Measurements on jet substructure at the LHC

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Standard Model at the LHC 2025, Durham

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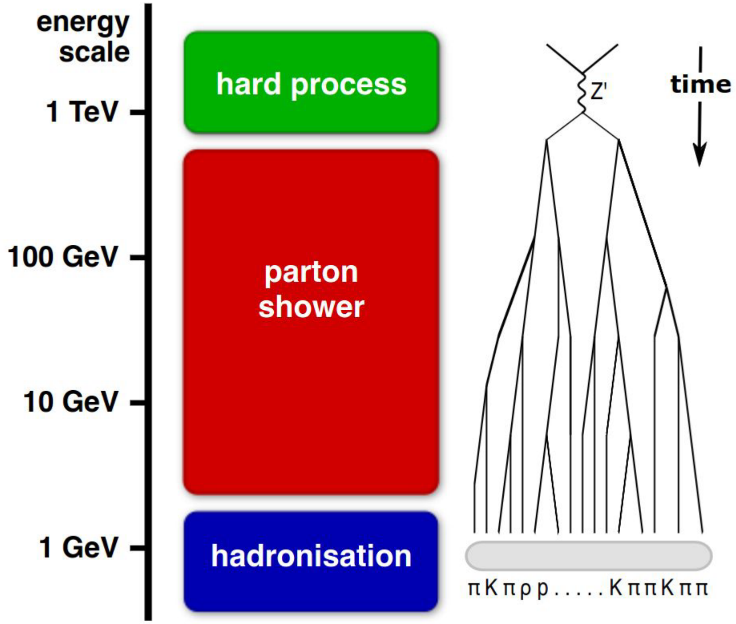
Jet substructure measurements

- probe of perturbative and non-perturbative QCD regimes (resummation methods, parton showers, hadronization, underlying event)
- can be used for tagging objects, mitigating effects of pile-up and underlying events



G. Salam's sketch

- This presentation focuses on 4 recent measurements:
  - Measurement of the primary **Lund jet plane** density in proton-proton collisions at $\sqrt{s}$ = 13TeV (CMS, JHEP 05 (2024) 116)
  - Measurement of the **Lund jet plane** in hadronic decays of **top quarks and W bosons** with the ATLAS detector (arXiv:2407.10879, submitted to EPJC)
  - Measurement of **jet track functions** in *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector (arXiv:2502.02062, submitted to Physics Letters B)
  - Measurement of **event shape variables** using charged particles inside jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV (CMS-PAS-SMP-22-004)

The Lund jet plane (LJP)

F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

- 2D representation of the phase space of splittings (emissions) within a jet
- Constructed by following the Cambridge–Aachen clustering tree in reverse; at each step we can calculate kinematic variables describing the branching:
  - emission opening angle:

$$\Delta R = \sqrt{(y^{\text{softer}} - y^{\text{harder}})^2 + (\phi^{\text{softer}} - \phi^{\text{harder}})^2}$$

  - momentum fraction of the emitted particle:

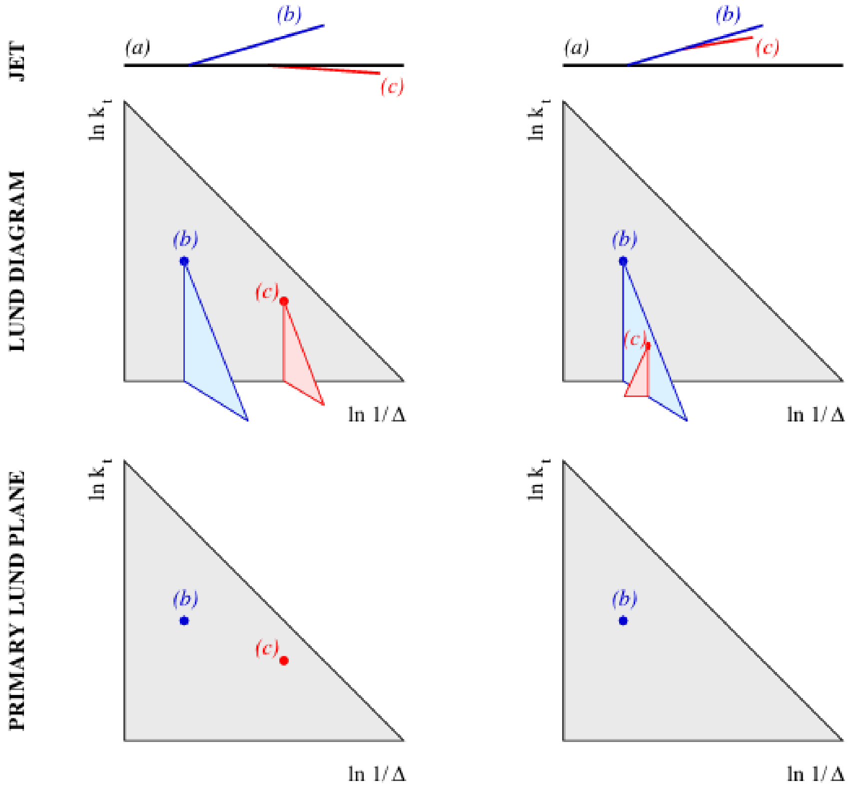
$$z = \frac{p_T^{\text{softer}}}{p_T^{\text{harder}} + p_T^{\text{softer}}}$$

  - transverse momentum of emitted particle relative to the emitter:

$$k_t = \Delta R p_T^{\text{softer}}$$

(in the limit $p_T^{\text{softer}} \ll p_T^{\text{harder}}$ and $\Delta R \ll 1$)

- The ***primary*** LJP is constructed only from the emissions along the hardest branch



