Yale

ALICE-PUBLIC-2021-002

Primary Lund jet plane density in pp collisions at 13 TeV with ALICE

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(on behalf of the ALICE Collaboration)

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Wright Laboratory

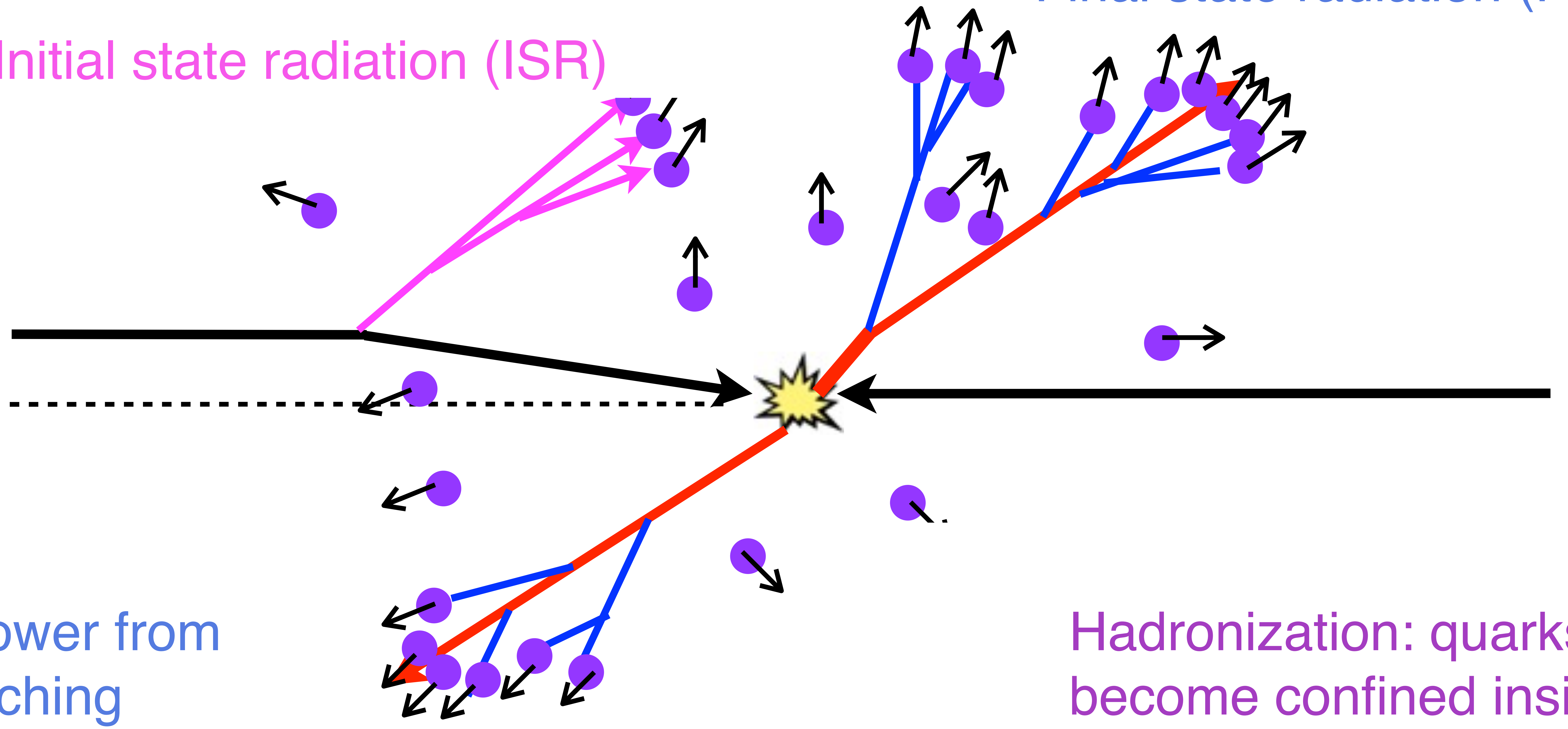
ALICE

ALICE

Jets as a probe of QCD

Final state radiation (FSR)

Initial state radiation (ISR)



Parton shower from
QCD branching

perturbative QCD
(pQCD) ~ln(1/*R*)

