QCD Measurements with ATLAS

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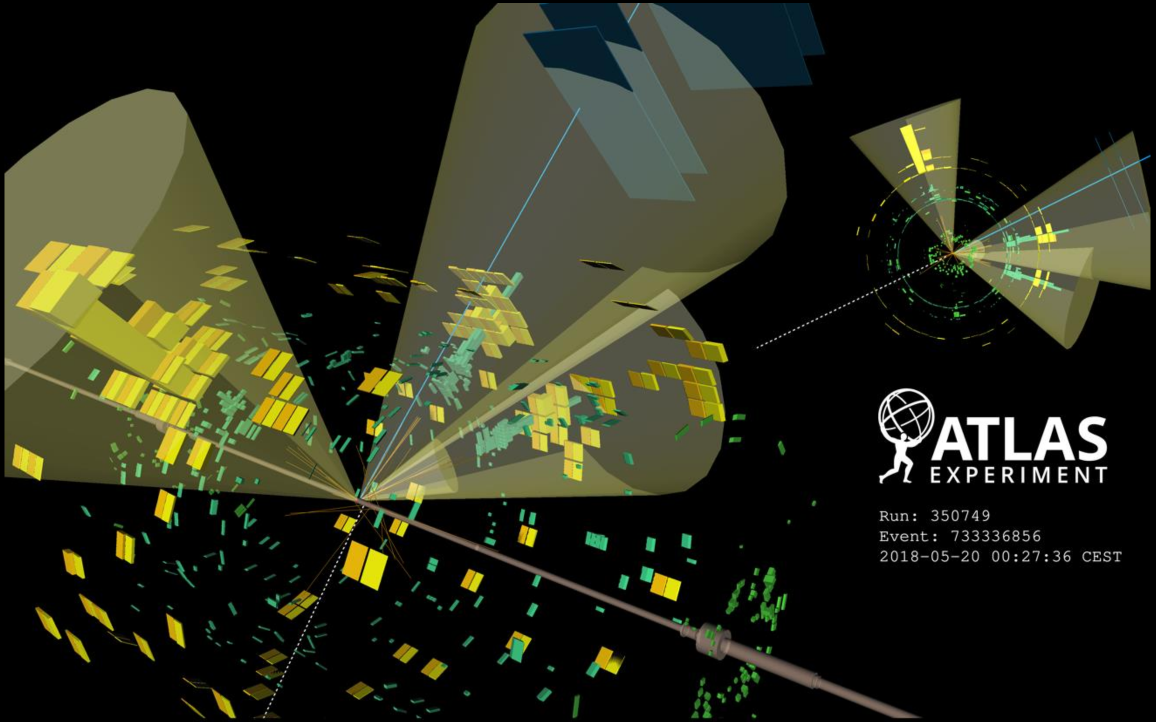
ATLAS EXPERIMENT

UNIVERSITY OF TORONTO

Introduction: QCD and Jet Substructure

- **Jet substructure (JSS)** measurements allow us to test QCD
- Provides a pathway to address open questions in QCD such as:
  - Hadronization and jet formation
  - Colour confinement
  - Non-perturbative QCD
  - Quark gluon plasma
  - And more…



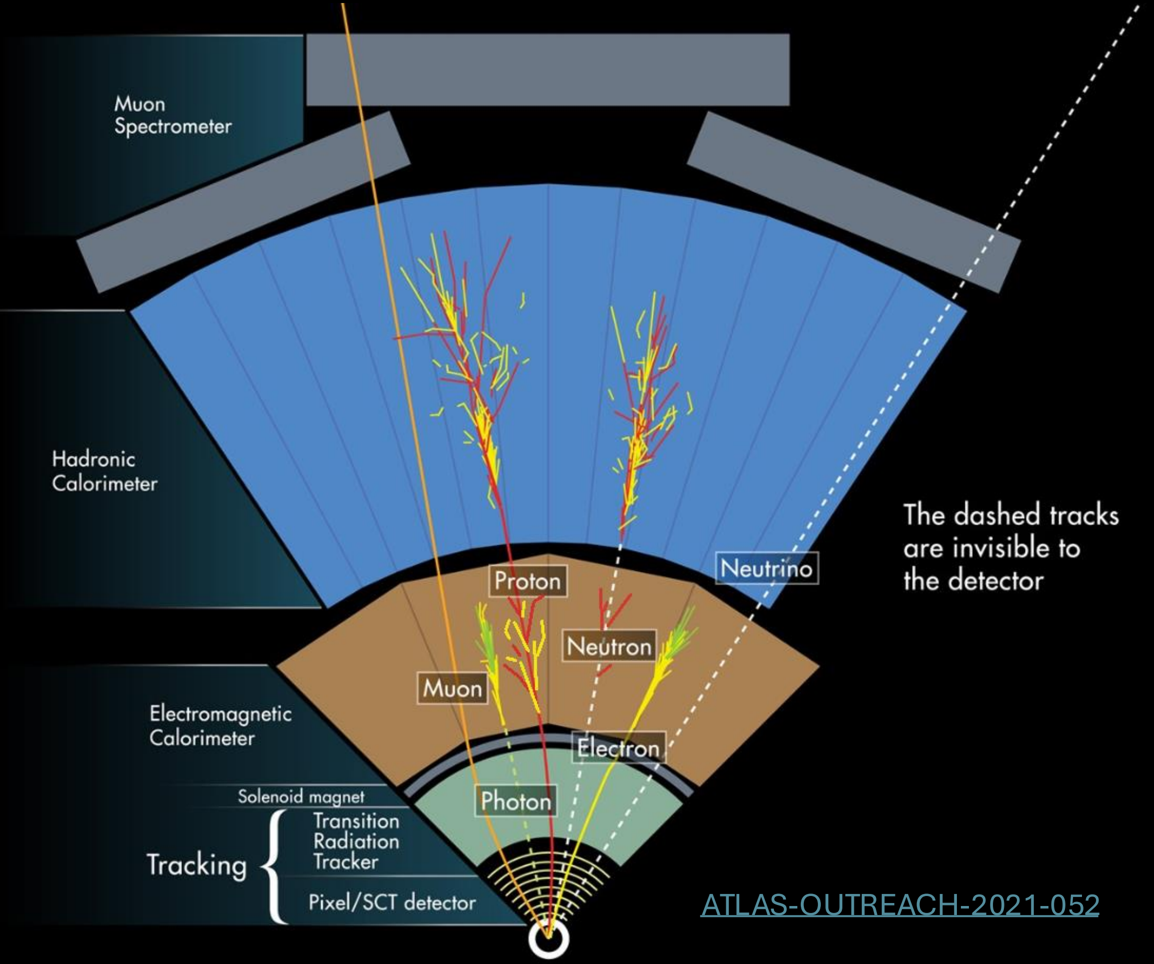
https://atlas.cern/Updates/Briefing/Advanced-Particle-Tagging

Introduction: The ATLAS Detector

- General purpose particle detector
- Inner detector (ID) in a 2 T magnetic field
    - Measures tracks of charged particles
    - Silicon pixel detector with fine granularity for resolving particle hits in dense jet cores

In this talk:

- Deposits in electromagnetic and hadronic calorimeters used to form particle flow objects (PFOs)
    - Associated with tracks measured by ID
- Jets can be reconstructed from PFOs using the anti-k_t algorithm given a radius parameter (ex: R=0.4 for small-R jets)
    - Assume selected jets for the analyses presented here are anti-k_t R=0.4 unless stated otherwise



The dashed tracks are invisible to the detector

ATLAS-OUTREACH-2021-052

Contents

In this talk, the following recent QCD measurements made by ATLAS in 2024 will be presented:

- Measurement of jet track functions in ATLAS run 2 data (ATLAS-CONF-2024-012)
- Measurements of jet cross-section ratios in 13 TeV proton–proton collisions with ATLAS (arXiv:2405.20206 **[hep-ex]**)
- Measurement of the Lund jet plane in hadronic decays of top quarks and W bosons with the ATLAS detector (arXiv:2407.10879 **[hep-ex]**)
- Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector (arXiv:2402.13052 **[hep-ex]**)