Primary LJP density

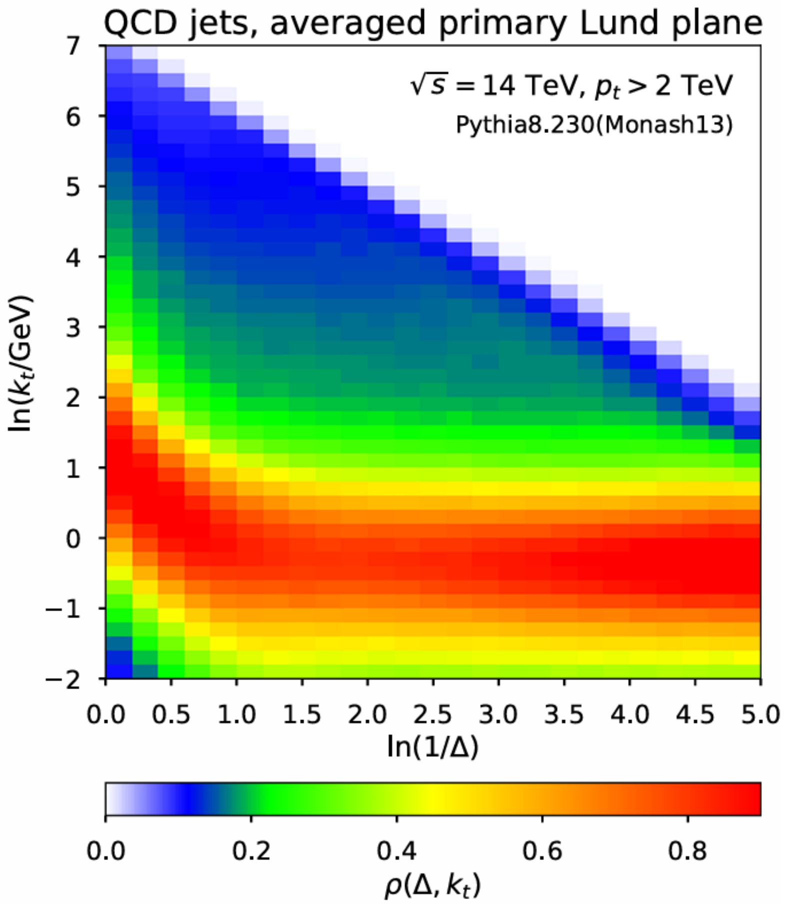
- Average density of emissions per jet and per unit area:

$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{\text{jets}}} \frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln\left(\frac{k_T}{\text{GeV}}\right) \mathrm{d}\ln\left(\frac{R}{\Delta R}\right)}$$

- At leading order and for $\Delta R \ll 1$, $\frac{k_T}{p_{T,\text{jet}} \Delta R} \ll 1$,

$$\rho(k_T, \Delta R) \simeq \frac{2}{\pi} C_R \alpha_s(k_T)$$

where $C_R = 3$ for g → gg or $C_R = 4/3$ for q → qg

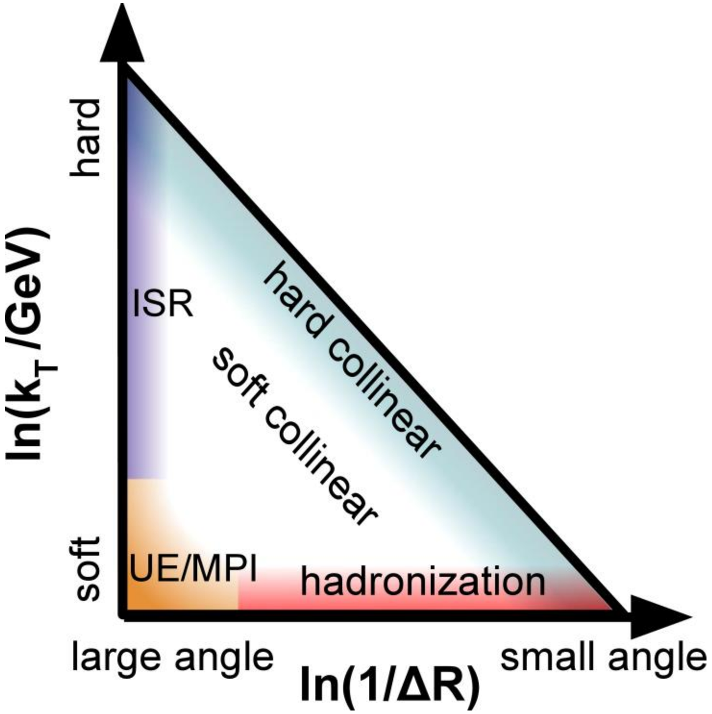


F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

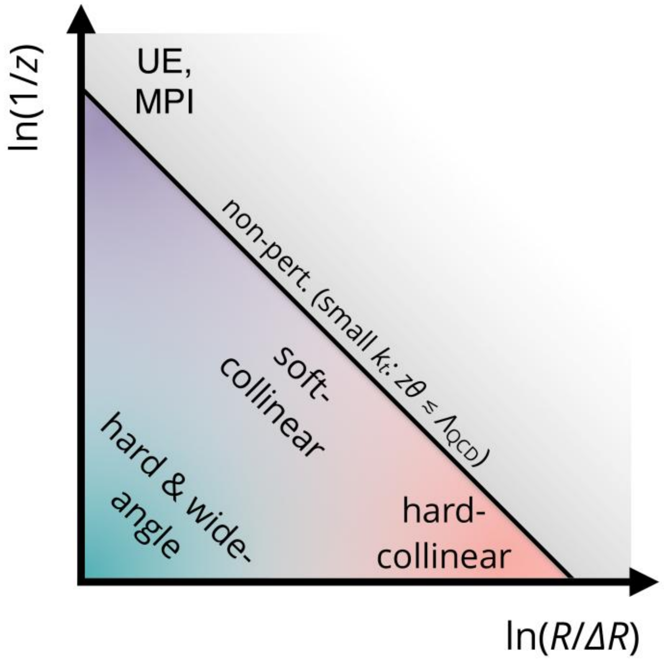
Factorisation of physical effects

- Different regions of the LJP are dominated by QCD emissions of different physical origins
- Measurements of the LJP are useful tools for providing MC generator tunes

CMS: k_T vs ΔR
- shower and hadronization regions more clearly separated (by cutting on k_T)
- more sensitive to detector smearing effects



CMS, JHEP 05 (2024) 116



ATLAS, PRL 124, 222002 (2020)

ATLAS: z vs ΔR
- more resilient to smearing effects (cancel in z since it’s a ratio)