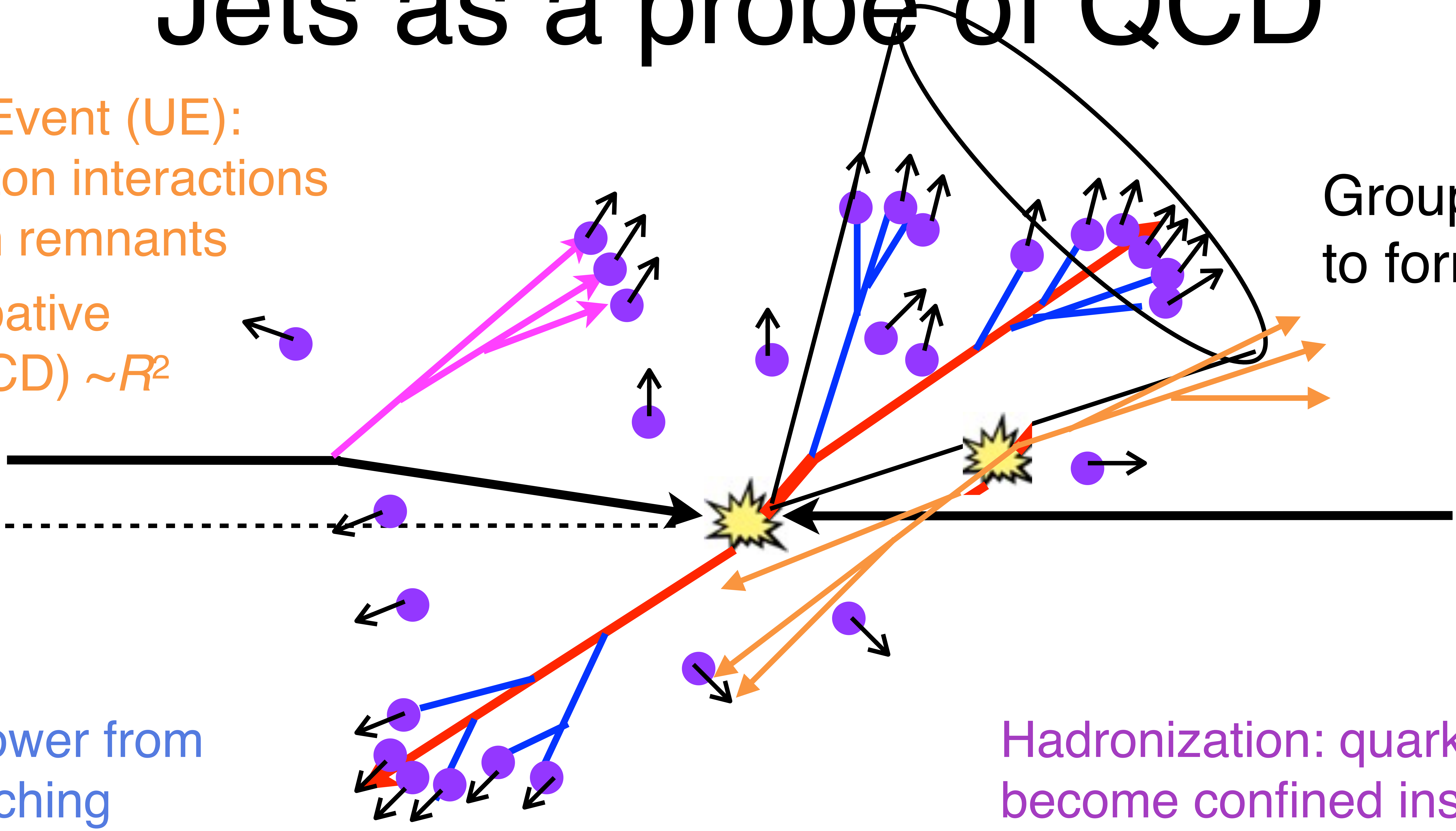
Hadronization: quarks and gluons
become confined inside hadrons

non-perturbative (NP) QCD
(npQCD) ~1/*R*

Jets as a probe of QCD

Underlying Event (UE): multiple parton interactions (MPI), beam remnants

non-perturbative QCD (npQCD) ~R^2



Grouped together to form jets!

Parton shower from QCD branching

perturbative QCD (pQCD) ~ln(1/R)

Hadronization: quarks and gluons become confined inside hadrons

non-perturbative (NP) QCD (npQCD) ~1/R

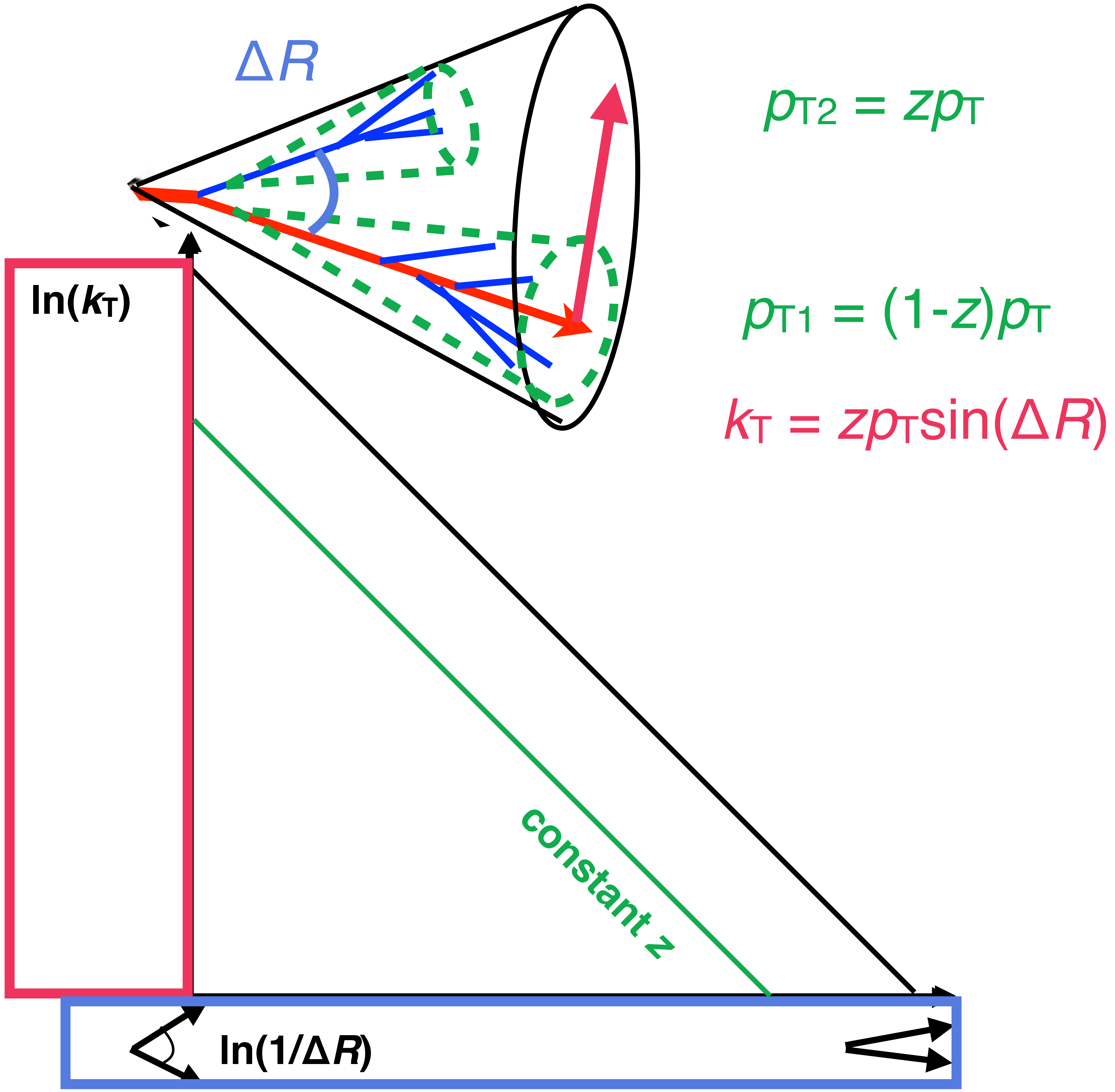
Primary jet Lund plane density

- Lund Diagram: phase space of jet splitting

Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)

