Measurements of Jet Substructure in Proton-Proton Collisions with ALICE

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On behalf of the ALICE Collaboration

ALICE

22nd edition

PANIC Lisbon Portugal

Particles and Nuclei International Conference

BERKELEY LAB

Jets are Rich in Substructure

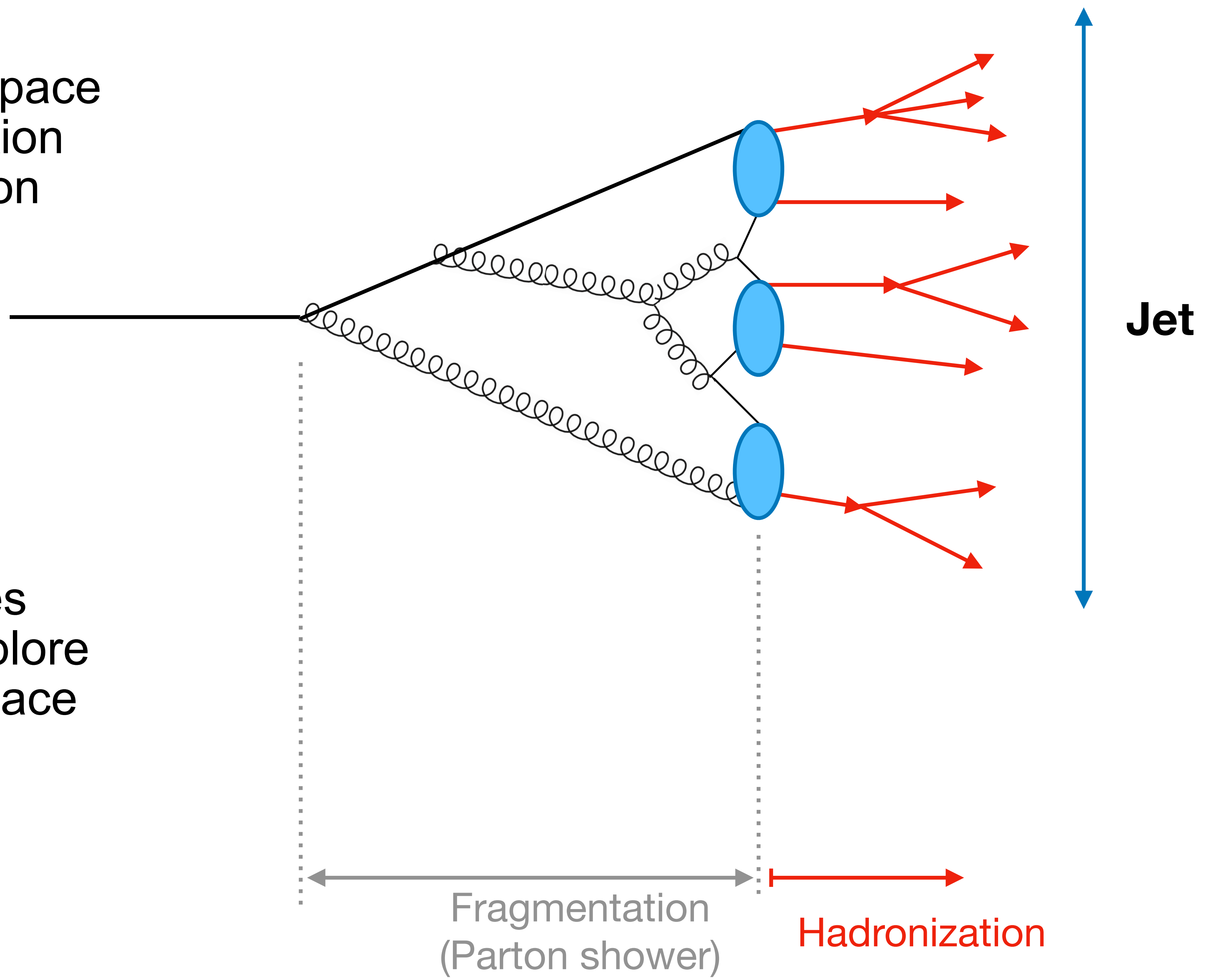
Significant scale difference between parton from hard-scattering and hadrons measured in detector

↓

Large phase space for jet formation and evolution

↓

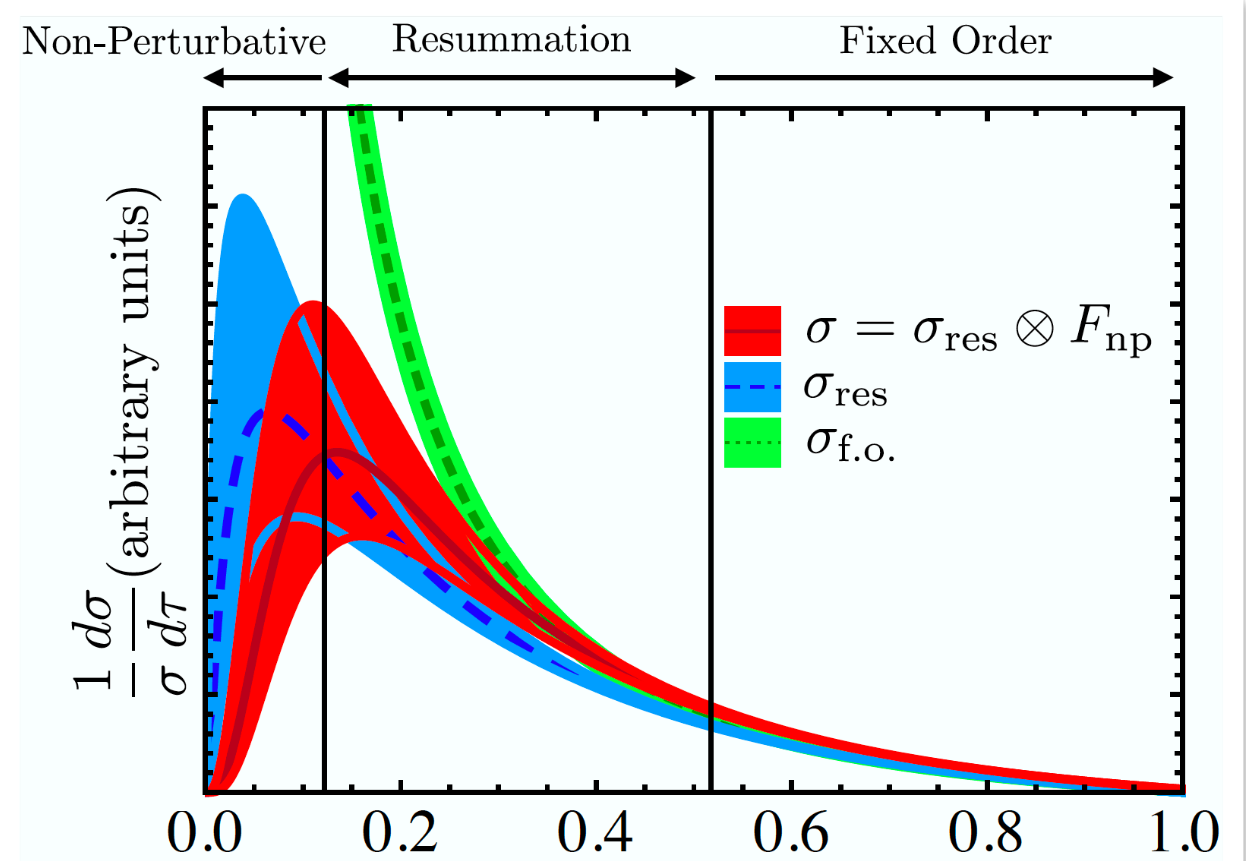
Suite of observables needed to explore this phase space



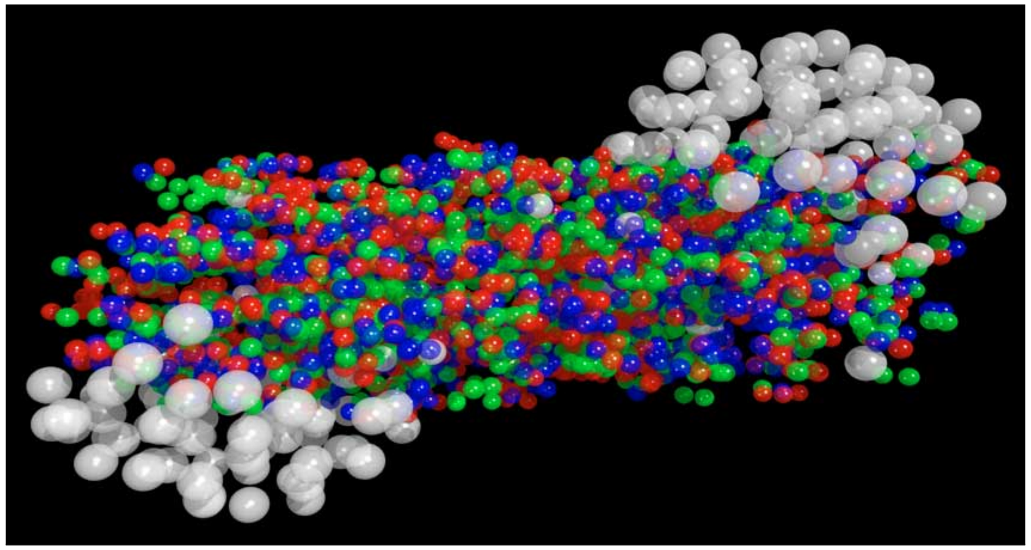
Jet Substructure Measurements in pp Collisions

Testing our understanding of QCD:

- ❑ Quark vs. gluon jets
- ❑ Validity of perturbative QCD predictions
- ❑ Study of non-perturbative physics (hadronization)
- ❑ Understanding interplay between the two



Phys.Rept. 841 (2020) 1



Baseline for measurements in heavy-ion collisions to study QGP

Charged-jets for substructure measurements:

- ❑ ALICE high-resolution tracking (ITS+TPC) → high-precision substructure measurement
- ❑ jet selection: $|\eta_{\rm jet}| < 0.9 - R$, $p_{\rm T}^{\rm constit.} > 150$ MeV/c

Grooming and Soft Drop

Grooming: systematically removing soft, wide-angle radiation from a jet to mitigate effects such as ISR, MPI, and pileup.

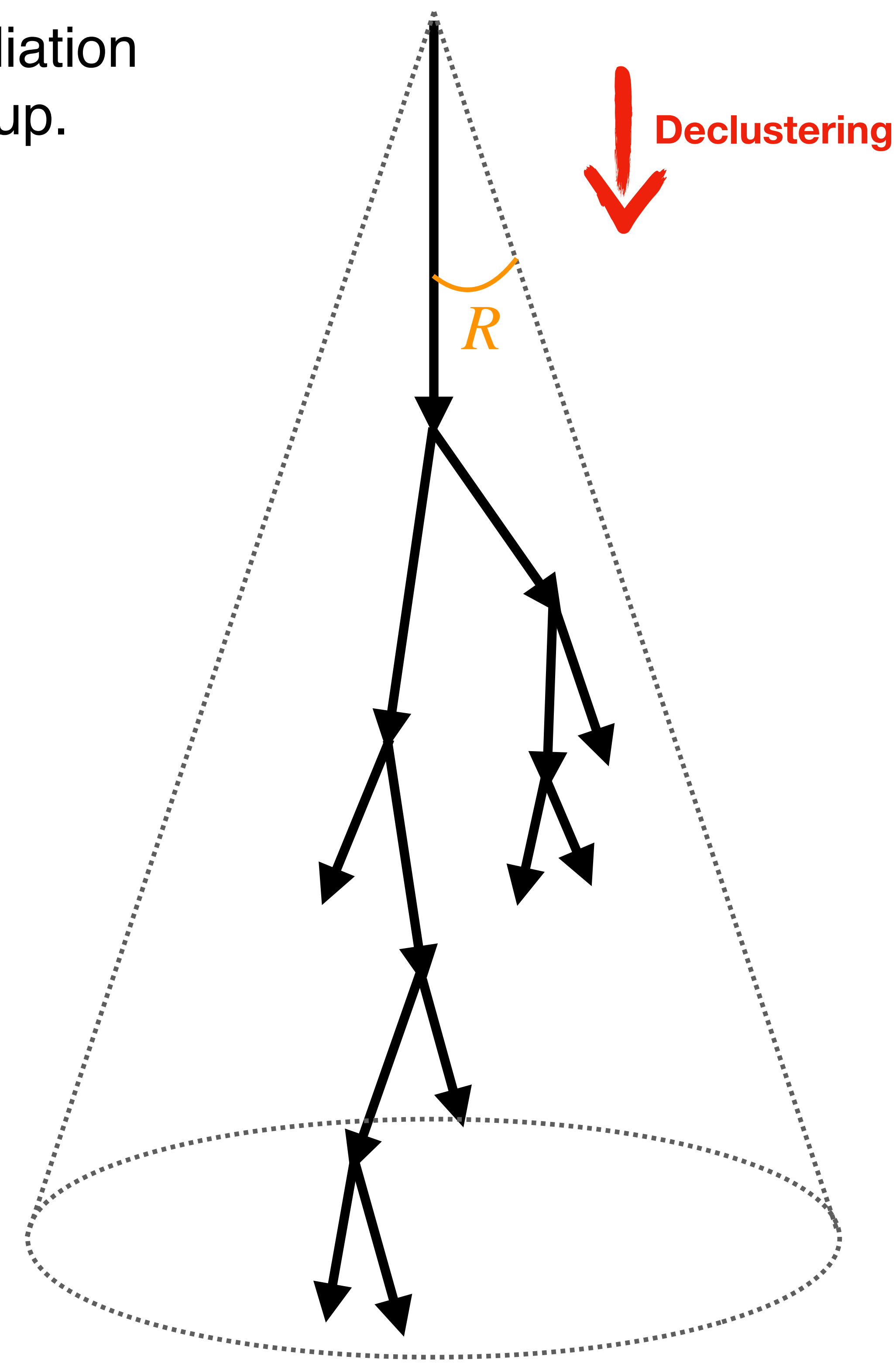
Soft Drop: JHEP 1405 (2014) 146 (1402.2657)