Jet Track Functions

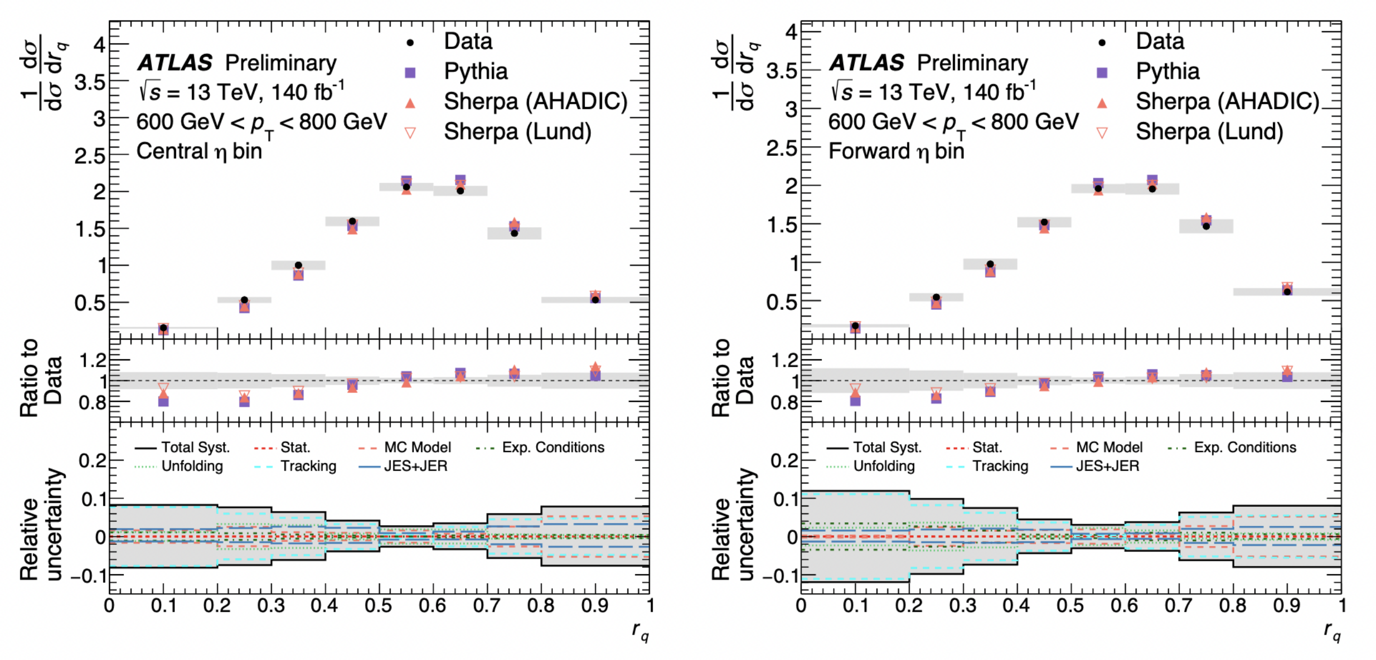
Jet Track Functions

Track functions:

- Ratio of p_T from all charged particles (tracks) to total p_T of a jet: $r_q = \frac{p_T^{\text{charged}}}{p_T^{\text{all}}}$
- Energy distribution of charged hadrons in jets
- Universal and non-perturbative
  - Cannot yet be calculated from first principles
  - Must be measured
- First moment (i.e. the average): $\langle r_q \rangle \sim \frac{2}{3}$ due to isospin symmetry
- Higher moments encode information about the hadronization process
  - Recall: nth moment is $\langle r_q^n \rangle$
- Scale evolution of these values tests QCD beyond DGLAP paradigm
- Insights into non-linear renormalization group (RG) evolution

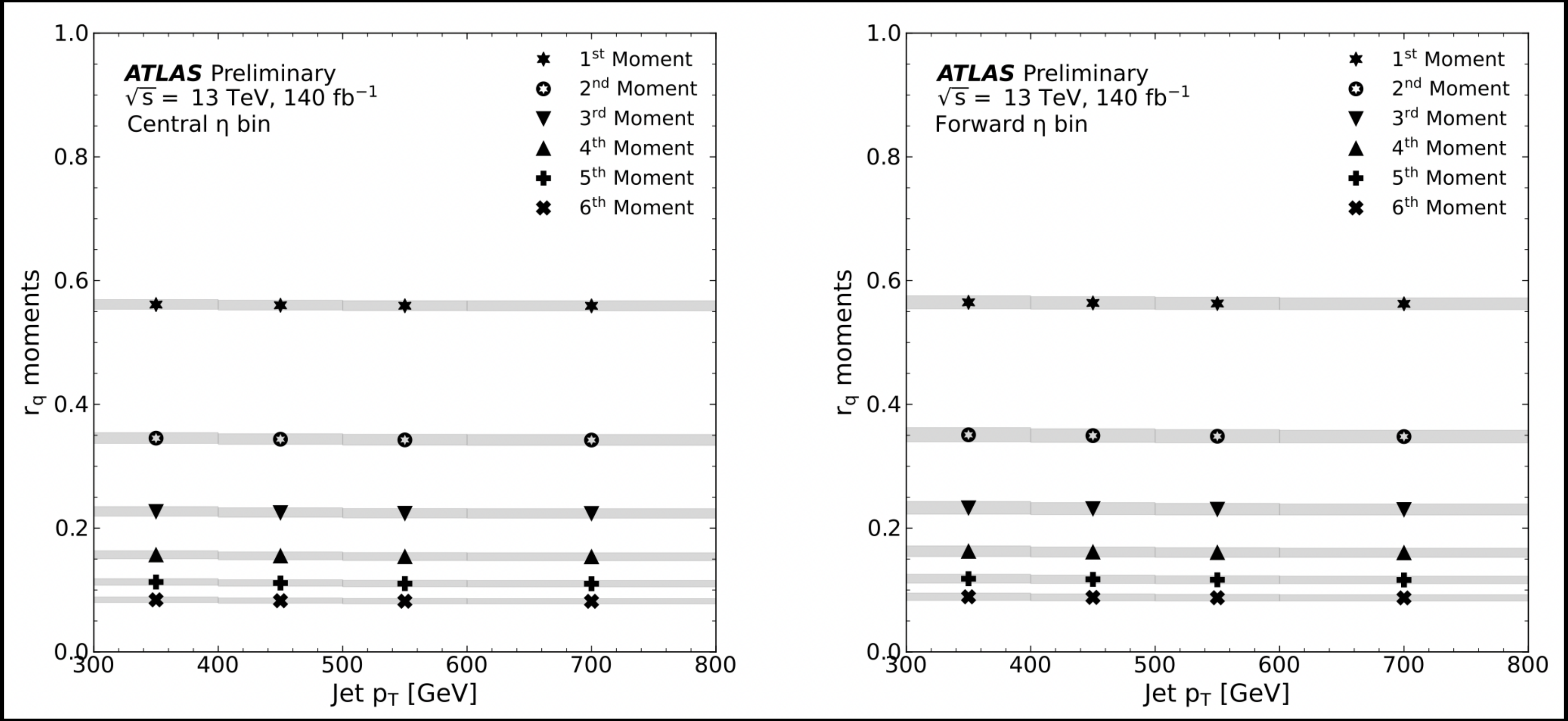
Results

- Cross-sections of r_q shown for central ($|\eta| < 2.5$) and forward ($|\eta| > 2.5$) regions
- General agreement between MC and data
  - Underestimation at low r_q and overestimation at high r_q



