UNIVERSITY OF OXFORD

ATLAS EXPERIMENT

News from ATLAS

02/12/2024

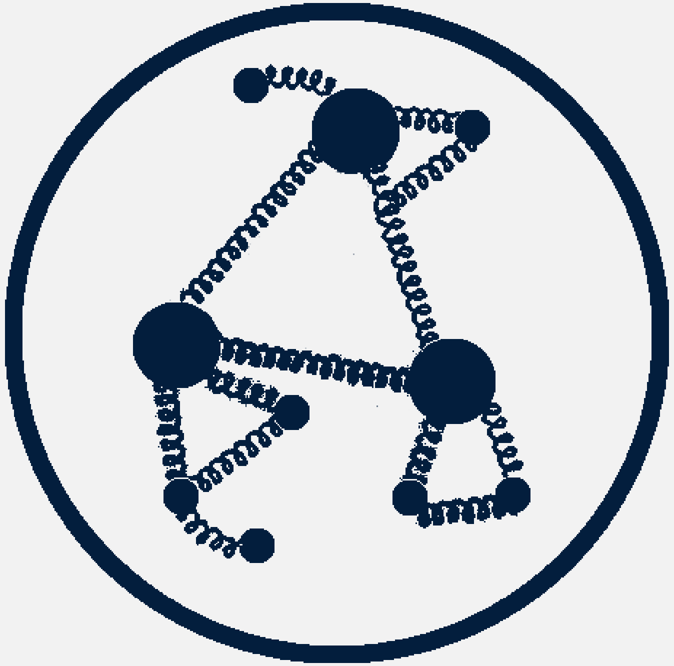
Eimear Conroy – University of Oxford

PDF4LHC 2024

Introduction

- Many new precision measurements released by ATLAS in the last year
  - See the ATLAS SM public page for a complete list
  - Legacy Run 2 measurements, + partial Run 3

- Today, will survey recent measurements which can be of interest to PDF fitters
  - Later: Maarten Boonekamp, Uncertainties in ATLAS EW measurements arising from PDFs



Jet Ratios

[Phys. Rev. D 110, 072019 (2024)]

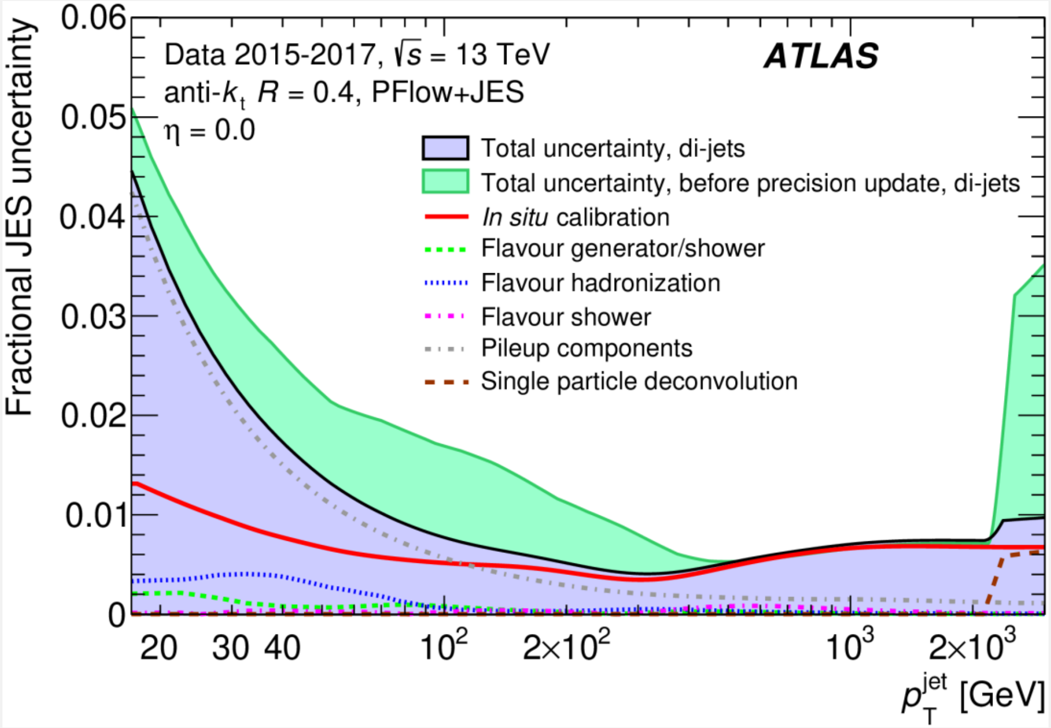
Jet cross-section ratios at 13 TeV

- Differential σ's in multiple observables
  - Target different facets of QCD
    - e.g. hard-scatter energy scale, fixed-order ME, FS energy flow
- First measurement of R_{32} in 13 TeV pp
  - $R_{32} \rightarrow \frac{\sigma_{3\ jets}}{\sigma_{2\ jets}}$
  - Reduces sensitivity to systematic uncertainties & PDFs
- Compare with NNLO fixed order predictions
- R_{43}, R_{42}, R_{54} also measured
  - Precision predictions not yet available
  - Reference for future developments

Experimental Measurement

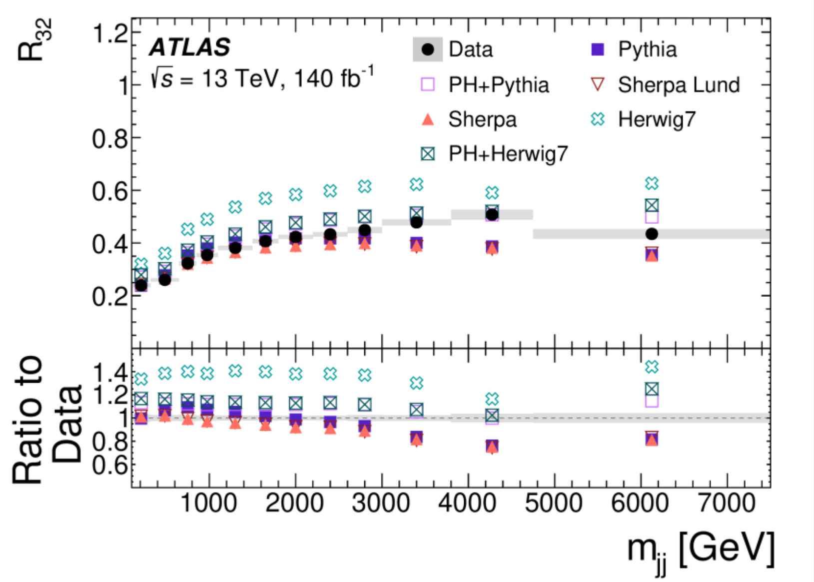
Jets:
anti-k_T, R=0.4, pT > 60 GeV, |y| < 4.5
Event:
$N_{jets} \geq 2$, H_{T2} > 250 GeV