After reclustering with C-A, decluster and check:

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} \overset{?}{>} z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

$$\Delta R_{12} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$$

z_{cut} and β free parameters



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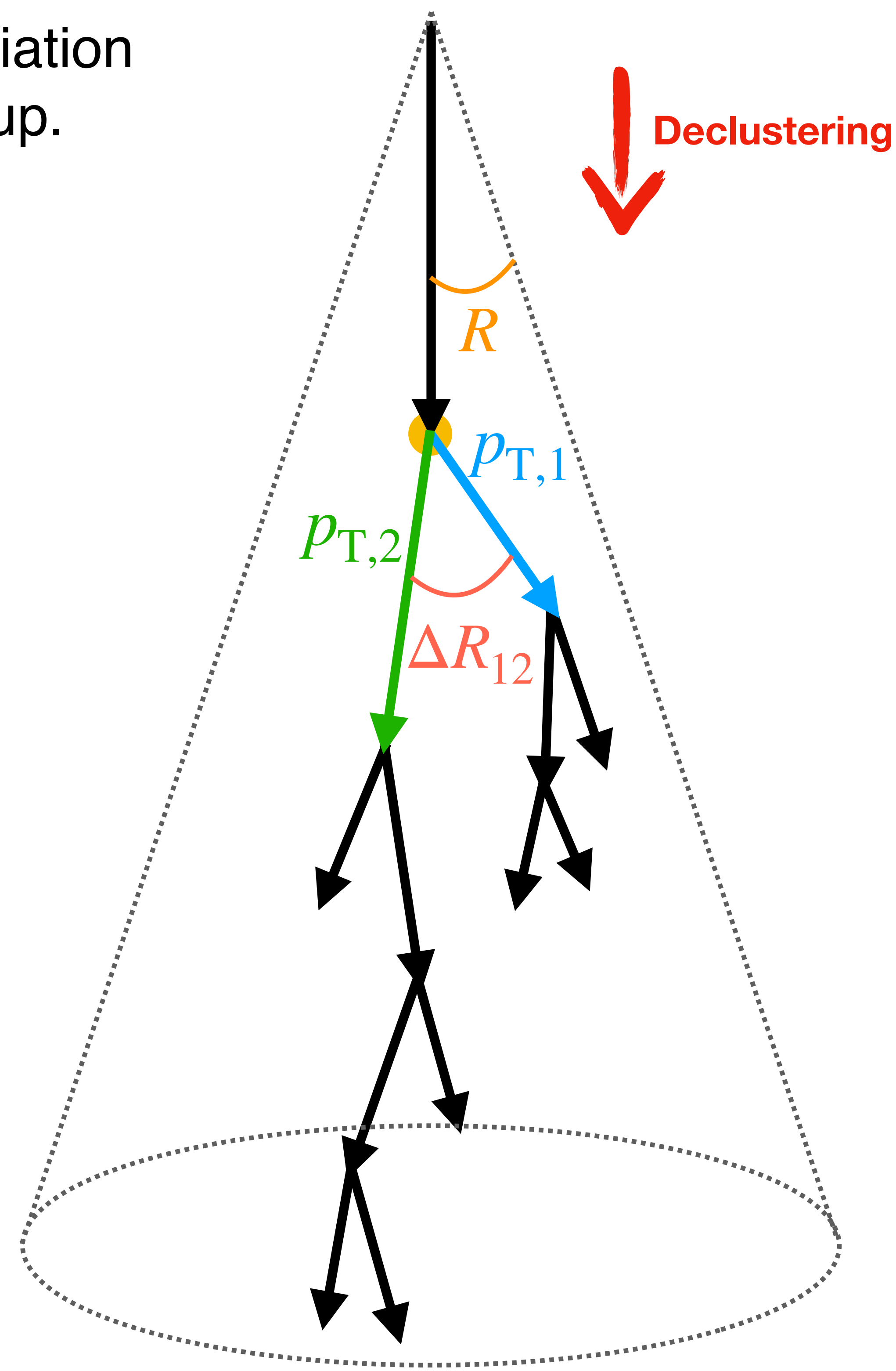
Check is the first split satisfies the SD condition



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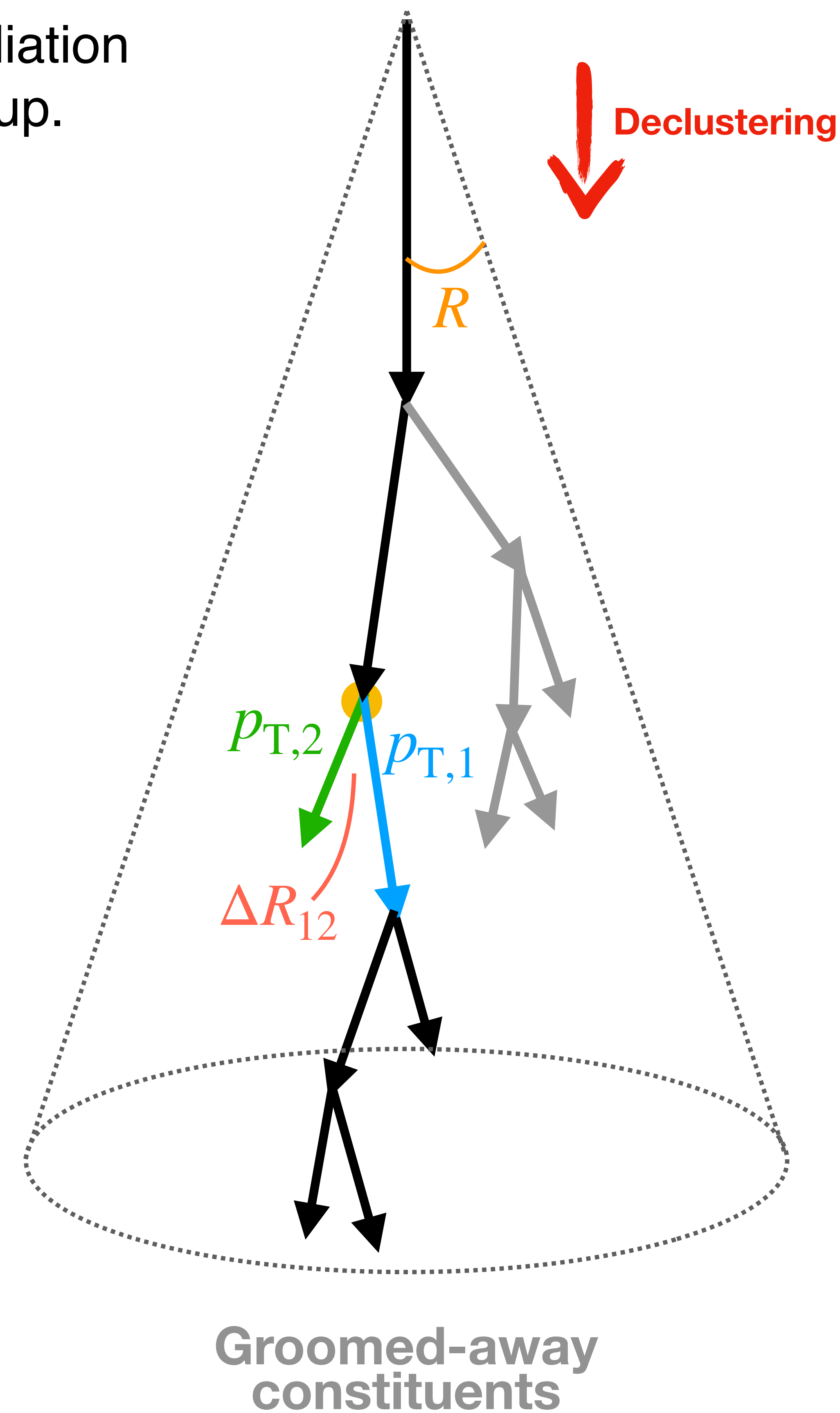
z_{cut} and β free parameters

It does not:

- Drop softer branch
- check if next split in harder branch satisfies SD condition



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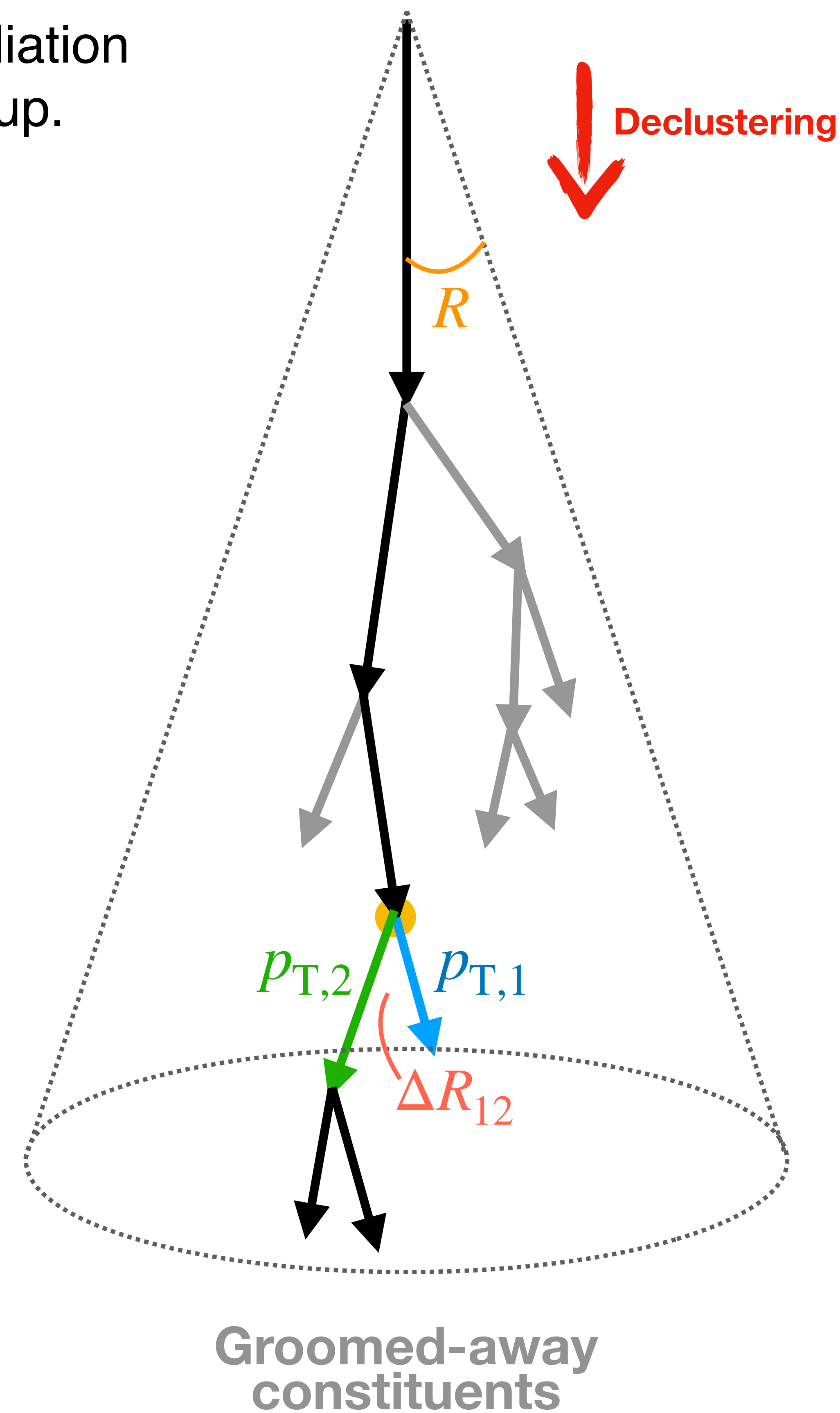