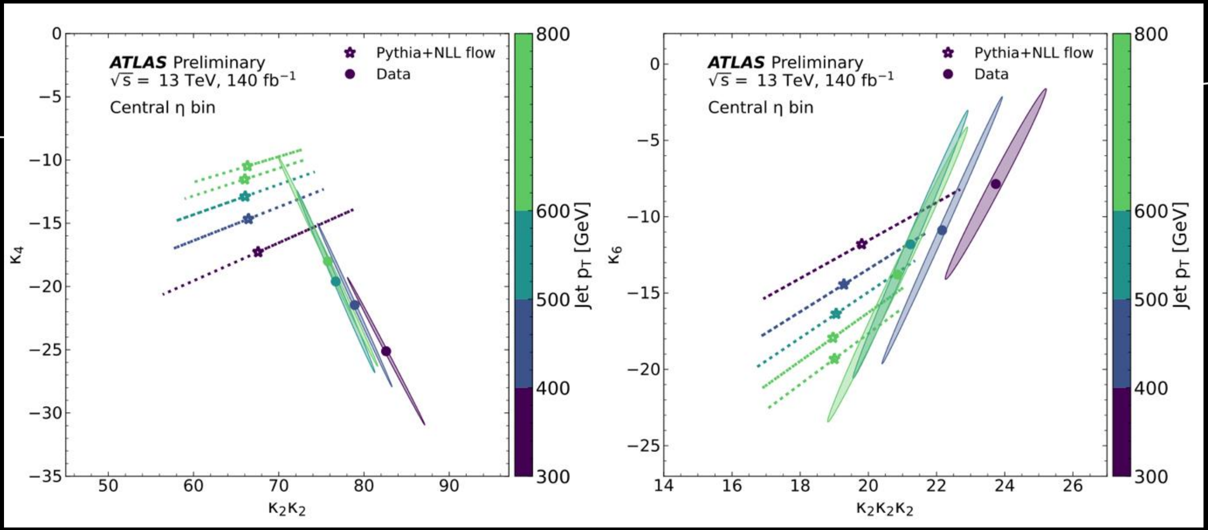
Extracted Moments

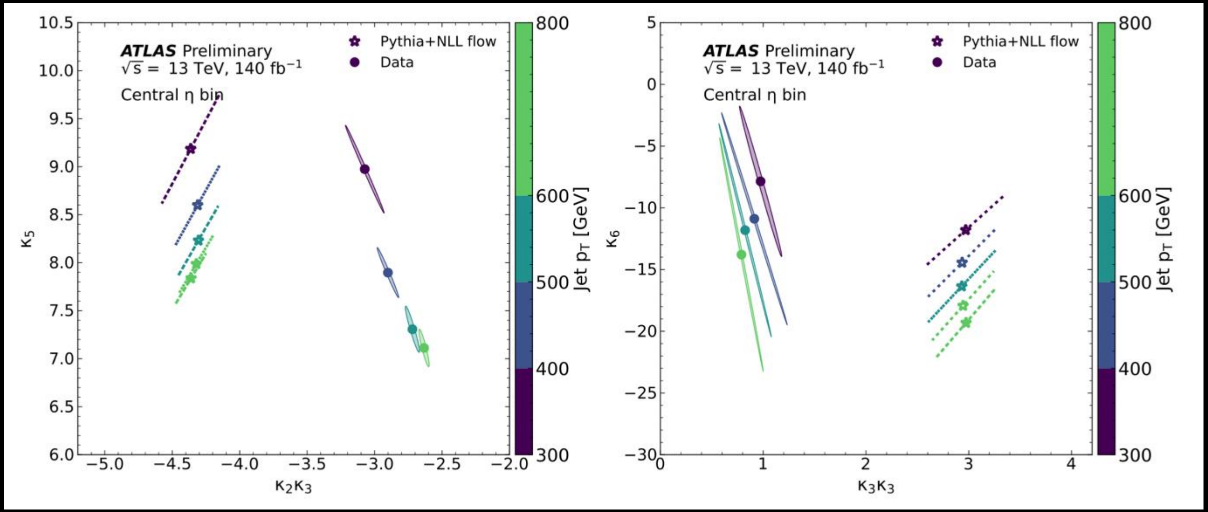
- Moment extractions use **OmniFold:** machine-learning based, data-driven correction for binning artifacts



Non-Linear RG Evolution

- Extracted moments of r_q expressed in terms of cumulants of distribution, κ_n
- Non-trivial RG flows theoretically determine energy dependence of relationships between cumulants
- Unfolded data compared to next-to-leading-logarithm (NLL) QCD predictions of the RG flow
- Theory predicts cumulants should converge to a fixed point at higher p_T
    - Top 2 figures in agreement
    - Bottom 2 figures → results flow in opposite directions, need further study to understand this discrepancy





Jet Cross-Section Ratios

Jet Cross-Section Ratios

- Measure cross-sections and their ratios in multijet events
- Goal is to compare data to MC to study and improve QCD predictions
- Separate observables chosen for sensitivity to:
  - Jet energy scale (JES) → tests accuracy of fixed-order matrix element predictions
  - Angular distribution of hadronic energy flow → indirectly tests our understanding of vector boson scattering/fusion (VBS/VBF) and parton distribution functions (PDFs)
- Observables:

Sensitive to JES

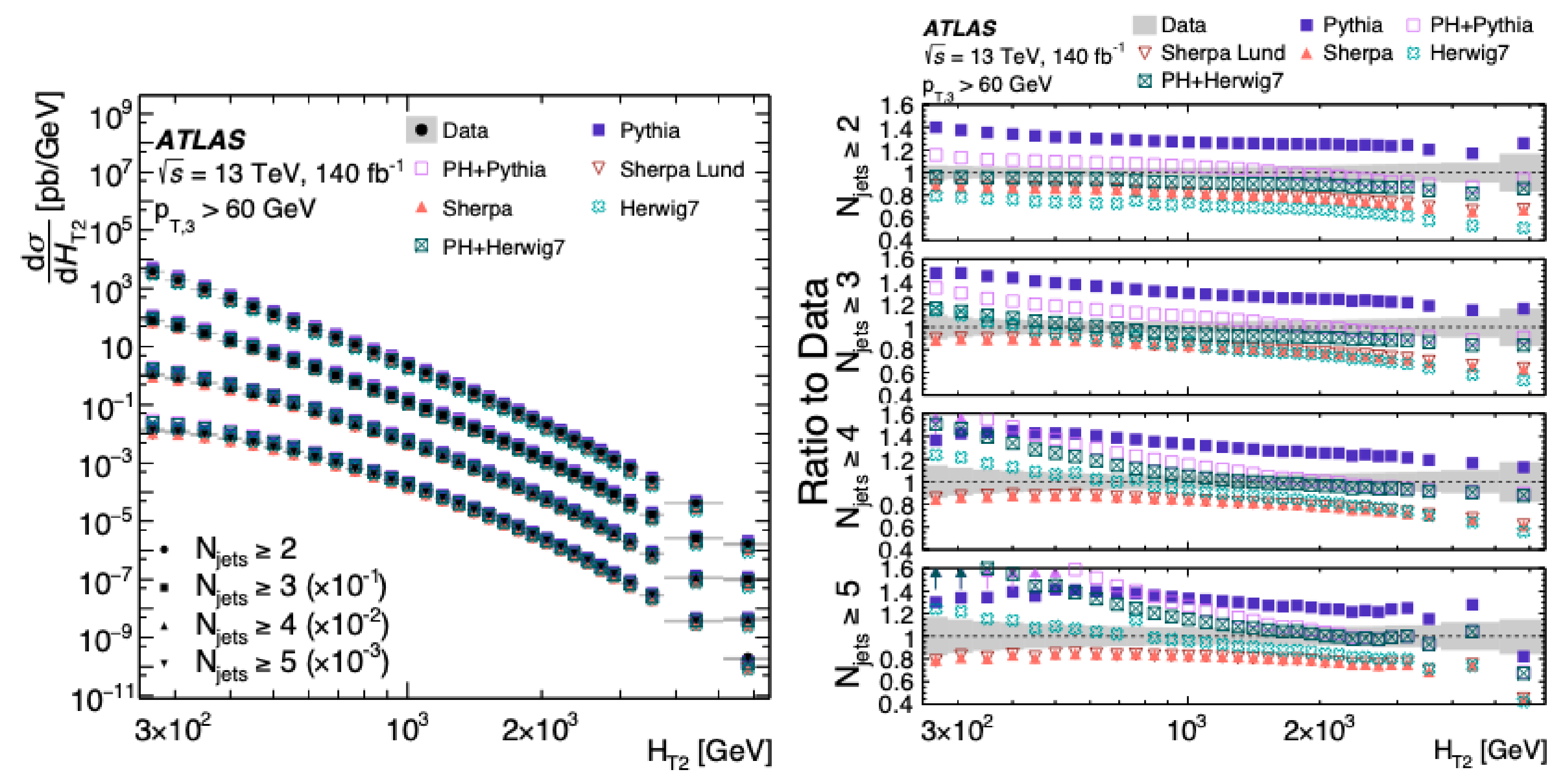
  - $H_{T2} = p_{T,j1} + p_{T,j2}$ → Sum of transverse momenta of the leading two jets
  - → Chosen as a proxy of the energy scale for the interaction
  - $p_T^{N\text{incl}}$ → Inclusive jet p_T distribution