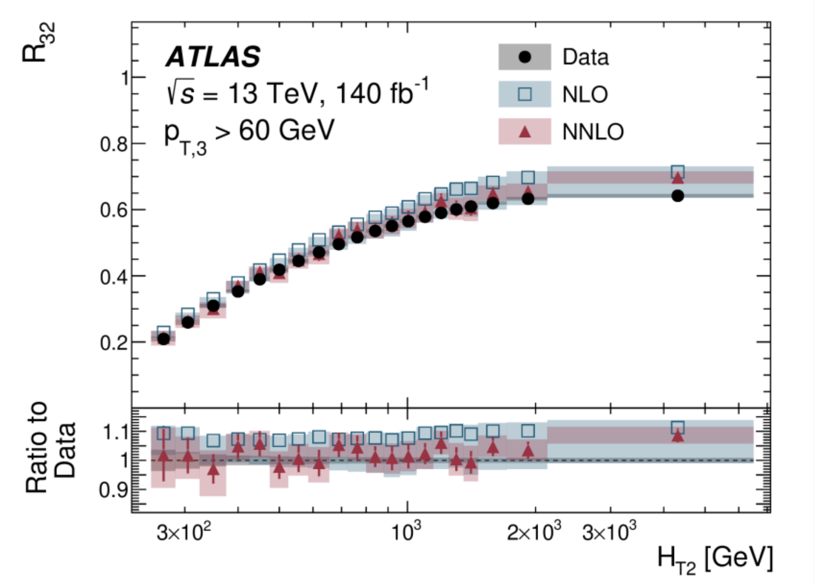
- Measure 140 fb^{-1} of $\sqrt{s}$ = 13 TeV pp data
- Observables:
  - $d\sigma/(dN_{jets}\, dH_{T2}\, dp_{T,3})$ vs H_{T2}, p_T^{Nincl}
    - Fixed order effects e.g. (HS scale, resummation)
  - R_{32} vs m_{jj}, Δy_{jj}
    - Large logarithmic corrections
- Reduced JES uncertainties:
  - Factorised sources of jet flavour response uncertainty:
    - 2x reduction, p_T^{jet} > 100 GeV
  - Updated inputs to high-p_T 'Single particle deconvolution':
    - 3x reduction p_T^{jet} > 2 TeV
- Unfolding:
  - Iterative Bayesian, double/triple differentially



Results

- High-precision: Uncertainties O(<10%)
- Compared to:
  - MC generators:
    - Pythia 8.230, Sherpa2.2.5, 2.2.11, Herwig7.1.6, Powheg2+Pythia8, Powheg2+Herwig7
  - Fixed-order predictions: NLO, NNLO
    - $\mu_r = \mu_f = \hat{H}_T = \sum_i p_{T,i}$
    - NP corrections from ratio $\frac{\text{hadron-level, with MPI}}{\text{parton-level, no MPI}}$
  - High Energy Jet: Resummed LL corrections
    - e.g. VBS/VBF
- **MC:** Significant differences at large m_{jj}, Δy_{jj}
- **NNLO:** H_{T2} modelled well across all $p_{T,3}$ bins
- **HEJ:** Good description of ratios in regions where log terms contribute





Z+HF

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

Z + heavy flavour jets

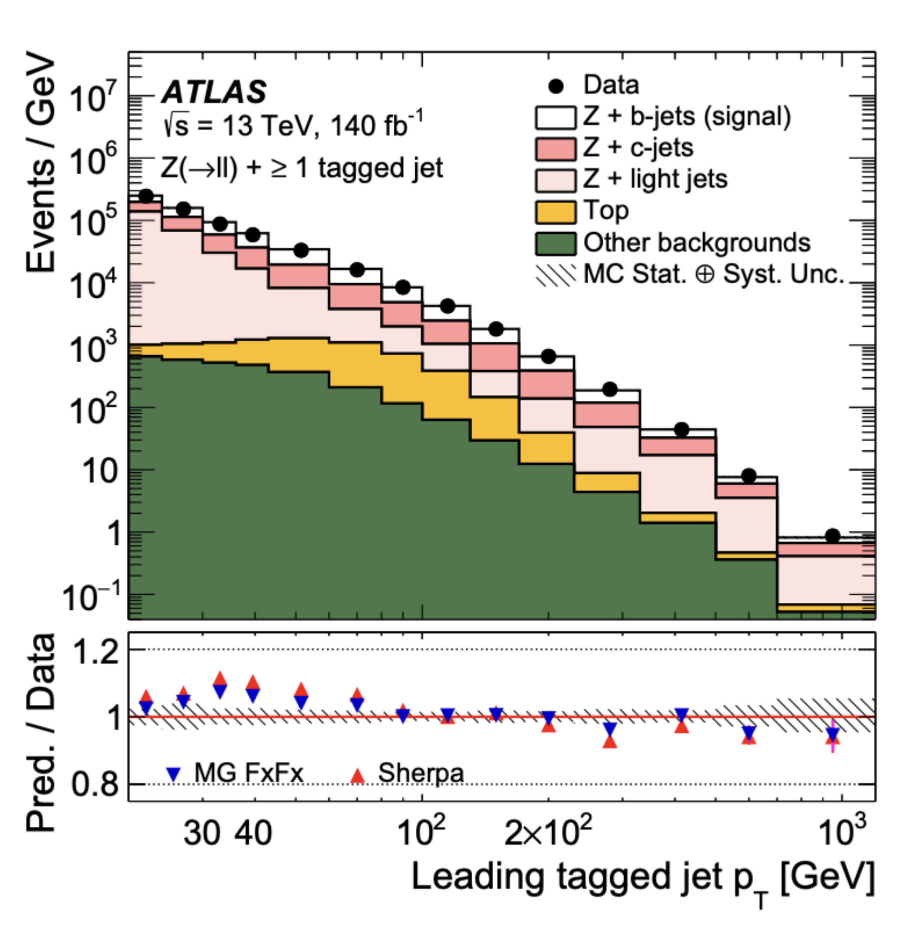
- Measure production cross-sections for Z boson with b- or c-jets in 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV
  - Important test of pQCD and proton structure
- Benchmark for MC generators
  - 4FS, 5FS etc. IRC-safe jet algorithms
  - Investigate intrinsic charm hypothesis
- Inclusive and differential cross-sections e and μ channels with ≥ 1 c-jet, ≥ 1 b-jet, ≥ 2 b-jets
  - Observables sensitive to pQCD, PDF models and MC generator validation