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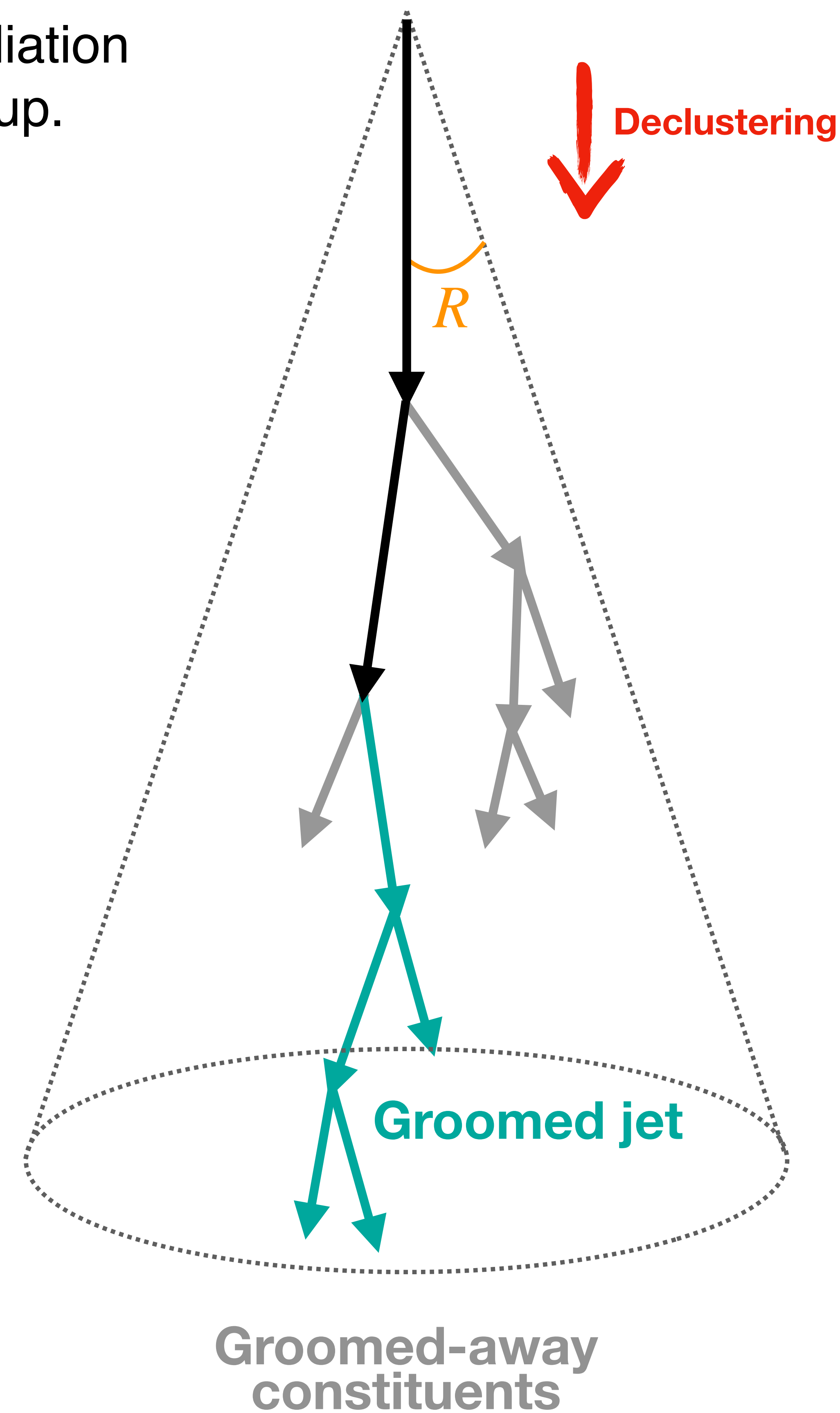
It does:

- What remains defines the groomed jet



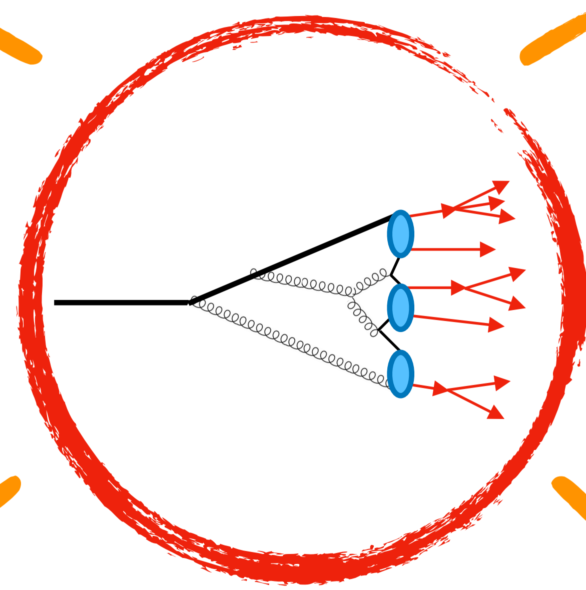
Jet-Substructure Measurements in ALICE

ALICE

Jet-axis Differences

Jet Angularities
arXiv:2107.11303

Groomed z_g and R_g
arXiv:2107.12984



Primary Lund Plane

First measurement of D^0-tagged Soft Drop z_g, R_g and n_{SD}
https://cds.cern.ch/record/2719005

First direct observation of the Dead-Cone Effect
arXiv:2106.05713

Inclusive / leading subjet z_r

N-subjettiness
arXiv:2105.04936

And many more

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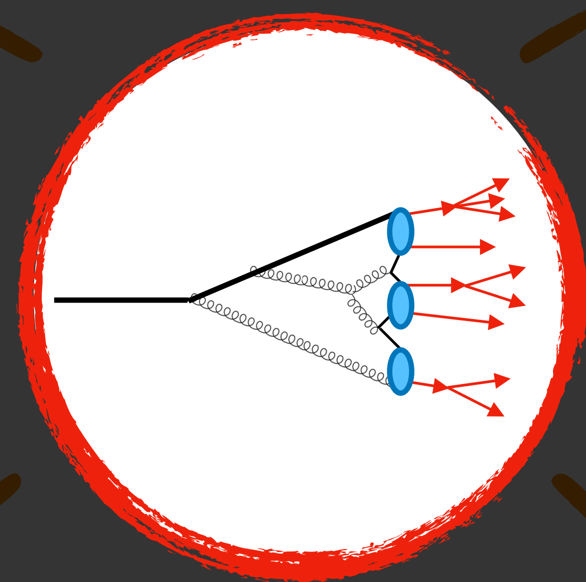

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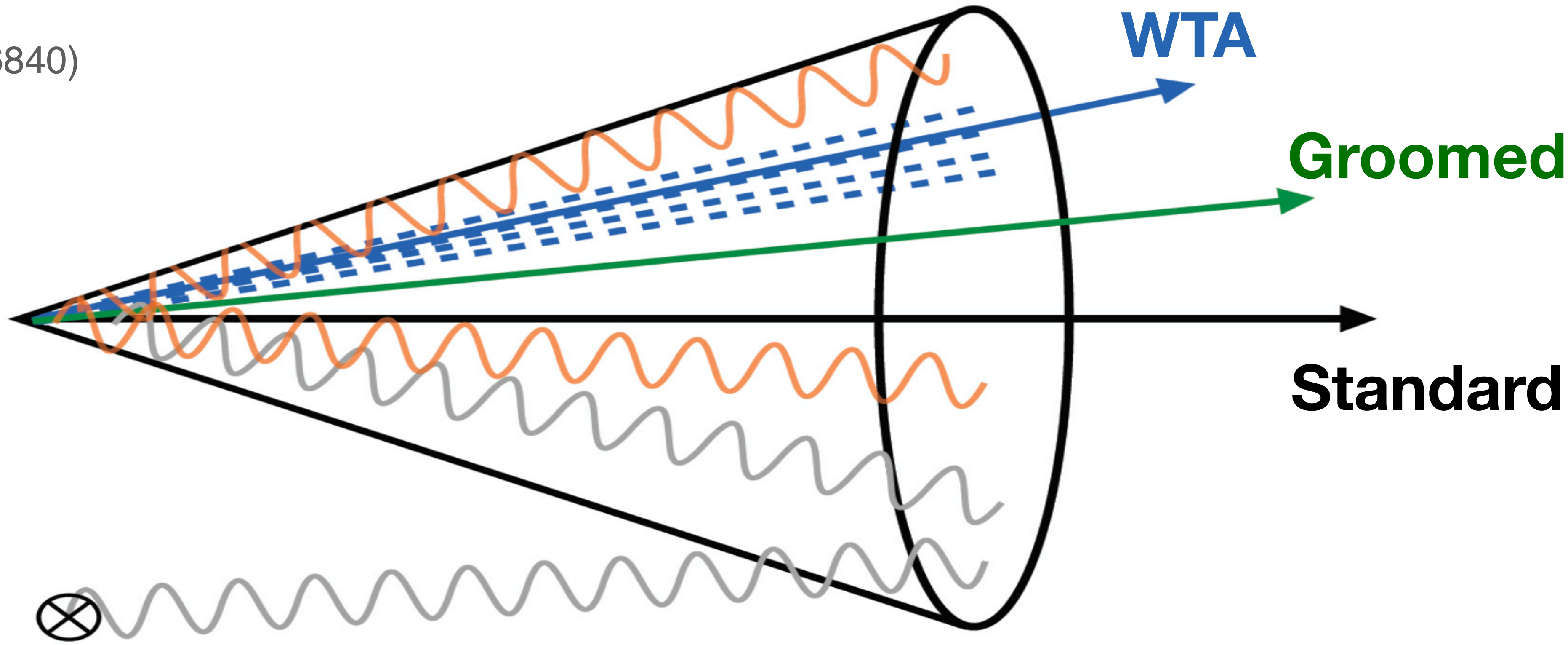
Jet-Axis Differences

JHEP 04 (2020) 211 (1911.06840)



- Standard axis:

  coordinates in (y, ϕ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Substructure observable: angular difference:

$$\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\phi_2 - \phi_1)^2}$$

  between two definitions of the jet axis

- Different levels of sensitivity to non-perturbative physics

Jet-Axis Differences

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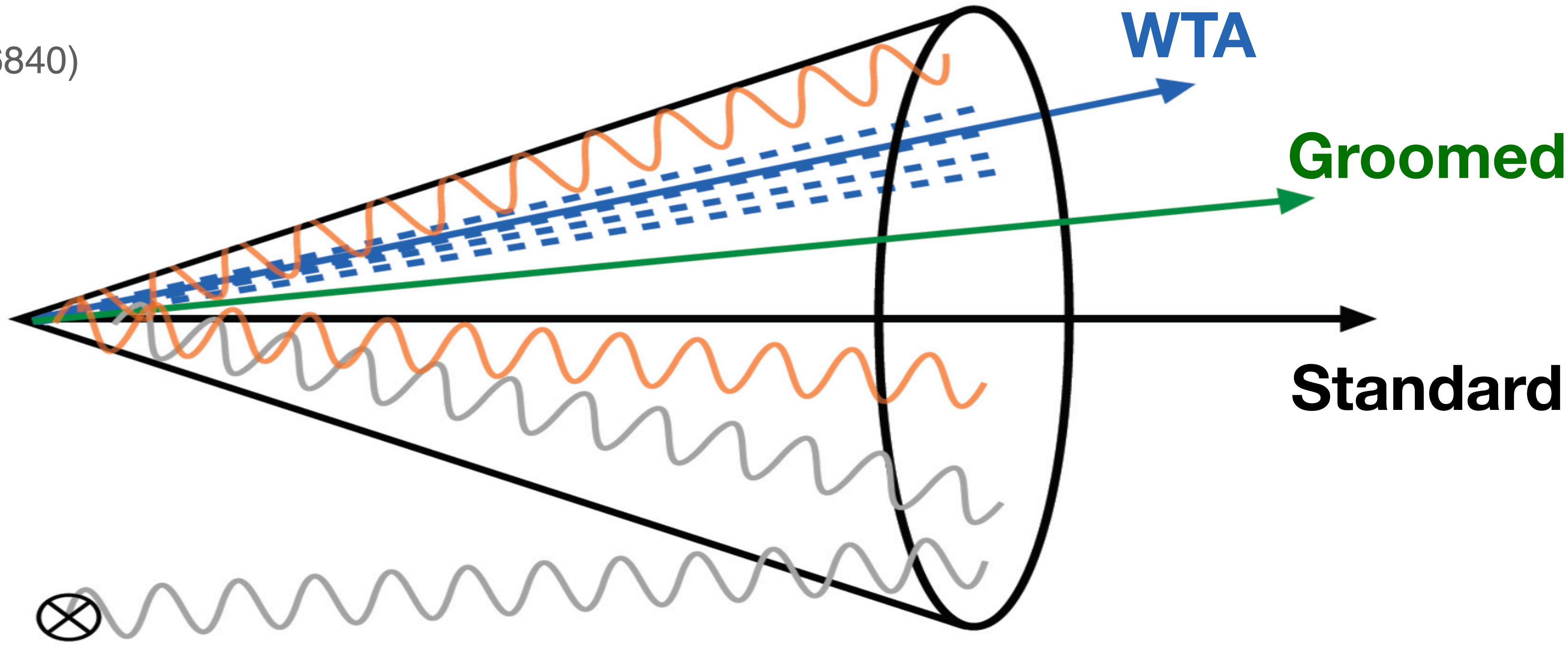