Sensitive to angular distribution

  - Δy_{jj} & $\Delta y_{jj,\max}$
  - m_{jj} & $m_{jj,\max}$

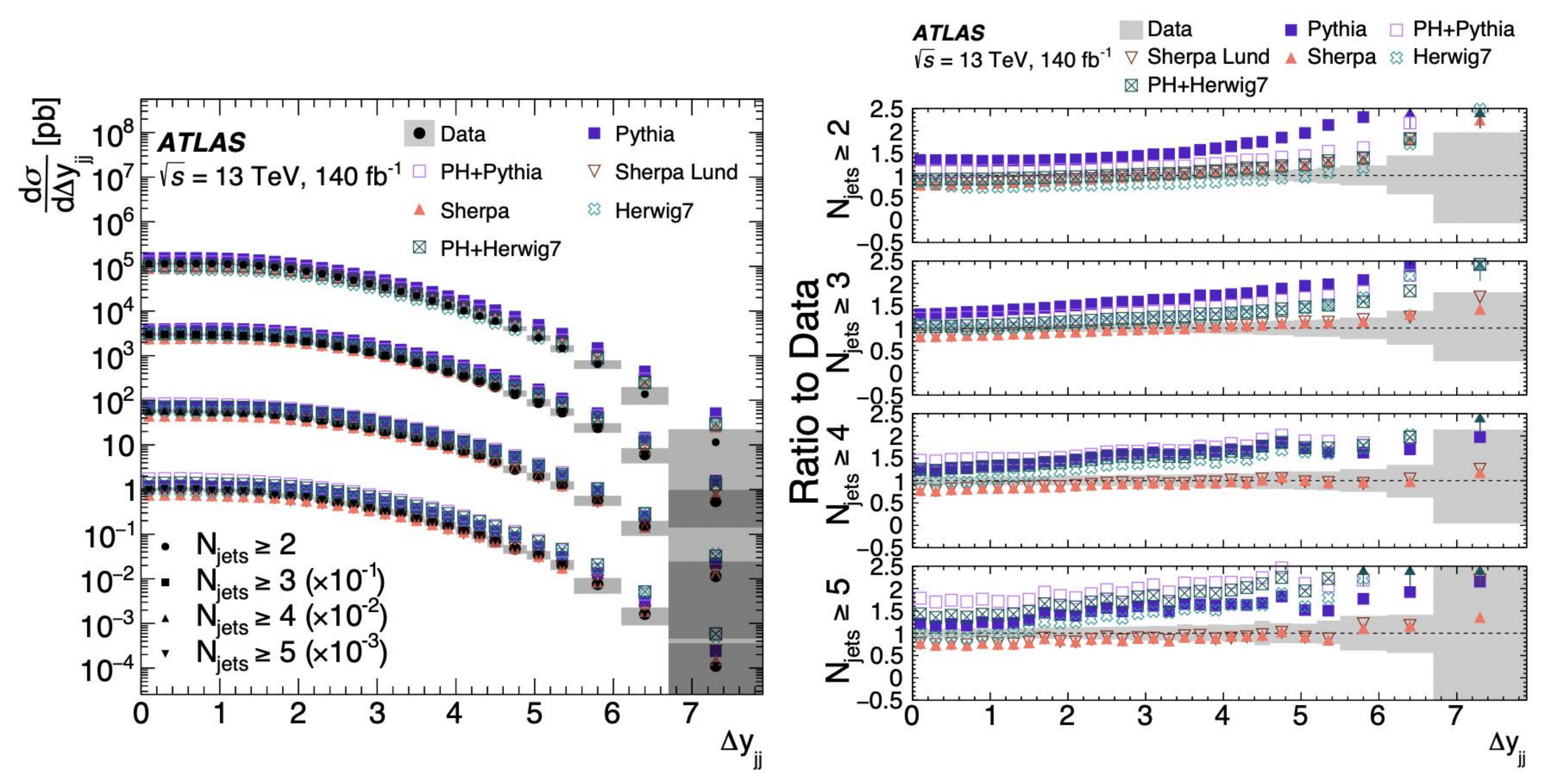
Results: Cross-Sections

- No single MC prediction can describe the data across all bins



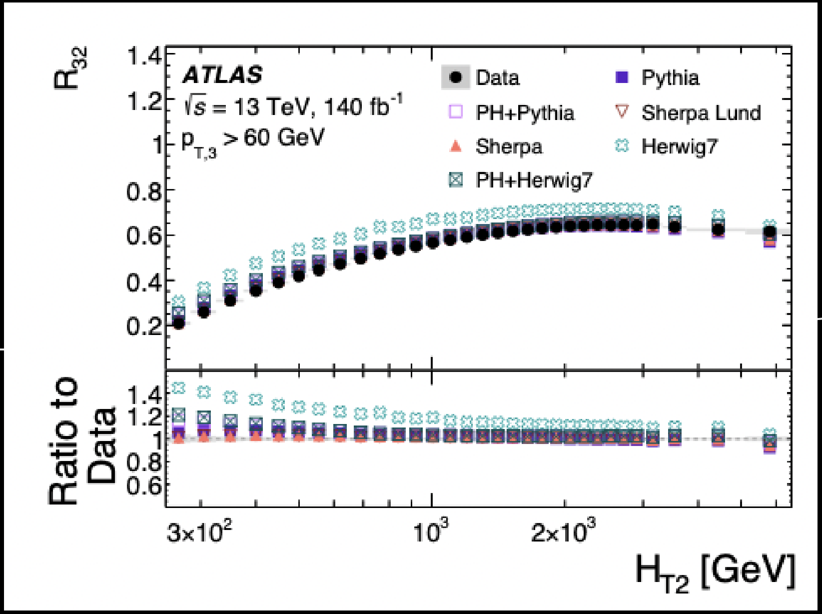
Results: Cross-Sections

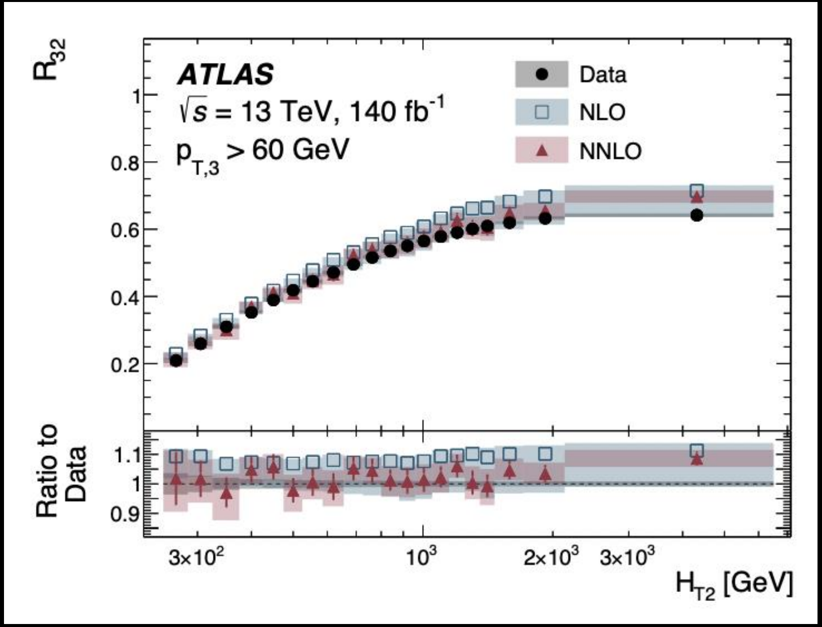
- Significant difference between data and MC for large Δy_{jj} and m_{jj}



Results: R_{32}

- Ratio of jet cross-sections of different multiplicities
- R_{32} → 3-jet to 2-jet cross section ratio
- Sherpa agrees well with data
- Herwig underestimates 2-jet cross-section
- Next-to-next-to-leading-order (NNLO) agrees well with data
- Next-to-leading order (NLO) overestimates R_{32}