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 $x_F = 2\|p_z(c)\|/\sqrt{s}$ [26] Cross-section ratio of $p_{\mathrm{T}}(Z)$ 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

- This measurement: More extreme phase space, higher integrated luminosity, advances in jet reconstruction and b-tagging, new data-driven methodologies

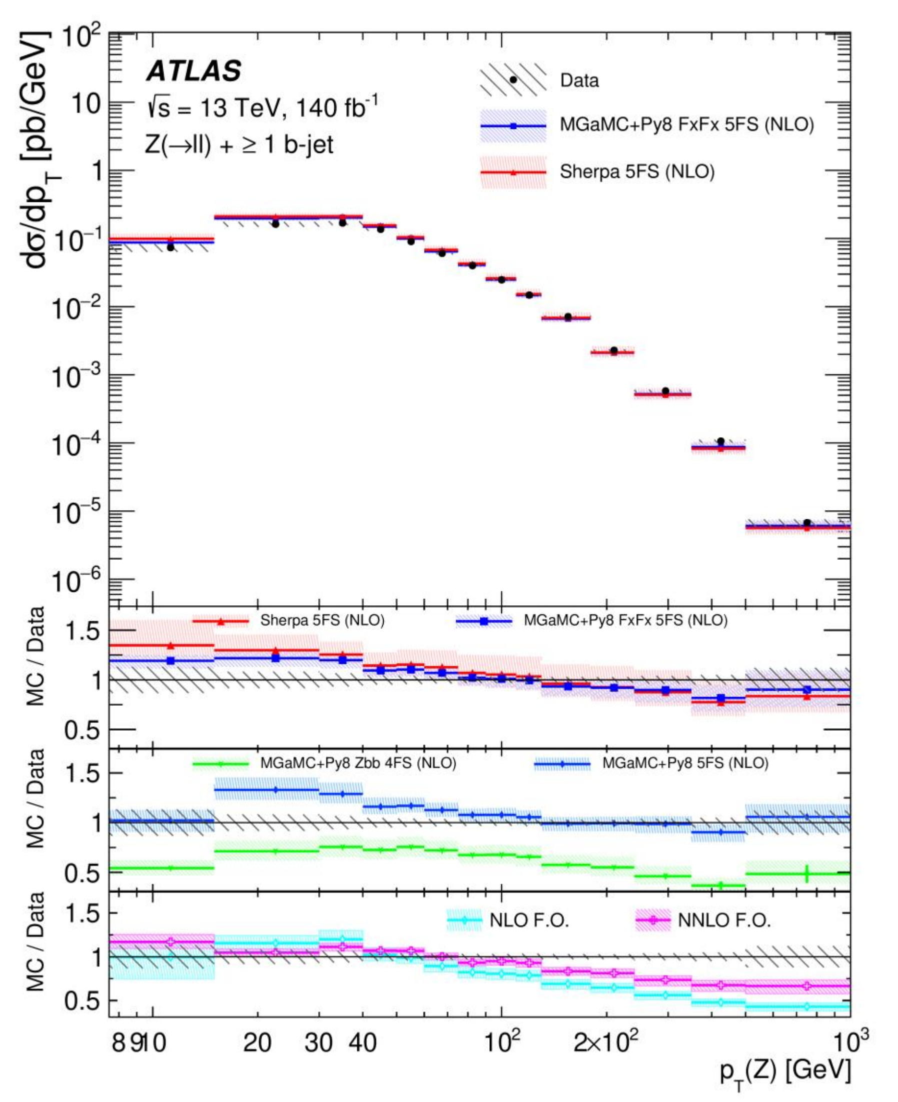
Experimental Measurement

- Select Z → ee, μμ with p_T > 27 GeV and jets with p_T > 20 GeV and |y| < 2.5 tagged as containing b/c quarks.
- Top, multijet backgrounds estimated via data-driven techniques, remaining backgrounds from MC
- Events categorised as Z+b-jets, Z+c-jets and Z+light jets,
  - From flavour fit in two signal regions (1-tag, 2-tag)
- Backgrounds subtracted and data unfolded using iterative Bayesian unfolding
- Unfolded distributions compared with predictions from state-of-the-art MC generators and from NNLO fixed-order predictions
  - Z + ≥ 1 c-jet measurements are also compared with several PDF sets with different contributions from IC.



Results

- First ATLAS Z+c measurement, improved precision for Z+b
- Comparison with MC (NLO ME interfaced to PS)
  - 5FS MadGraph5 (FxFx) + Pythia 8.2, Sherpa 2.2.11 describe Z+b within uncertainties
  - 4FS MadGraph systematically underestimates Z+1b
  - All generators underestimate the Z+c
- 5FS NNLO fixed-order predictions with flavour dressing
  - Z+1b: Similar performance to multi-leg generators
  - Z+c: Predictions underestimate data even more than MC
- Madgraph samples using PDFs with different IC content compared with Z+c
  - No significant difference observed