- k_T: relative transverse momentum of subjets

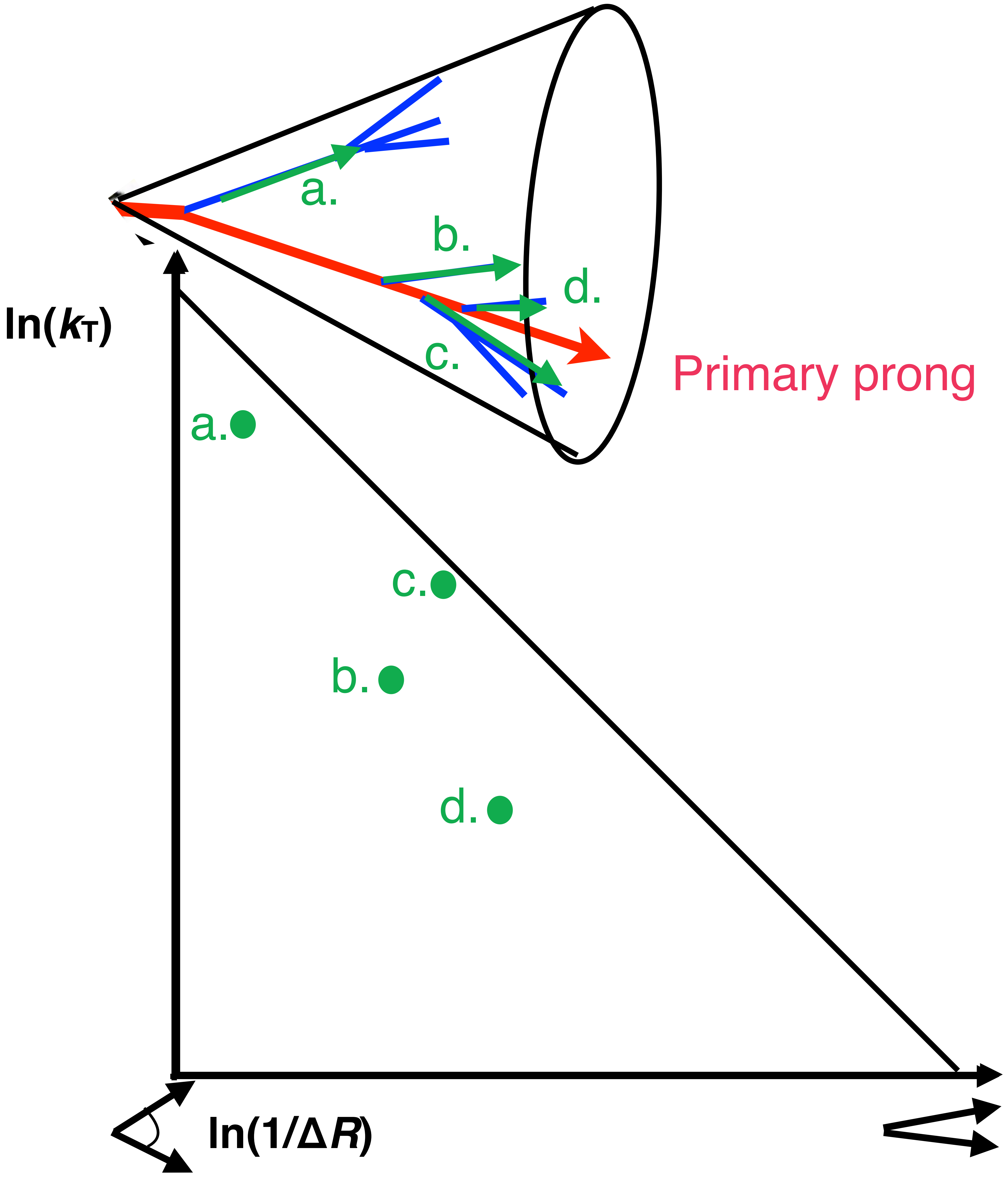
- ΔR: opening angle between subjets



Primary jet Lund plane density

- Primary Lund jet plane is filled with splittings from the hardest prong

Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)