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- Groomed axis:
  standard axis of groomed jet

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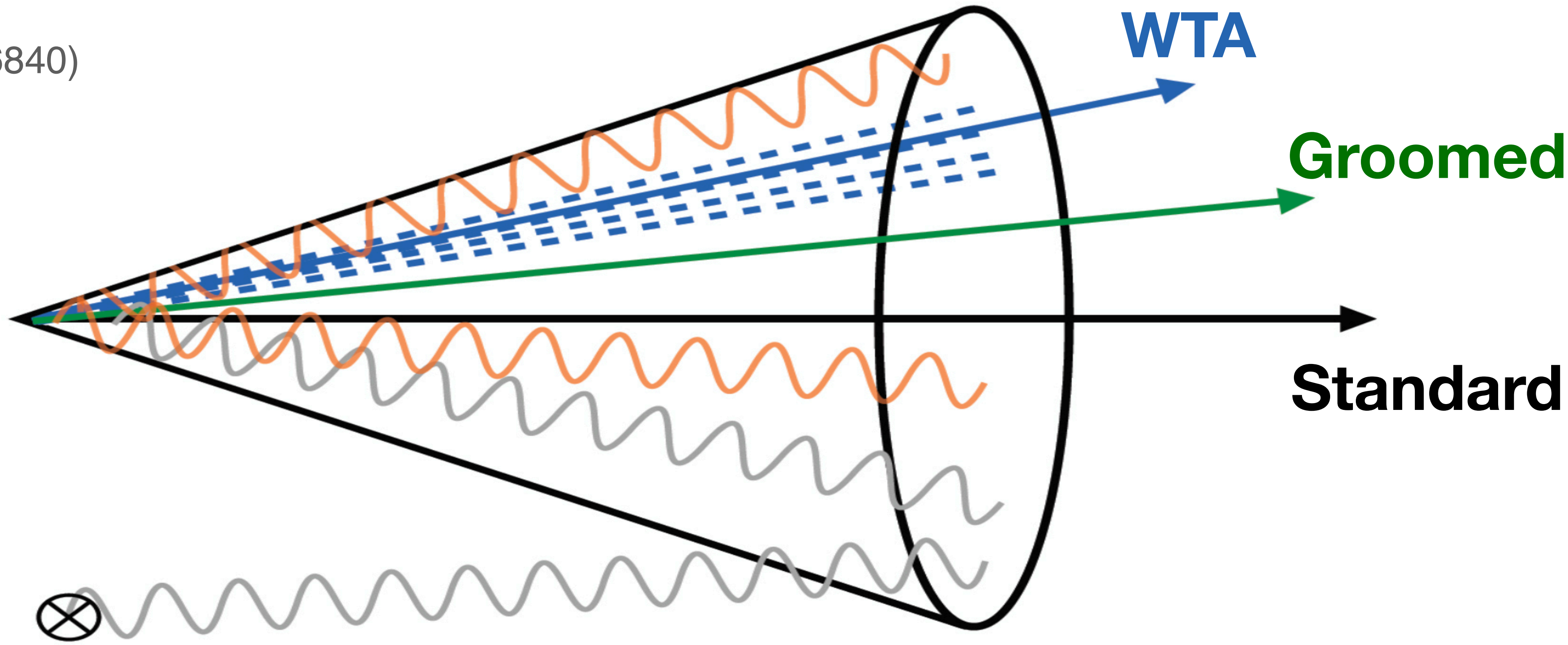


- Standard axis:
  coordinates in (y, ϕ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Groomed axis:
  standard axis of groomed jet

- Winner-Takes-All (WTA) axis:
  - recluster jet with CA algorithm
  - $2 \rightarrow 1$ prong combination by taking direction of harder prong and $p_{\mathrm{T,\,tot}} = p_{\mathrm{T,\,1}} + p_{\mathrm{T,\,2}}$
  - Resulting axis insensitive to soft radiation at leading power

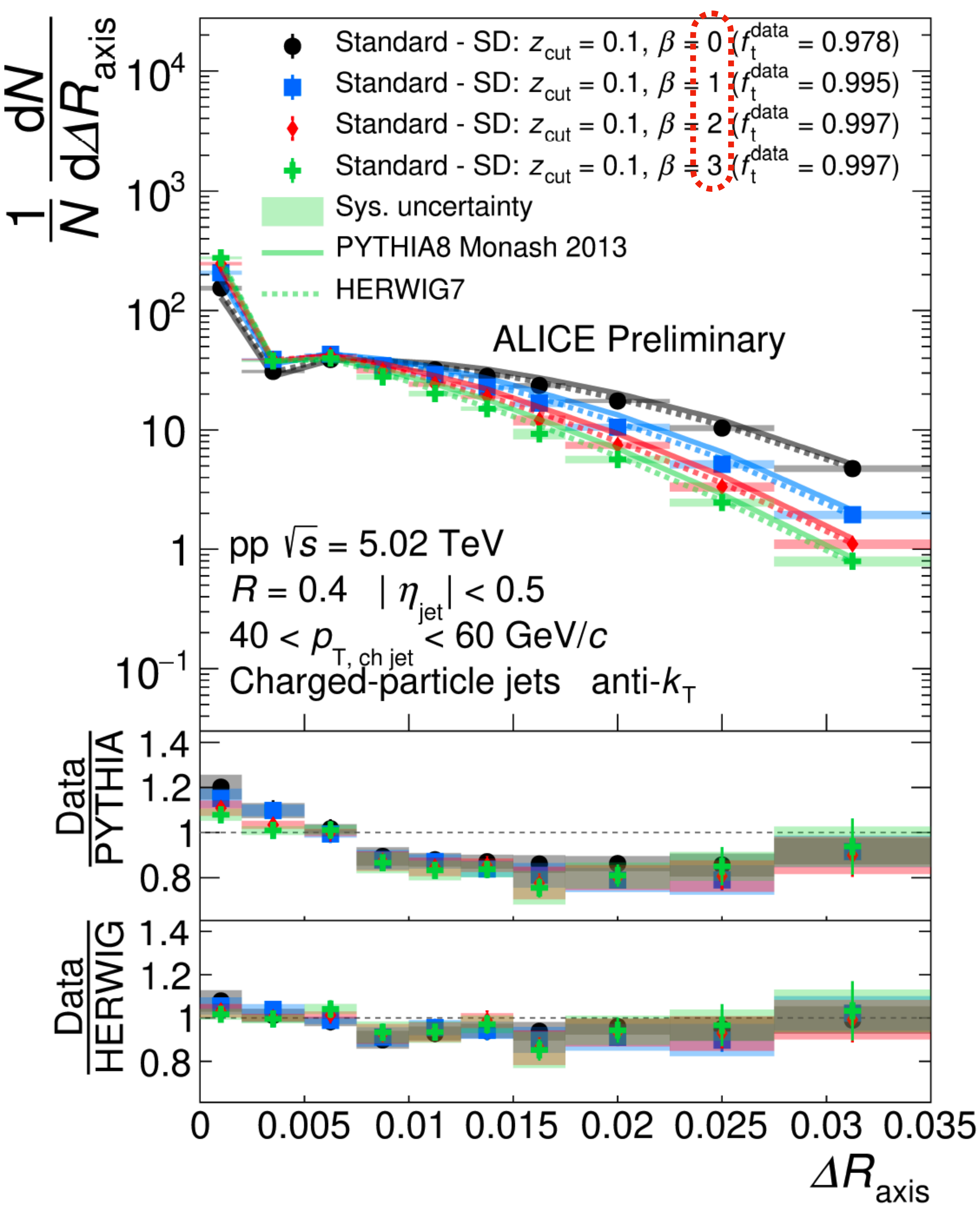
- Substructure observable: angular difference:

$$\Delta R_{\mathrm{axis}} = \sqrt{(y_2 - y_1)^2 + (\phi_2 - \phi_1)^2}$$

between two definitions of the jet axis

- Different levels of sensitivity to non-perturbative physics

Standard—SD Distributions



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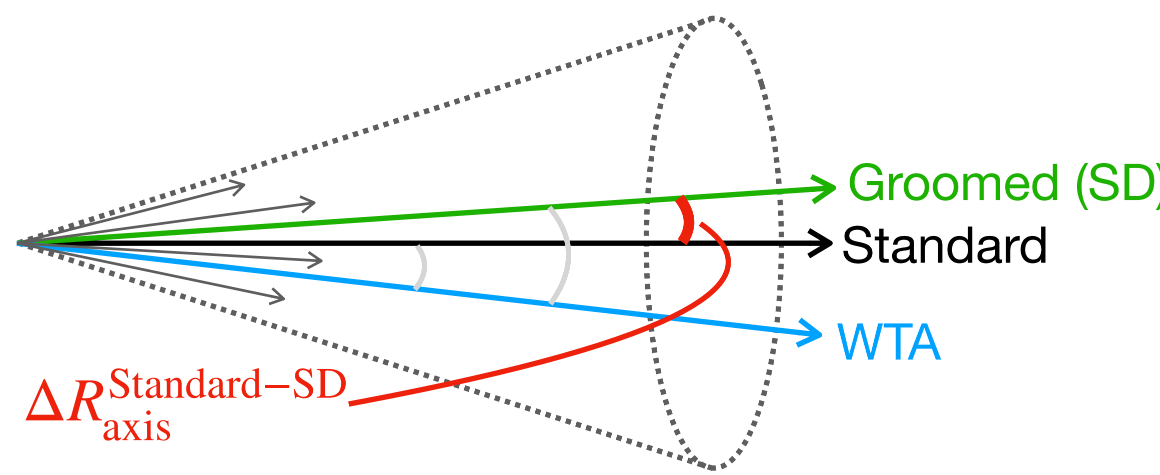
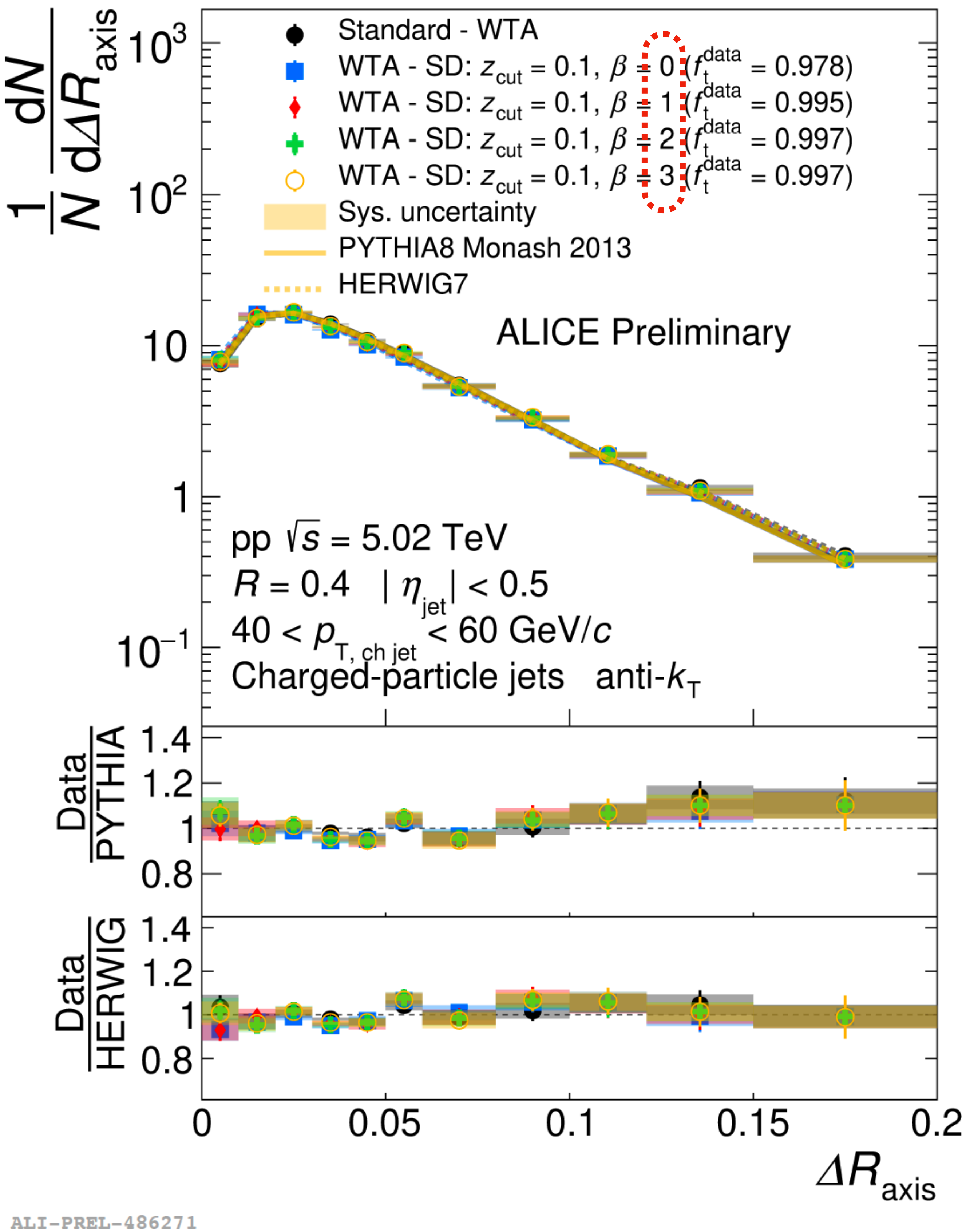