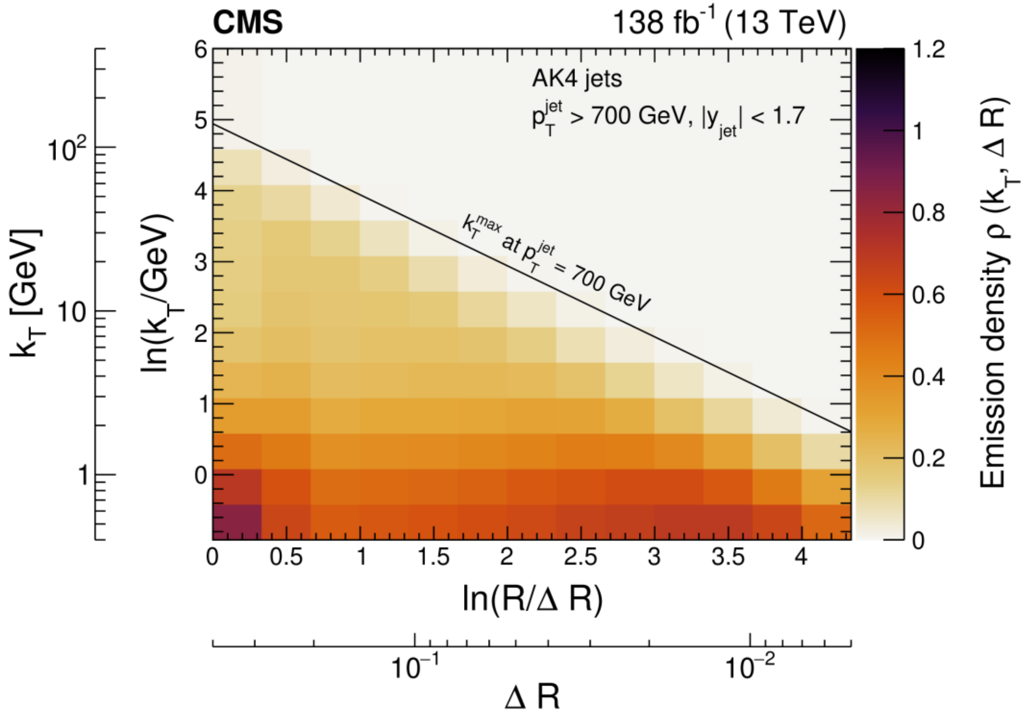
LJP measurements at the LHC

- Primary LJP densities:
  - ATLAS in dijet events: PRL 124, 222002 (2020)
  - ALICE in inclusive low-pT jets: ALICE-PUBLIC-2021-002
  - **CMS in inclusive jets: JHEP 05 (2024) 116**
  - **ATLAS in top and W jets: arXiv:2407.10879, submitted to EPJC**
- ALICE dead-cone effect observation: Nature 605 (2022) 440-446
- ATLAS Lund subjet multiplicities (PLB 859 (2024) 139090)

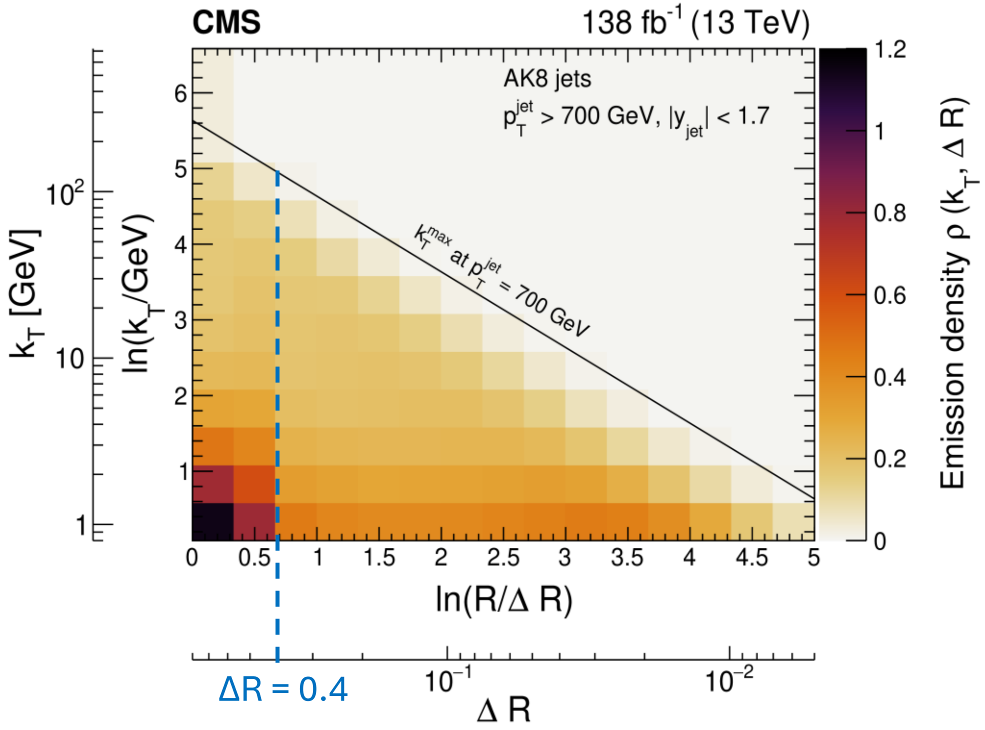
CMS primary LJP density measurement in inclusive jet production

- p_T > 700 GeV
- charged particle tracks used for substructure
- first measurements in large-radius jets → mitigates clustering effects
- multidimensional unfolding

R = 0.4 (standard for Run 2)

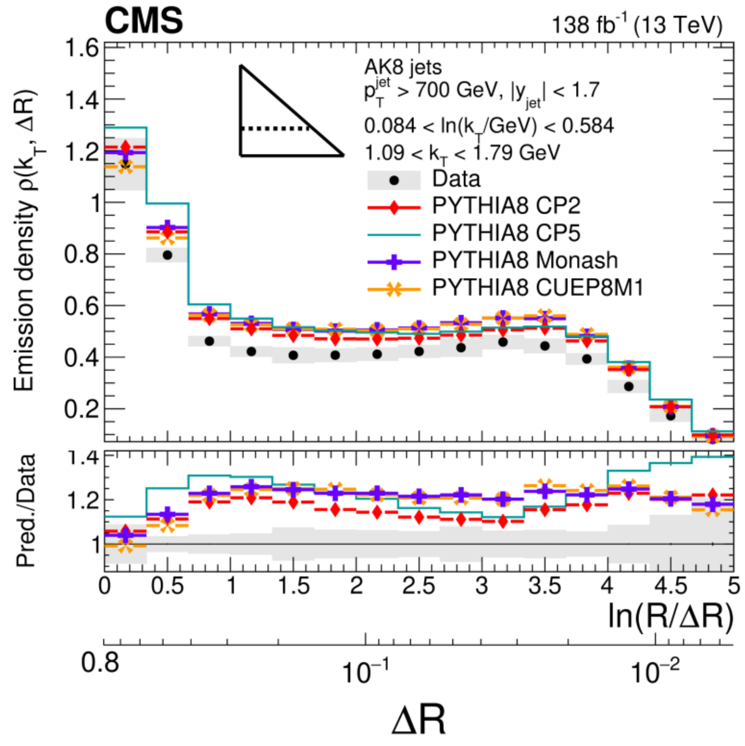


R = 0.8 (access to large ΔR and high k_T)