The Lund Jet Plane in Top and W Decays

The Lund Jet Plane (LJP)

$$\Delta R^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

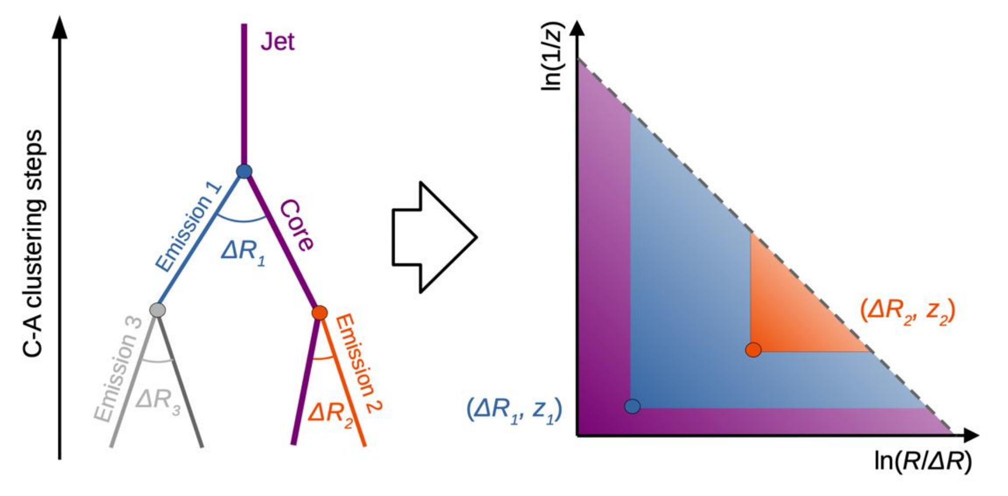
Angular separation of proto-jets

$$z = \frac{p_T^j}{p_T^i + p_T^j}$$

Relative transverse momentum of emission

- 2D JSS observable representing the kinematics of parton showers and hadronization
- Jets are reconstructed using the CA algorithm which combines particles into proto-jets based on:
  - Distance between particles in (y, ϕ) plane
  - Radius parameter of the jet algorithm (ex: R=0.4 for small-R jets)
- LJP is constructed by starting with the finished jet and going through pairs of proto-jets in previous steps of the shower
- Lower-pT proto-jet (j) is the emission
- Higher-pT proto-jet (i) is the core

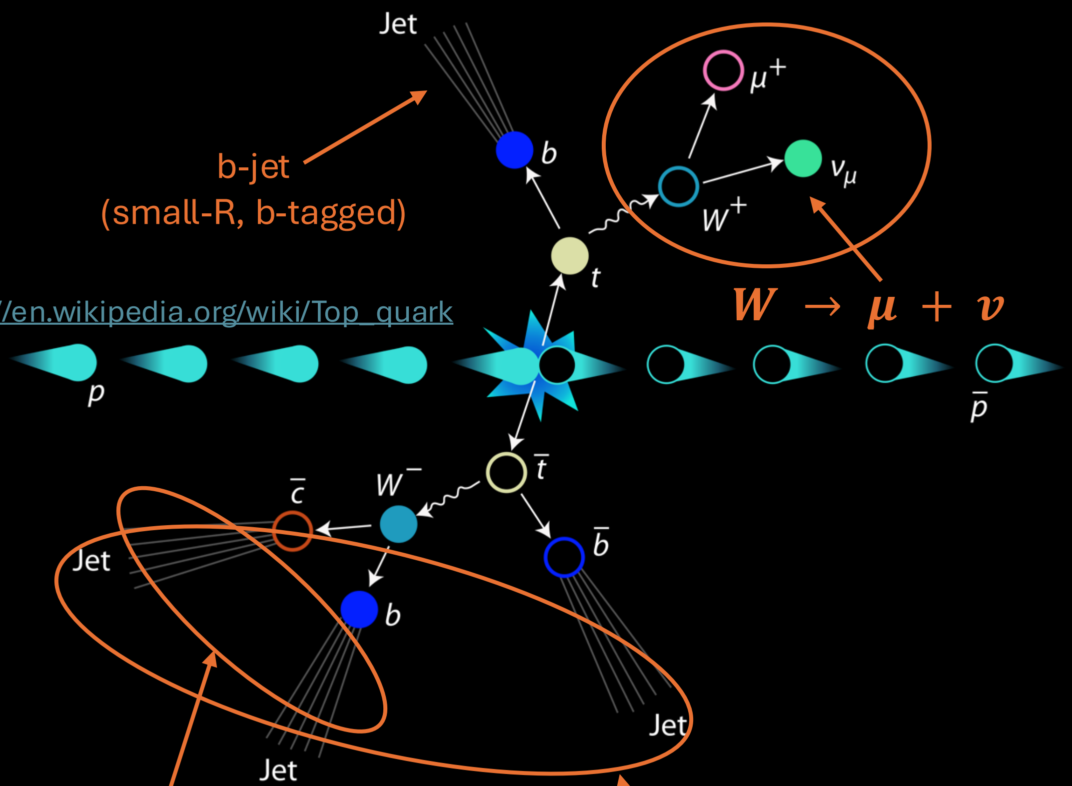
$$p_T^j < p_T^i$$



Variables $\ln(R/\Delta R)$ and $\ln(1/z)$ plotted for each emission from the core branch. Colored areas indicate size of phase space in which subsequent emissions may appear.

LJP Measurements in Top and W Jets

- Select anti-k_t jets with R = 1.0 **(large-R jets)** with $p_T > 350$ GeV
- Must contain full decay products of either:
  1. Top quark
  2. Daughter W boson
- Selecting $t\bar{t}$ events where:
  - Top quarks decay to W and b quark
  - One W decays hadronically into jets
  - Other W goes to electron or muon + neutrino
- Jet classified as either ‘top jet’ or ‘W jet’ based on decay topology
- Motivation:
  - Improve MC generators in modelling decays of heavy quarks and bosons
  - Improve jet tagging algorithms
  - Probe jet structure, evolution, hadronization, etc.



b-jet
(small-R, b-tagged)

$W \rightarrow \mu + \nu$

https://en.wikipedia.org/wiki/Top_quark

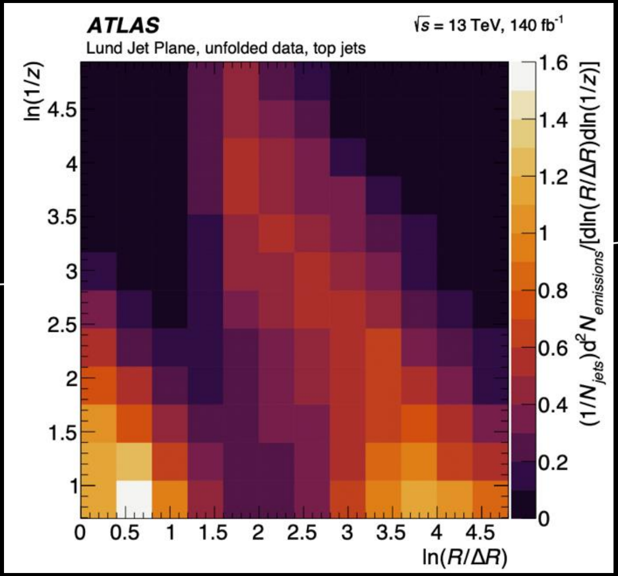
W jet
(60 < m < 100 GeV)

Top jet
(m > 140 GeV, contains 2 b-jets)