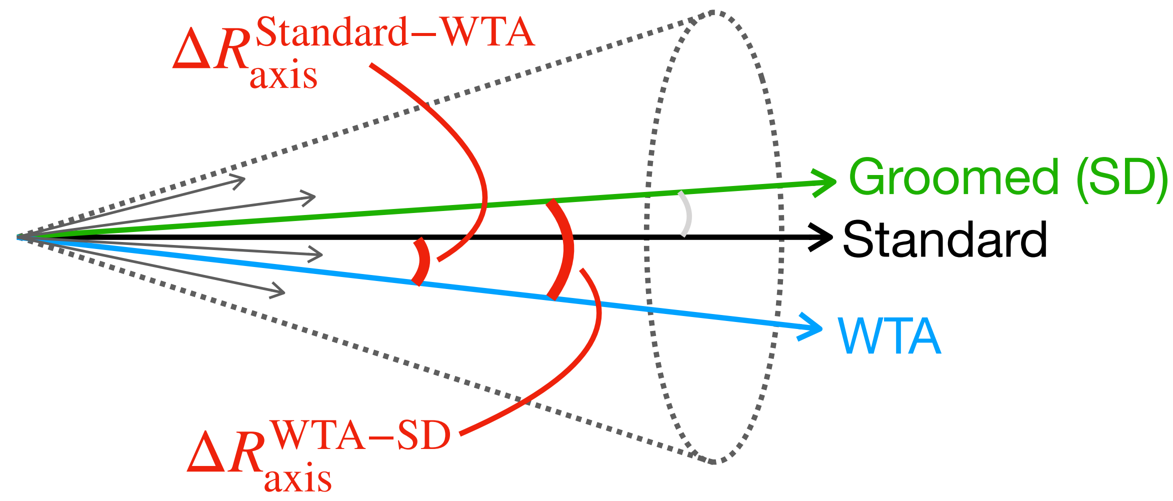
- Probes effect of soft, wide-angle radiation on jet direction → Sensitive to non-perturbative physics
- Shape better described by HERWIG than PYTHIA
- Distributions are narrow: grooming does not change the jet axis significantly
- Stronger grooming → larger ΔR_{axis}

Distributions measured for $p_T^{ch\ jet} \in (20, 100)$ GeV/c

Charged jets

WTA—Standard/SD Distributions





- Distributions are broader: WTA axis has higher probability to be misaligned wrt Standard/SD axis
- Distributions are insensitive to grooming
- Well described by HERWIG and PYTHIA
- Outlook: Comparisons to pQCD calculations and measurement in Pb-Pb collisions

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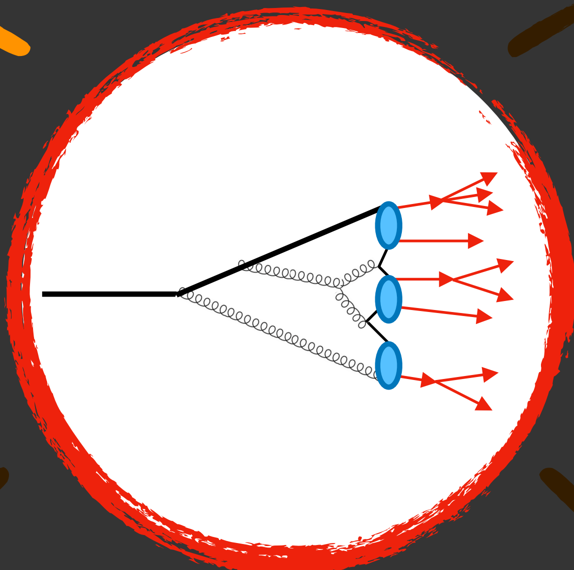

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Jet Angularities

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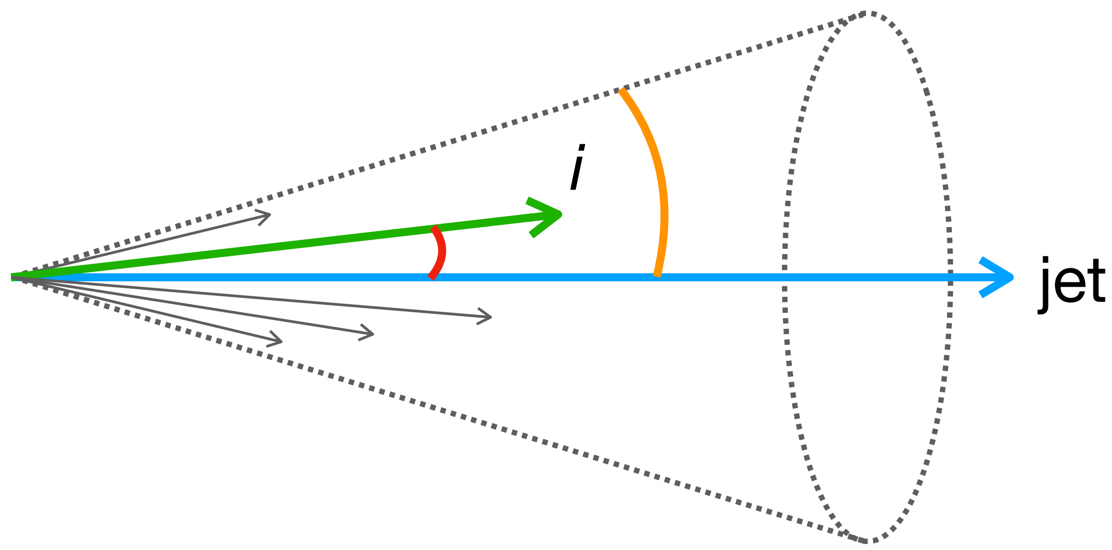
Includes both transverse-momentum and angular components with relative weights given by continuous parameter α

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \right) \left(\frac{\Delta R_{\mathrm{jet},i}}{R} \right)^\alpha$$



$\alpha > 0 \;\rightarrow$ IRC-safe observable

Groomed angularities ($\lambda_{\alpha,g}$): same expression as λ_α but sum only runs over constituents of groomed jet

Examples of jet angularities:

- $\lambda_1 \equiv$ jet girth
- $\lambda_2 \equiv$ jet thrust

systematic variation of α to test pQCD calculations and universality of non-perturbative shape functions.

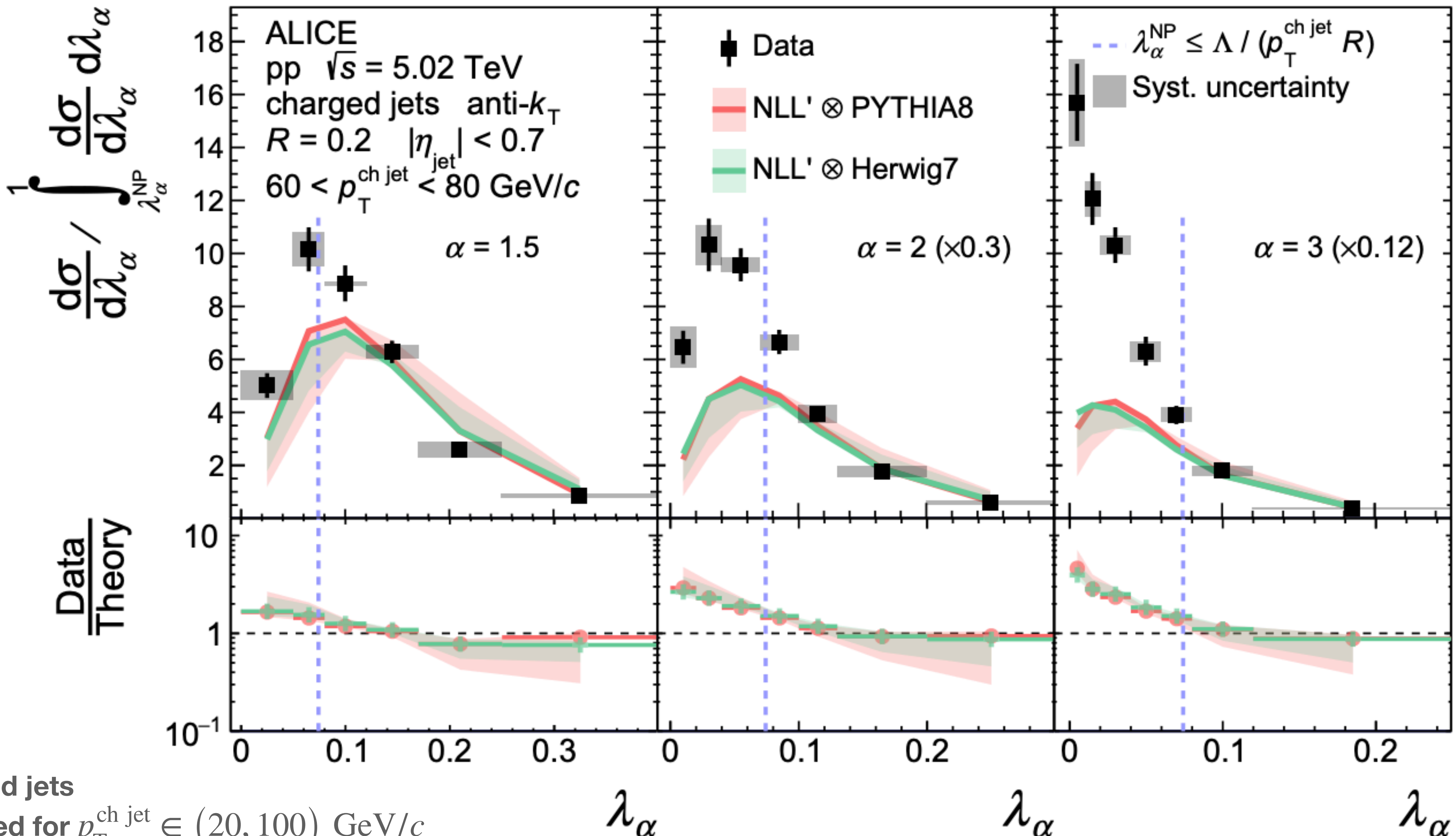
JHEP 11 (2014) 129

Jet Angularities

arXiv:2107.11303

JHEP 1804 (2018) 110

- Small λ_α: non-perturbative regime
- Large λ_α: perturbative regime
- Good agreement with SCET calculations in perturbative regime

