Jet substructure measurements and precision measurements of multijet production with the ATLAS experiment

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On behalf of the ATLAS Collaboration

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ATLAS EXPERIMENT

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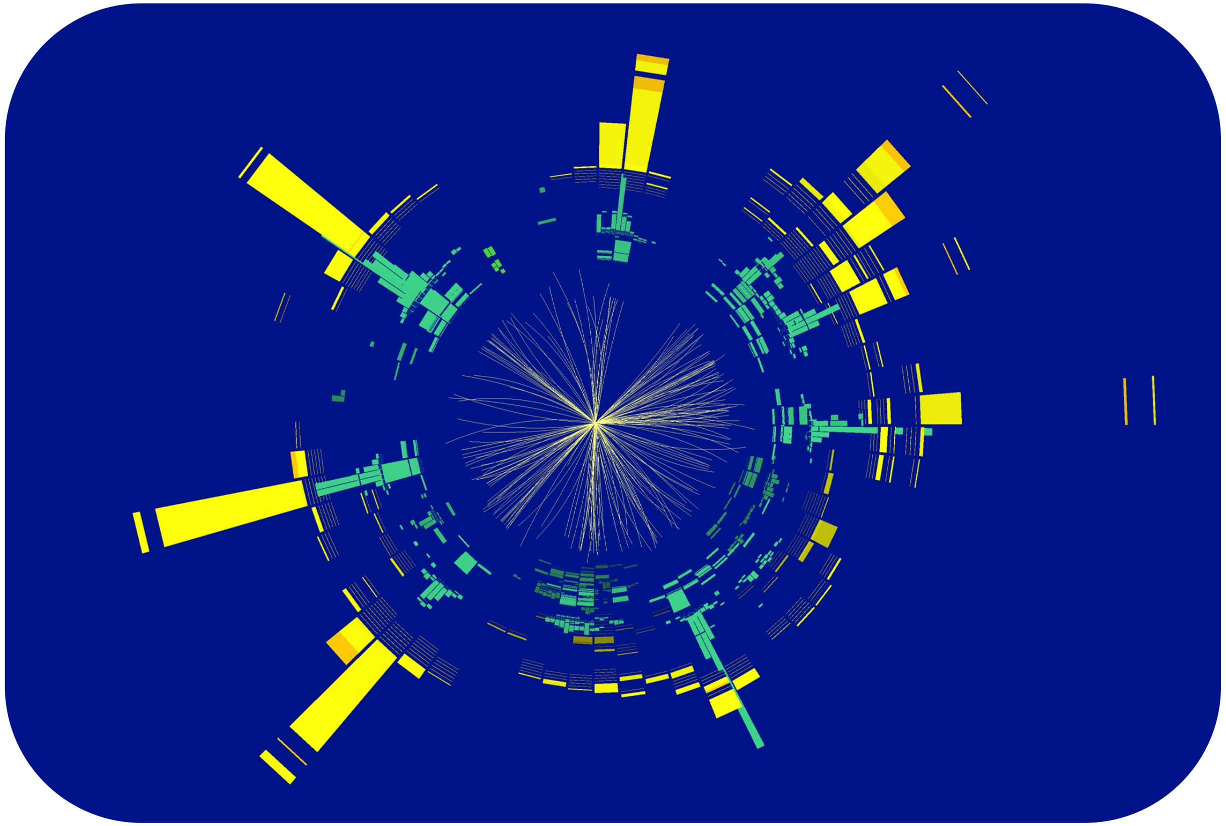
Outline

- Test of various QCD aspects in pp collisions at the LHC
- Improving parton shower modelling

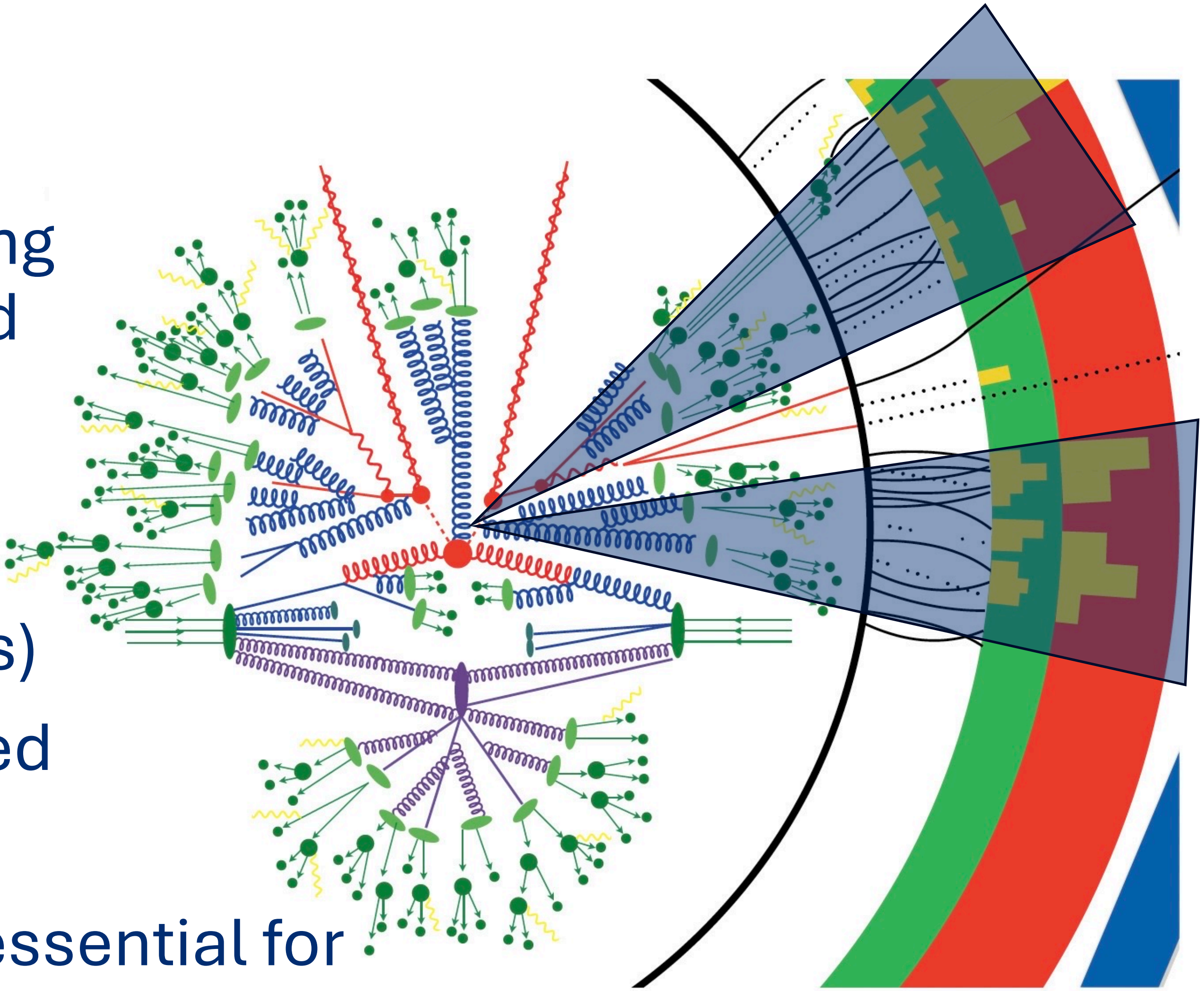
- Lund jet plane in dijet events
- Event isotropies



Motivation

- Jets produced in hard scattering process, production described by perturbative QCD, now at NNLO in α_S
- Proton structure described by PDFs (non-perturbative effects)
- Jet substructure is also affected by soft emissions

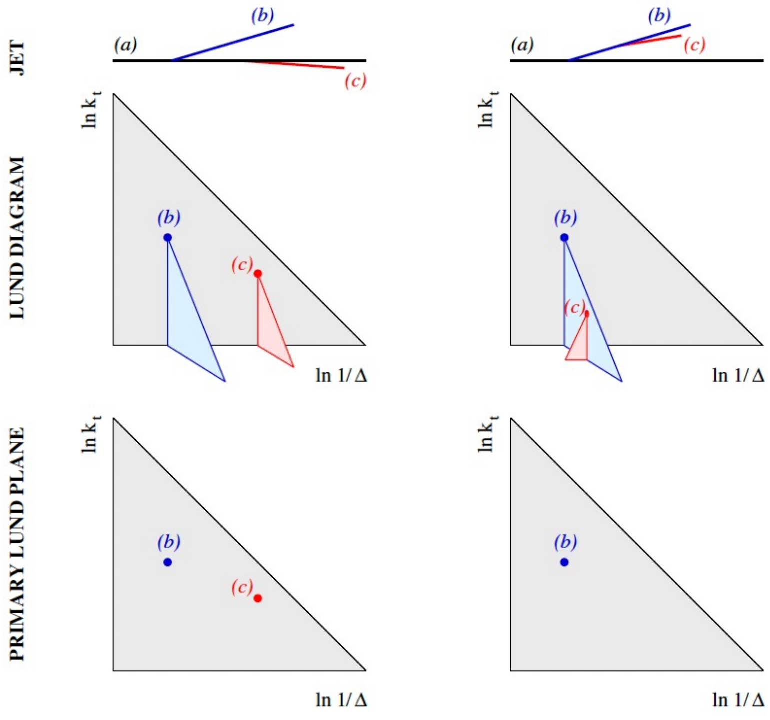
→ Understanding QCD is essential for everything at the hadron colliders

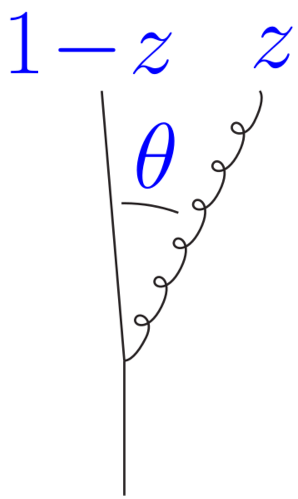

Original credit: Benjamin Nachman

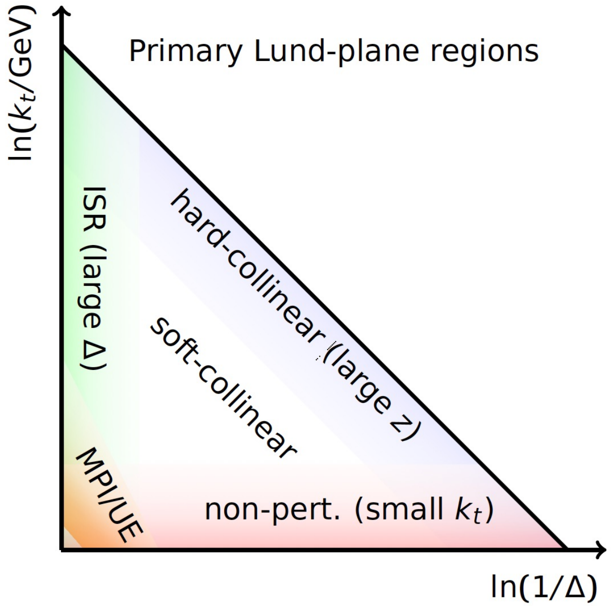
Lund plane

- Lund diagrams are a theoretical representation of the phasespace within jets
- Brings many soft-drop related observables into a single framework

- Experimentally: recluster a jet with a C/A algorithm and then decluster following the hardest branch



