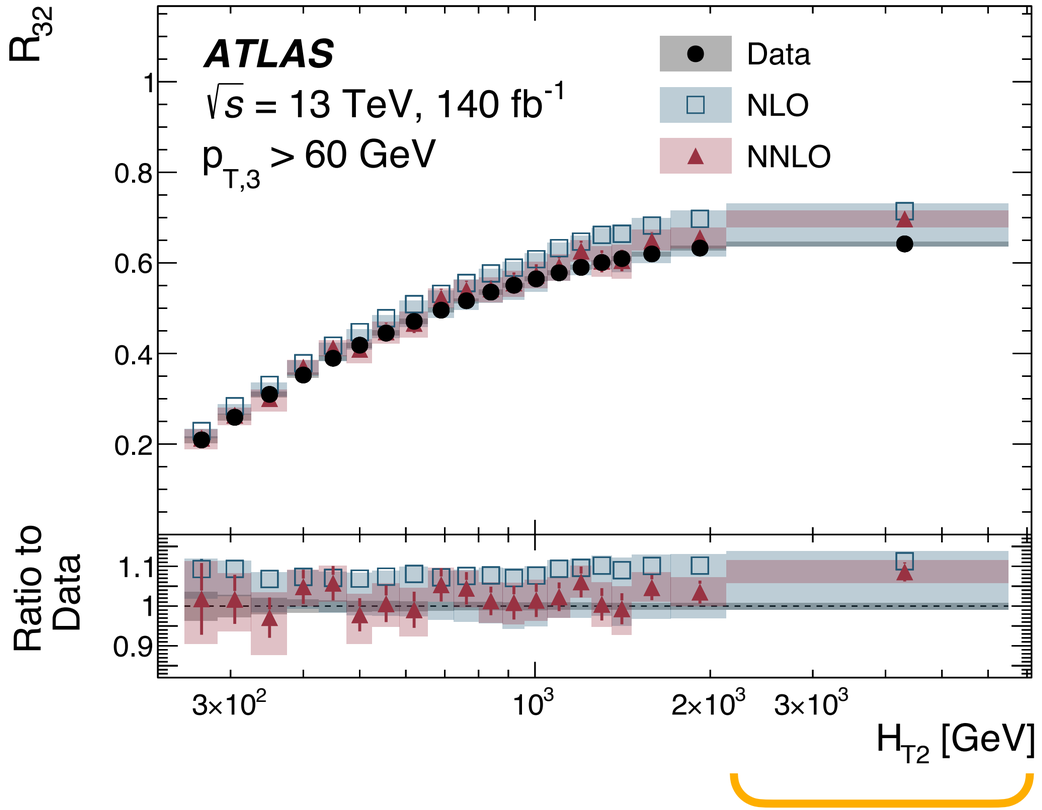
$H_{T,2} = p_{T,1} + p_{T,2}$, sensitive to **fixed-order effects**

m_{jj}, sensitive to **PDF, VBF/VBS modelling**

→ Input for **improvement of theoretical predictions and MC generators, α_S extraction**

Jet cross section ratios

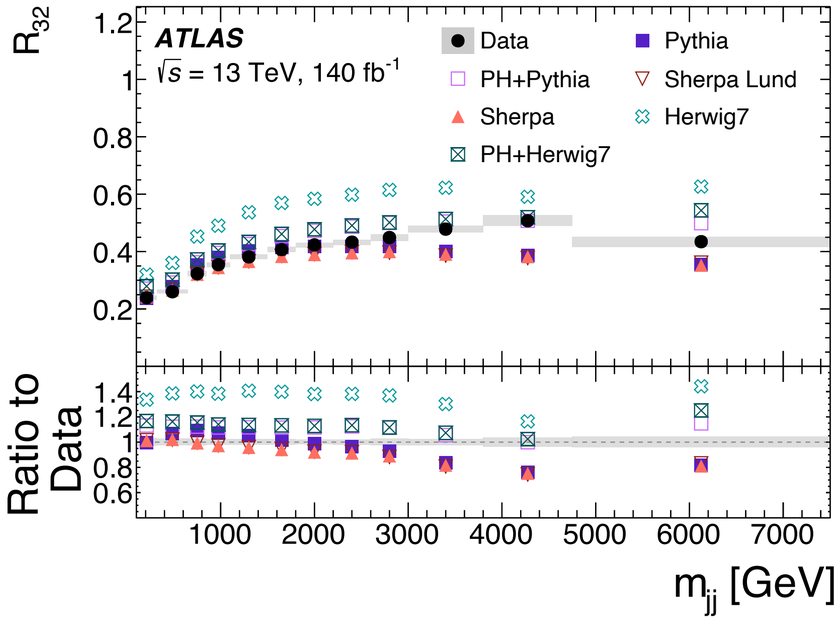
- $R_{3/2}$ a function of $H_{T,2}$
- $p_{T,3}$ cut determines sensitivity to **resummation effects** (final state characterised by two different scales)
- **NLO** predictions from **NLOJet++**, **NNLO** from **Czakon et al.** + NP multiplicative corrections
- **NNLO** gives **accurate description** of value and shape, **NLO** tends to **overestimate**
- **NNLO** slightly **overestimates** where **resummation effects** plays a more important role **(larger H_{T2} lower $p_{T,3}$ cuts)**