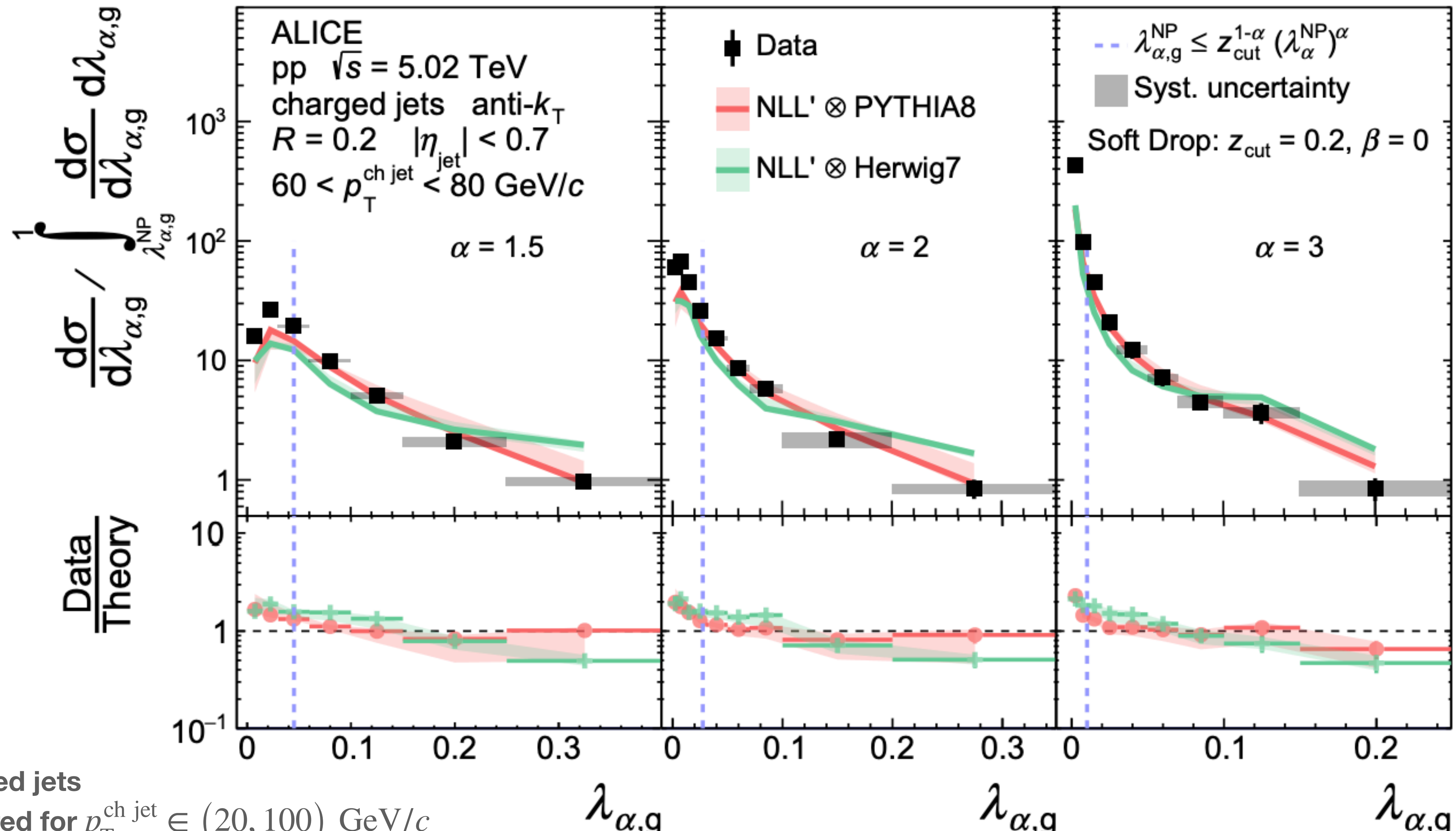


Charged jets measured for $p_T^{ch\ jet} \in (20, 100)$ GeV/c

Groomed Jet Angularities

arXiv:2107.11303 JHEP 1804 (2018) 110

- First-ever measurement of the groomed jet angularities
- Extension of perturbative region (with respect to ungroomed)
- Good agreement with SCET calculations



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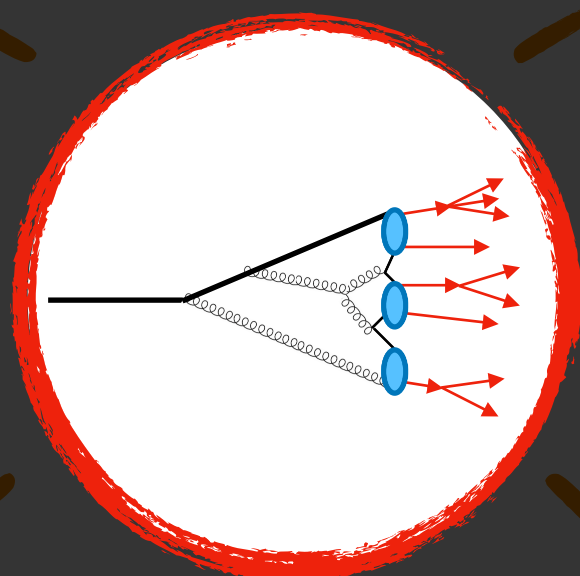

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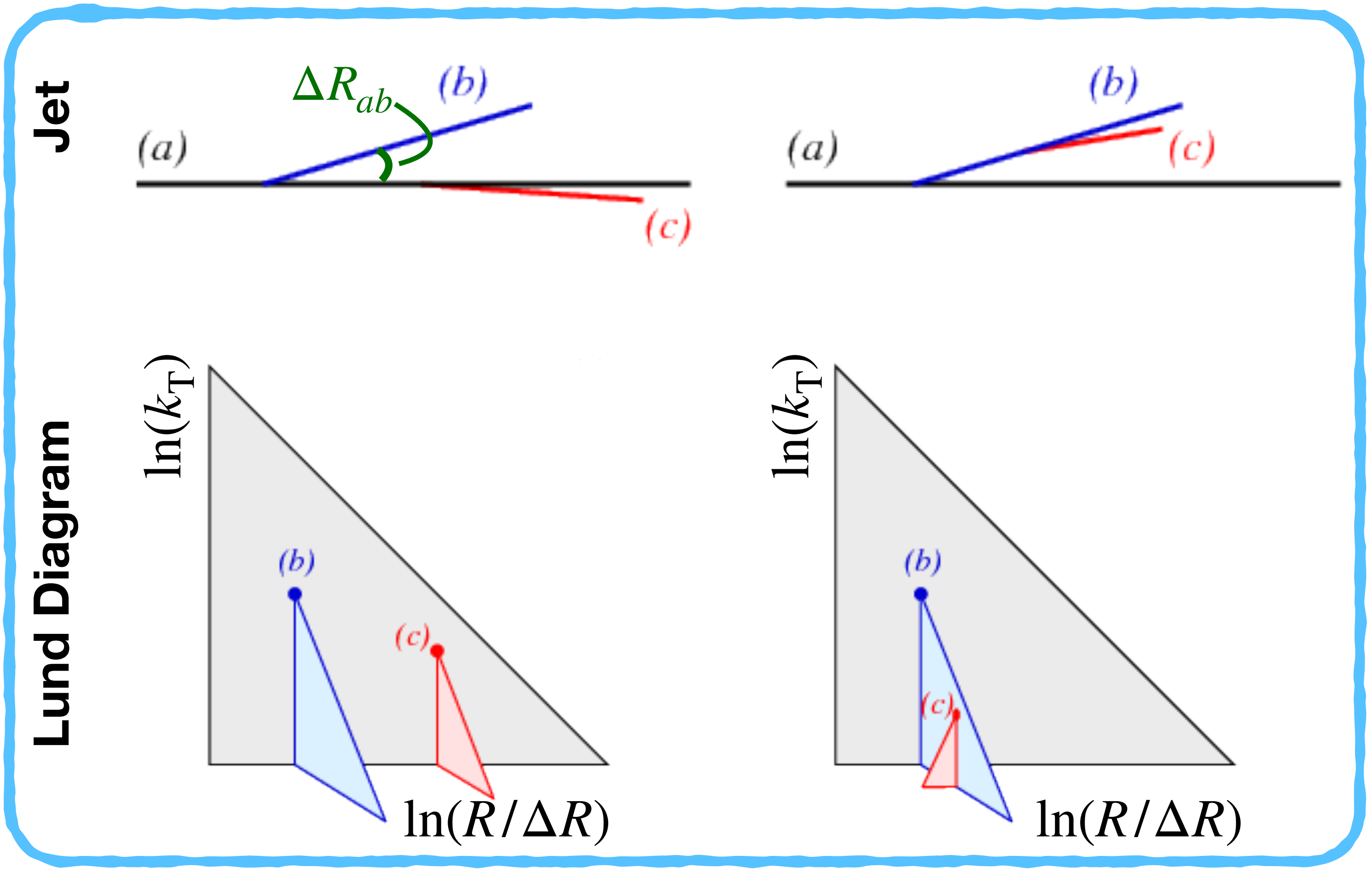
Lund Map and Planes

JHEP 12 (2018) 064

$$\Delta R_{ab} = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}$$

$$k_{\mathrm{T}} = p_{\mathrm{T},b} \Delta R_{ab}$$

- Representation of the internal structure of jets
- Phase-space for emission from each particle corresponds to triangular region in the $(\ln(R/\Delta R), \ln(k_{\mathrm{T}}))$ plane
- Useful to interpret MC parton shower algorithms and resummation of logarithmically enhanced terms in perturbation theory



Primary Lund Plane: coordinates from emissions from harder prong

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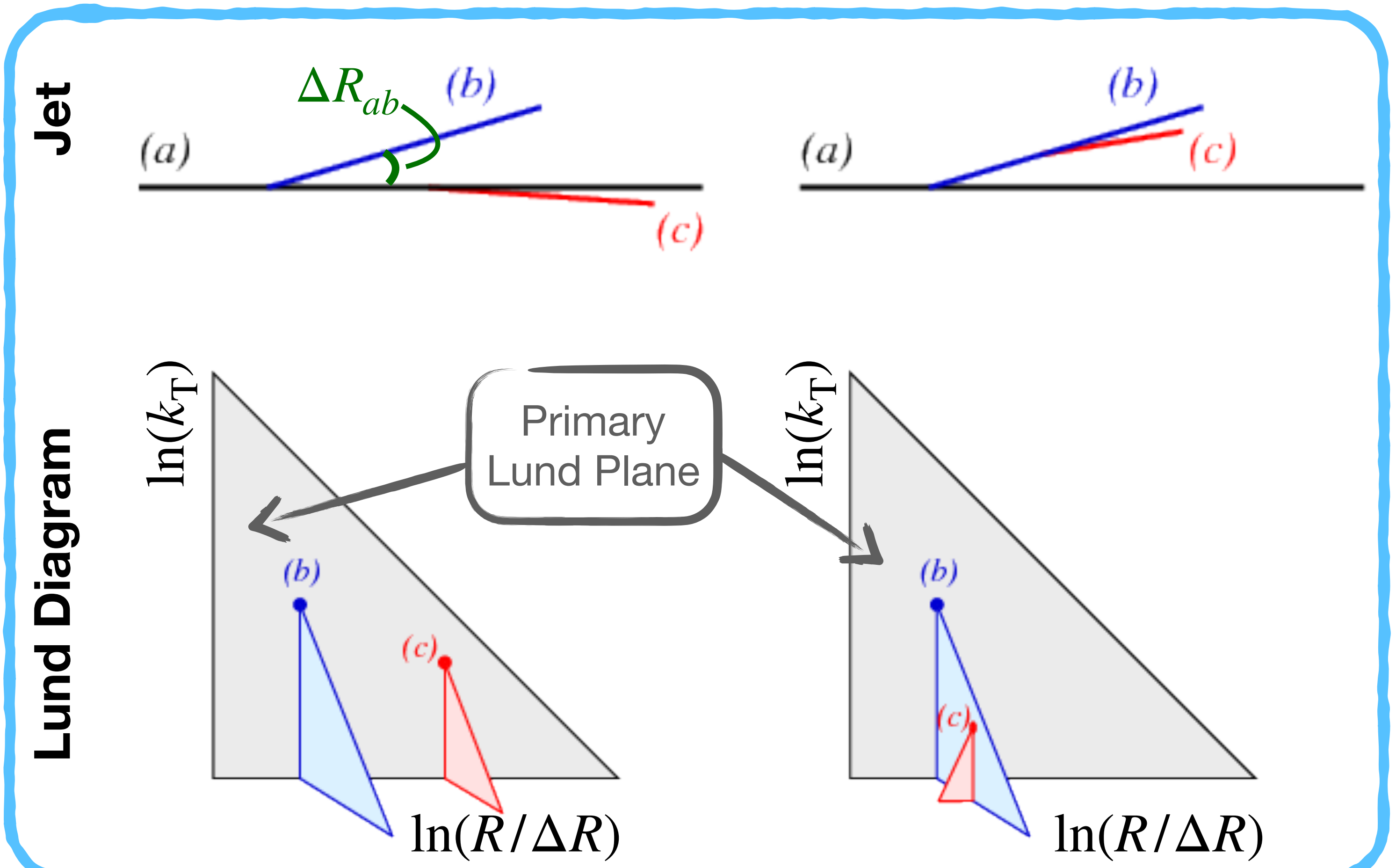