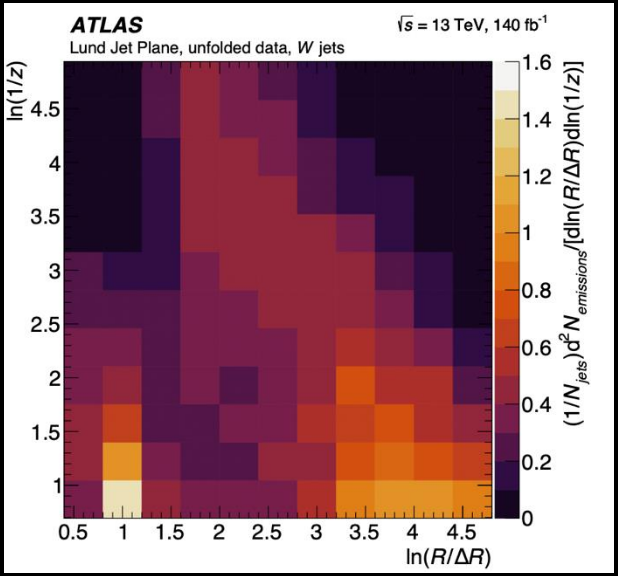
Results

- Measured density of emissions in the LJP for top and W jets
- Bottom left region contains decays of high-pT top quarks and W bosons
  - For top jets, peak is shifted to wider angles (larger ΔR) due to top mass > W mass
- Average number of emissions per jet is:
  - Top jets: $6.74 \pm 0.02\ (\text{stat.}) \pm 0.13\ (\text{syst.})$
  - W jets: $6.02 \pm 0.04\ (\text{stat.}) \pm 0.22\ (\text{syst.})$
  - Implies on average ~1 extra emission for top jets
- High density of emissions in perturbative – non-perturbative transition region where $k_T = \Lambda_{\text{QCD}}$
  - Density of emissions proportional to $\alpha_s(k_T)$
  - Running of α_s causes increase in emissions
- Upper right corner $k_T < \Lambda_{\text{QCD}}$, large non-perturbative corrections
  - Number of emissions is suppressed

Top jets



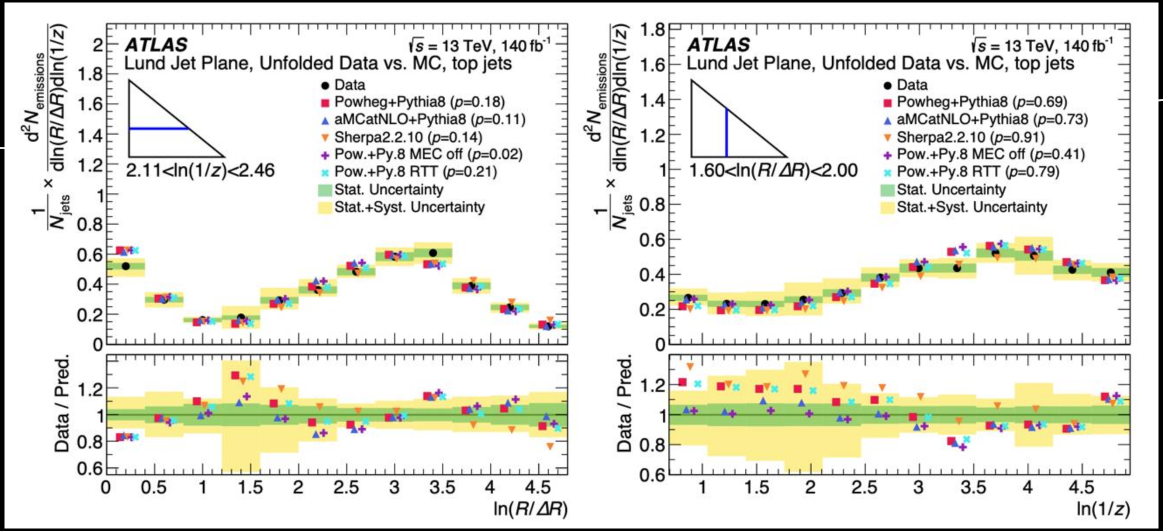
W jets



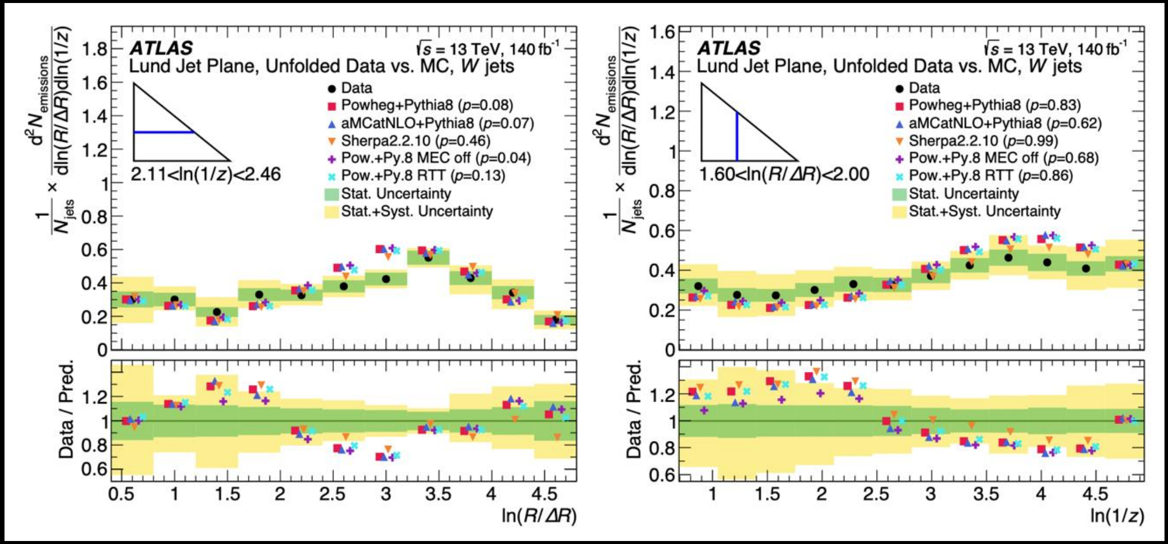
Comparison with MC

- Disagreement between data and MC in large regions of the spectra
- Sizeable differences in central region of LJP, especially for W jets
- Large amount of statistical uncertainty, precision could improve with larger dataset

Top jets



W jets



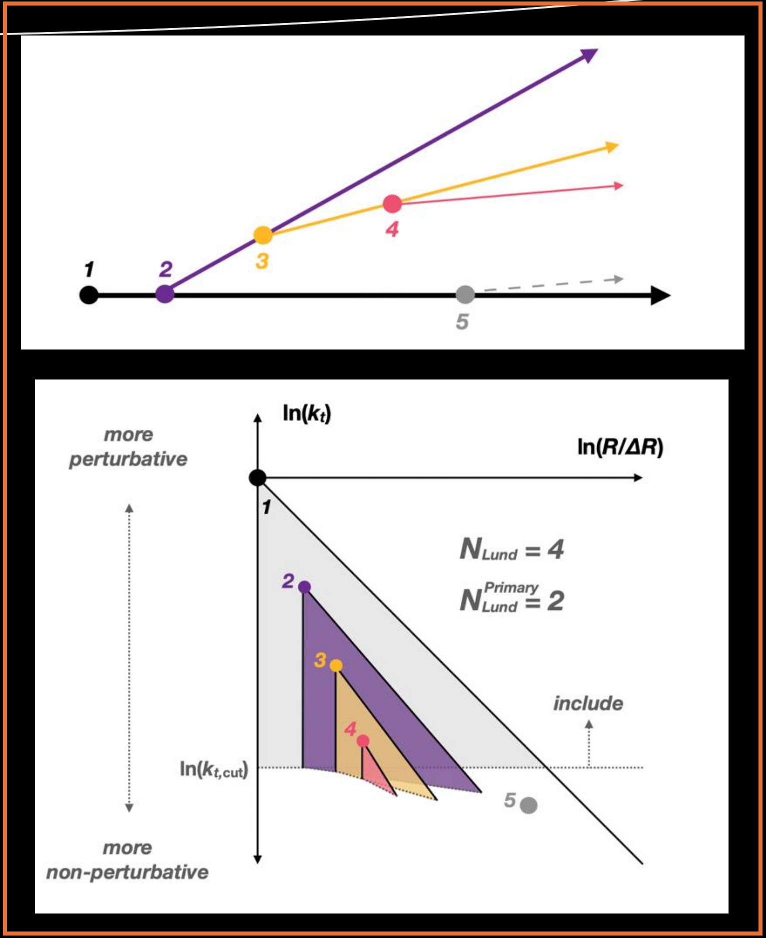
Lund Subjet Multiplicities

Lund Subjet Multiplicity

$$k_t = p_{\mathrm{T}}^{\mathrm{emission}} \cdot \Delta R(p^{\mathrm{emission}}, p^{\mathrm{core}})$$