Primary jet Lund plane density

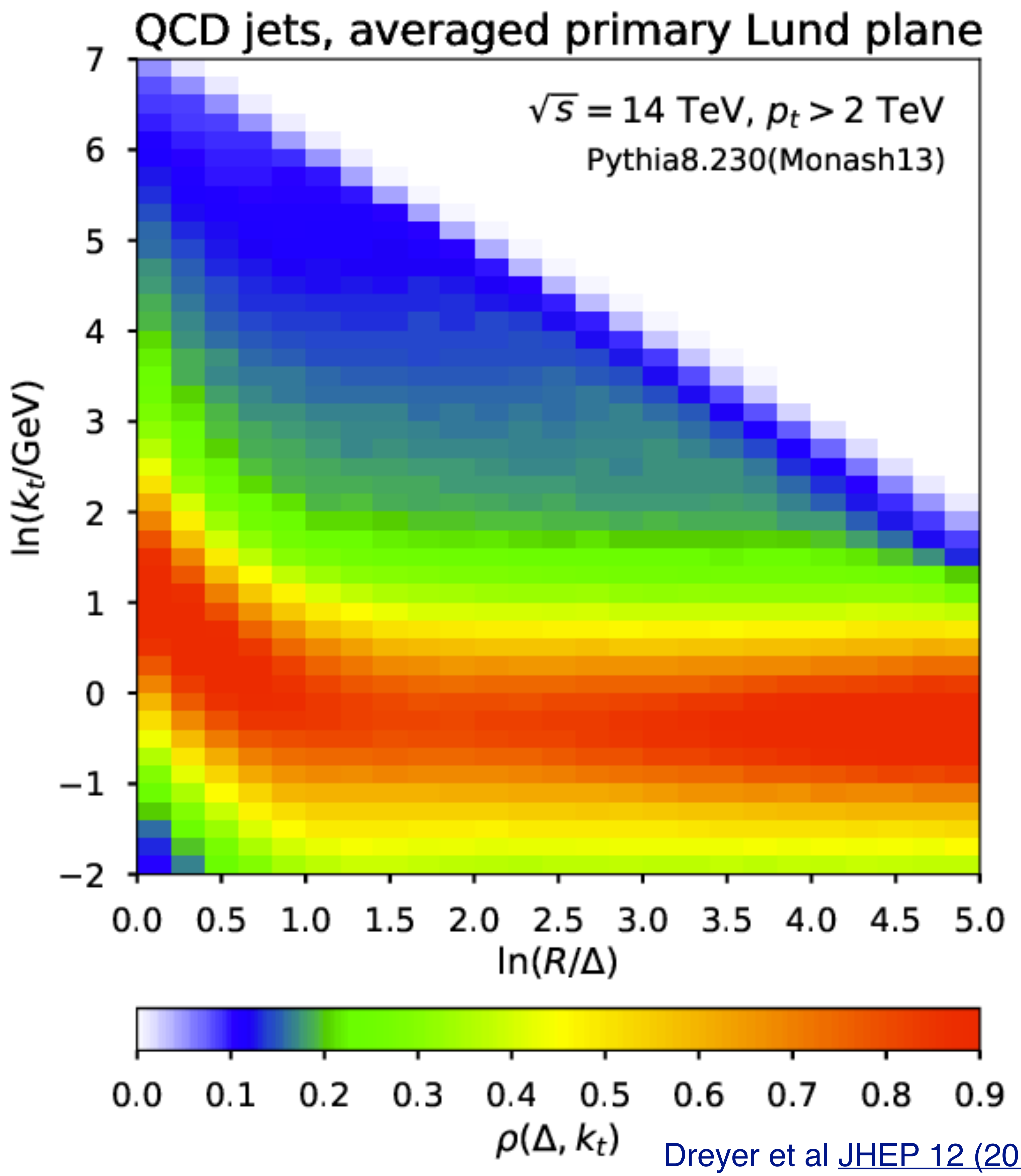
- Primary Lund jet plane is filled with splittings from the hardest prong

Andersson et al ZPC43 (1989)

- At leading order the emissions populate the plane uniformly

- Running of the coupling constant sculpts the plane!

$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi} d\ln(z\theta) d\ln(\frac{1}{\theta})$$



Dreyer et al JHEP 12 (2018)