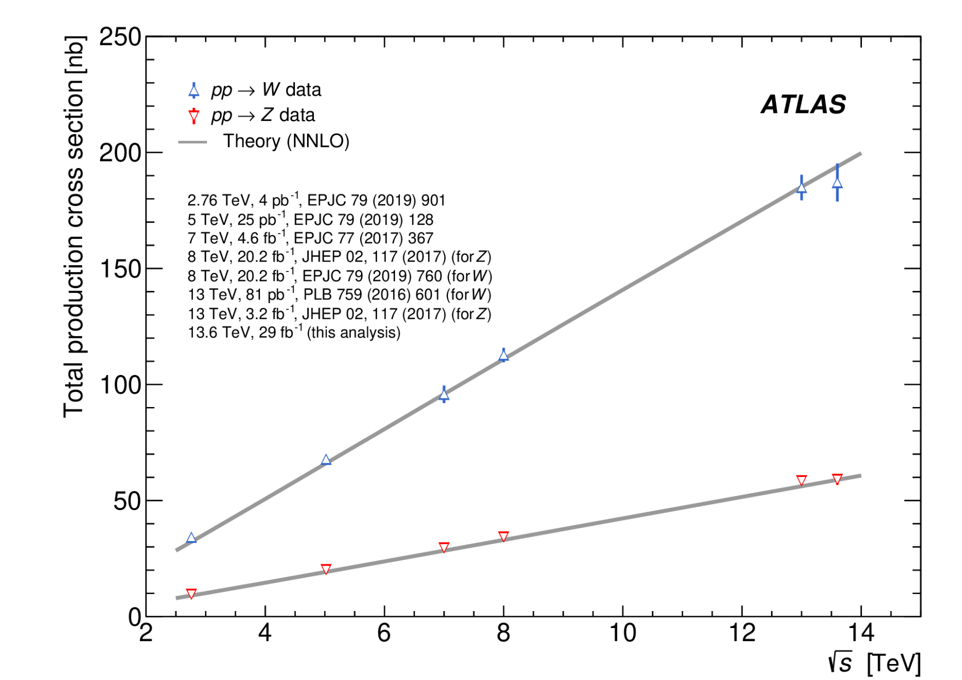


W/Z at 13.6 TeV

Phys. Lett. B 854 (2024) 138725

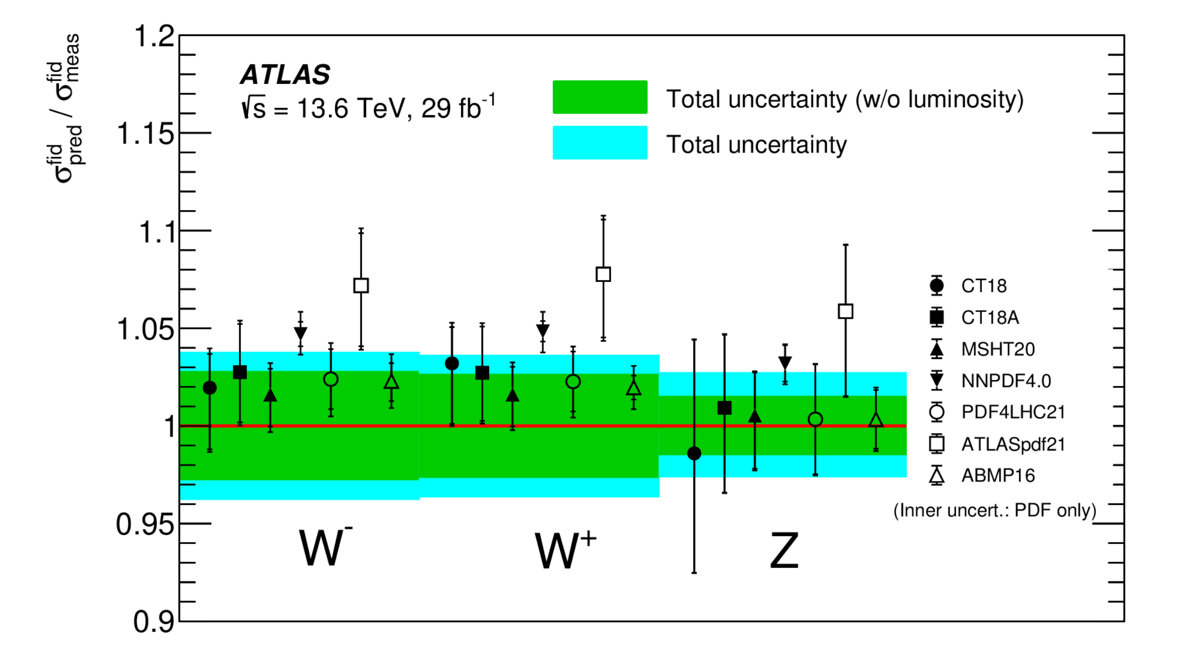
Vector boson production at 13.6 TeV

- Precision measurements of the $W^{\pm}$ and Z cross sections and their ratios
  - Probe QCD and proton structure
  - Previously measurement by ATLAS at $\sqrt{s}$ = 2.76, 5, 7, 8, and 13 TeV.
  - Experimental precision has reached percent level
- This measurement:
  - Inclusive fiducial and total cross sections of W^{+} W^{-}, their ratio, and ratios to the Z using 29 fb^{-1} of 2022 pp collisions at $\sqrt{s}$ = 13.6 TeV
  - Ratios between ttbar and $W^{\pm}$ cross sections
- Perform profile-likelihood fits to the inclusive data in the four single-lepton channels
- Compare with predictions from DYTurbo and ReneSANCe at NNLO+NNLL in QCD, NLO EW, using various modern PDFs.
- Also test dependence of the cross sections on $\sqrt{s}$



Results

- Fiducial cross-sections:
  - W^+: 4250±150 pb
  - W^-: 3310±120 pb
  - Z: 744±20 pb
  - Good agreement with the SM predictions
- W ratios with ttbar slightly overestimated by certain predictions
- Total cross section vs √s compared with CT14NNLO predictions.
  - Good agreement observed between data and prediction