Transverse momentum of emission relative to core

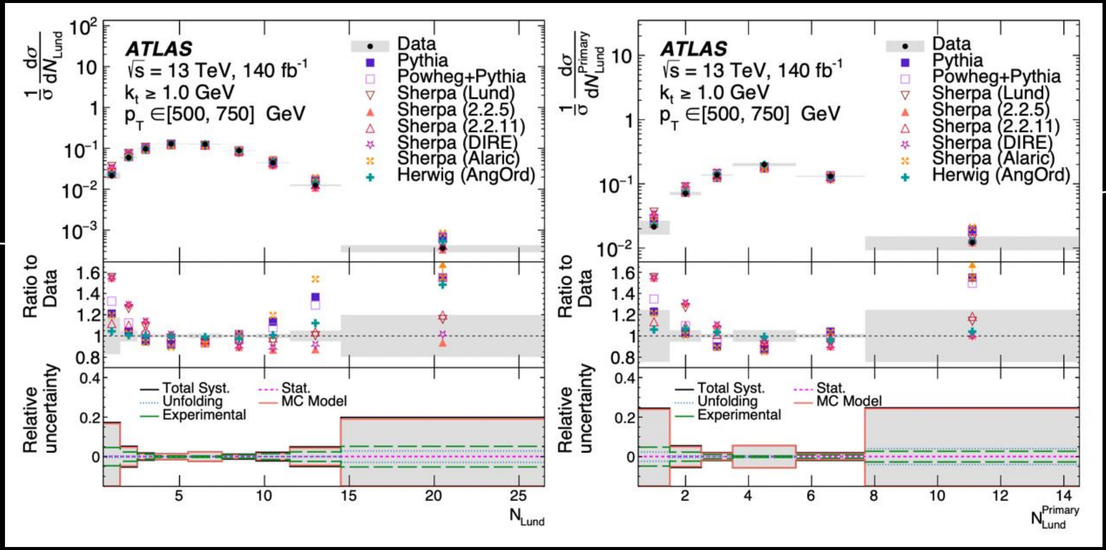
- Counts number of subjets in the clustering history
- Subjet must be above a minimum k_T to be counted in Lund multiplicity
- N_{Lund} → full count in the whole LJP
- $N_{\mathrm{Lund}}^{\mathrm{Primary}}$ → only counting along the primary clustering (jet core)
- Ex: ‘5’ doesn’t pass the k_T cut and isn’t counted
- Motivation:
  - Improve parton shower MC algorithms (PSMCs) by incorporating double-soft splittings → emissions of 2 soft gluons or a quark-antiquark pair (beyond tree-level in QCD)
  - Lund multiplicity will test for inclusion of double-soft splittings



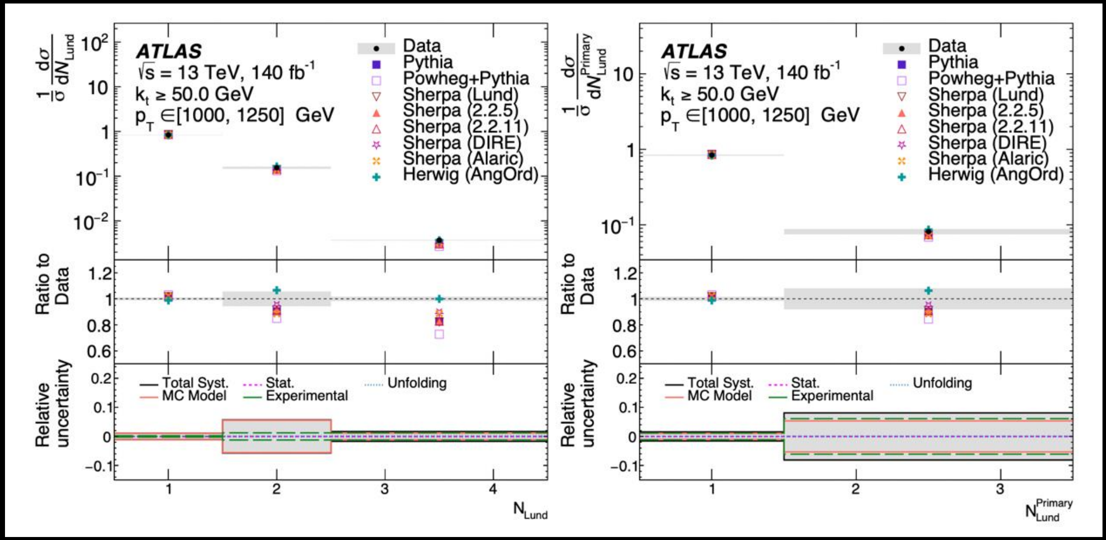
Results

- Cross-section distribution of Lund multiplicities shown for k_T thresholds of 1 GeV and 50 GeV
- Most MC generators don't descried data well, especially for low and high multiplicities
- Herwig performs the best
- For smaller k_T cuts (≤ 2 GeV), Sherpa does better at high multiplicity where more non-perturbative emissions are allowed

$k_T \geq 1.0$ GeV



$k_T \geq 50.0$ GeV

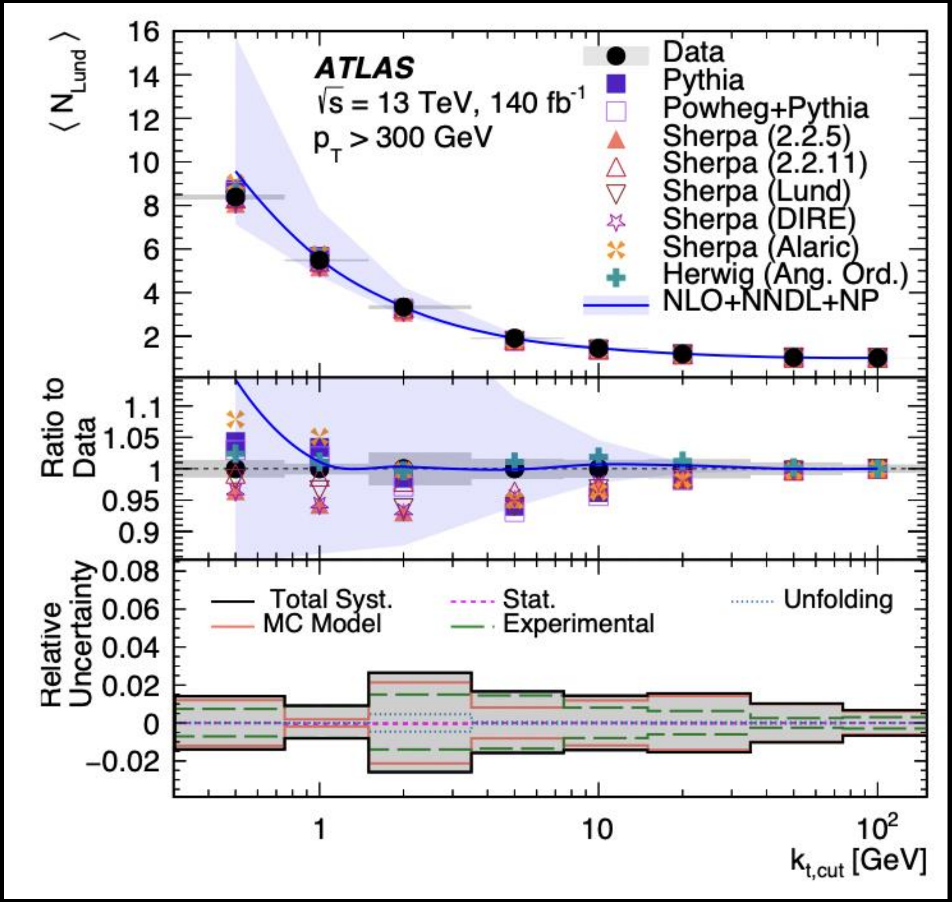


N_{Lund}

$N_{\text{Lund}}^{\text{Primary}}$

Results

- Distribution of average Lund multiplicity vs k_T cut plotted
- Herwig agrees best
- Resummed analytic prediction (NLO+NNDL+NP) in good agreement with data in perturbative region ($k_T > 2$ GeV)



Conclusion

Summary

- Several exciting new QCD measurements provide us insights into jets and their formation and substructure
- These better our understanding and modelling of QCD in several ways
- Track functions of jets were measured → extrapolated statistical moments allow for the study of non-linear renormalization group evolution
- Jet cross-section ratios measured to test MC methods
- Lund jet plane measured for the first time in $t\bar{t}$ events → help to improve modelling of heavy quark/boson decays
- Lund multiplicities measured to improve parton shower modelling