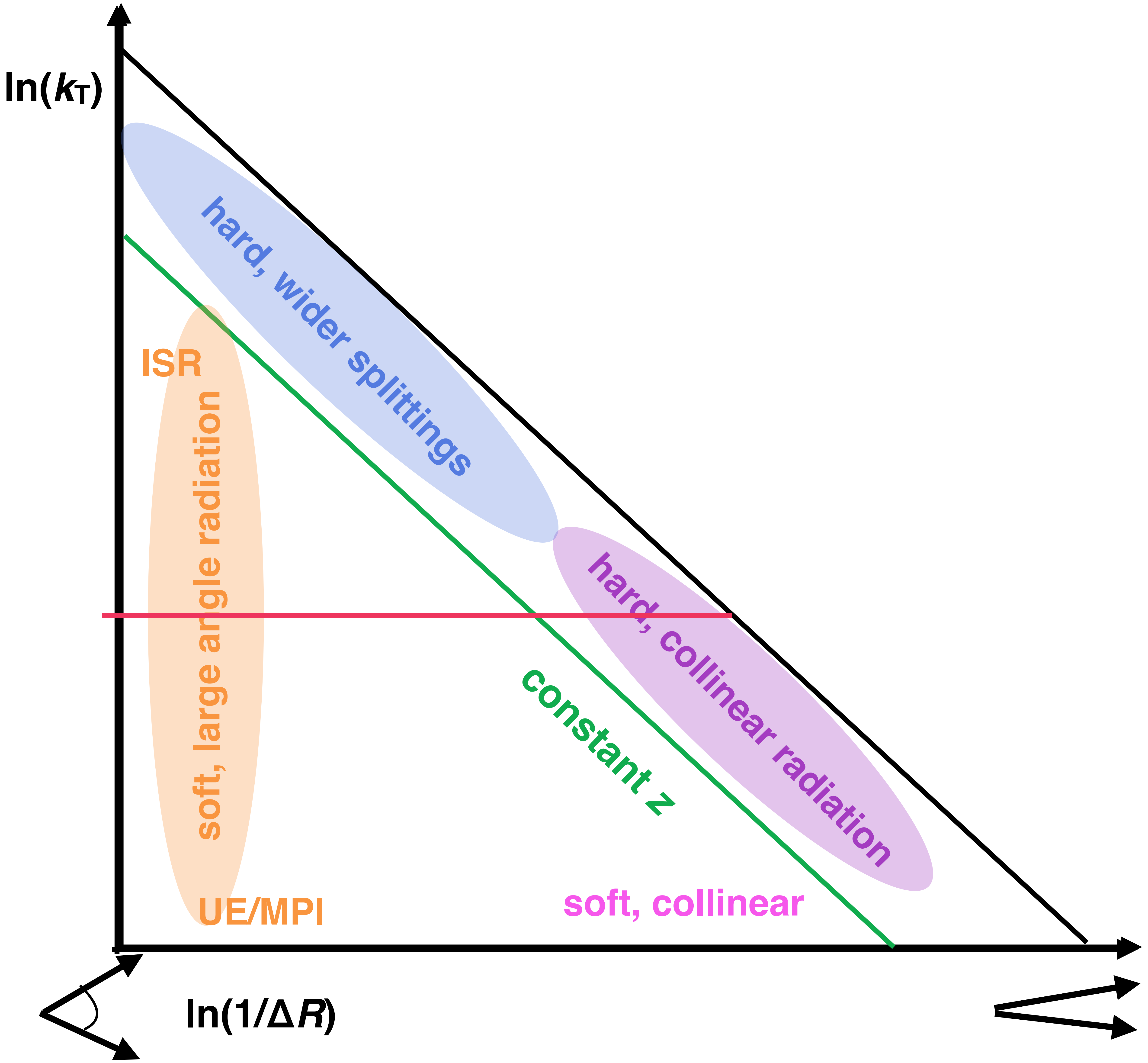
Exploring the phase space of QCD

- Lund diagram can be used to isolate regions of QCD phase space

*Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)

- $\log(k_T) > 0$ separates perturbative from non-perturbative regime

- Isolate different QCD effects like ISR, UE, MPI, hadronization, perturbative vs. non-perturbative emissions, etc. and tune MC models