CMS Lund plane slices

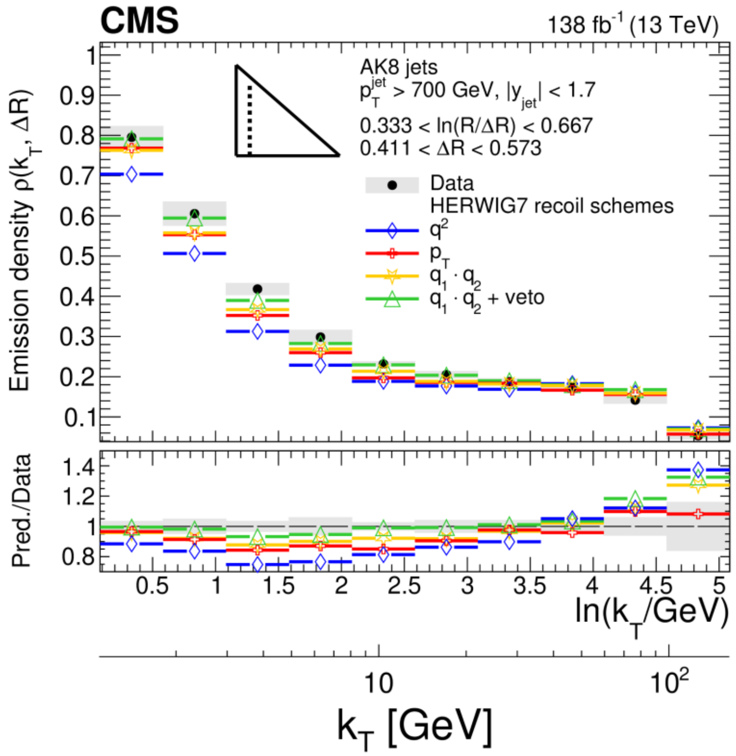
Low k_T (~ 1 GeV) - hadronization region, comparison to several Pythia8 tunes



PYTHIA8 CP5 overestimates the number of emissions by 15-20% (default CMS PYTHIA 8 underlying-event tune)

Possibility for improvement: include FSR cutoff k_T as a free parameter in future event generator tuning

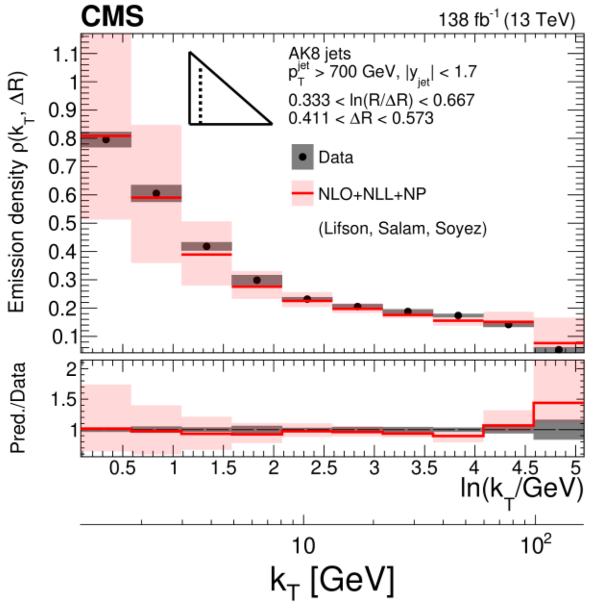
Large-angles, comparison to different Herwig7 recoil schemes



best described by Herwig7 angle-ordered with $q_1 \cdot q_2$ + veto

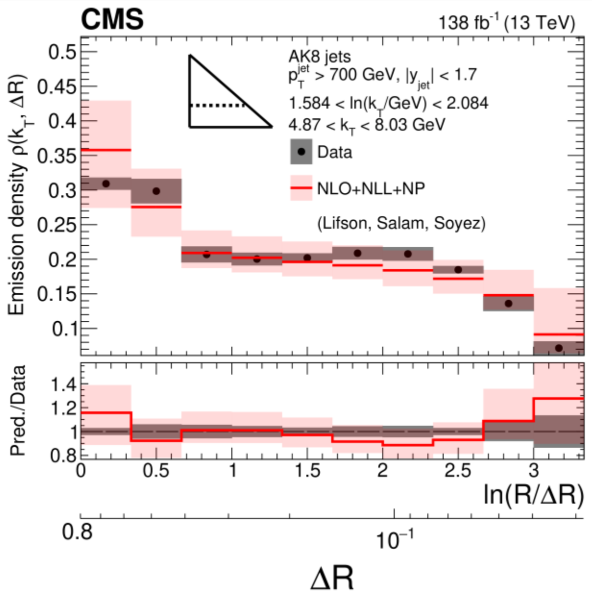
Comparison to parton-level pQCD predictions

- NLL accuracy, matched to NLO, with non-perturbative corrections
- parton-level calculations corrected to the hadron level using bin-by-bin corrections derived from MC
- nonperturbative corrections mostly affect $k_T < 5$ GeV



$4.87 < k_T < 8.03$GeV – pQCD calculation reliable and hadronisation corrections not large

- resummation of nonglobal logarithms → increased density at large ΔR



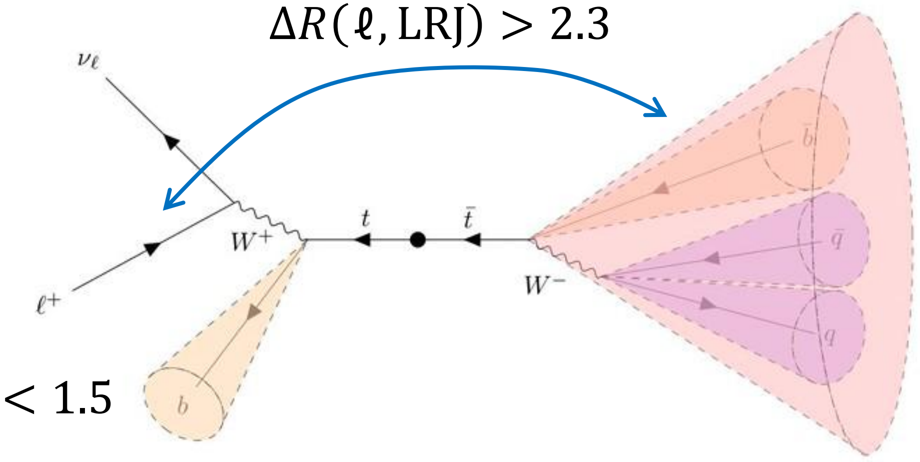
- predictions consistent with unfolded data