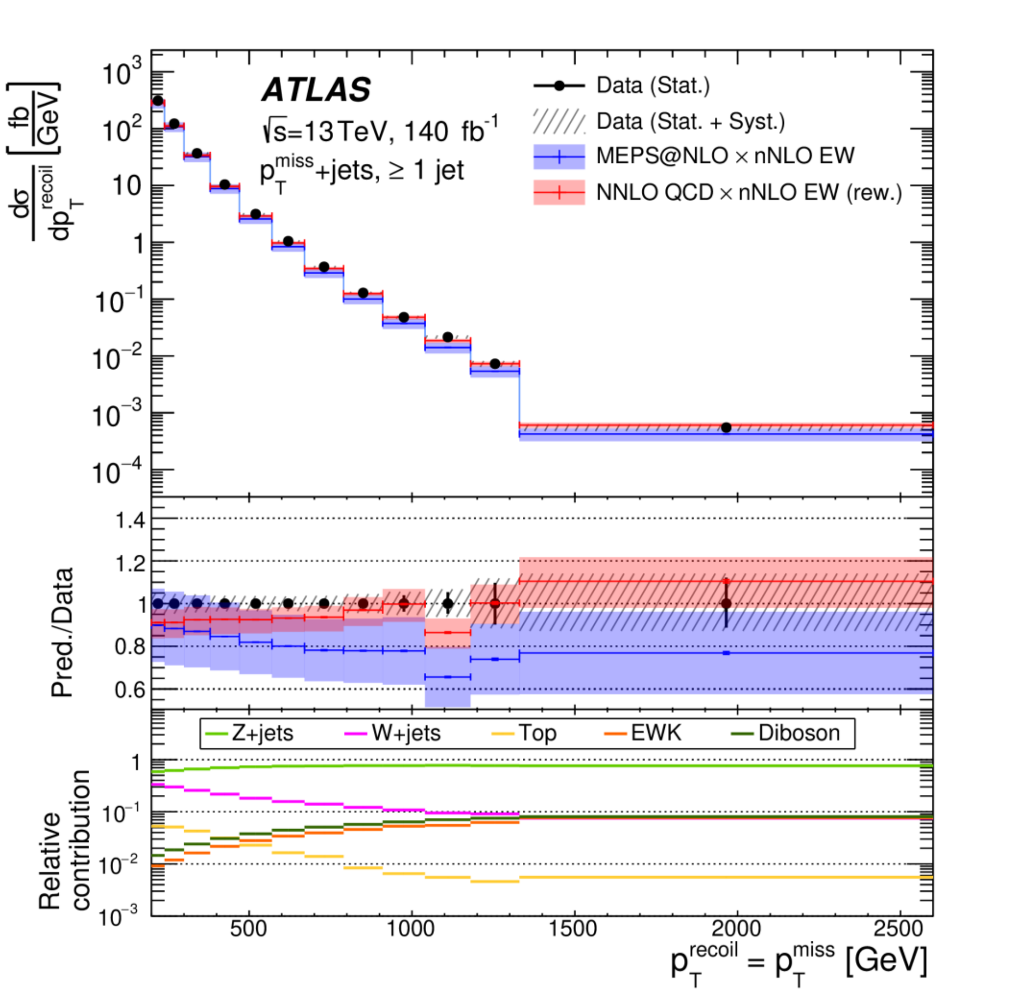


Unfolded MET+jets

JHEP 08 (2024) 223

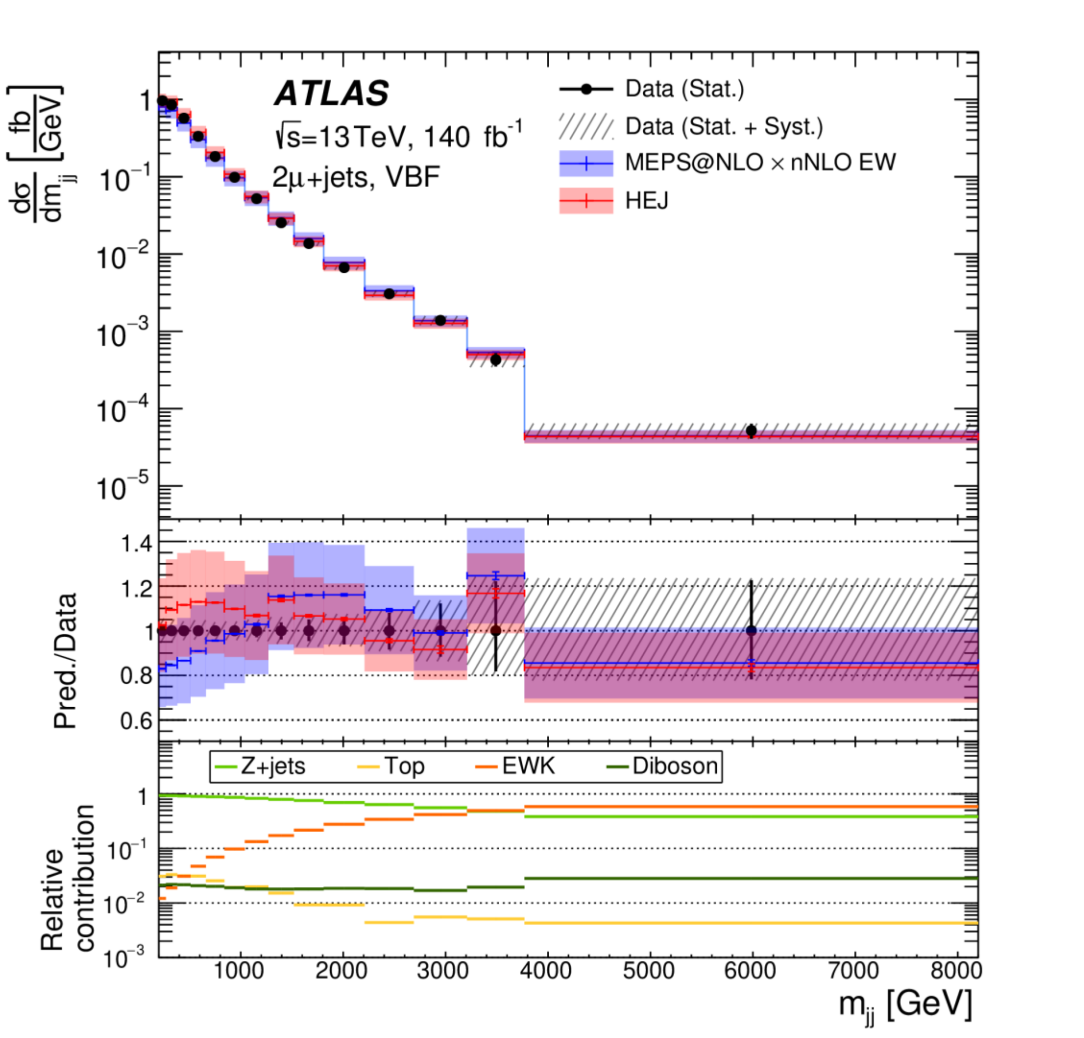
Unfolded p_T^{miss} with jets

- Precision measurement of p_T^{miss} with jets, inclusive, little model dependence,
  - ≥ 1 jet and VBF phase spaces
  - First such ATLAS measurement using the full 140 fb^{-1} of $\sqrt{s}$ = 13 TeV Run 2 pp data
- Measured cross-section for $Z \to \nu\nu$ production, differential in p_T^{miss}
  - $\Delta\phi_{jj}$ and m_{jj} in the VBF phase-space
- Presented alongside auxiliary measurements of hadronic recoil against isolated lepton and photons
  - Same phase space
  - Modelling effects and systematic uncertainties cancel out in ratio