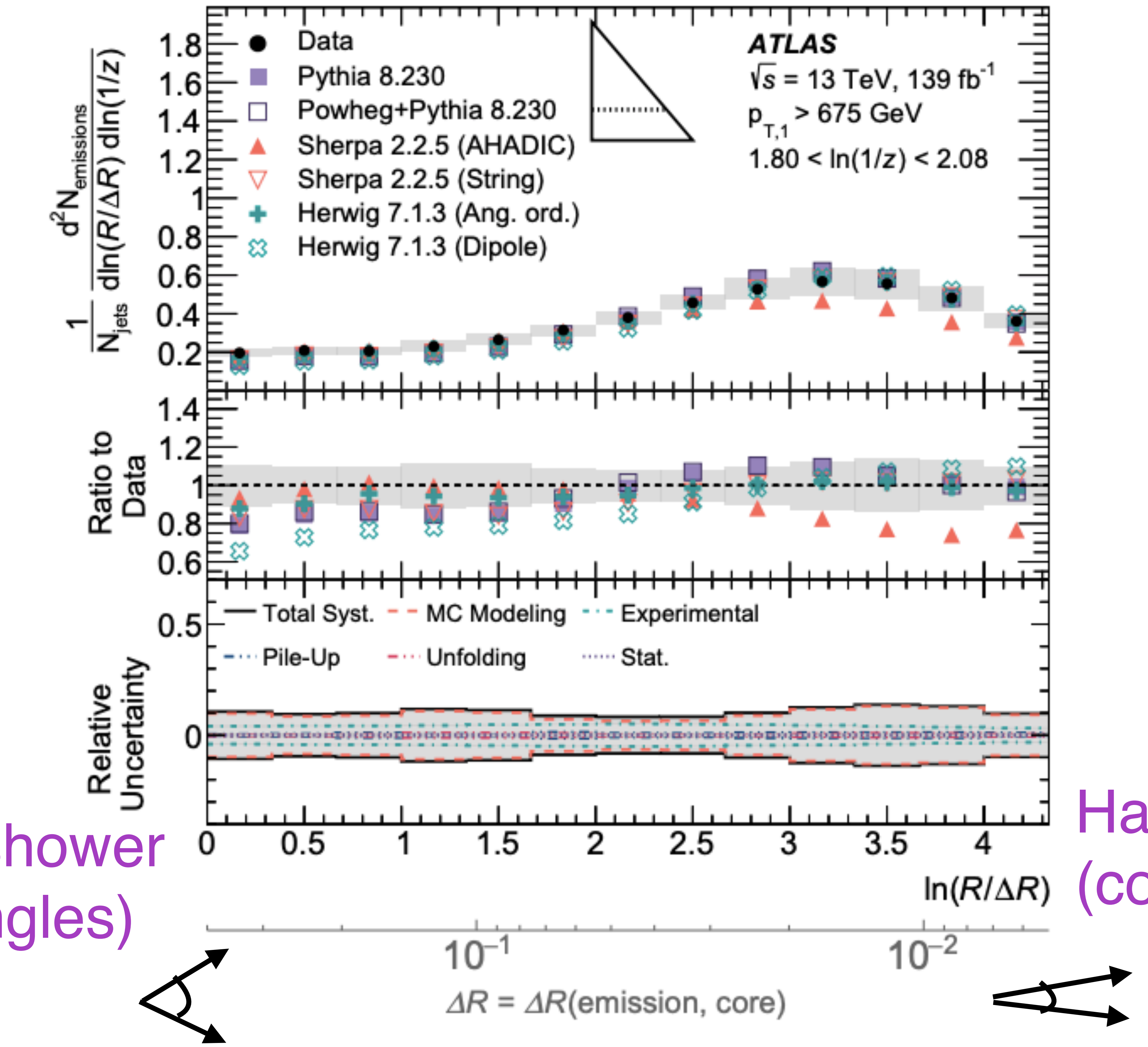


arXiv:1808.03689

Lund plane: high p_T

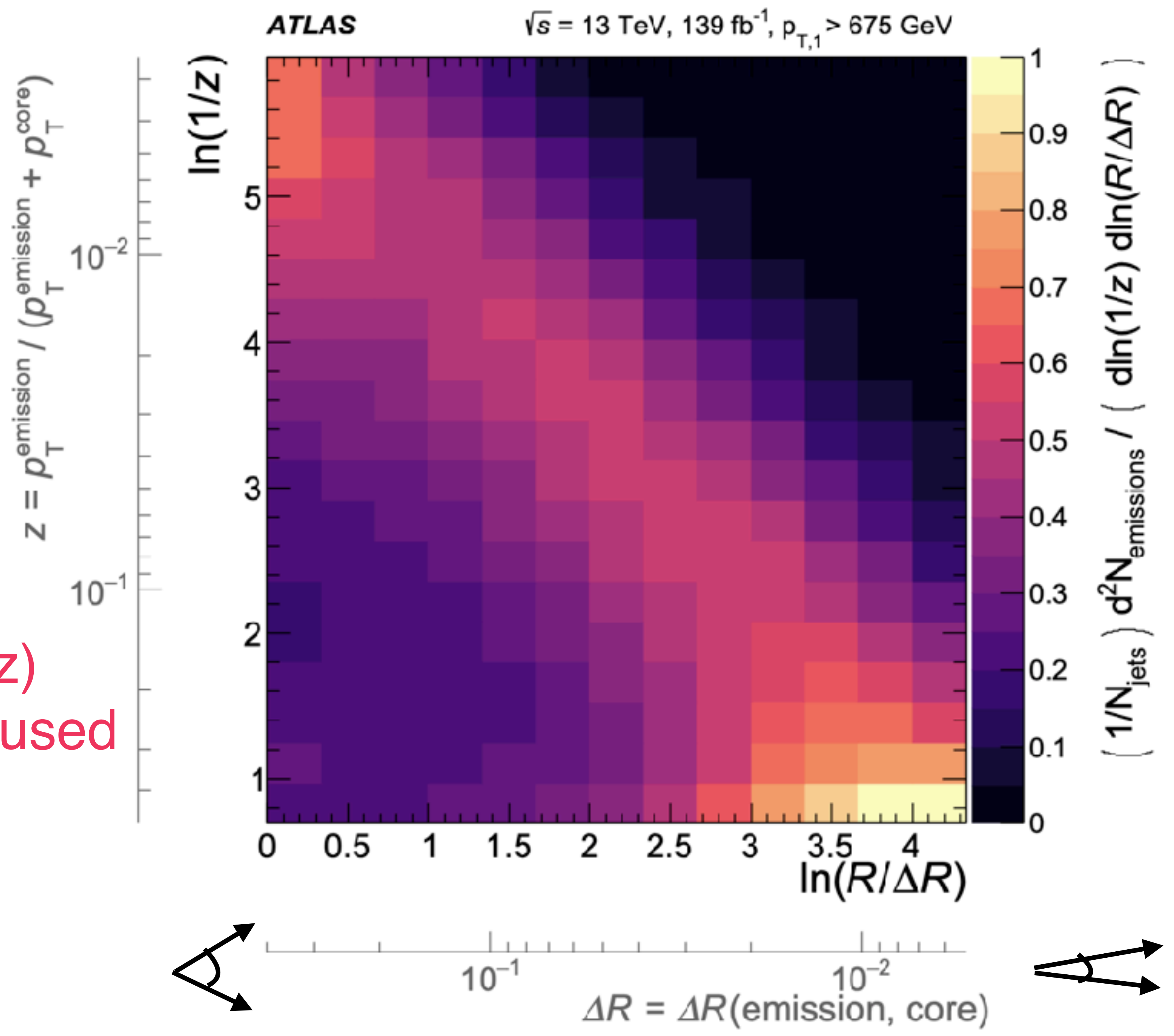
[ATLAS PRL 124 (2020) 222002](#)

- ATLAS Lund plane density fully corrected to particle level for $p_T > 675$ GeV using 3D unfolding in jet p_T and axes of Lund plane



Parton shower (wide angles)

Hadronization (collinear)