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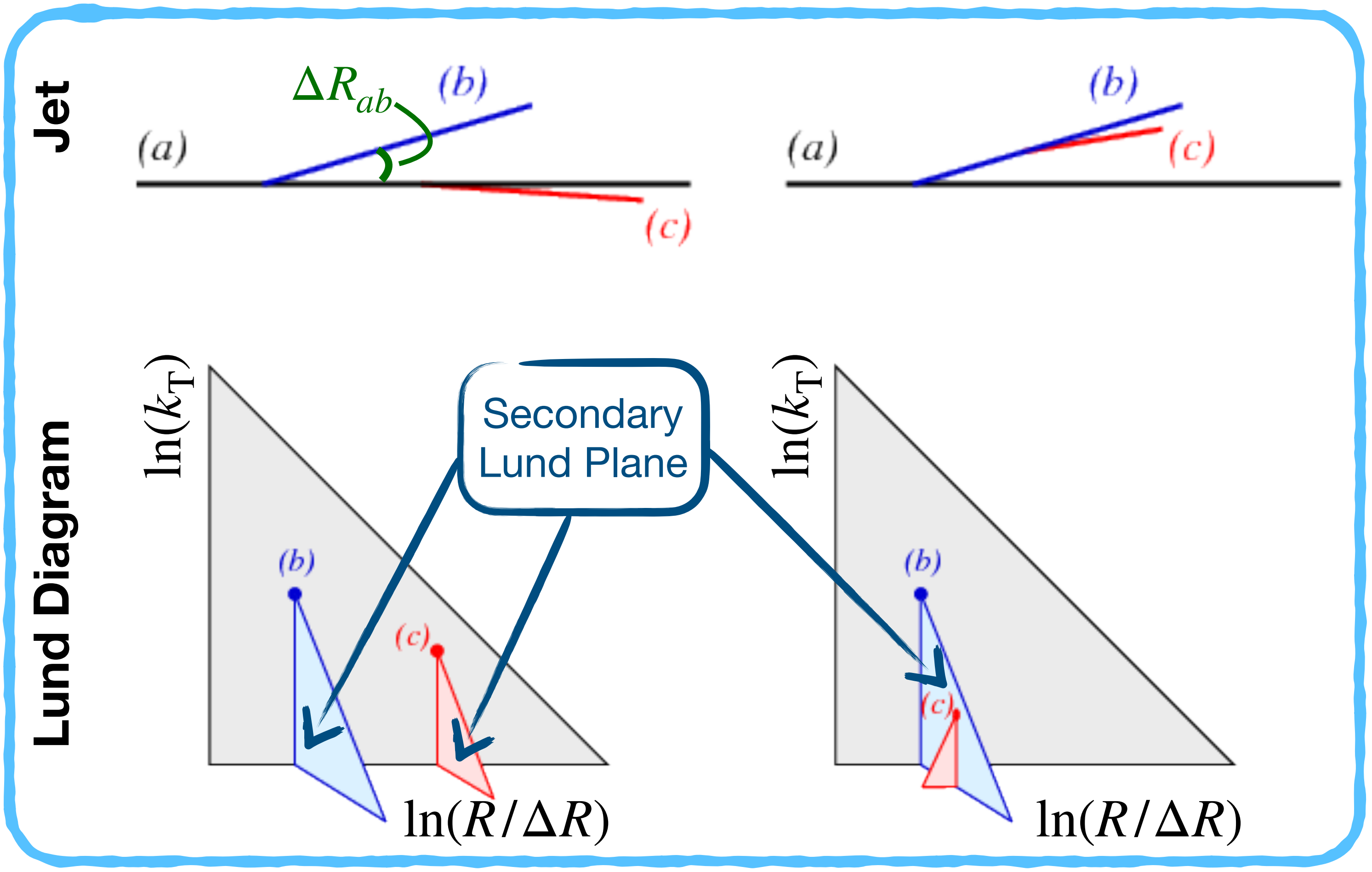

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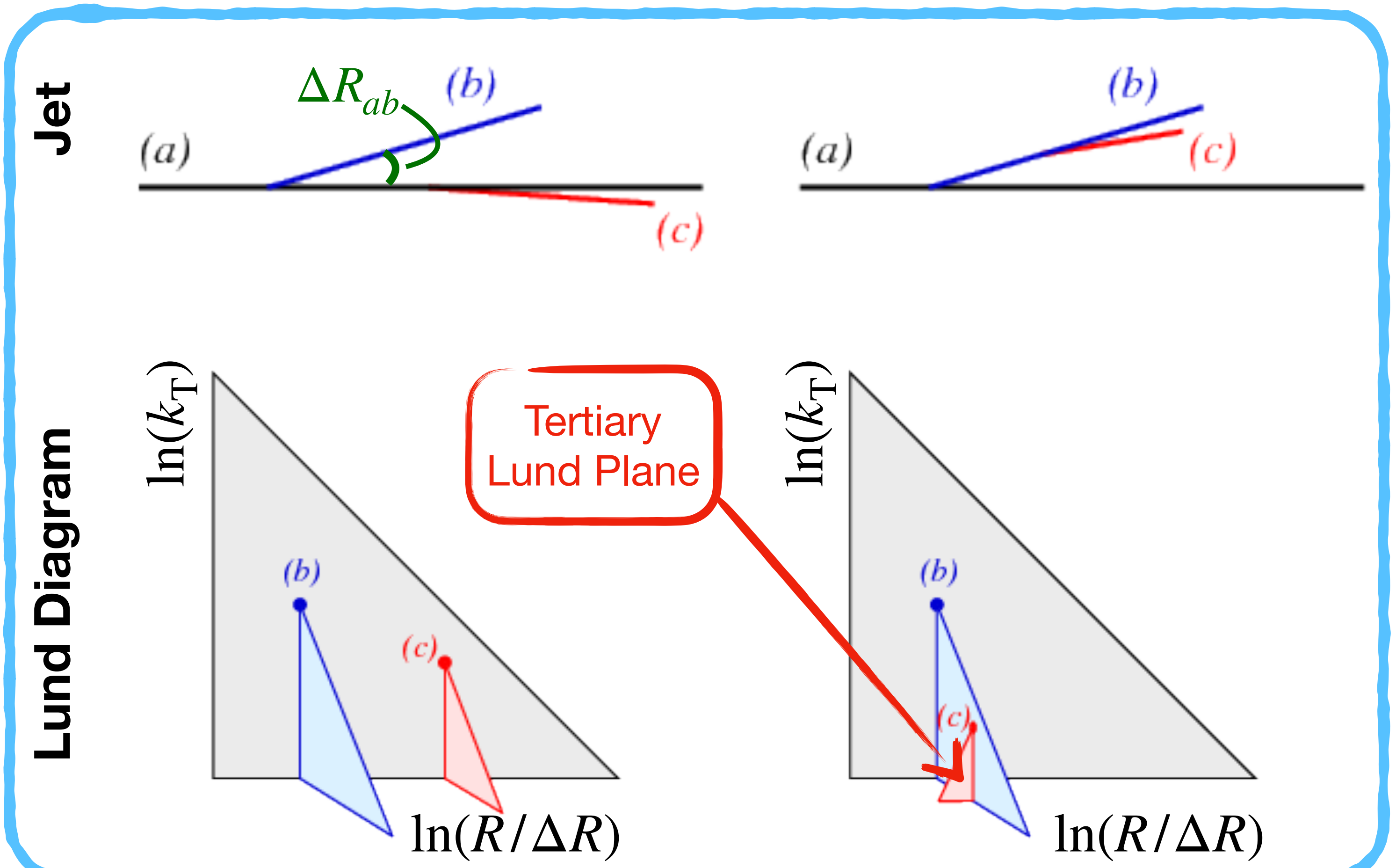

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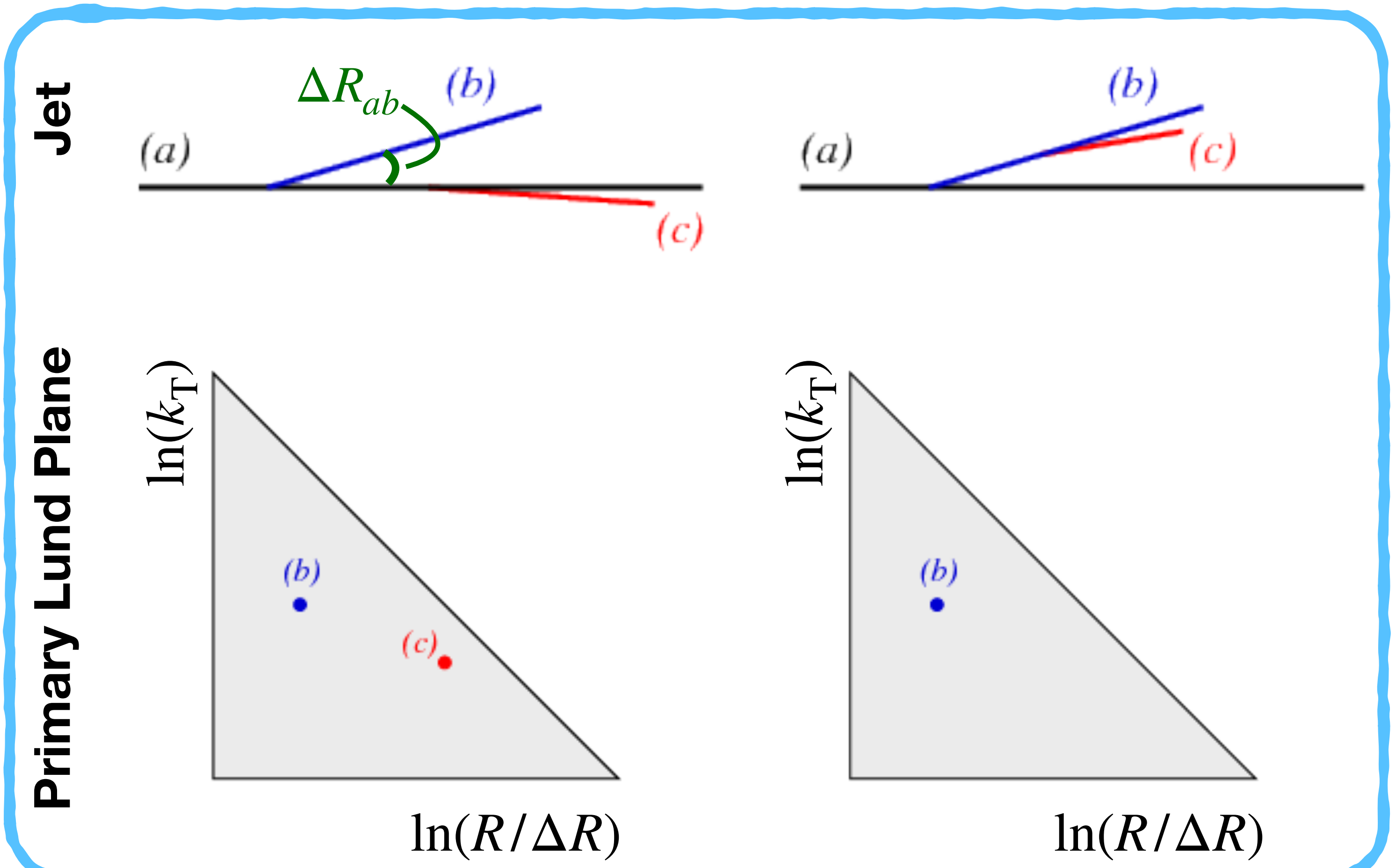