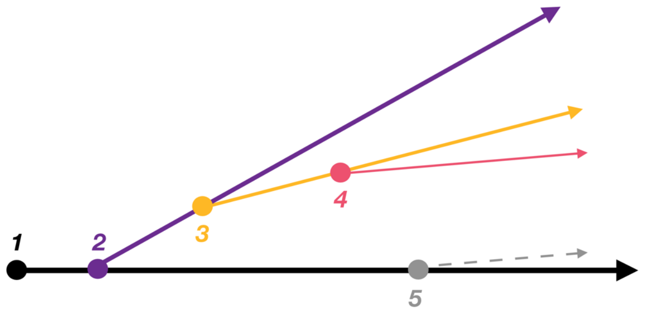


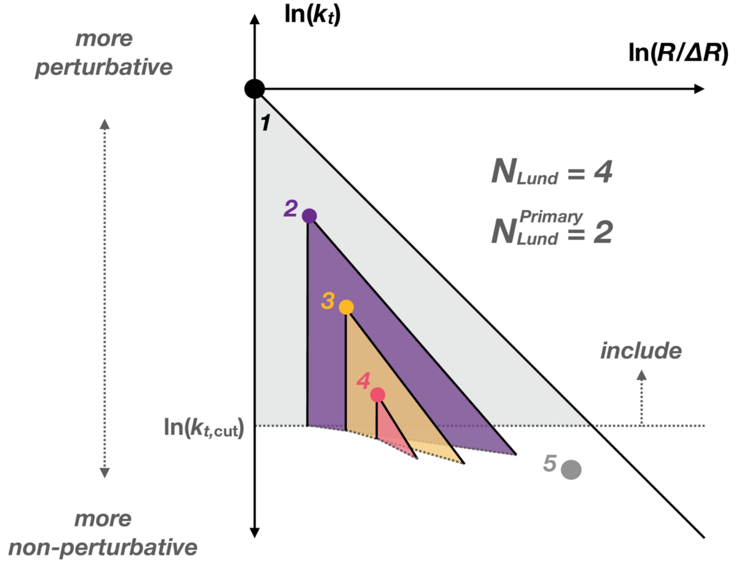


https://arxiv.org/pdf/2402.13052

Measurement of Lund subjet multiplicities

- N_{Lund} and $N^{\text{Primary}}_{\text{Lund}}$ subjet multiplicity (number of subjets above specified p_T)
- Measured in ATLAS **dijet** events at $\sqrt{s}$=13TeV
- 8 different emission (k_t) requirements
  (0.5 GeV, 1 GeV, 2 GeV, 5 GeV, 10 GeV, 20 GeV, 50 GeV, 100 GeV)
- Measured differentially in jet p_T and relative-rapidity bins (separating more-central and more-forward)
- Compared to state-of-the-art PS Monte Carlo and to the analytical NLO+NNDL calculation



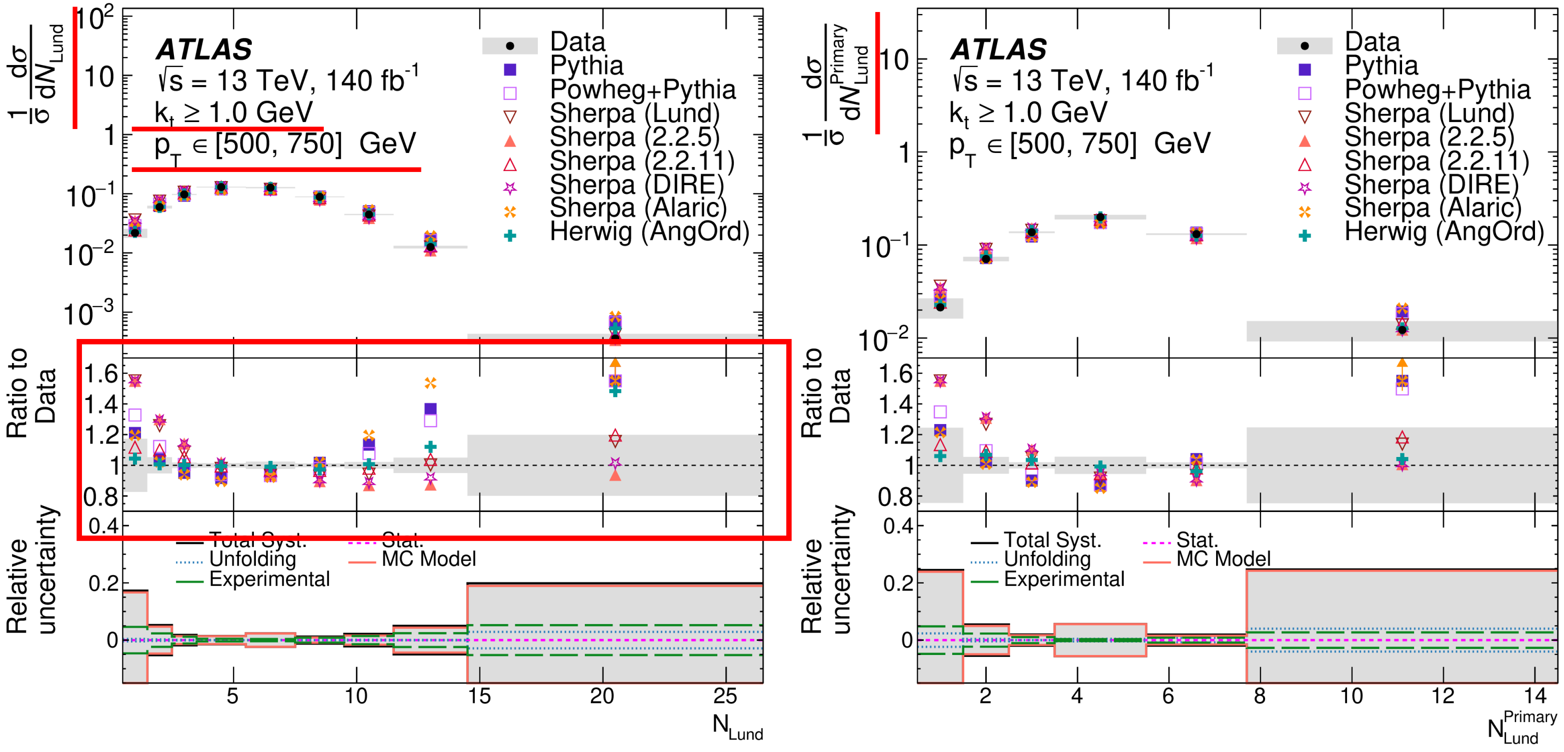


$$k_t = p_T^{\text{emission}} \times \Delta R(p^{\text{emission}}, p^{\text{core}})$$

Lund subjet multiplicity analysis selection

- Dijet events, p_T>120 GeV and |y|<2.1, balanced p_T^{Lead}<1.5x$p_T^{Sublead}$
- All tracks with p_T>500MeV within ΔR=0.4 of selected jets are reclustered using the C/A algorithm
- Emission k_T rescaled by the charged/total p_T
- Data unfolded using iterative Bayesian unfolding using the nominal Pythia MC
- JES (2—4%) and track reconstruction uncertainties are typically the dominant systematical uncertainties

Lund subjet multiplicity



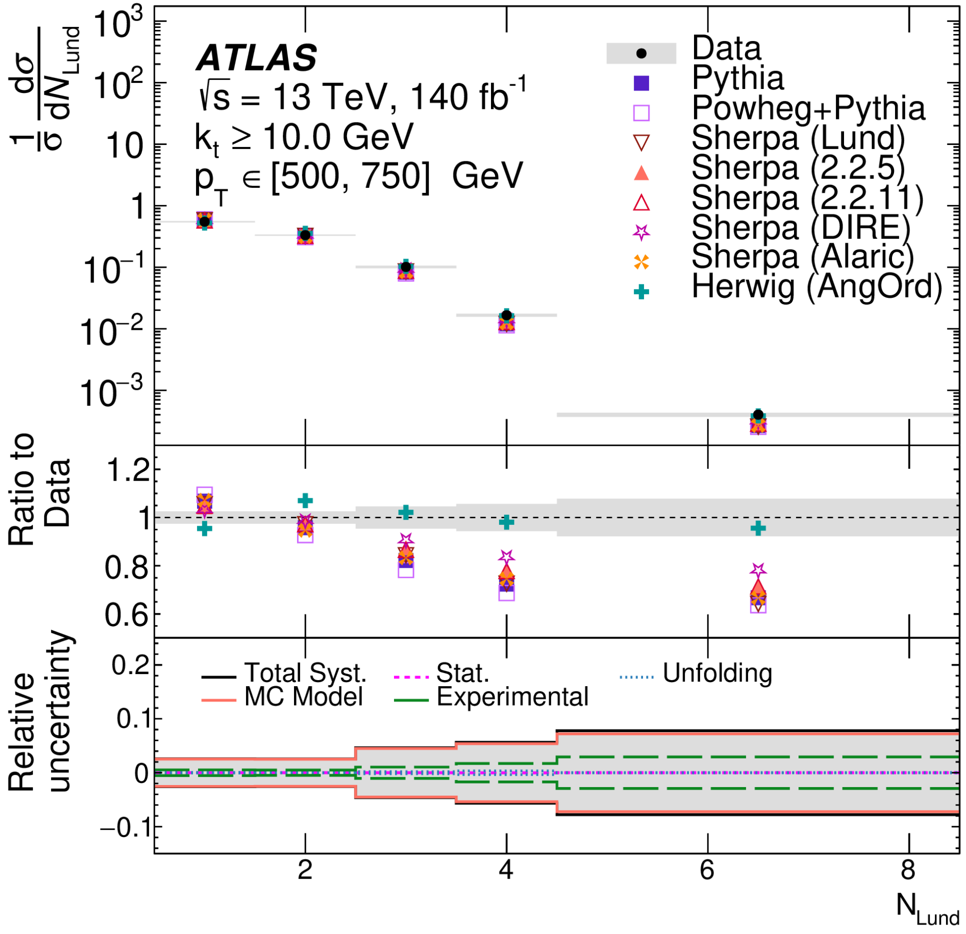
MC Models:

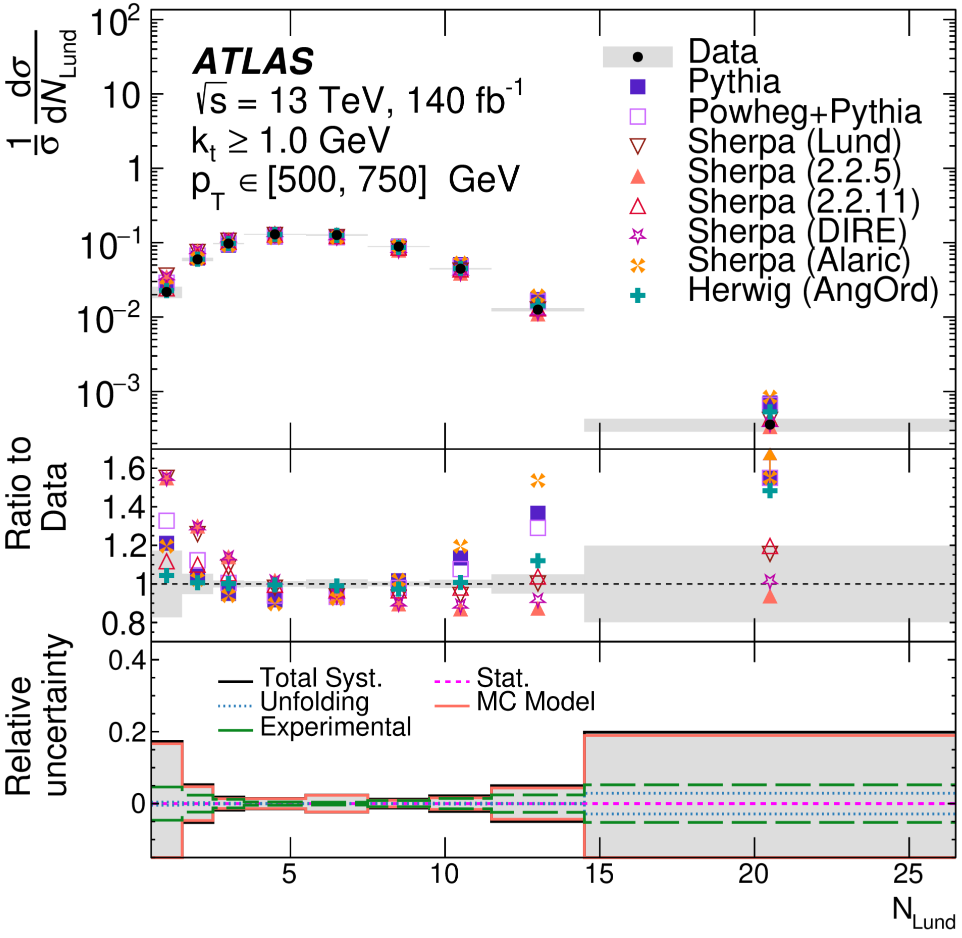
- **Pythia 8.230**
  - p_T ordered PS evolution
- **Sherpa 2.2.5** (x2)
  - AHADIC cluster model
  - Lund string model
- **Sherpa 2.2.11** (x2)
  - p_T ordered
  - DIRE
- **Herwig 7.1.3**
  - Angle ordered PS
- **Powheg+Pythia**
- **Sherpa 3 + ALARIC**