Results

- Unfolded measurements generally agree well with state-of-the-art SM predictions, except for the m_{jj} distribution
  - In the VBF region, alternative prediction for V+jets using the high energy jets framework provides a better m_{jj} description
- Measured cross-section ratios used to reproduce limits on two example Dark Matter models
  - Derived constraints are found to be only marginally weaker than for dedicated searches



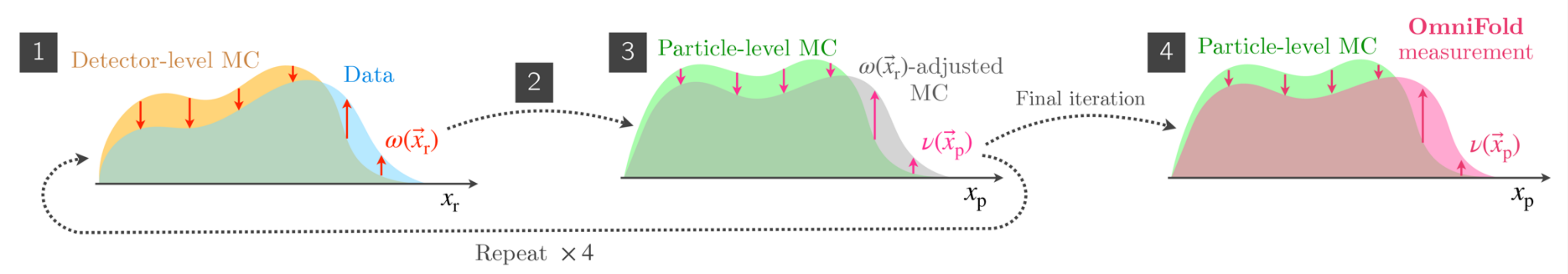
Unbinned Z+jets

arXiv:2405.20041 [hep-ex]

Submitted to: Phys. Rev. Lett

Unbinned Z+jets production

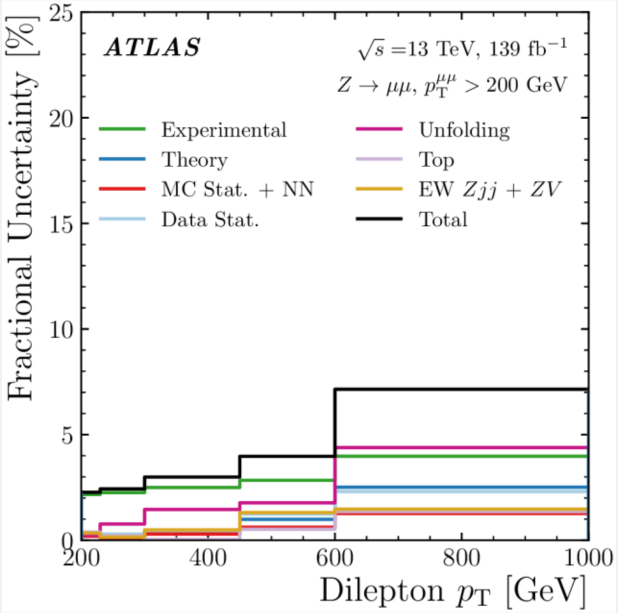
- Z production: Standard candle process at the LHC
  - Very pure samples, sensitive to a diverse range of QCD phenomena.
  - Probes the strong force, improve MC generators and searches for deviations from the Standard Model
- Most previous measurements unfold using regularized matrix inversion → Must characterise events using small no. of observables in predetermined bins
- This analysis - Omnifold
  - Uses DNNs to process high-dimensional, unbinned inputs.
  - OmniFold learns a correction (event weights) to an initial set of simulated events
- This result constitutes:
  - A precision Z+jets measurement of 24 observables
    - 139 fb^{-1} of Z/y* → μμ events from the full Run 2 pp at √s = 13 TeV
  - Proof-of-principle application of the OmniFold method



Signal Extraction & Unfolding

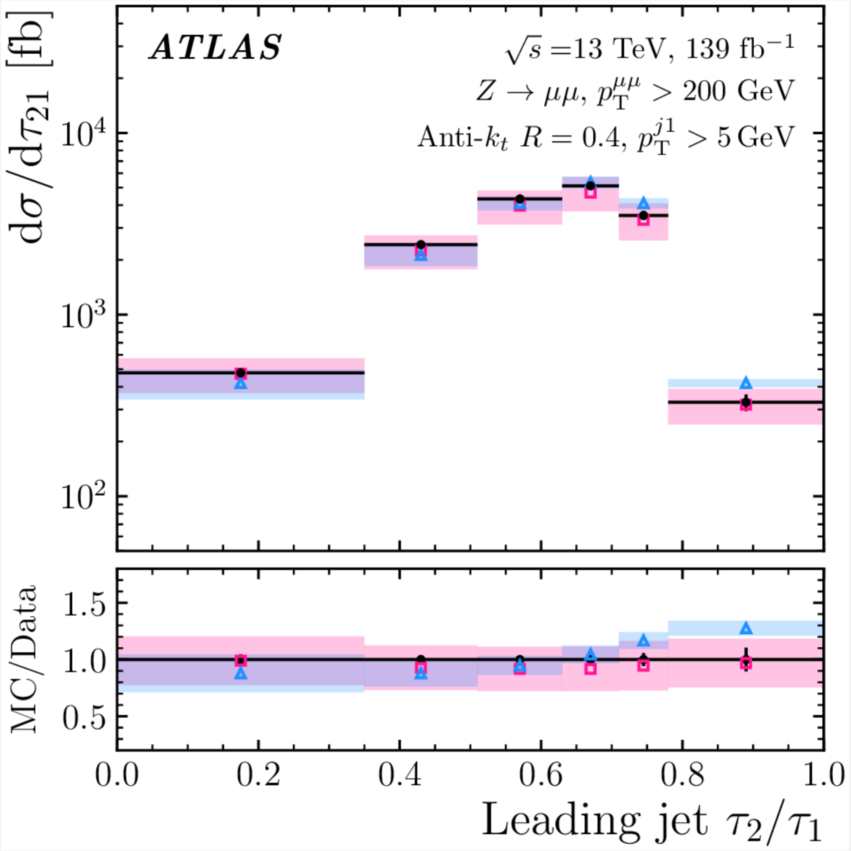
- Measurement presented unbinned particle-level dataset
  - Flexibility in re-use, and new observables can be constructed from the 24 measured observables
- Backgrounds ~ 0.2% due to top processes.
  - Small → not subtracted, assigned as an uncertainty.
- Unfolded for five iterations using MadGraph5+ Pythia 8.24, Sherpa2.2.11, both using NNPDF3.0 at NNLO
- Final output = Particle-level simulated sample with additional event weights, from which cross-sections can be extracted
- Validated using a "pseudo-data" sample constructed by reweighting the particle-level quantities in the alternative MC sample