Lund plane from top and W jets

arXiv:2407.10879

- The first measurement of the Lund jet plane in top-jets and W-jets
- First LJP study in large-R jets in ATLAS and first with R = 1.0

$\Delta R(\ell, \mathrm{LRJ}) > 2.3$



$\Delta R(\ell, \mathrm{b\ jet}) < 1.5$

Top jet selection

$m_{\mathrm{LRJ}} > 140$ GeV

$\Delta R(\mathrm{b\ jet, LRJ}) < 1.0$

W jet selection

$60\ \mathrm{GeV} < m_{\mathrm{LRJ}} < 100\ \mathrm{GeV}$

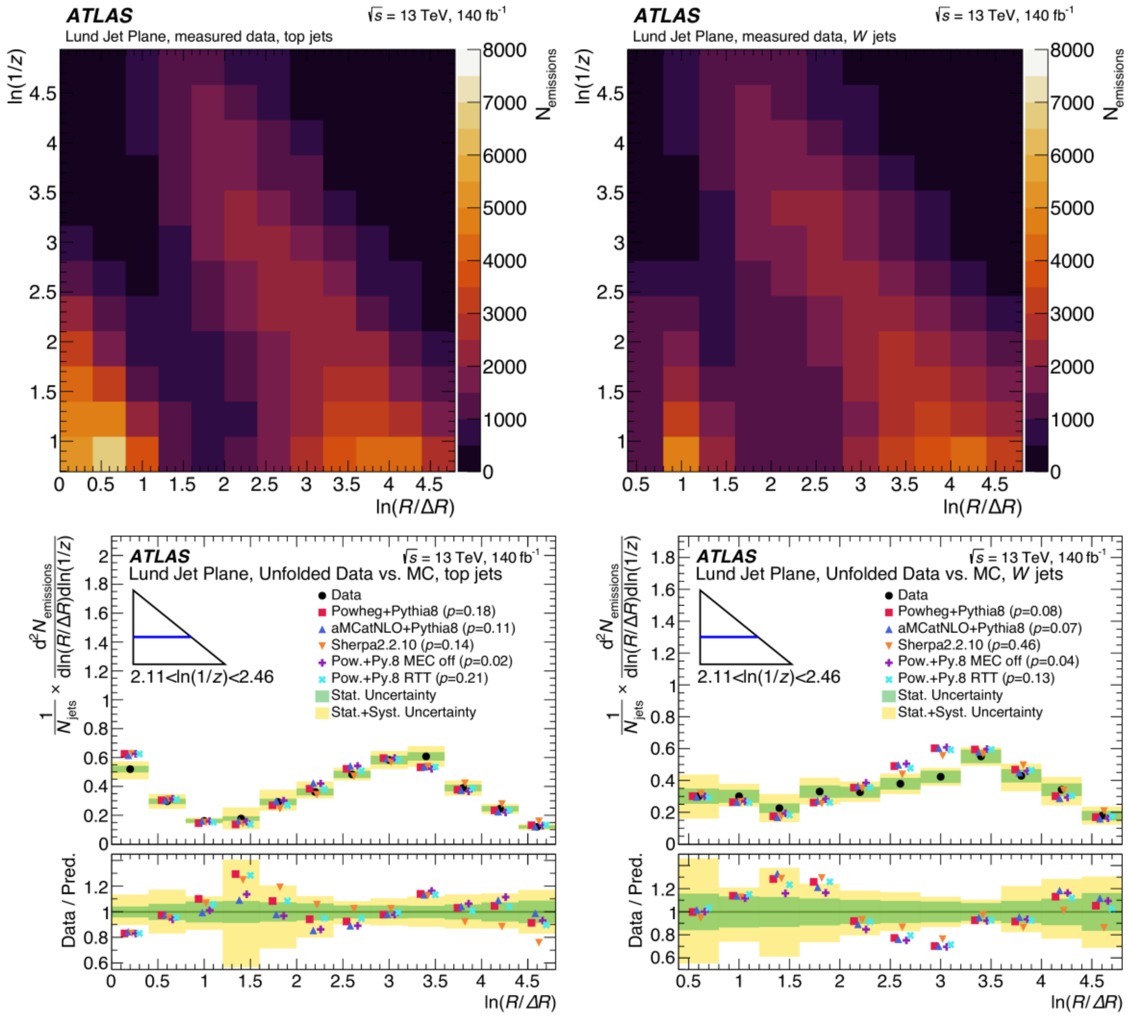
$\Delta R(\mathrm{b\ jet, LRJ}) > 1.0$

Lund plane from top and W jets

arXiv:2407.10879

- Highest density for hard and wide-angle emissions
  - peak shifted towards wider angles for top jets due to higher mass
- Density of emissions unfolded using iterative Bayesian unfolding (IBU) and compared with predictions from other generators
  - Signal modelled with POWHEG+PYTHIA8
- Good agreement
  - But for W jets, no generator agrees with measurements across whole plane
  - For top jets, disagreements also observed for smaller subregions
- Large modelling uncertainties in the majority of the plane

top jets W jets



Measurement of jet track functions

arXiv:2502.02062

- Track functions characterize the **transverse momentum fraction**

$$r_q = p_{\mathrm{T}}^{\mathrm{charged}} / p_{\mathrm{T}}^{\mathrm{all}}$$

  carried by **charged hadrons** from a fragmenting quark or gluon

- Track functions are **non-perturbative** → must be measured
- r_q distributions measured in high-p_{T} jets in **dijet events**
- **Moments of** r_q as a function of p_{T} extracted
  - moment higher than first moment not previously measured
  - encode interesting correlations in the hadronization process
  - scale evolution provides a test of QCD beyond the DGLAP paradigm

Extracting moments of distributions

ATLAS EXPERIMENT

arXiv:2502.02062

- nth moment is expectation value of r_q^n, estimated using central bin values:

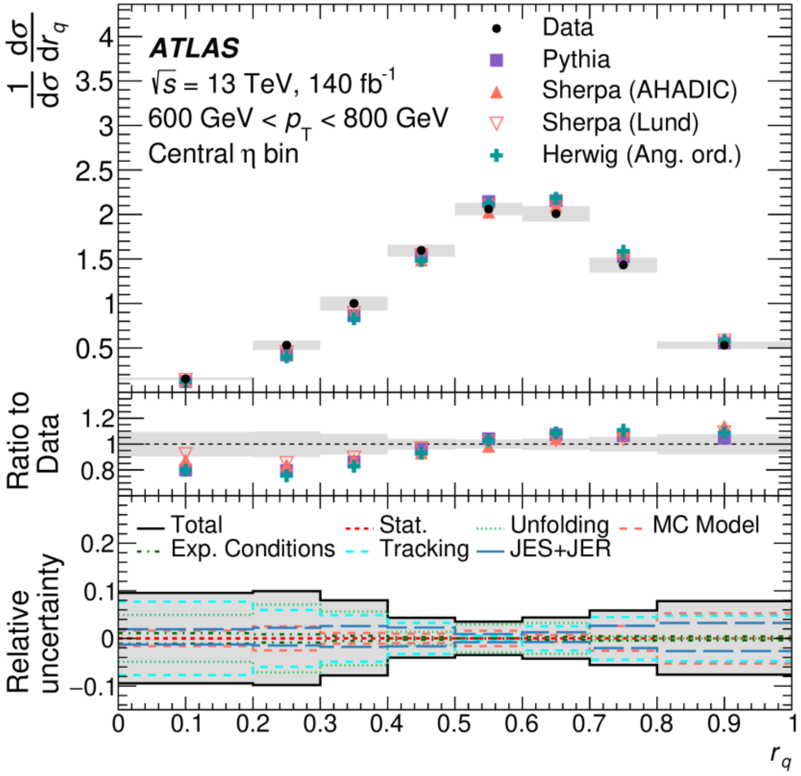
$$m_n = \sum_i {r_q^n}_i N_i$$

- The data are corrected for detector effects using **IBU**
- **OmniFold** used for **data-driven** correction for binning artifacts in the moment extractions

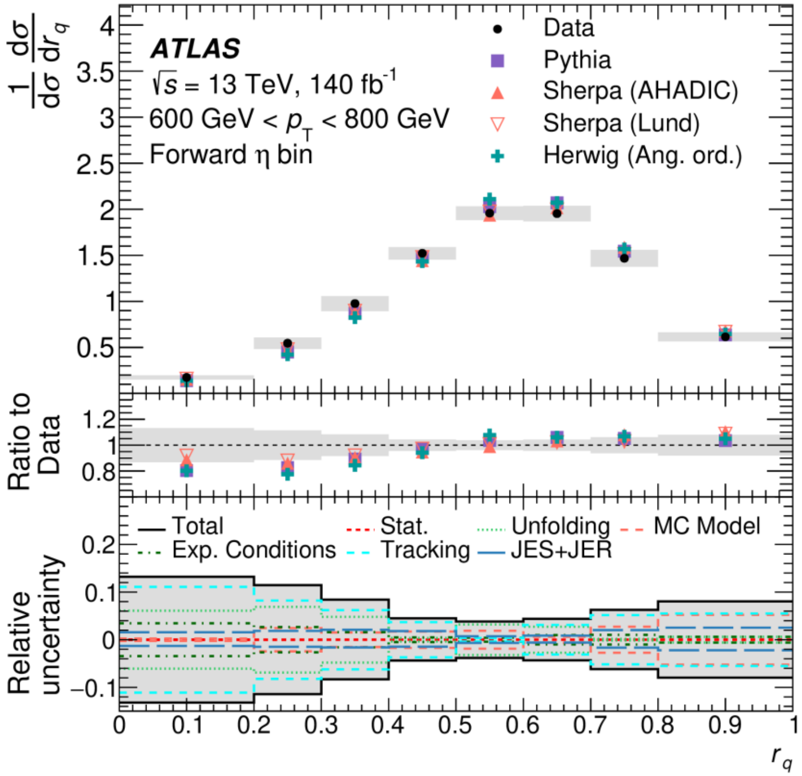
r_q distributions

arXiv:2502.02062

Central η bin



Forward η bin

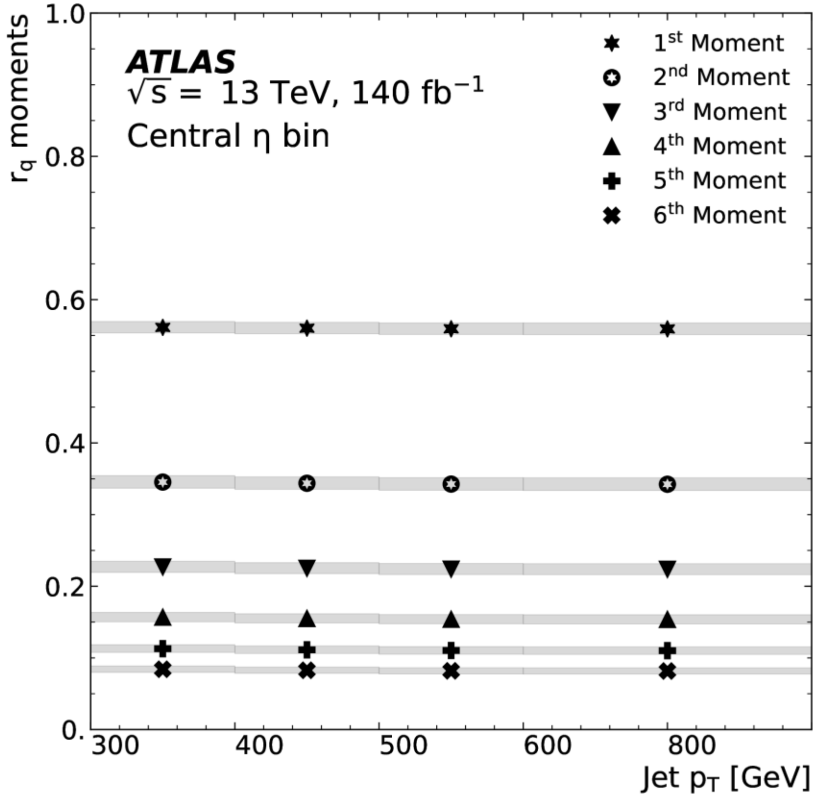


- Agree with MC within uncertainties, but underestimated at low r_q and overestimated at high r_q