- DIRE includes higher-order splittings but not at NLL accuracy ALARIC is NLL accurate

Perturbative

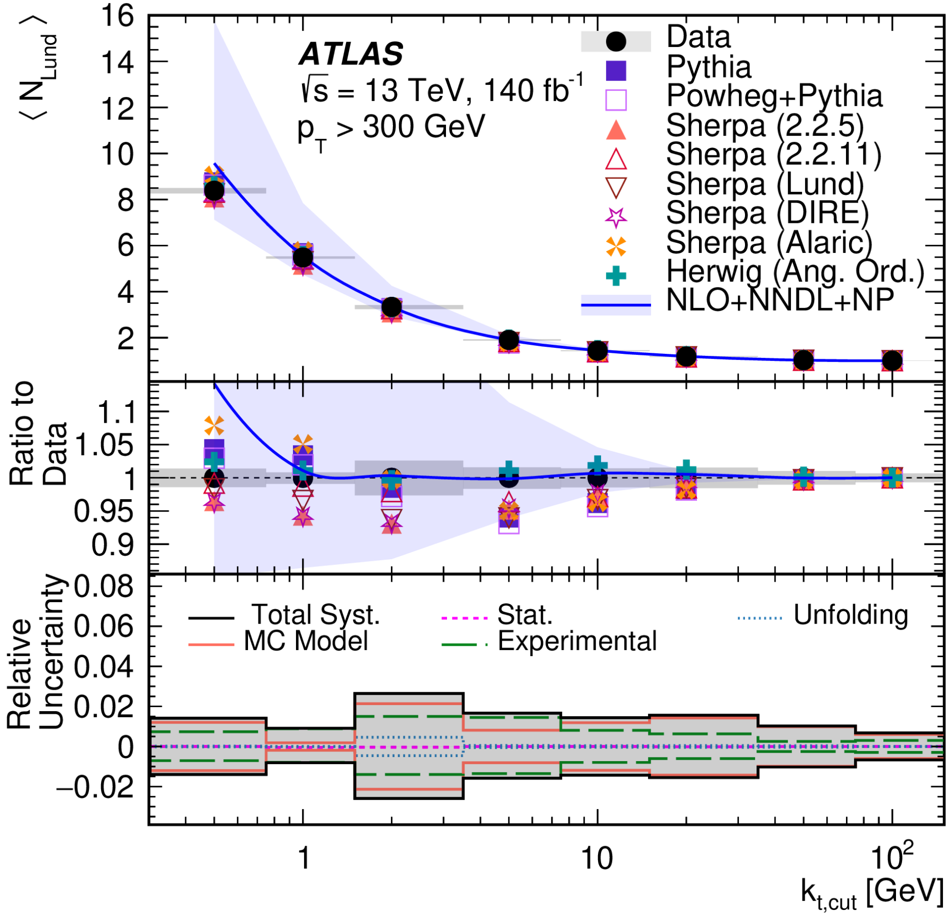
Non-perturbative

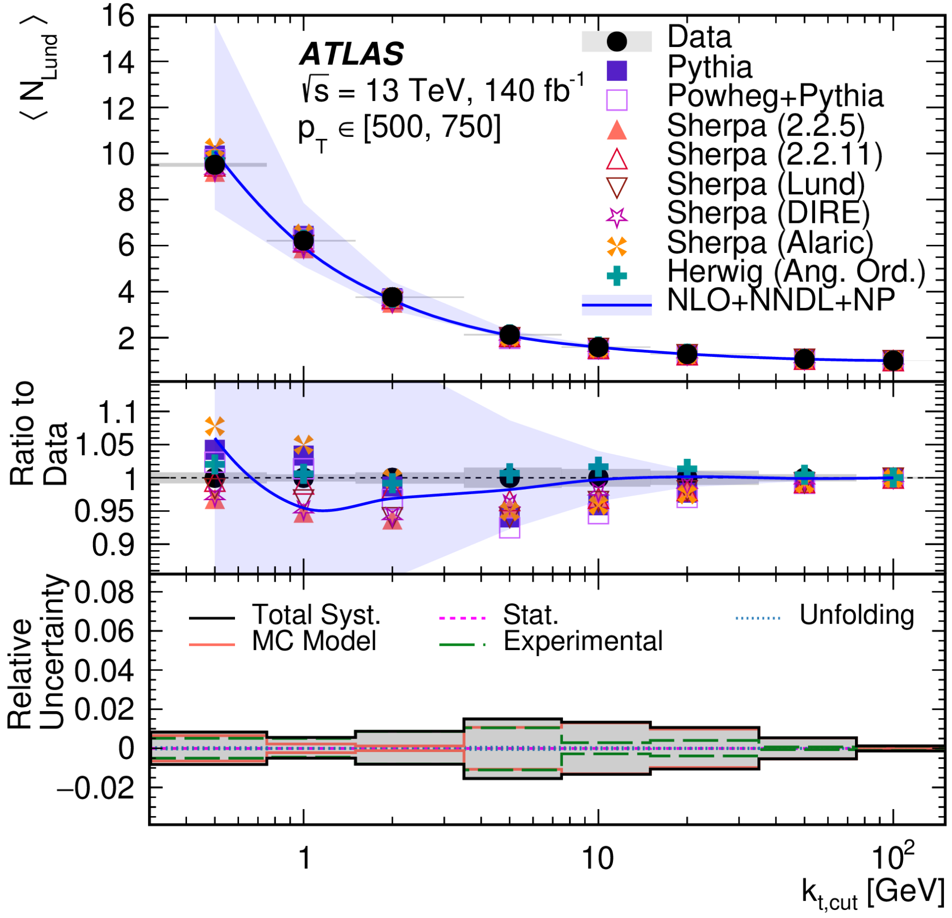




- Herwig gives best overall description of multiplicities
- Sherpa best when non-perturbative (low k_t) emissions allowed

Comparison with analytical calculations





NLO+NNDL+NP prediction provided by authors of JHEP 04 (2023) 104

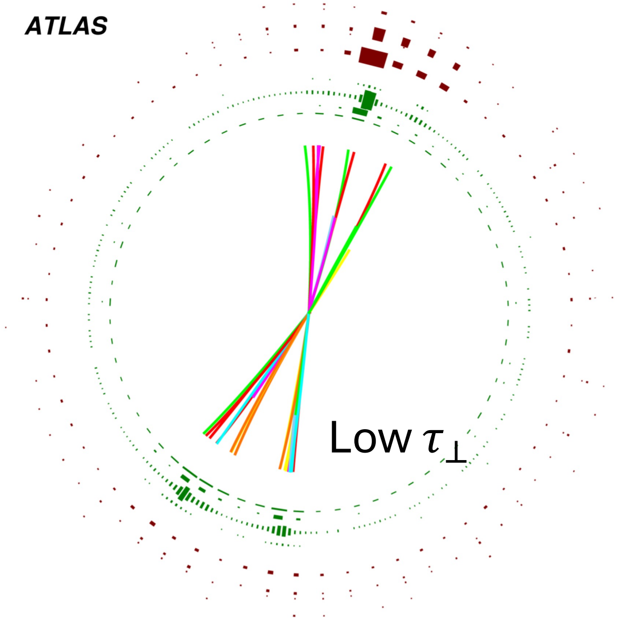
Event shape variables

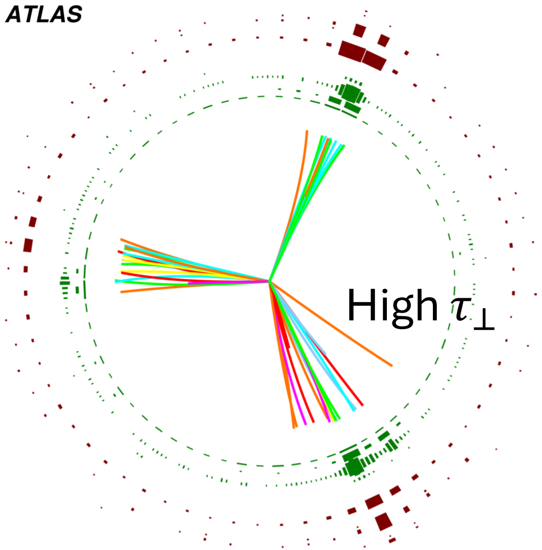
- Family of observables which characterize the event topology and/or energy flow in collider events
- Thrust, thrust minor, sphericity, aplanarity

event isotropies

Example: **Transverse thrust** – thrust axis $n_\perp$ to which the projections of p_T are maximised, $0 \leq \tau_\perp < 1 - 2/\pi$

$$T_\perp = \max_{\hat{\boldsymbol{n}}_\perp} \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_\perp|}{\sum_i p_{\mathrm{T}i}} \qquad \tau_\perp = 1 - T_\perp$$





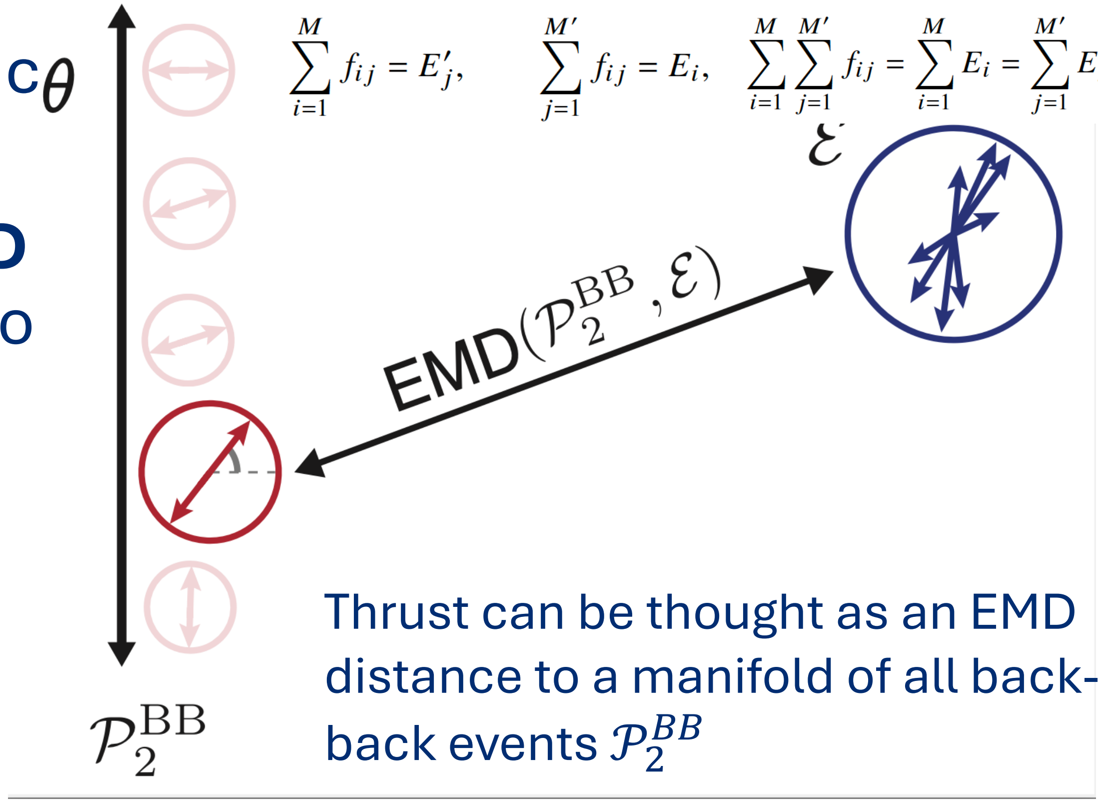
JHEP 10 (2023) 060

Event shapes as a geometrical problem

$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta},$$

- Event shapes together with other concepts unified through a geometric language JHEP07 (2020) 006
- Energy (Earth) mover‘s distance **EMD** = a measure of distance between two probability distributions = minimal amount of work to rearrange one event $\mathcal{E}$ into another $\mathcal{E}$‘

$$\sum_{i=1}^{M} f_{ij} = E'_j, \qquad \sum_{j=1}^{M'} f_{ij} = E_i, \qquad \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} E_i = \sum_{j=1}^{M'} E_j = E_{\mathrm{tot}}$$