	Particle-level
Muon multiplicity	2 (opposite sign)
Muon pT	> 25 GeV
Muon $\|\eta\|$	< 2.5
$m_{\mu\mu}$	∊ (81,101 GeV)
$p_T^{\mu\mu}$	>200 GeV
Jet algo.	Anti-k_T, R=0.4
Charged hadron/track p_T	> 500 MeV
Jet $\|\eta\|$	< 2.4



Results

- Total fiducial cross section: 1,808±42 fb.
- Differential measurements of 24 observables:
  - Measurement more precise than the predictions, especially. Sherpa.
  - MadGraph generally models the data better than Sherpa
- Additional “derived” results constructed from the nominal measurement
- These results demonstrate that:
  - Collider data can be unfolded in an unbinned manner
  - Result can be re-analysed at the event level
- Flexibility makes it possible to probe kinematic regimes and observables not originally foreseen



Conclusion

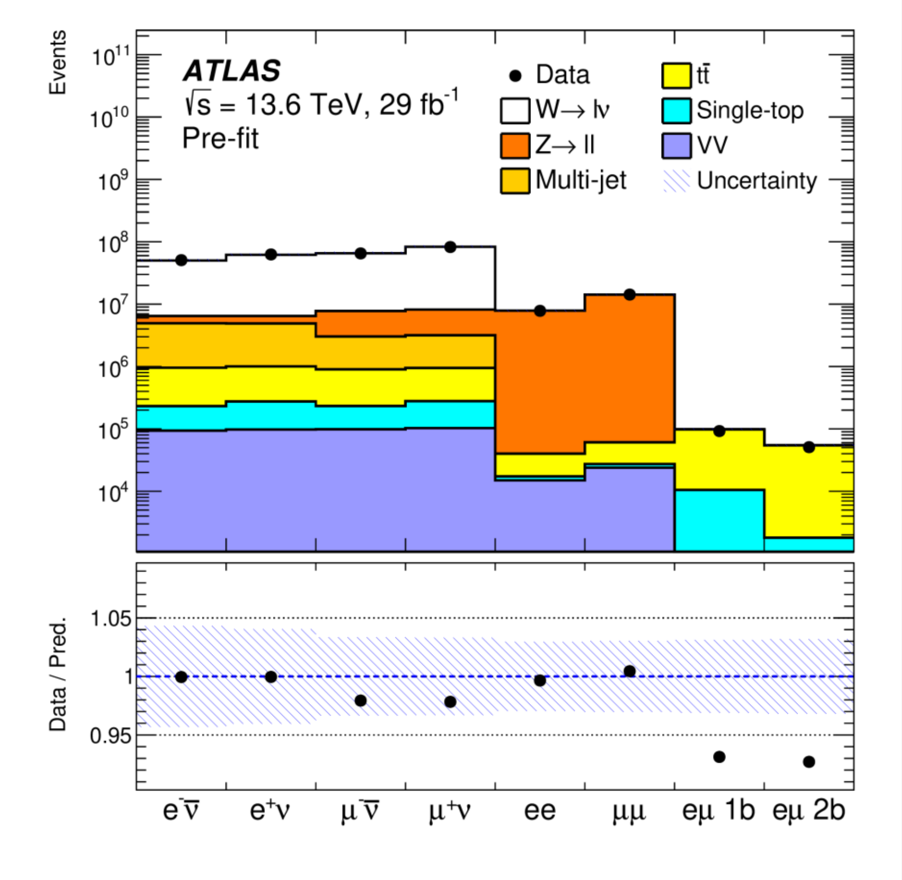
- Many new precision measurements released by ATLAS in the last year, which can be of interest to PDF fitters:
  1. Jet Ratios: **Phys. Rev. D 110, 072019 (2024)**
  2. Z+HF: **Eur. Phys. J. C 84 (2024) 984**
  3. W/Z at 13.6 TeV: **Phys. Lett. B 854 (2024) 138725**
  4. Unfolded MET+jets: **JHEP 08 (2024) 223**

- The “Omnifold” unfolding method provides the flexibility for measurements to be re-used and probe kinematic regimes and observables not originally foreseen

Backup

W,Z @ 13.6 TeV Background estimation

- Backgrounds from EW and top-quark processes estimated using MC
- Multi-jet (MJ) background estimated from data
- W-boson:
  - PLH fits to the data in MJ – enriched fitting region
  - Discriminating variables: E_T^{miss} and m_T^W.
  - CR1: $E_T^{miss} < 25$ GeV $m_T^W < 50$ GeV, anti-isolated leptons
  - CR2: $E_T^{miss} > 25$ GeV $m_T^W > 50$ GeV, anti-isolated leptons
  - MJ templates created for each W-boson decay channel by slicing the CR1 and CR2
- Z-boson:
  - Conservative upper limit from the number of charge misidentified leptons found from $m_{\ell\ell}$ sidebands in a same-sign lepton selection
  - Found to be small, and neglected