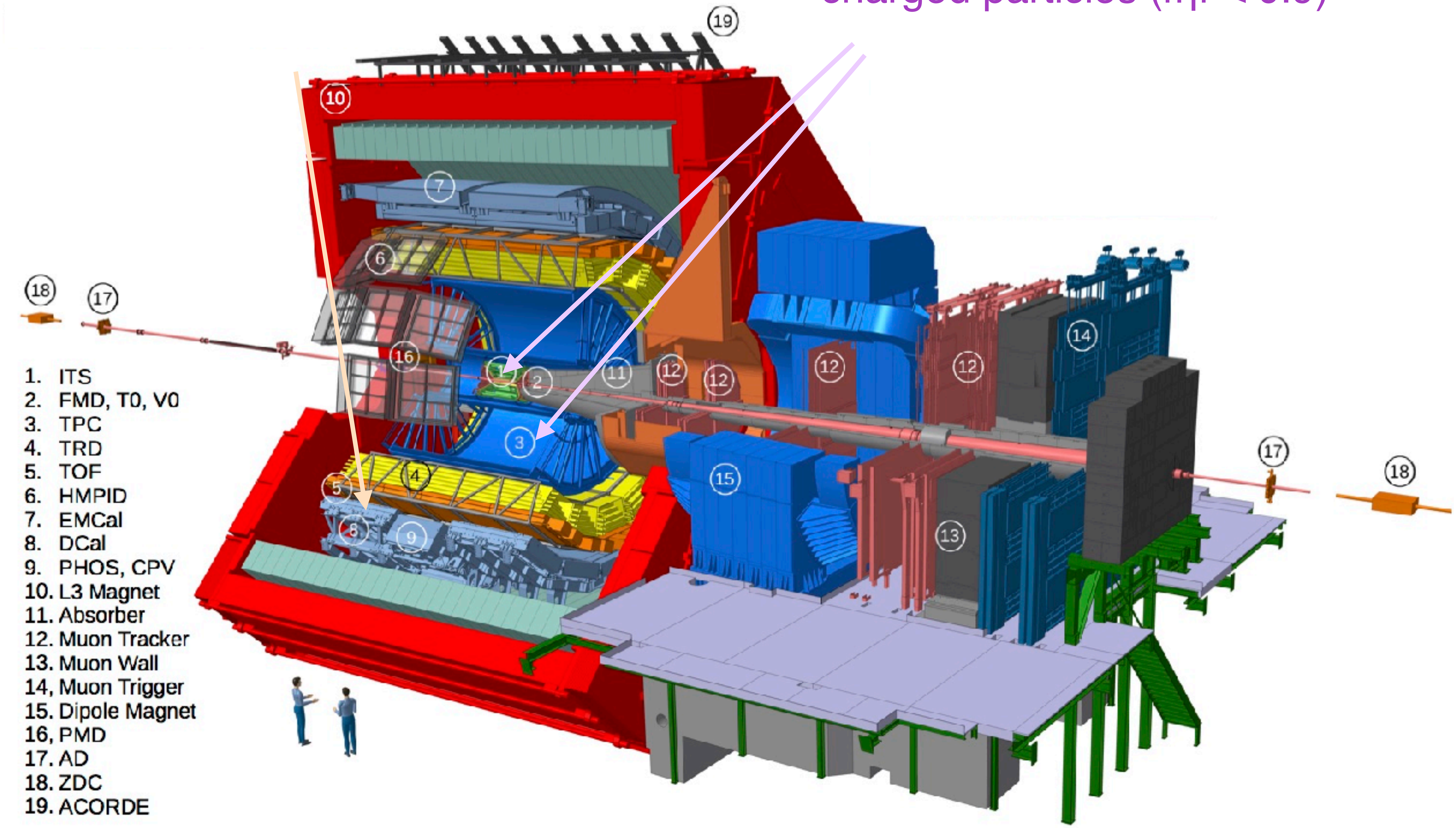


ln(1/z) axis used

- Projections in regions of the Lund plane isolate regions of QCD phase space to compare to generators

ALICE detector

Time Projection Chamber (TPC) and Inner Tracking System (ITS) measures charged particles ($|\eta| < 0.9$)

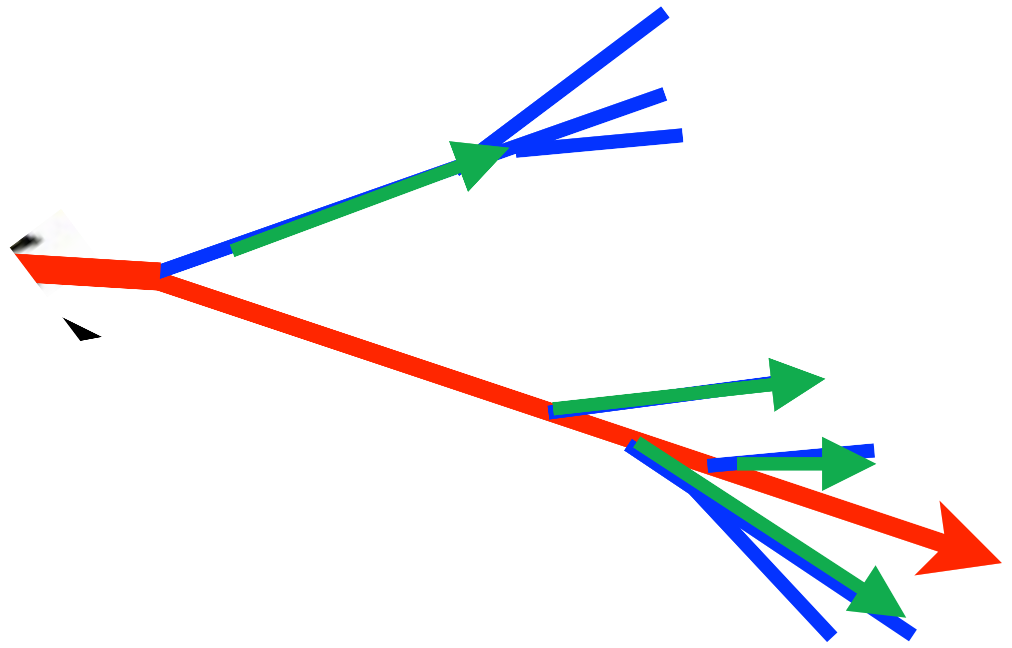


Charged particle jets from tracks contain only the charged component of the jet

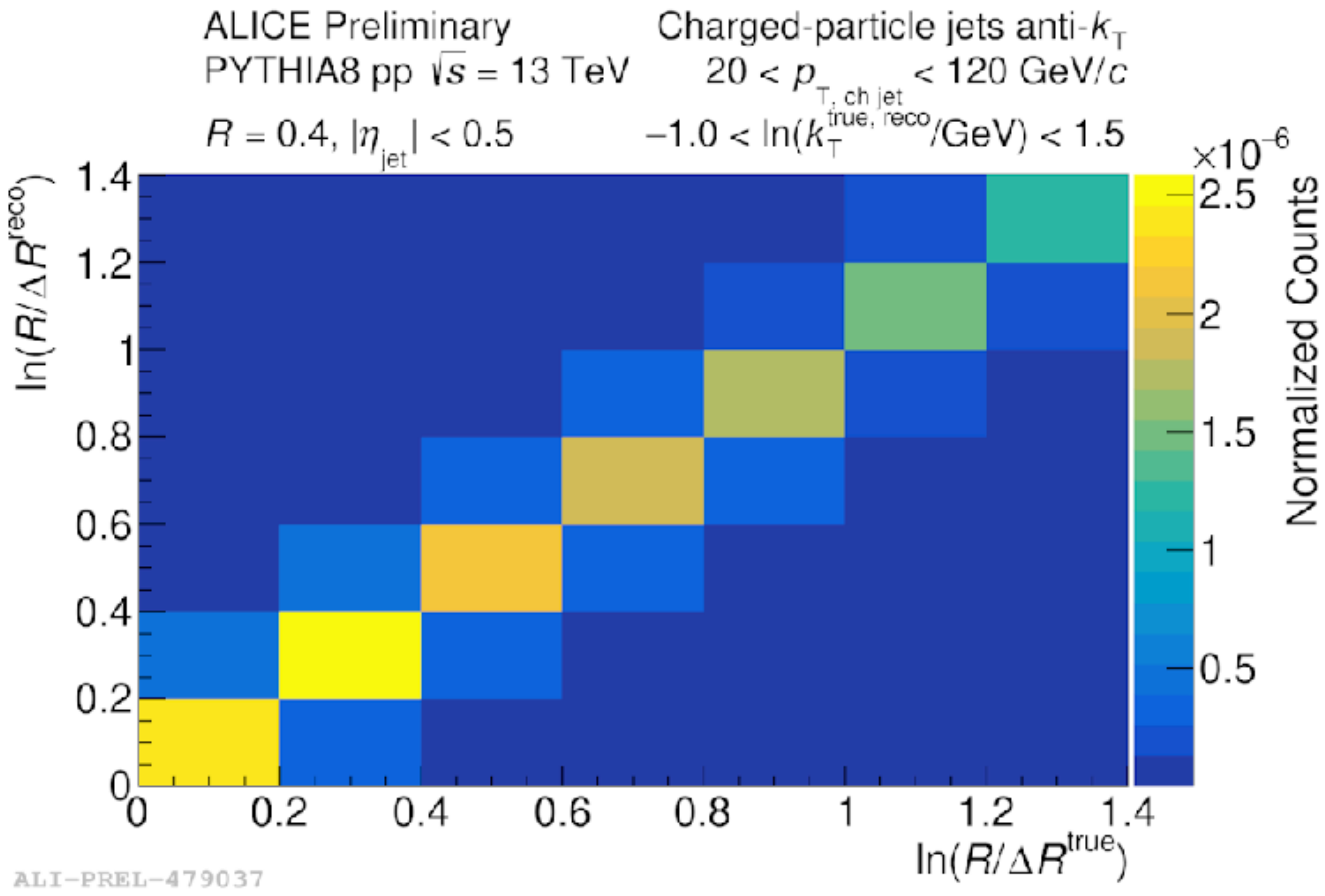
High precision tracking allows for jet substructure measurements at lower values of jet p_T than ATLAS measurement