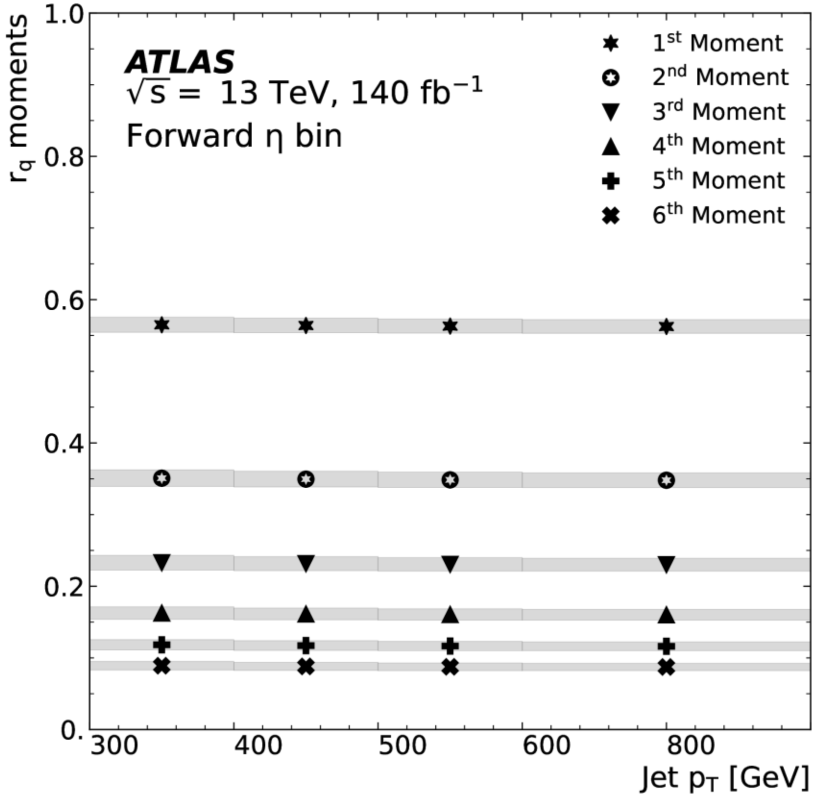
Moments of r_q as function of jet p_{T}

arXiv:2502.02062

Central η bin



Froward η bin



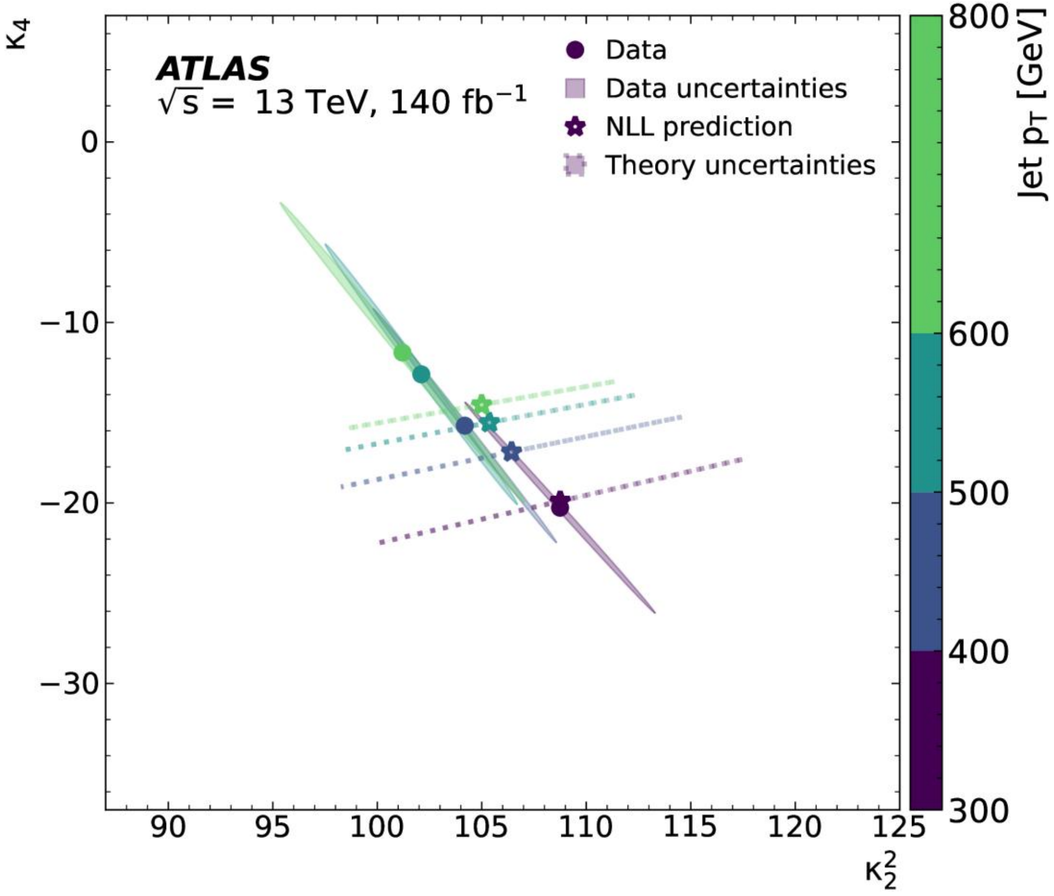
Renormalization group flows

arXiv:2502.02062

- Cumulants κ_n can be expressed in terms of central moments, e.g.

  $\kappa_2 = \mu_2, \kappa_4 = \mu_4 - 3\mu_2^2, \ldots$

- Energy dependence of the relationship between pairs of these cumulants is theoretically determined by renormalization group flows
- Good data-theory agreement



Measurement of event shape variables using charged particles inside jets

- First CMS study that uses charged particles inside jets to evaluate event shape variables
- Event shape variables:
  - constructed from four-momenta of final-state objects (charged particles in this case)
  - sensitive to QCD predictions in multijet production
  - minimal impact of systematic uncertainties
- Multijet events selected using dijet triggers

Event shape variables

- designed to have higher values for multijet, spherical events and lower values for back-to-back two-jet events
- P denotes scalar sums

maximizes $T_\perp$, defines the thrust direction

- Complement of transverse thrust:

$$\tau_\perp \equiv 1 - T_\perp, \qquad T_\perp \equiv \max_{\vec{n}_\mathrm{T}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \vec{n}_\mathrm{T}|}{\sum_i p_{\mathrm{T},i}}$$