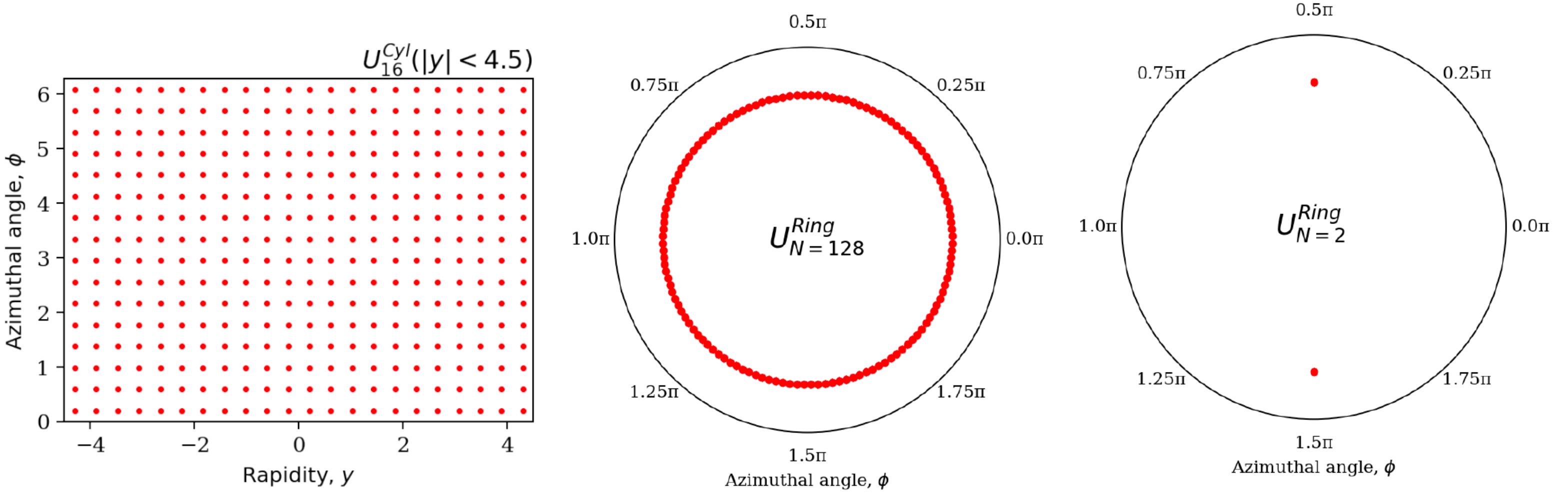
Thrust can be thought as an EMD distance to a manifold of all back-to-back events $\mathcal{P}_2^{BB}$

Event isotropies

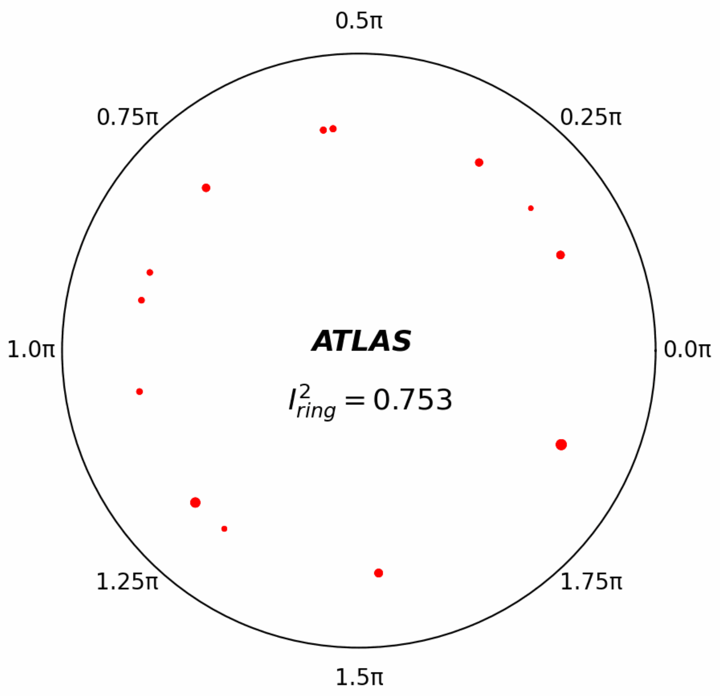
- EMD problem can be solved using **Optimal Transport** methods
- Event isotropies – how far is a collider event $\mathcal{E}$ from a symmetric radiation pattern $\mathcal{U}$, $\mathcal{J}$=EMD($\mathcal{E}$,$\mathcal{U}$) $\mathcal{J}\in[0,1]$
- Completely isotropic events $\mathcal{J}$=0

3 different $\mathcal{U}$ geometries considered

Geometry	Ground Measure	$\mathcal{U}$
Cylinder	$\theta^{\text{cyl}}_{ij} = \frac{12}{\pi^2+16y^2_{\text{max}}}\left(y^2_{ij}+\phi^2_{ij}\right)$	$\mathcal{U}^{\text{cyl}}_N(\lvert y\rvert < y_{\text{max}})$
Ring	$\theta^{\text{ring}}_{ij} = \frac{\pi}{\pi-2}\left(1-\cos\phi_{ij}\right)$	$\mathcal{U}^{\text{ring}}_N$
Ring (Dipole)	$\theta^{\text{ring}}_{ij} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1-\cos\phi_{ij}\right)$	$\mathcal{U}^{\text{ring}}_2$



Visualisation of the optimal transport calculation



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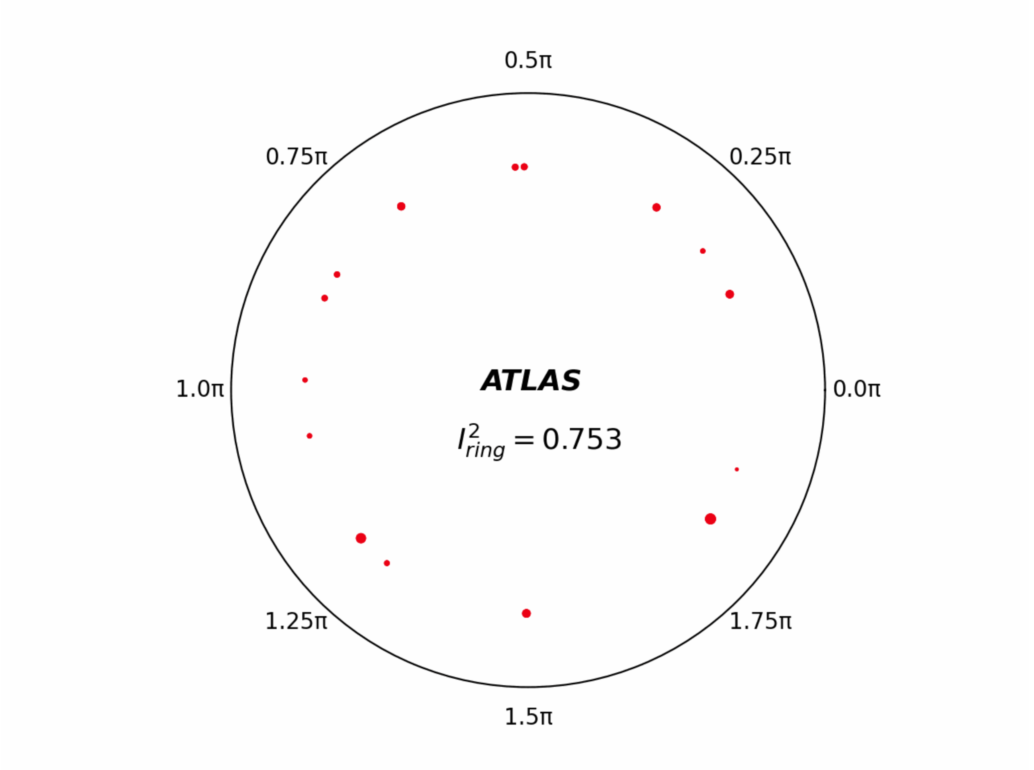

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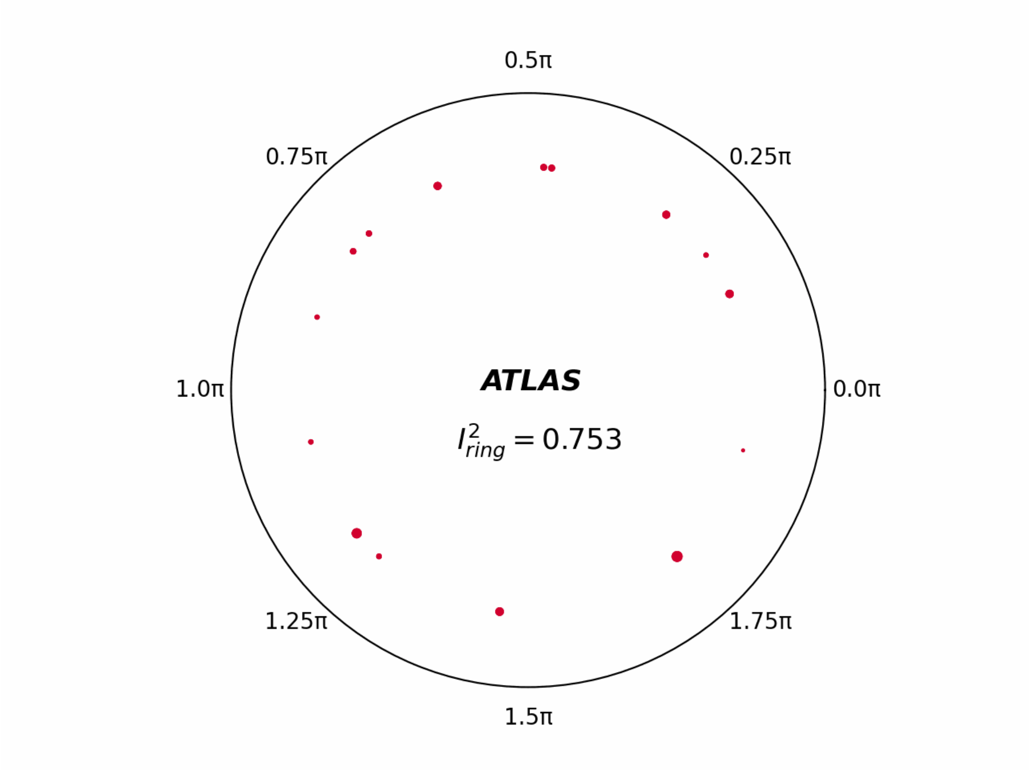

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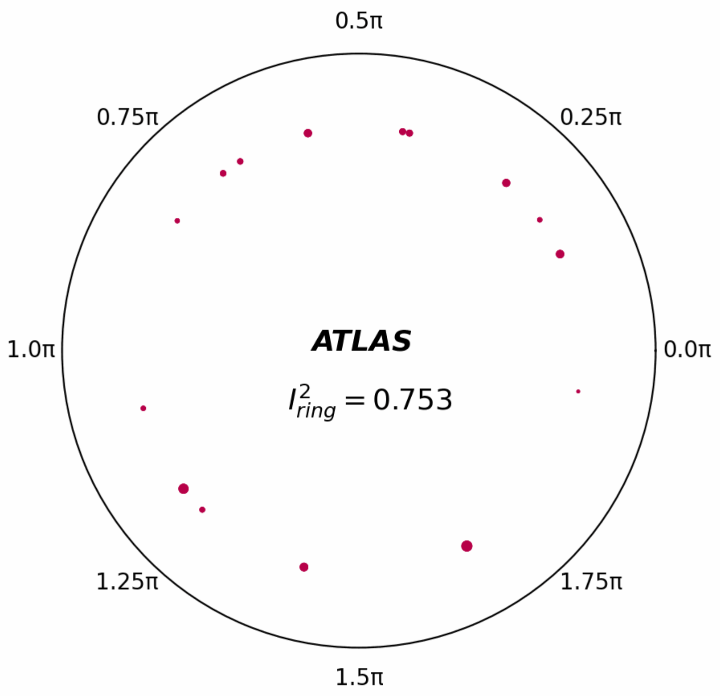