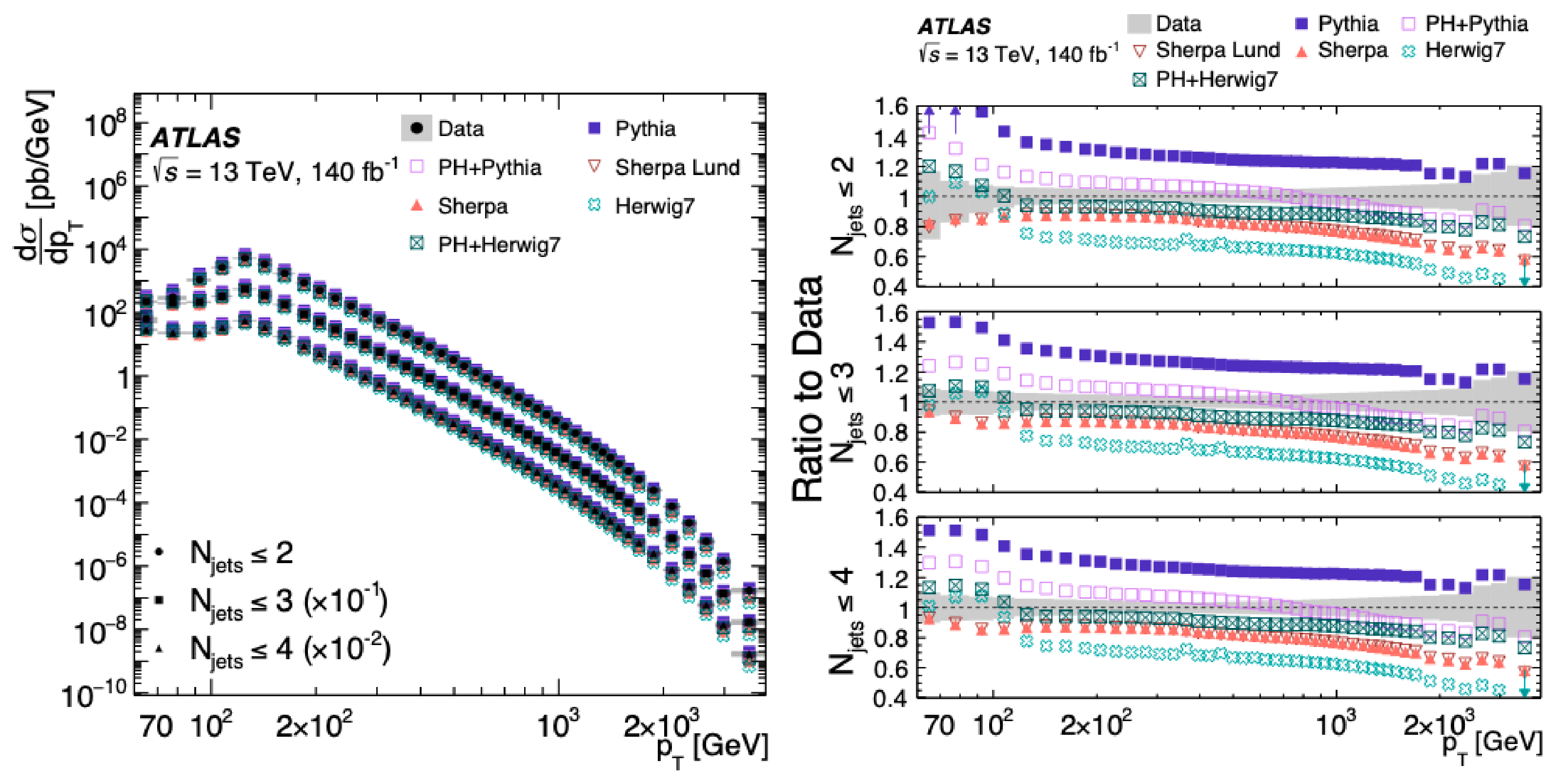
Thank you!

Backup

Jet Cross-Section Ratios

Results: Cross-Sections

- No single MC prediction can describe the data across all bins



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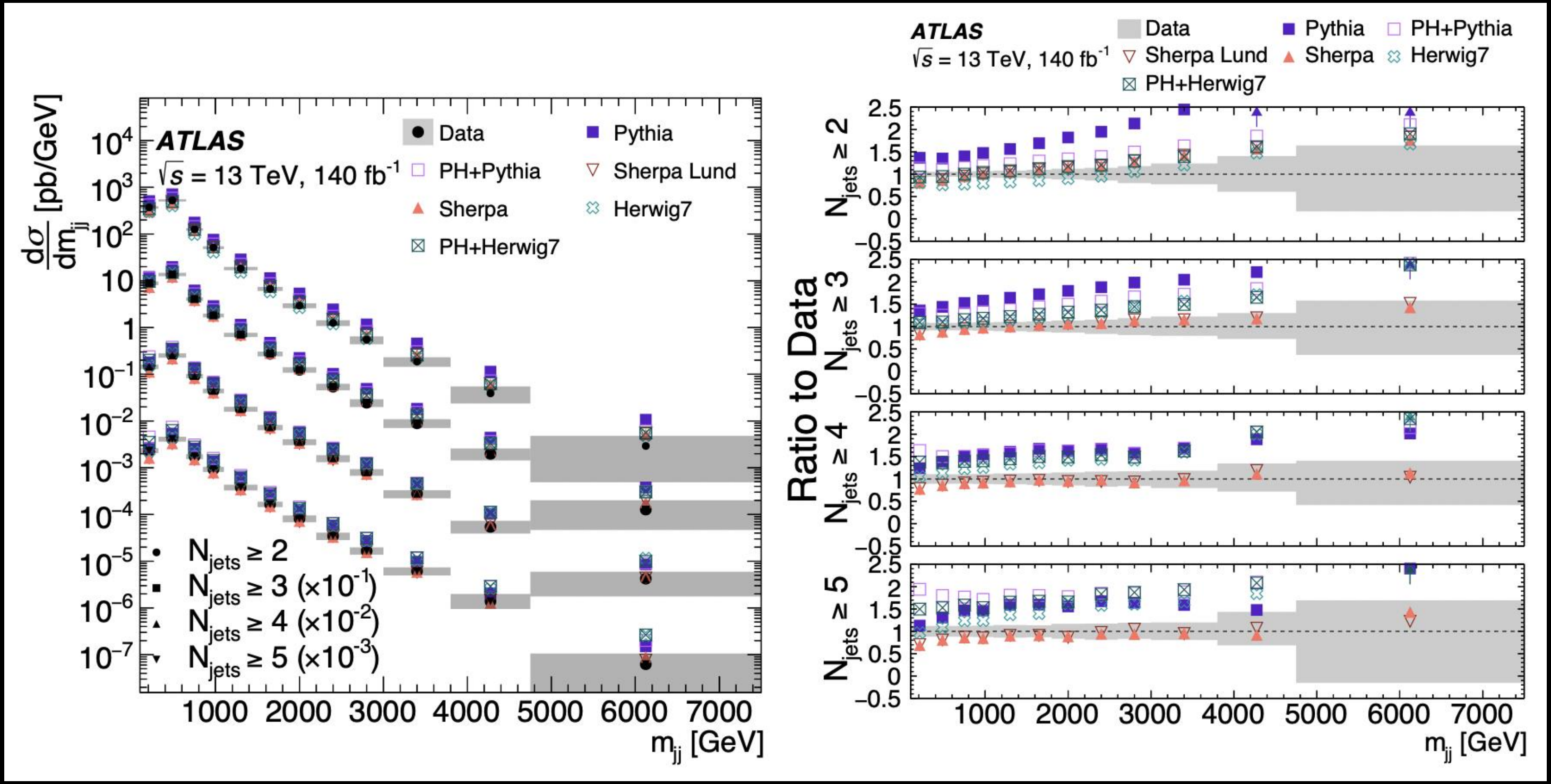

Results: Cross-Section Ratios

- Ratios of jet cross-sections of different multiplicities
- Ex: R_{42} → 4-jet to 2-jet cross section ratio
- Sherpa agrees well with data
- Herwig underestimates 2-jet cross-section