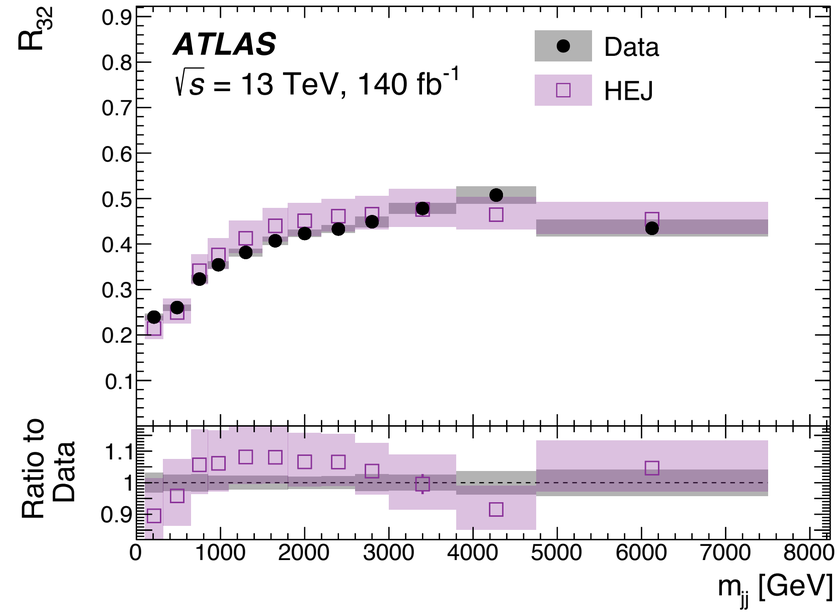


Jet cross section ratios

- $R_{3/2}$ a function of m_{jj}
- Large m_{jj} values target **large logarithmic corrections**
- **High Energy Jets (HEJ)** framework used for prediction **including resummation to all order in** $\alpha_S \log(\hat{s}/p_T^2)$ (characteristic of **VBS/VBF**), matched to fixed order accuracy
- Uncertainty from QCD scale variation
- **HEJ** predictions **provide better modelling of** $R_{3/2}$ than MC generators tested

→ Insights into **VBS/VBF modelling**



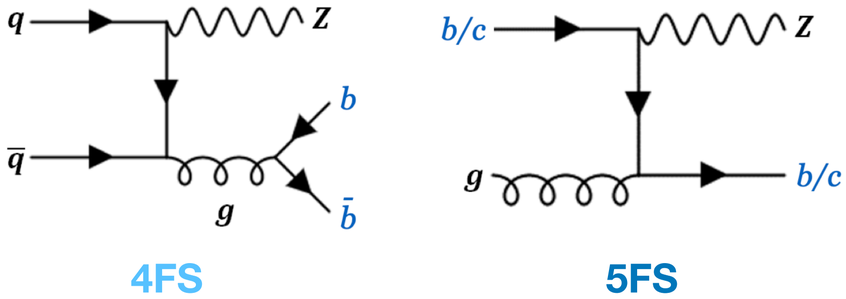


Z + heavy flavour jets

Eur. Phys. J. C 84 (2024) 984

First measurement in ATLAS!