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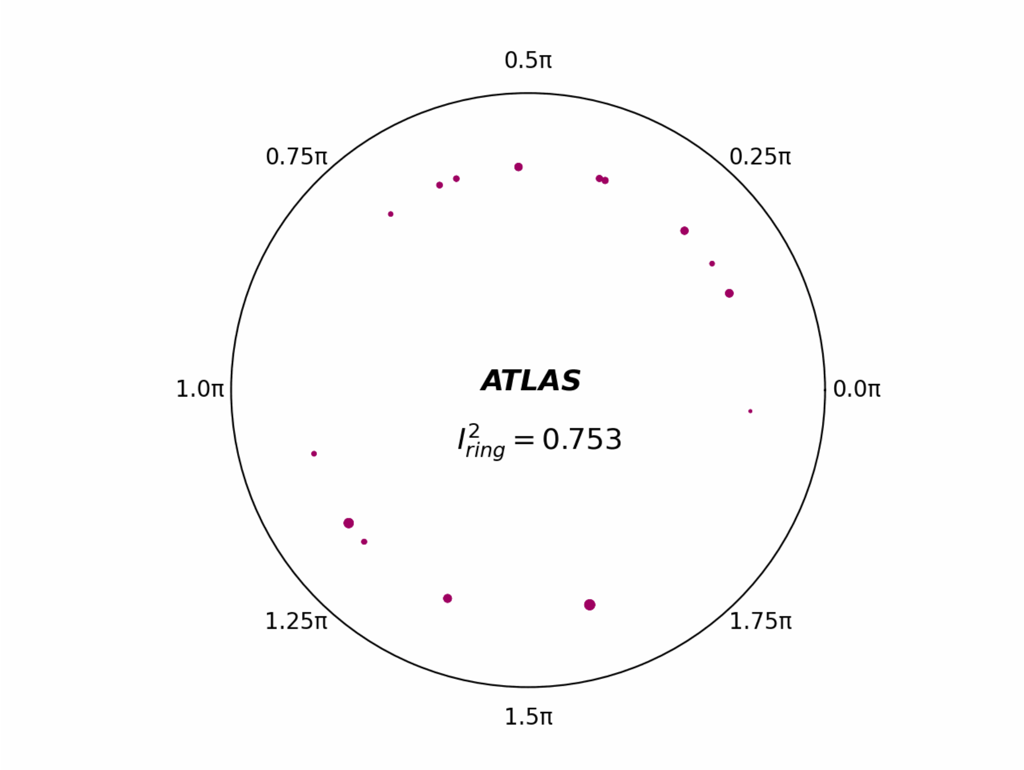

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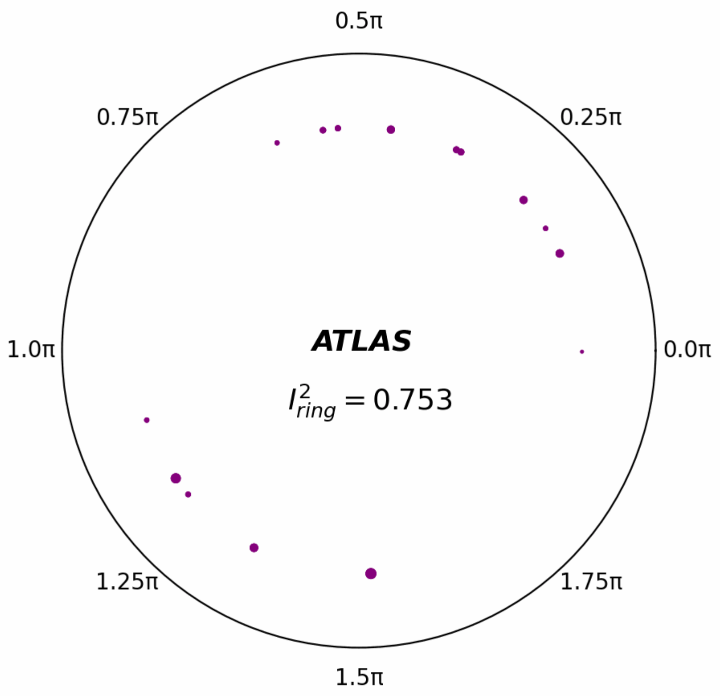

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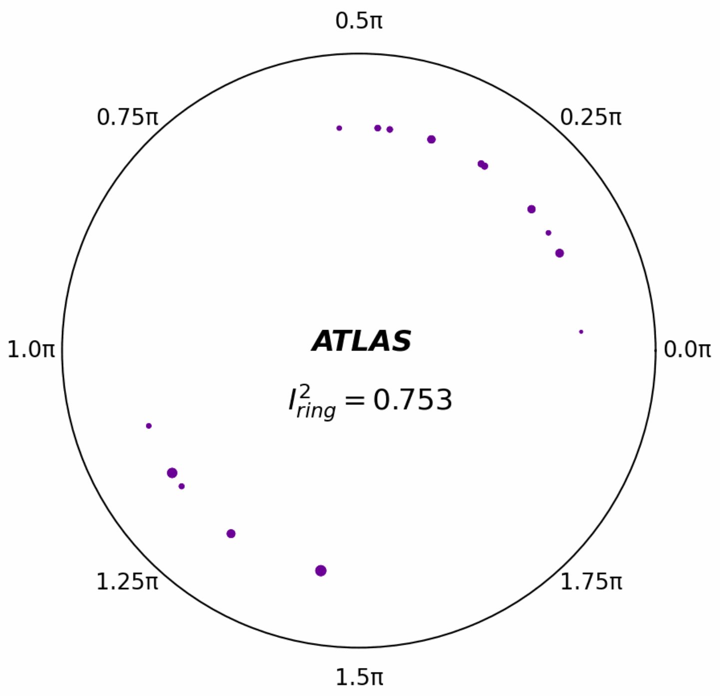

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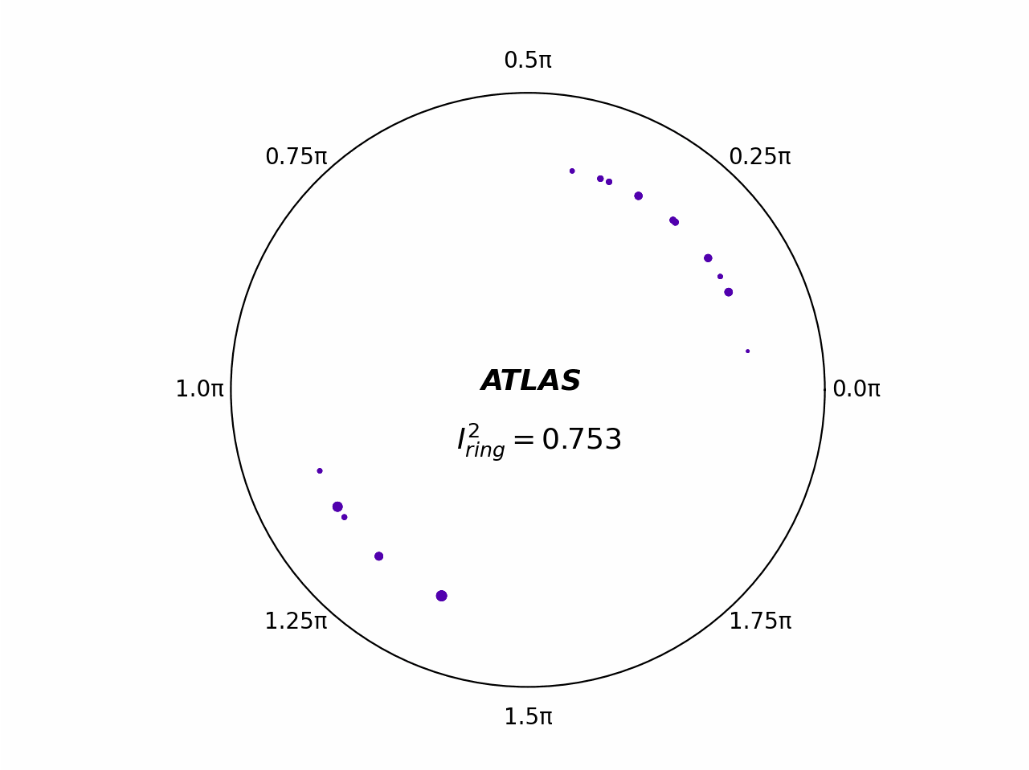

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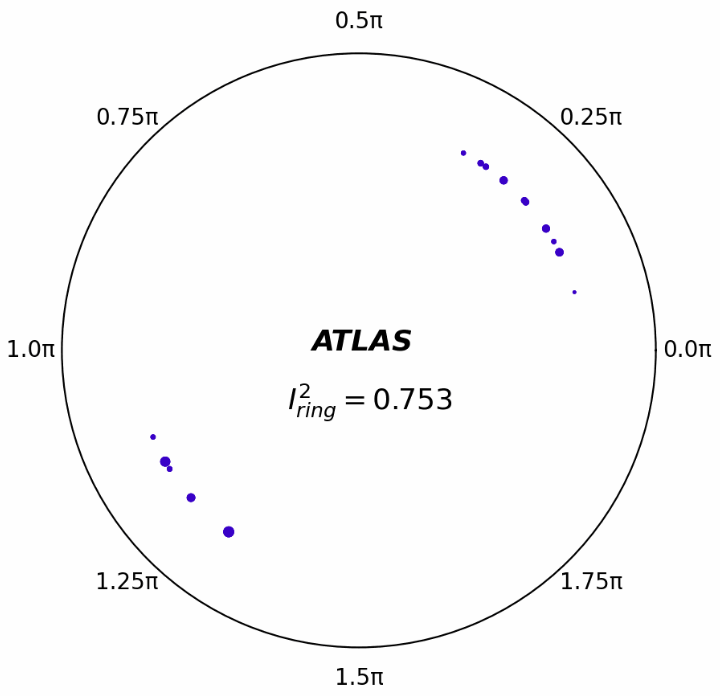

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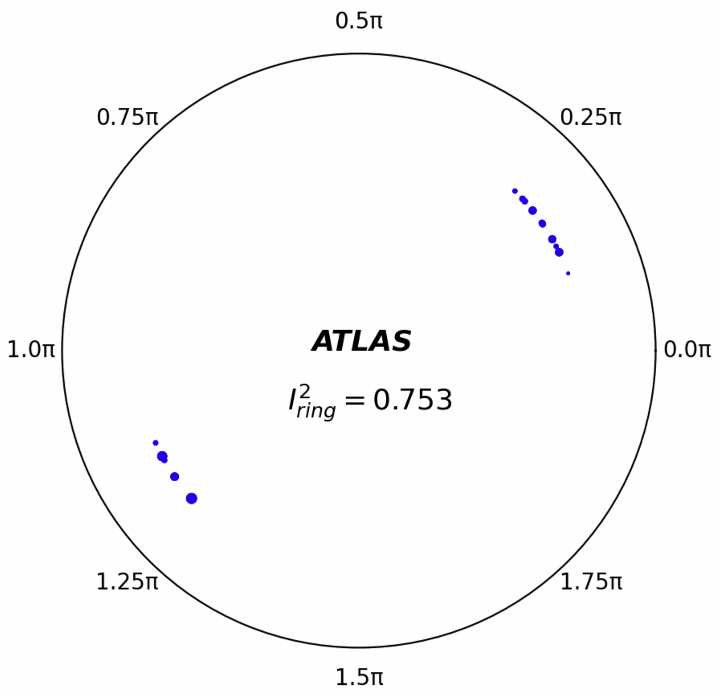