  - more dependent on initial hard scattering

- Third-jet resolution parameter:

$$Y_{23} \equiv \frac{\max\left(p_{T,3}^2, \left[\min(p_{T,i}, p_{T,j})^2 \frac{(\Delta R_{\mathrm{i,j}})^2}{R^2}\right]\right)}{P_{12}^2}$$

  - If more than three final-state particles, they are recombined with the distance parameter R = 0.4 until only 3 particles pseudo-particles left in the final state
  - sensitive to clustering and substructure

- Jet broadening:

$$B_X \equiv \frac{1}{2P_T} \sum_{i \in C_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

X refers to upper part of the event U where all particles have $\vec{p}_T \cdot \vec{n}_T > 0$ or lower part L where $\vec{p}_T \cdot \vec{n}_T < 0$

$$B_T = B_U + B_L$$

- Jet masses:
  normalized squared invariant mass of the jets in the upper and lower regions

$$\rho_X \equiv \frac{M_X^2}{P^2}$$

$$\rho_{\mathrm{Tot}} = \rho_U + \rho_L$$

Corresponding quantity in transverse plane: ρ_{Tot}^T

Jet masses and jet broadening depend more on nonperturbative QCD.

Event shape variables - results

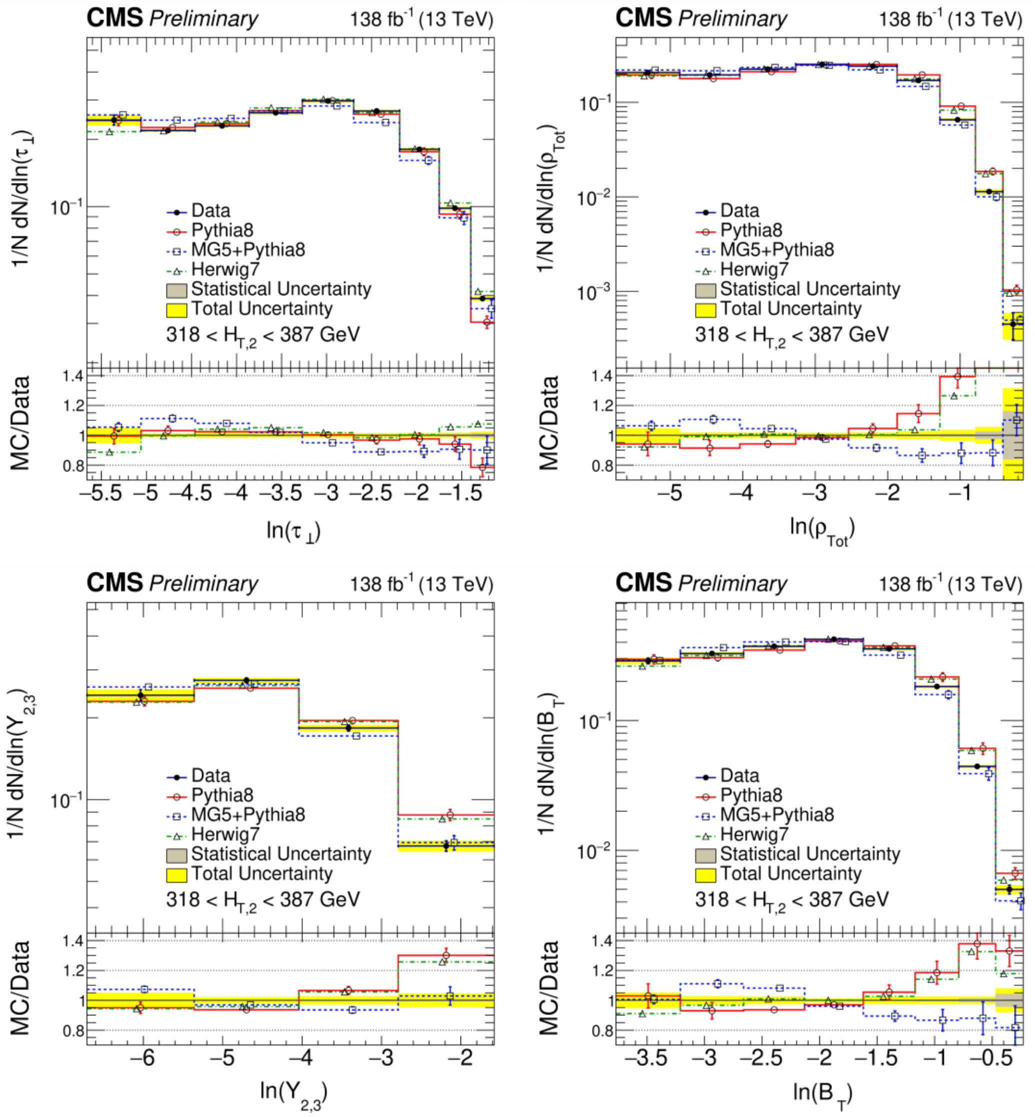
$H_{T,2}$ = average p_T of the leading and sub-leading p_T jets

- Pythia 8 and Herwig 7 – good agreement with data for $\tau_\perp$ and ρ^T_{Tot}, overestimate spherical, multijet events for $\rho_{\mathrm{Tot}}, Y_{23}, B_T$

⇒ improvements needed for modelling of fragmentation and hadronization

- For Pythia 8, agreement with data improves with $H_{T,2}$, but not for Herwig 7
- MG5+ Pythia 8 predictions underestimate spherical, multijet events for $\tau_\perp, \rho^T_{\mathrm{Tot}}, \rho_{\mathrm{Tot}}$, B_T; disagreement increases with $H_{T,2}$
  - agreement only good for Y_{23}

⇒ issues in the combination of matrix element calculations with the parton showers



Summary

- Jet track function analysis
  - provides results that, when incorporated into theoretical calculations, will enable precision comparisons between data and theory for track-based jet substructure observables
  - Provides a test of QCD **beyond the DGLAP paradigm**
- Event shape observables measurements indicate improvements needed for modelling of fragmentation and hadronization, and issues in the combination of ME calculations with the PS
- Lund jet plane measurements:
  - In W jets, all predictions are incompatible with the measurement
  - In top quark jets, disagreement with all predictions is observed in smaller subregions of the plane, and with a subset of the predictions across the fiducial plane
  - The ATLAS and CMS measurements could be used to improve different aspects of physics modeling in event generators (hadronization, parton showers, better modelling of hadronic decays of heavy quarks and bosons), or to improve the performance of jet taggers

Backup

Lund plane from top and W jets: Comparison with MC predictions

arXiv:2407.10879