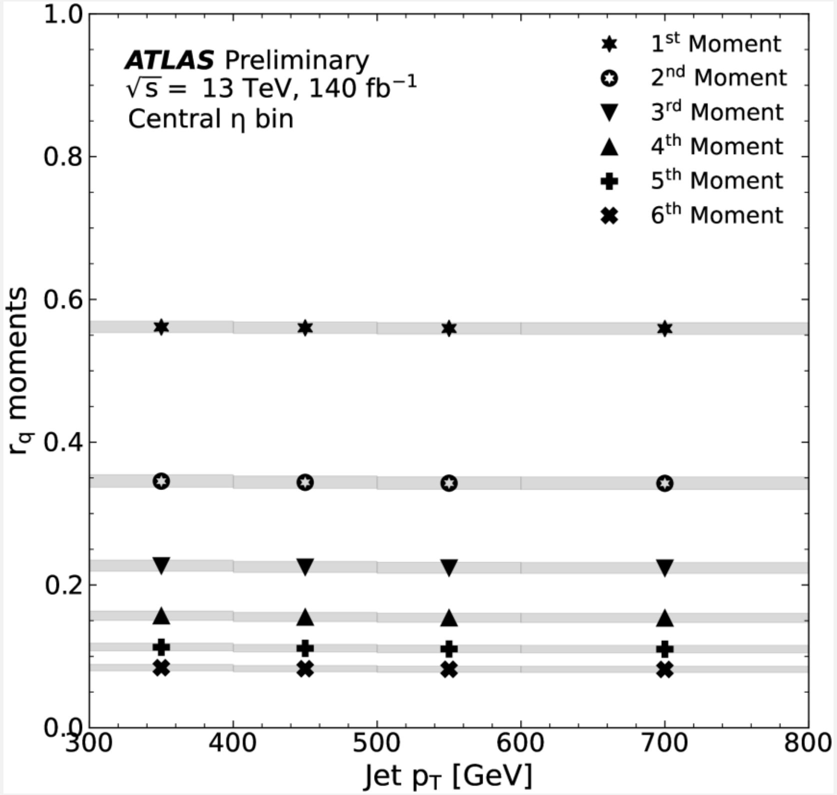


Jet Track Functions

ATLAS-CONF-2024-012

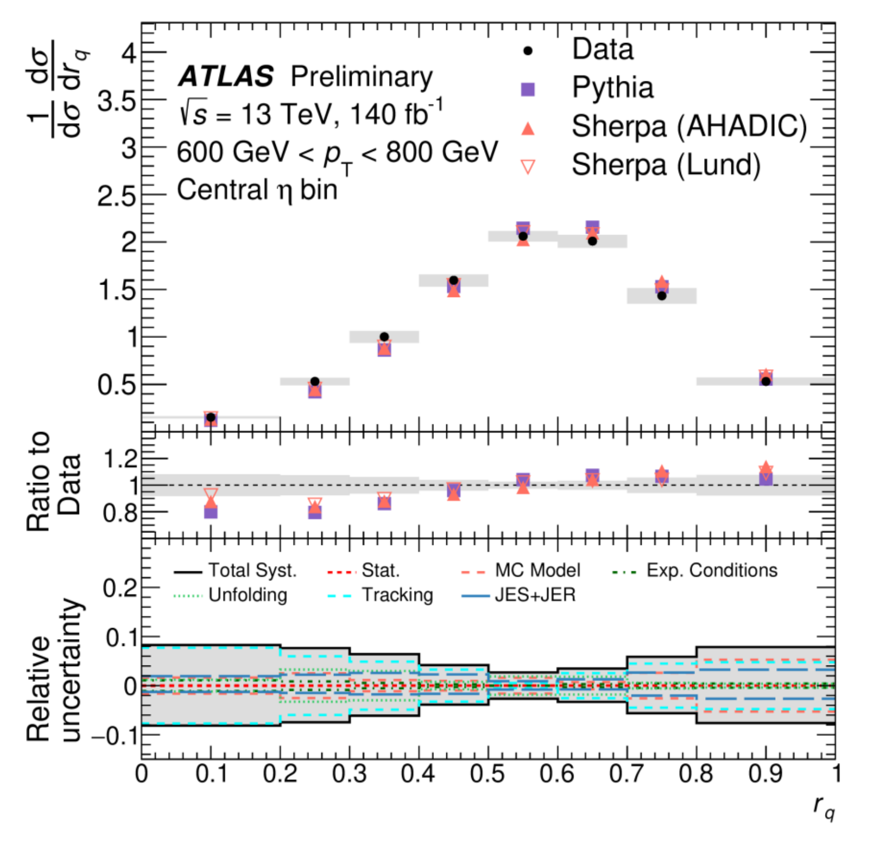
Goal & Experimental Highlights

- Many jet substructure measurement utilise track-based observables (angular precision of tracking detectors)
  - To interpret these, must understand correlated fragmentation of quarks and gluons.
- Described by universal, non-perturbative track functions (multi-hadron observables)
  - Standard fragmentation functions are single-hadron observables
- Characterise the transverse momentum fraction (r_q) carried by charged hadrons from a fragmenting quark or gluon
  - $r_q = p_T^{charged} / p_T^{all}$
    - First moment $\langle r_q \rangle \sim 2/3$ (approximate isospin symmetry), standard fragmentation functions
    - Higher moments encode interesting correlations in the hadronization process
  - Explicit r_q values needed for precision jet substructure calculations on tracks,
  - Scale evolution of r_q tests QCD beyond the DGLAP paradigm
    - Correlations in the hadronization process have non-linear renormalization group evolution
- This study measures r_q distributions in dijet events at $\sqrt{s}$ = 13TeV in 140 fb^{-1} Run 2 data



Signal Extraction & Unfolding

- Measurement performed differentially in r_q in different regions of jet p_T and rapidity-orderings
  - Extract moments of r_q as a function of the jet p_T
- Data corrected for detector bias using Iterative Bayesian Unfolding (2 iterations), and Pythia 8.2 MC
  - The jet p_T, r_q, and η regions are unfolded simultaneously
- OmniFold used as a novel data-driven correction for binning artifacts in the moment extractions
- Leading uncertainties:
  - Theory: Jet fragmentation modelling (~5% in tails ~2% in bulk)
  - Experimental: Inclusive tracking efficiency (~8% in central η and 12% in forward η)
  - Unfolding: Regularisation bias (mainly subdominant, up to ~12% at large p_T)



Results

- Cross-section as a function of r_q compared to predictions from several MC generators**)**
  - Typically agree with the data within uncertainties**,** underestimations at small r_q and overestimations at large r_q
- Moments and cumulants extracted from the r_q distribution as a function of the jet pT (shows slow evolution)
  - The energy dependence of the relationship between pairs of cumulants is determined by renormalization group flows (RG flows)
  - Govern scale dependence of correlations in the hadronization process
  - As energy increases, cumulants should converge towards fixed values (quark-/gluon-initiated jet composition)
- Compared to an analytical QCD prediction at next-to-leading-logarithm (NLL) of the RG flow
  - $\kappa 2$ $\kappa 2$ and $\kappa 2$ $\kappa 2$ $\kappa 2$ consistent with the picture of flow towards a fixed point
  - Not $\kappa 2$ $\kappa 3$ and $\kappa 3$ $\kappa 3$ (flowing in opposite directions)