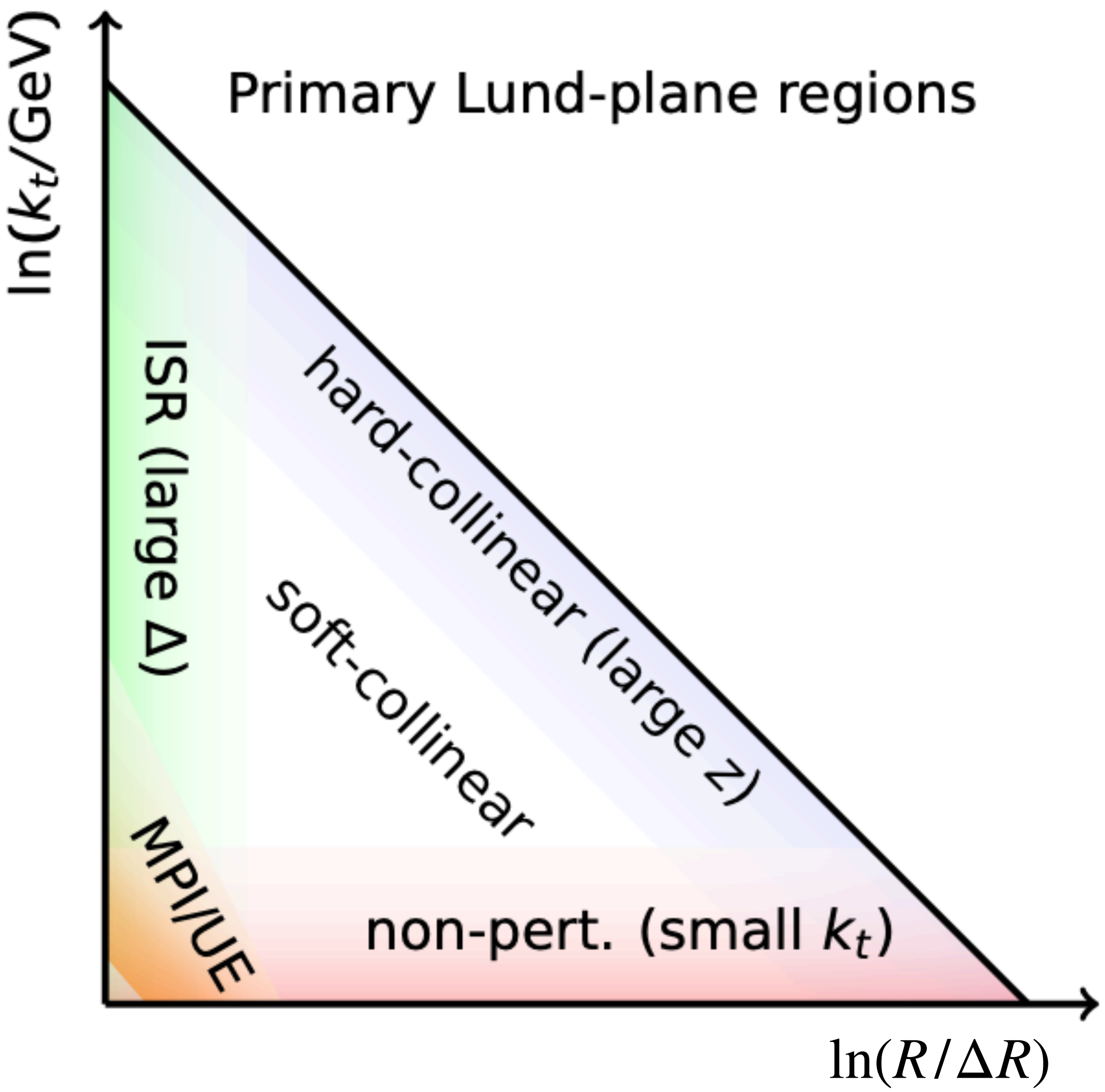

Primary Lund Plane: coordinates from emissions from harder prong

Primary Lund Plane

- Fully-corrected results
- Slight tension with some models

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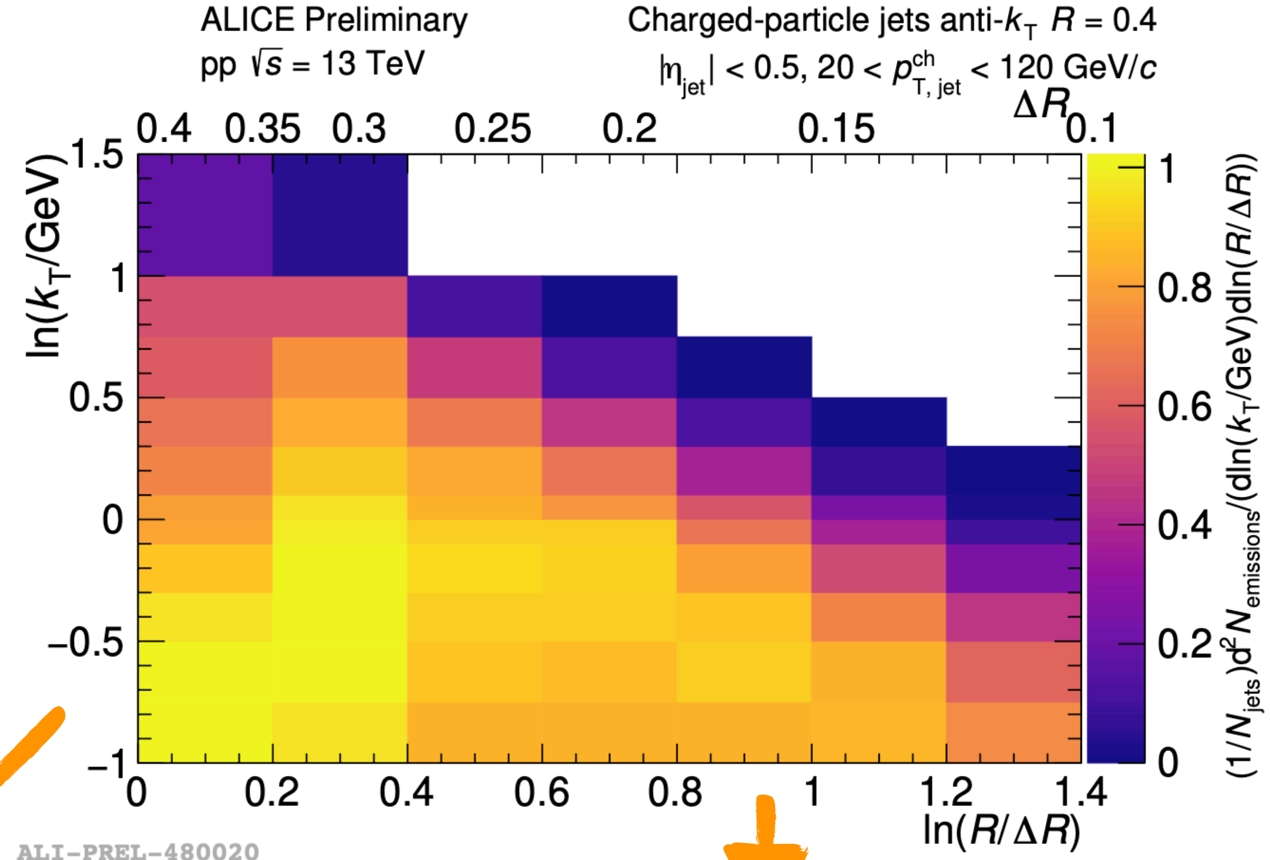

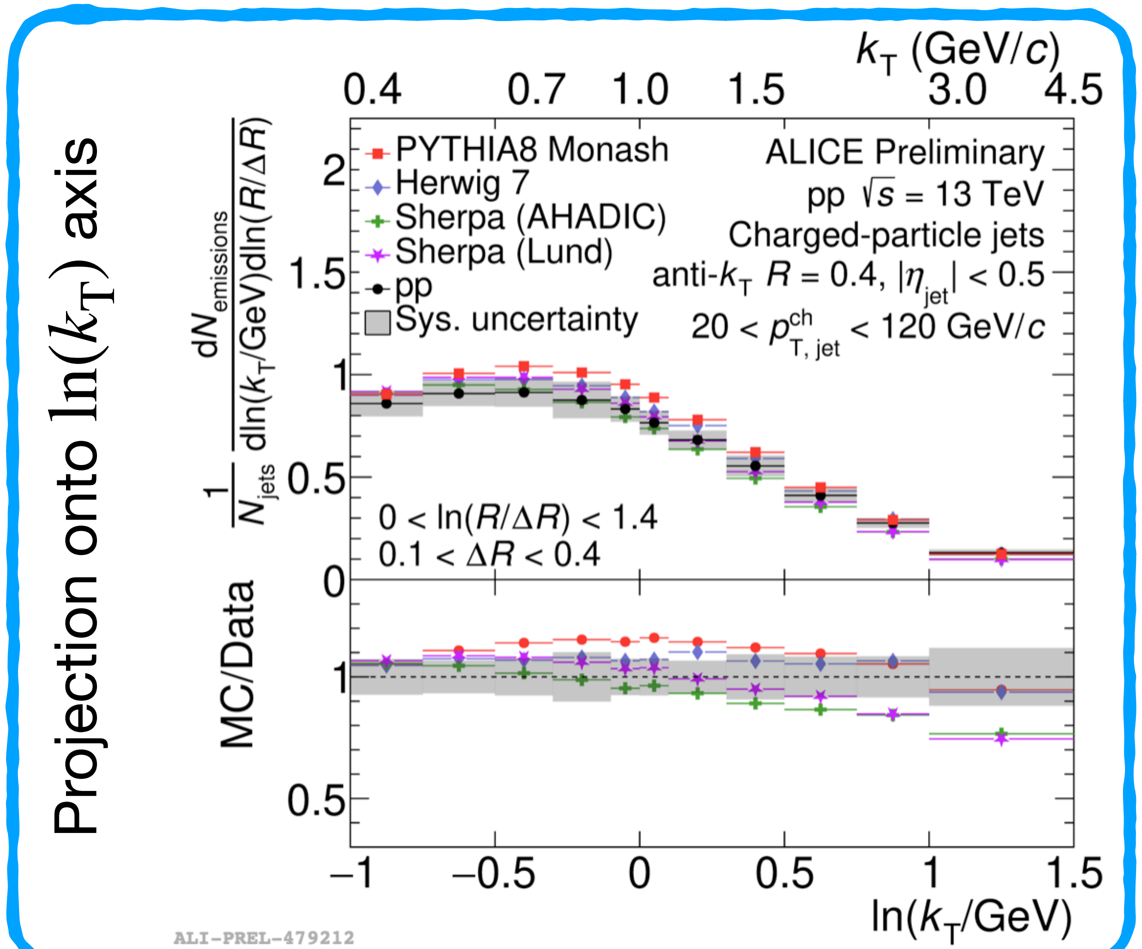

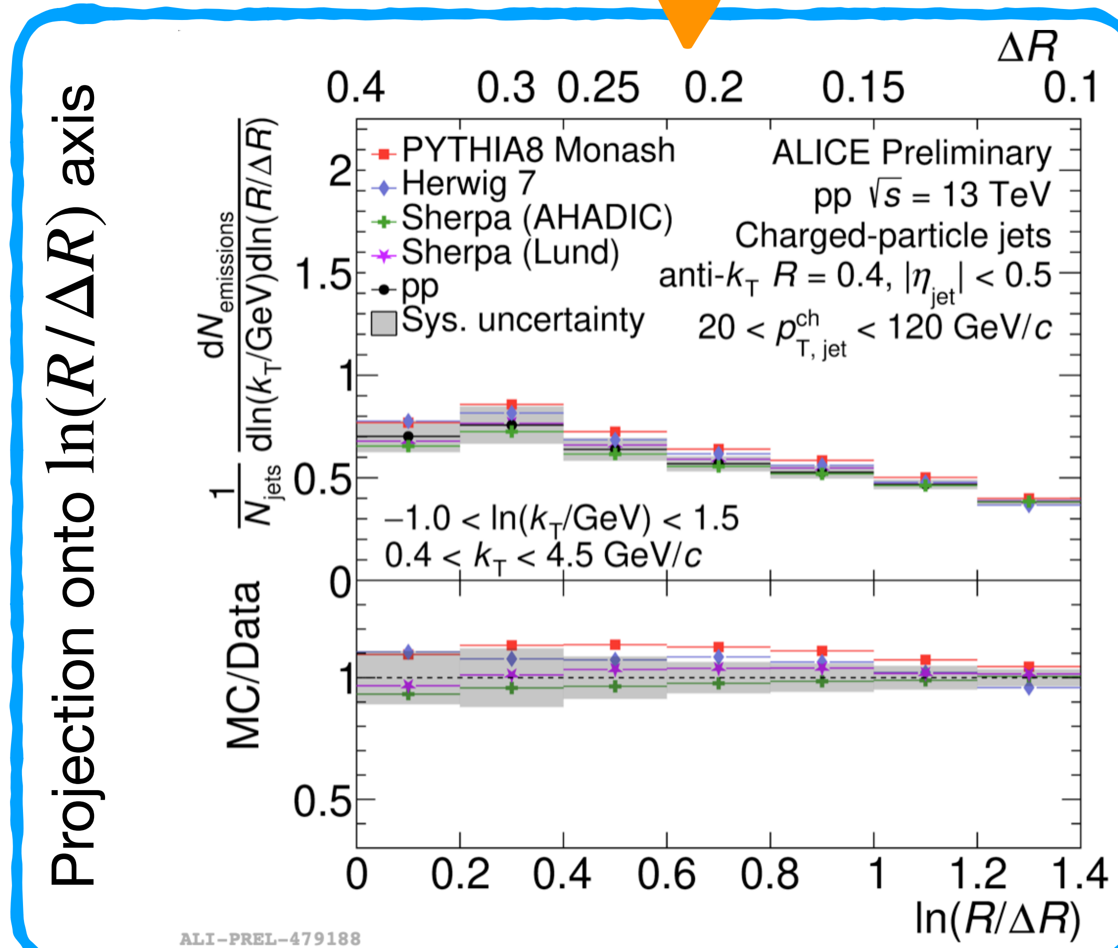

Summary

- Measurements of jet substructure in proton-proton collisions provide new insights into our understanding of QCD and the interplay between perturbative and non-perturbative physics
- Charged jets can be measured with higher precision → ideal for substructure
- A suite of jet-substructure observables is needed to probe the entire phase space of jet formation and evolution.
- ALICE has a broad program measuring jet substructure in pp collisions:
  - Jet-axis differences
  - (un)groomed angularities
  - Primary Lund Plane
  - Many many more not discussed