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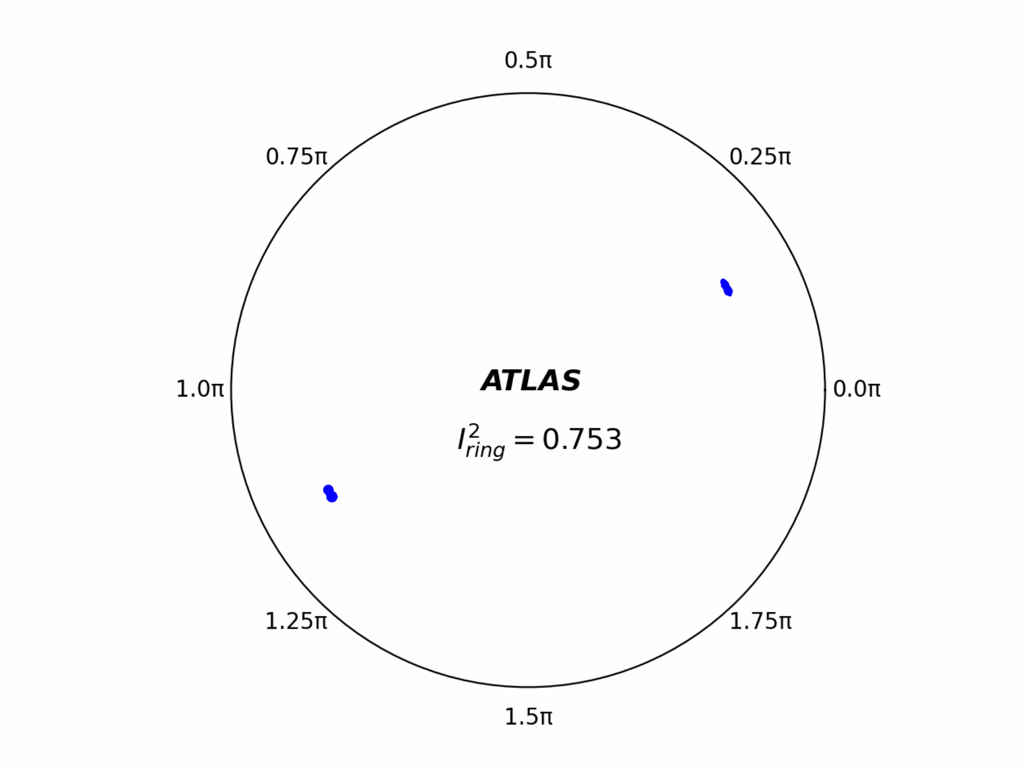

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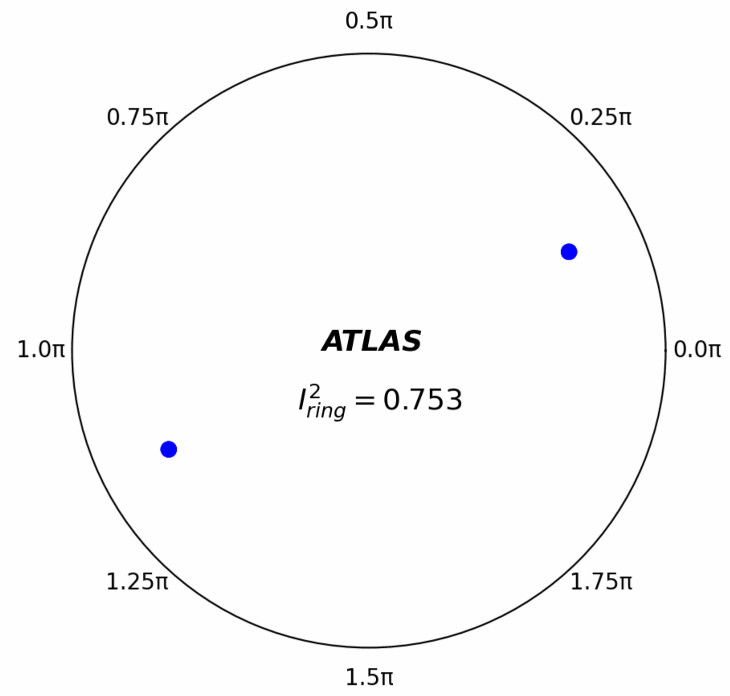
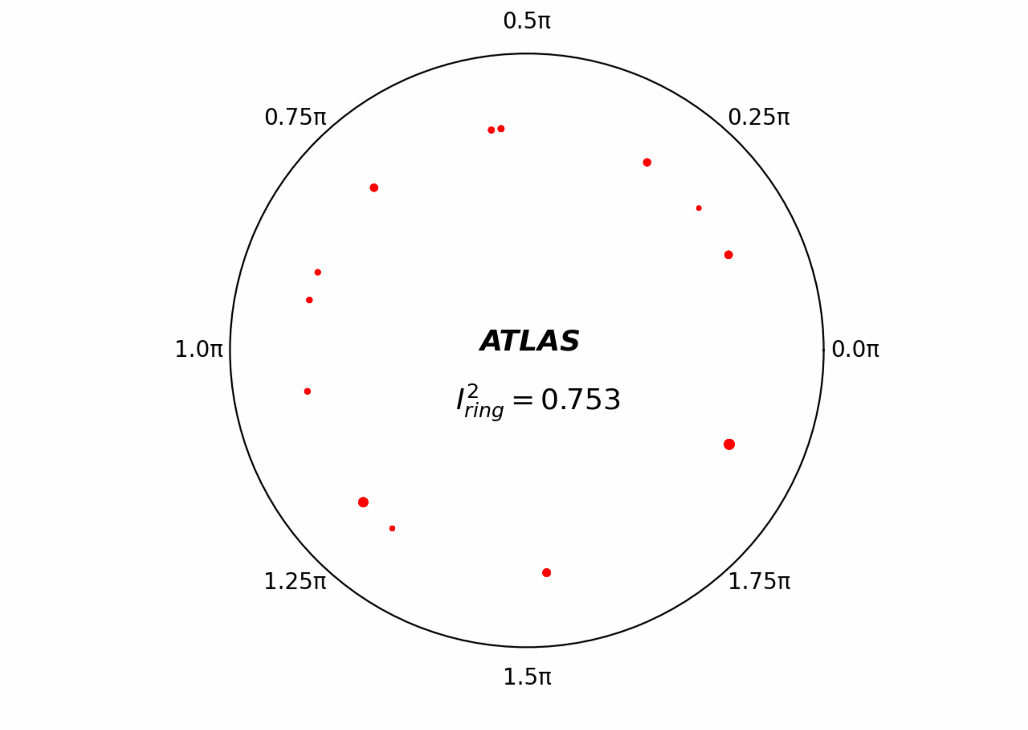
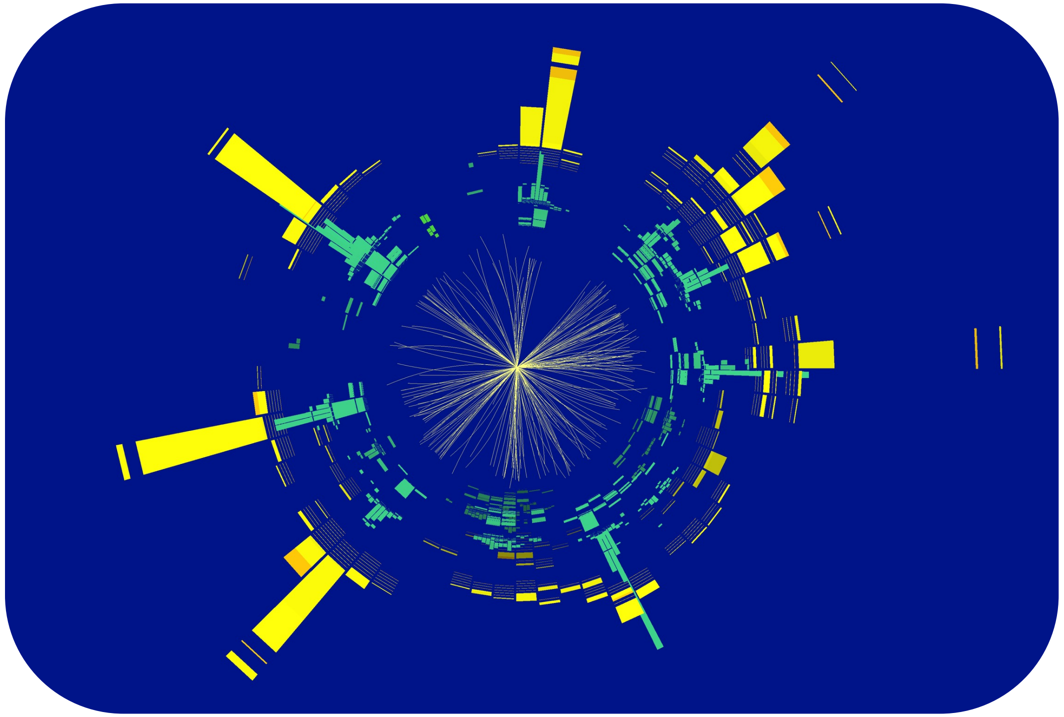


Visualisation of the optimal transport calculation

Run 300687, Event 1358542809 – The most isotropic ($1-I_{Ring}^{N=128}=0.922$) has 12 jets with p_T>60 GeV



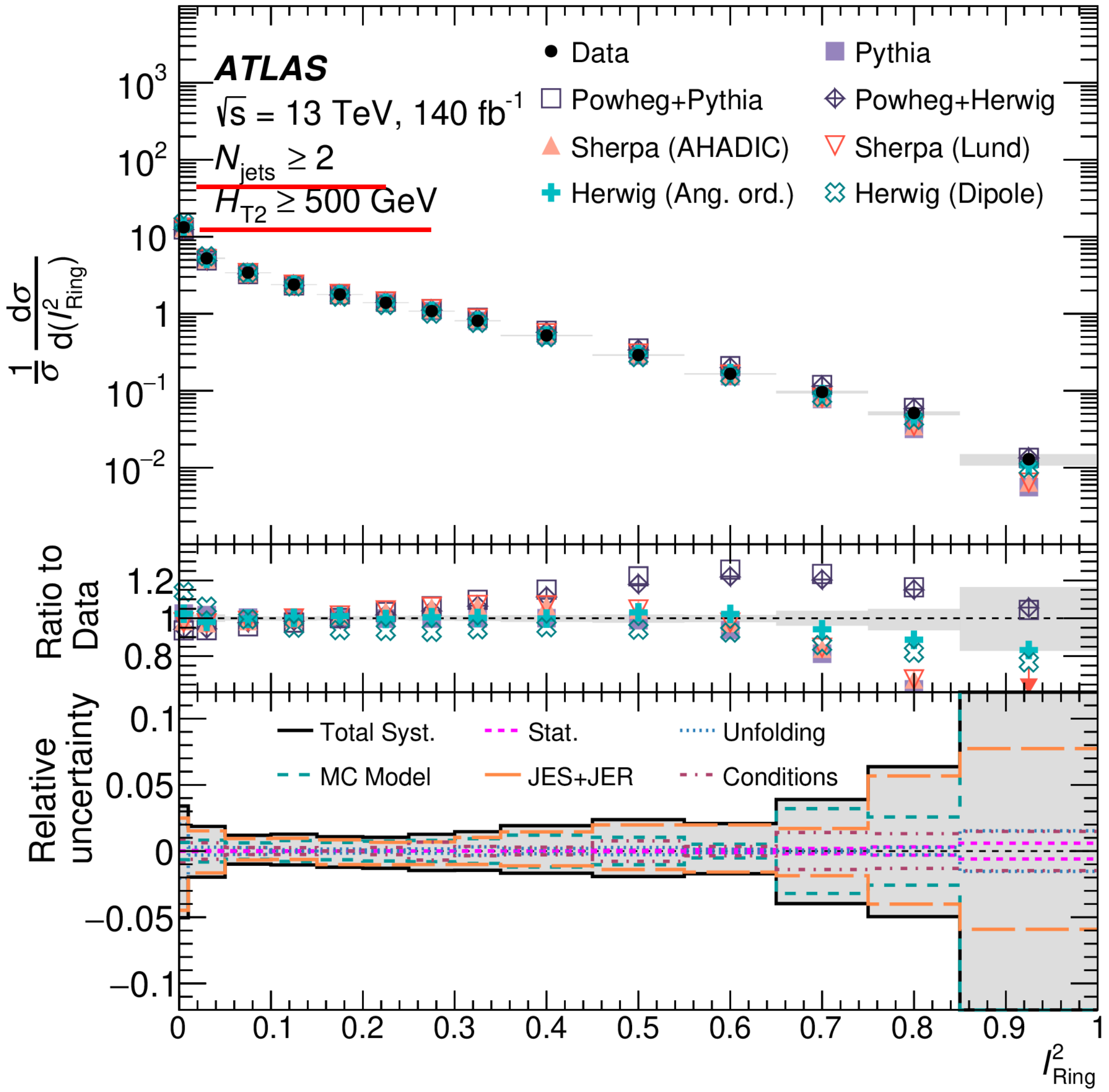


Event isotropies

- $N_{jet} \geq 2$, $H_{T2} \geq 500$ GeV
- 3 isotropies binned in N_{jet} (≥ 2,3,4,5) and H_{T2} (≥ 500,1000,1500 GeV)

MC Models:

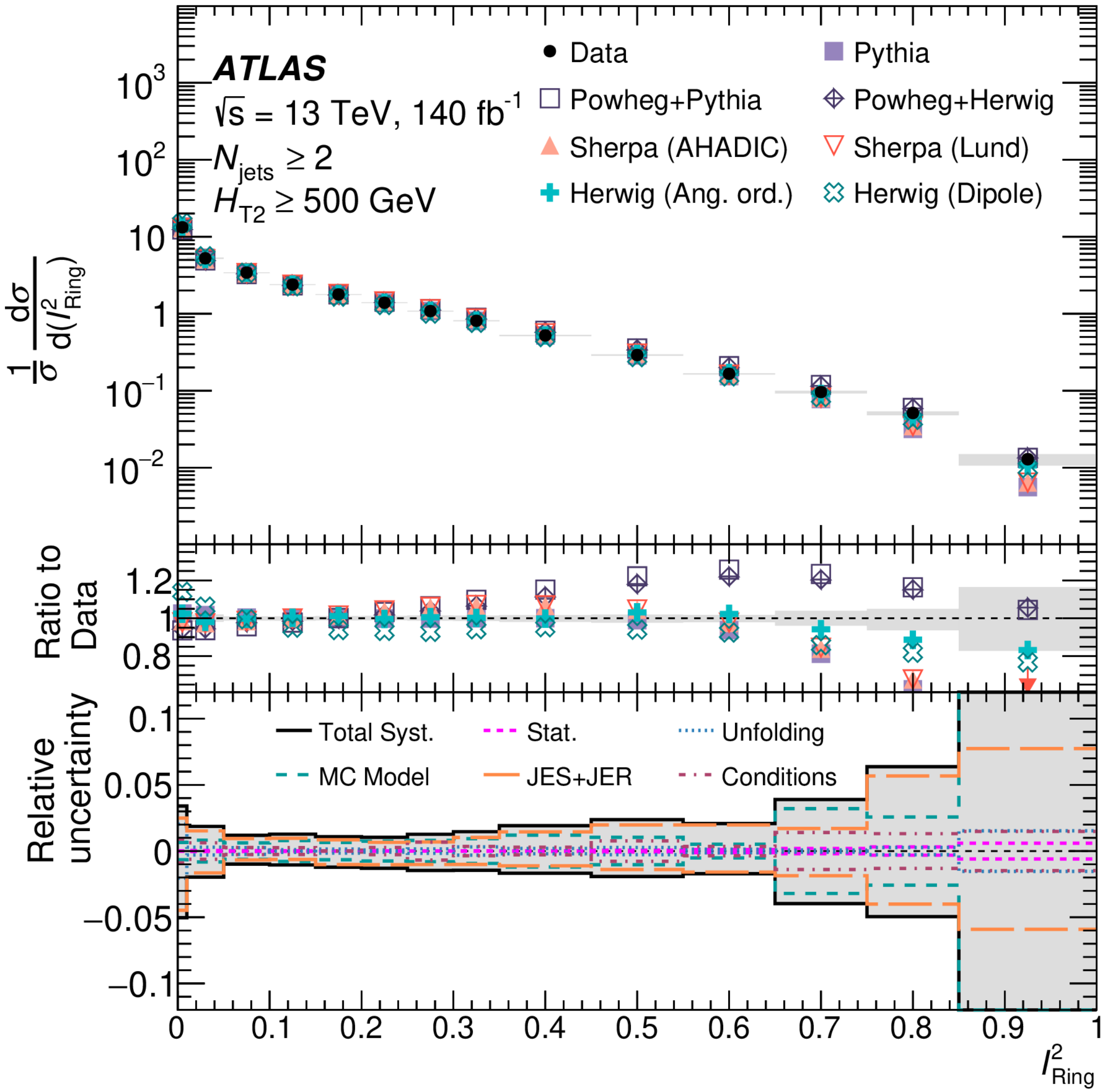
- **Pythia 8.230**
- **Sherpa 2.2.5** (x2)
  - AHADIC cluster model
  - Lund string model
- **Herwig 7.1.3**
  - Angle ordered PS
  - Dipole PS
- **Powheg**
  - **+Pythia**
  - **+Herwig**



Well balanced dijets ⟷ Symmetric 3-jet event

Event isotropies – I^2_{Ring}

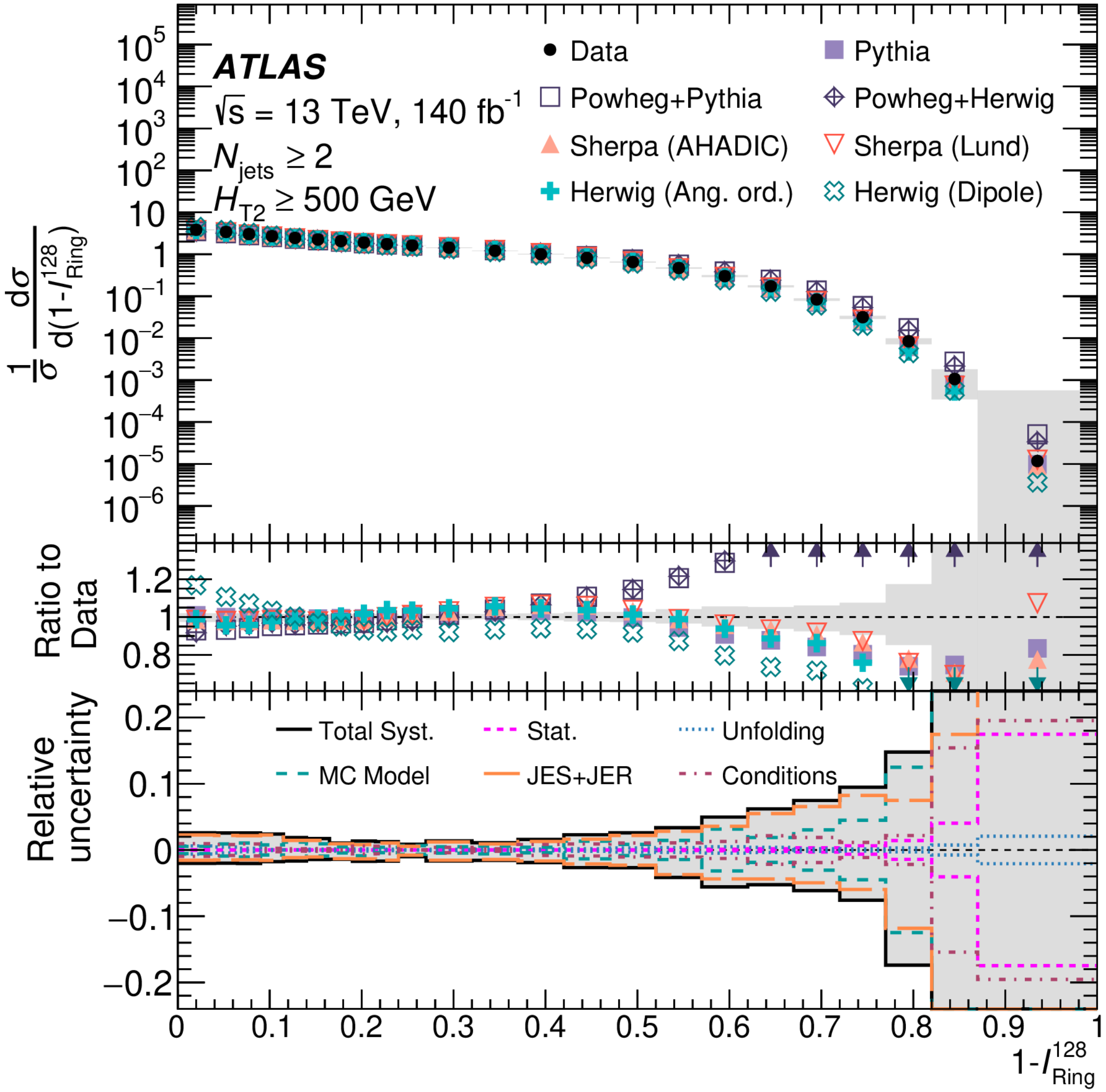
- $N_{jet} \geq 2$, $H_{T2} \geq 500$ GeV
- 3 isotropies binned in N_{jet} (≥ 2,3,4,5) and H_{T2} (≥ 500,1000,1500 GeV)
- Overall, the isotropic region is best described by NLO MC
- No significant differences are observed between the cluster and Lund string hadronisation models for the Sherpa samples



Well balanced dijets ⟷ Symmetric 3-jet event

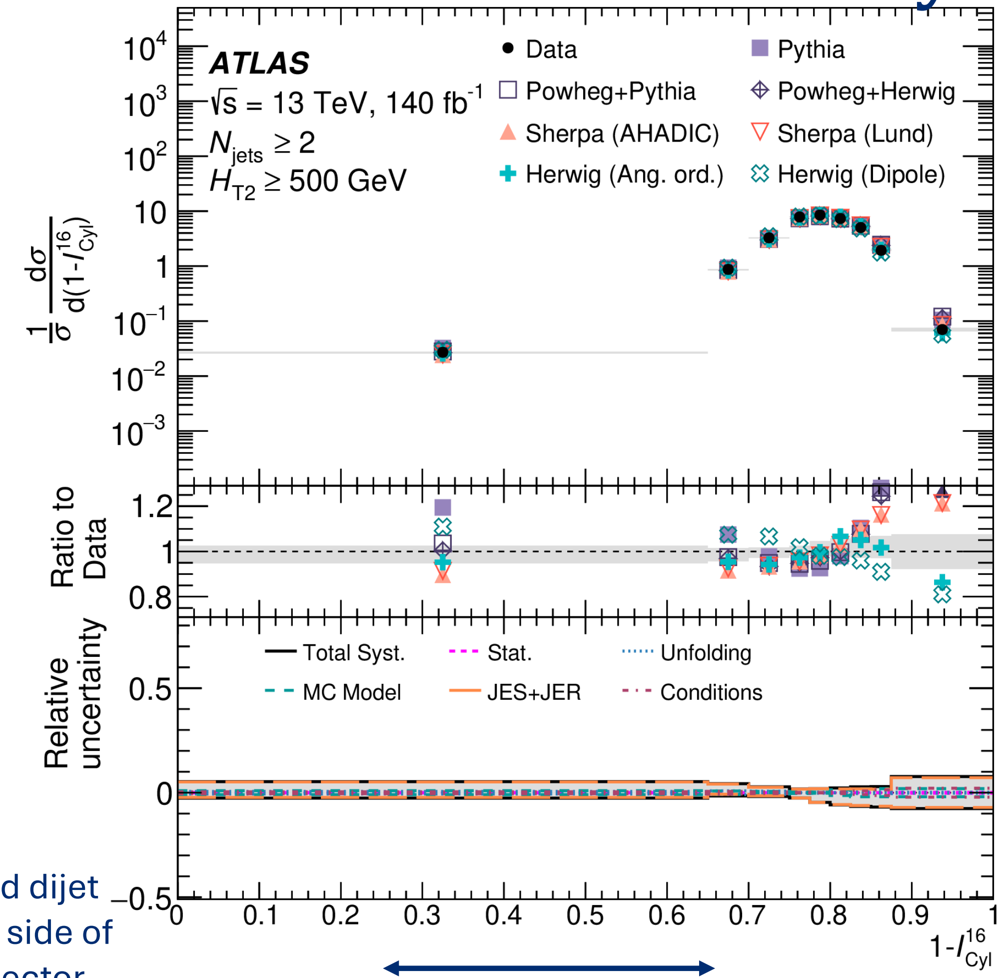
Event isotropies – I_{Ring}^{128}

- Dynamic range – 6 orders of magnitude
- Quality of modelling very different from I_{Ring}^{2} (Powheg+Pythia/Herwig very different from other MC)
- Herwig dipole predicts relatively more dijet-like events than angular ordered