- Differential cross-section measurement of **Z+b**, **Z+2b** and **Z+c processes**, at $\sqrt{s}$= 13 TeV with the full Run-2 ATLAS dataset ($140\,\text{fb}^{-1}$)
- Sensitive to various effects:
  - **Flavour number schemes**:
    - **4FS:** u, d, s, **c** in the PDF, massive b-quark
    - **5FS:** u, d, s, **c**, **b** in the PDF
  - **PDF model and intrinsic charm** (**IC**) in PDF

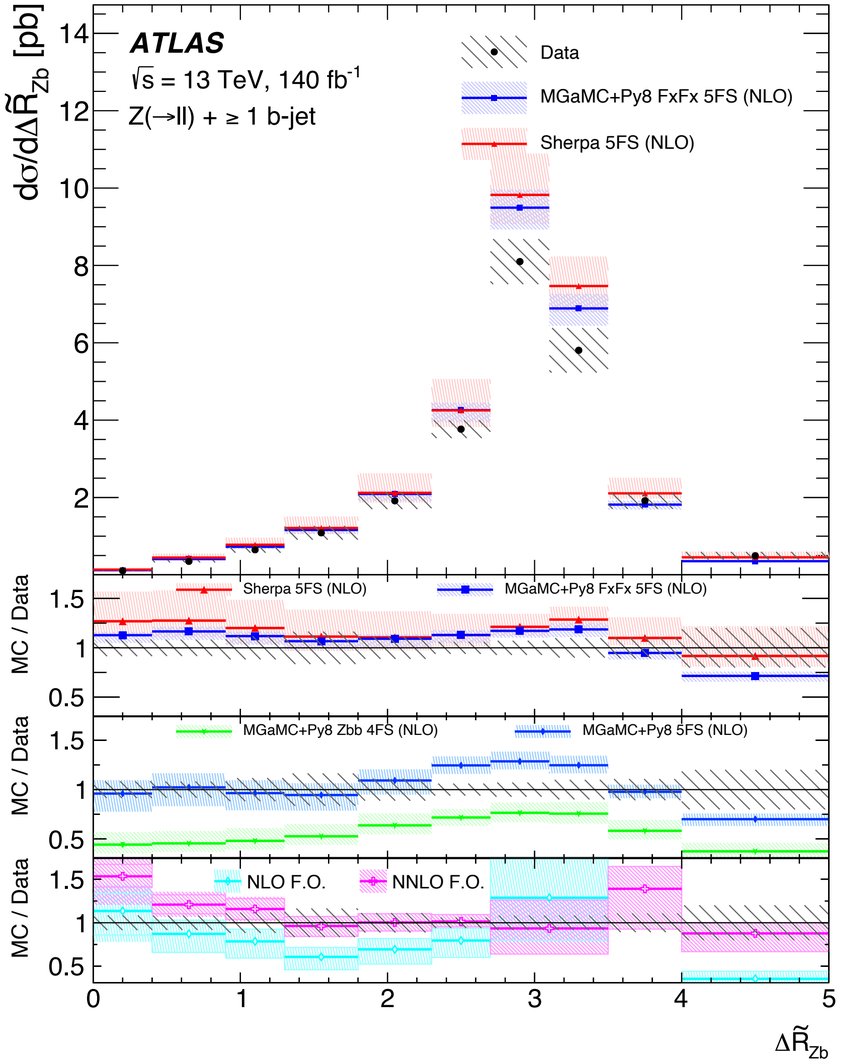


4FS 5FS

→ Input for **improvement of theoretical predictions and MC generators tuning**

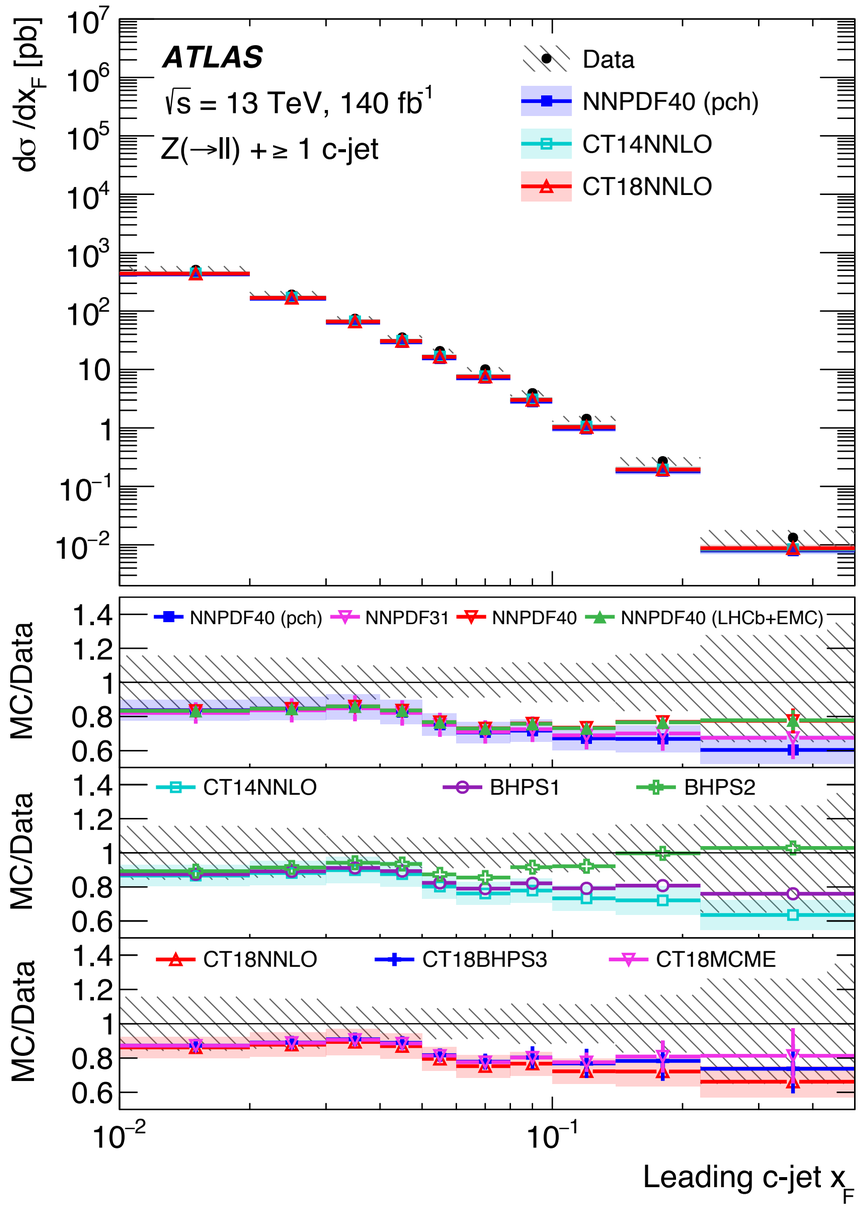
Z + heavy flavour jets

- Cross section as a function of $\Delta\tilde{R}(Z,b)$ the **angle between Z and leading b-jet**, in **Z+b** events
- Sensitive to **presence of additional radiation**, distinctive feature of **4FS** versus **5FS**
- Systematics dominated by flavour tagging and JES/JER
- Compared with **various MC generators**, **fixed-order NLO** and **NNLO** predictions
  - **MC generators** describe data well, except around π
  - **5FS** provides **good description, 4FS underestimates** data across the full spectra
    → lack of bg-initiated processes
  - **NLO** discrepancies **improved with NNLO**



Z + heavy flavour jets

- Cross section as a function of **the Feynman-x variable** $x_F(c) = 2\,|p_Z(c)|/\sqrt{s}$, 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** ($\langle x_C \rangle \sim 2\,\%$) improves agreement, but large measurement and modelling unc
    → non conclusive yet
  - Marginal improvement for more realistic scenarii (**BHPS1**, **NNPDF** and **CT18** families)



Summary

- Recent results from **ATLAS** measuring a variety observables, enabling **precise study of QCD** in **various regimes (and more)**, including:
  - Measurement of collinear W boson emission from high energy jets**,** sensitive to **EW** and **pQCD**
  - *First measurement* of the LJP for jets initiated by W bosons, sensitive to **modelling of $t\bar{t}$ events**
  - Measurement of cross section ratios of inclusive jet multiplicity bins, sensitive to α_S, **fixed-order effects**, **PDF** and **VBF/VBS modelling**
  - Measurement of differential cross-section measurement of Z+b and Z+c processes, sensitive to **flavour schemes and intrinsic charm**

Thank you for your attention!