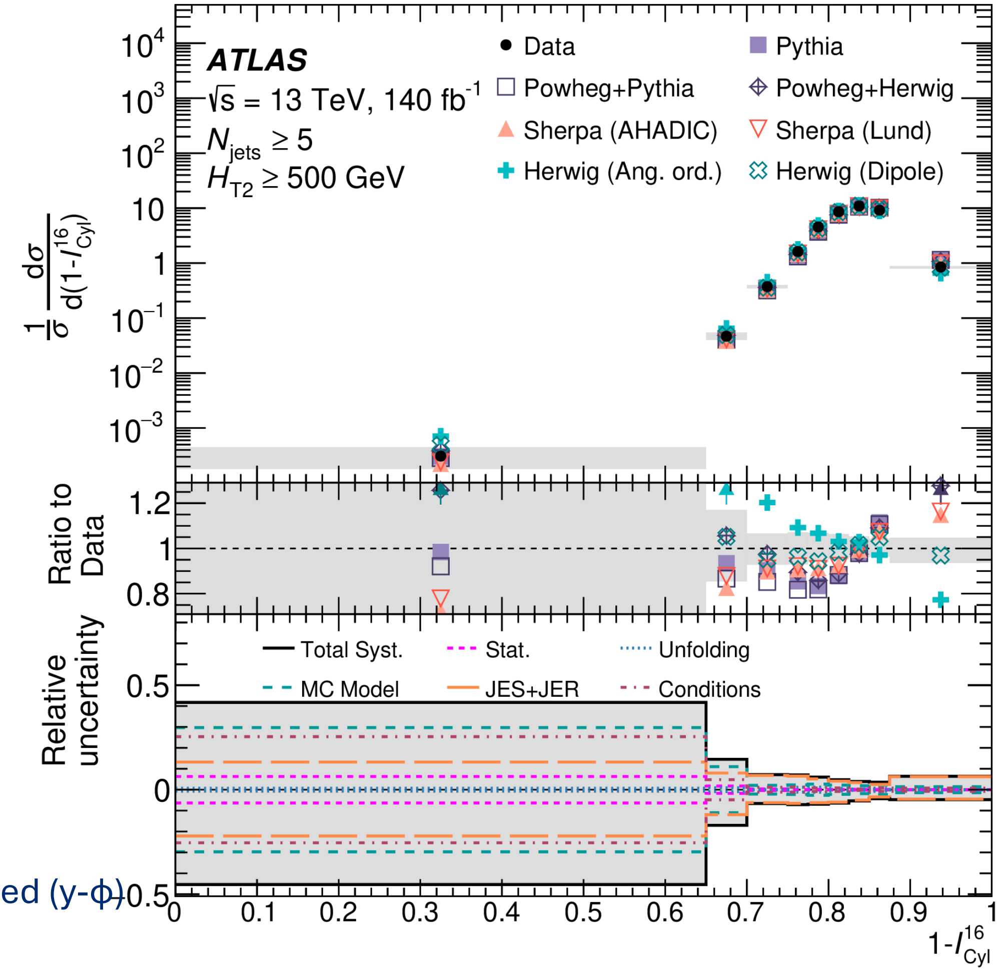


Balanced dijets ⟷ Isotropic multijet

Event isotropies – I_{Cyl}^{16}



Jet multiplicity



Forward dijet on one side of the detector

Evenly populated (y-ϕ) multijet events

Summary

- ATLAS QCD program probes both its soft and hard aspects
- **Lund plane multiplicities** and **Event isotropies** measurements presented
- Further details can be found in the retrospective publications

Thank you

Name of the project: Fundamental constituents of matter through frontier technologies (FORTE)
Registration number: CZ.02.01.01/00/22_008/0004591

Co-funded by
the European Union

MINISTRY OF EDUCATION,
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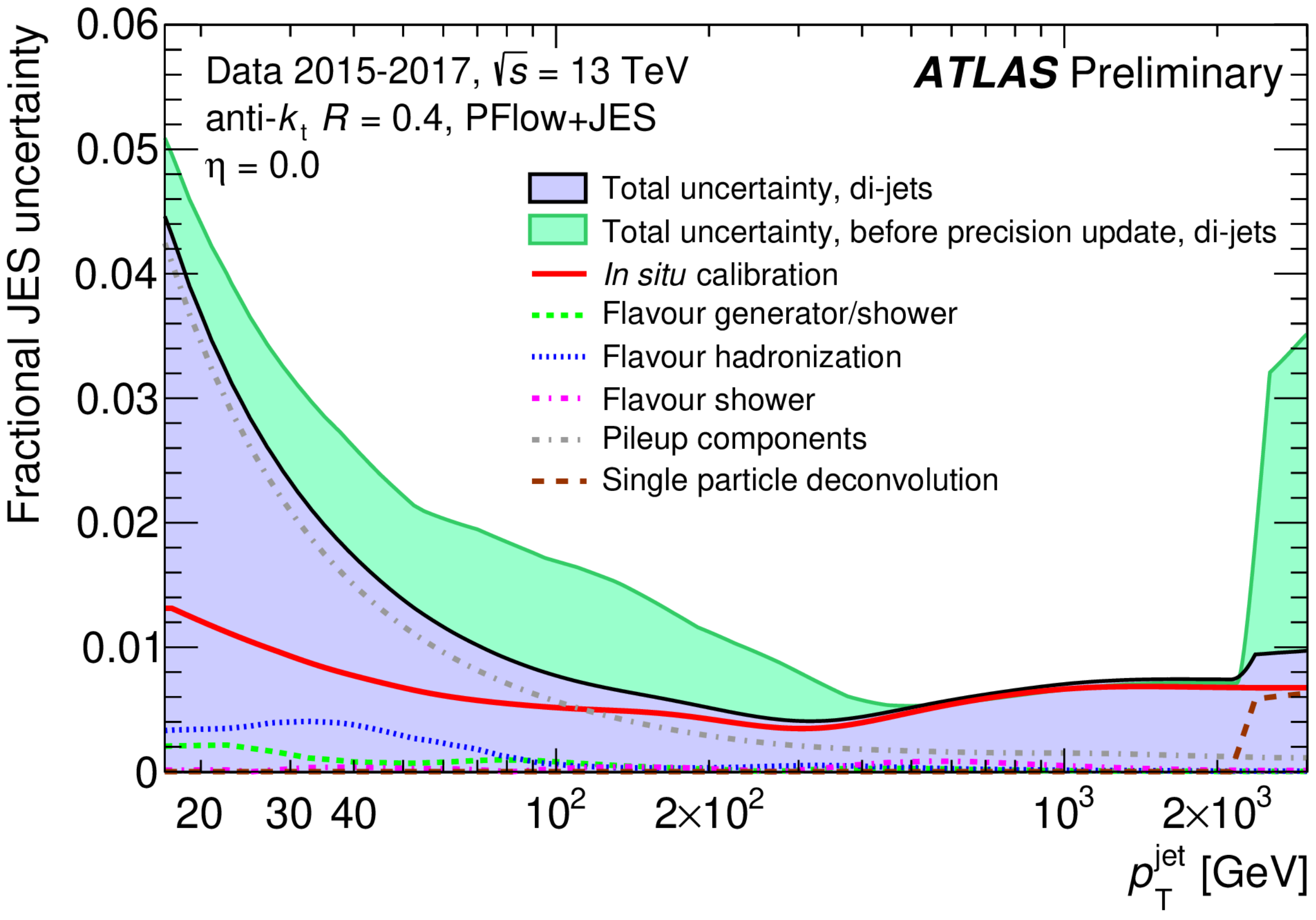
FORTE

Backup

ATLAS jets and jet energy scale

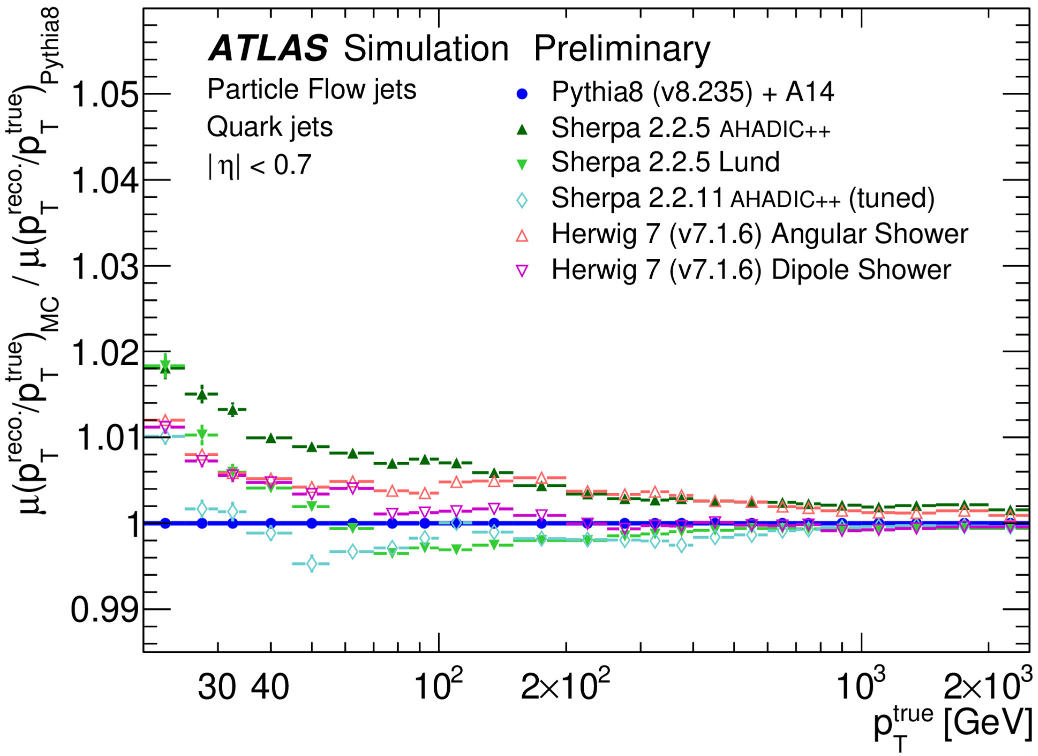
- Anti-k_T R=0.4 used by default
- (Large R=1.0 in certain analyses, R=0.2 subjet analyses)
- PFlow objects (combination of calorimeter+tracker information)

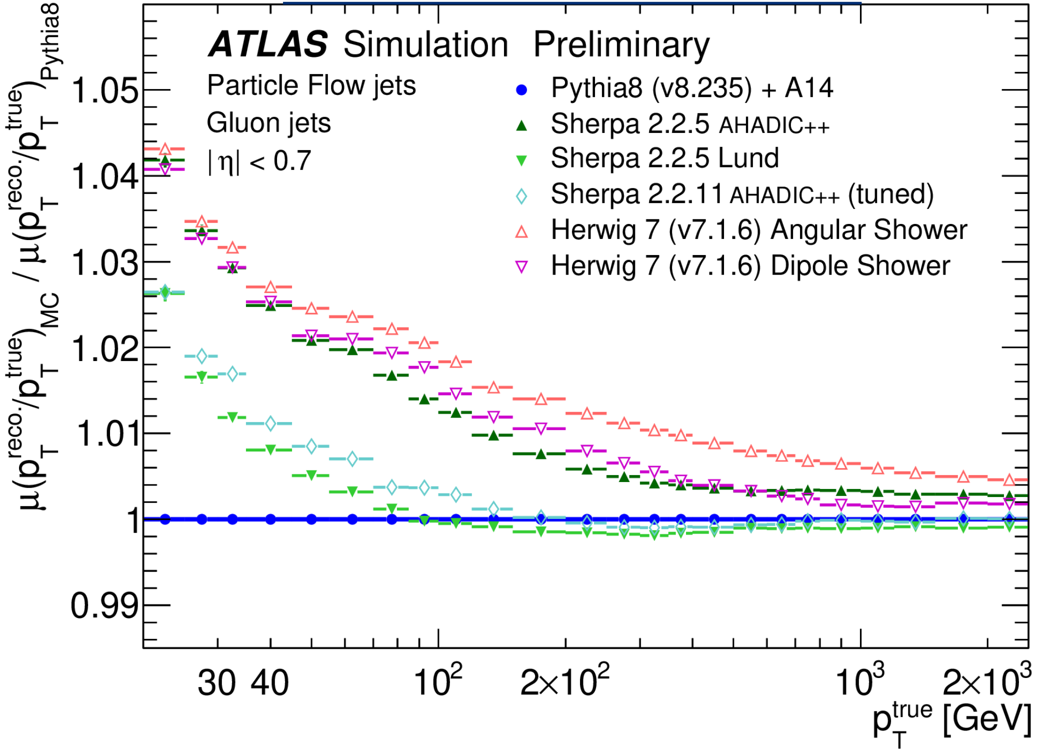
JETM-2023-005



Jet response for quark- and gluon-initiated jets

ATL-PHYS-PUB-2022-021





- Jet response varies by 1–2% depending on hadronization model in the simulation
- Fraction of energy carried by baryons (and kaons to lesser extent) varies significantly between generators