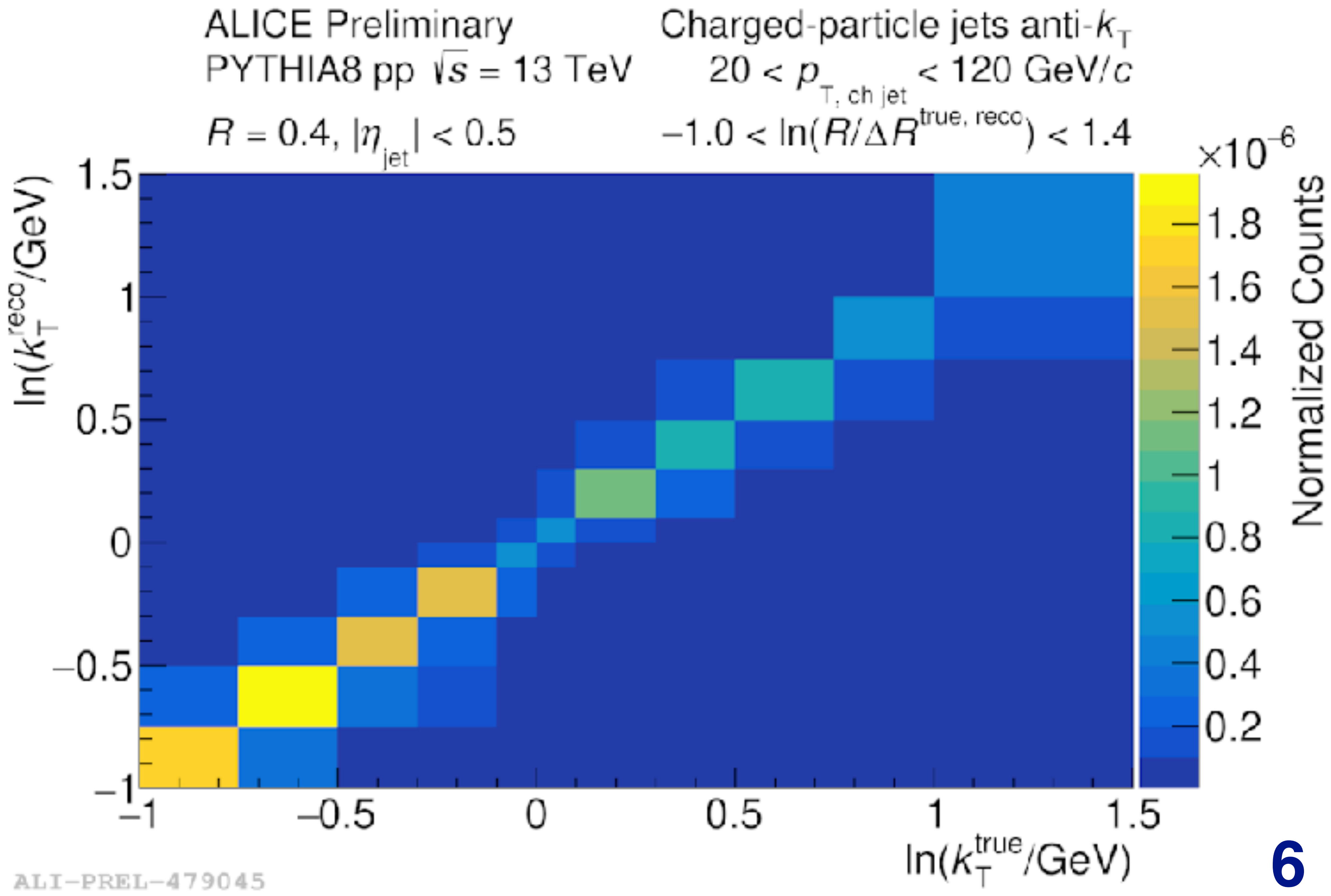
Lund plane: mid p_T

- Measurement of the primary Lund plane density at intermediate p_T (~20-120 GeV/c) with ALICE 13 TeV pp data
  - NP effects (hadronization, UE) play a dominant role
- Recluster anti-k_T $R = 0.4$ jets with C/A algorithm and follow splittings from the leading prong



- Fully correct with 3D unfolding in p_T, ln(k_T), ln(R/ΔR)
  - Response: match individual splittings between truth (PYTHIA8 pp jets) and reconstructed level (detector simulation)





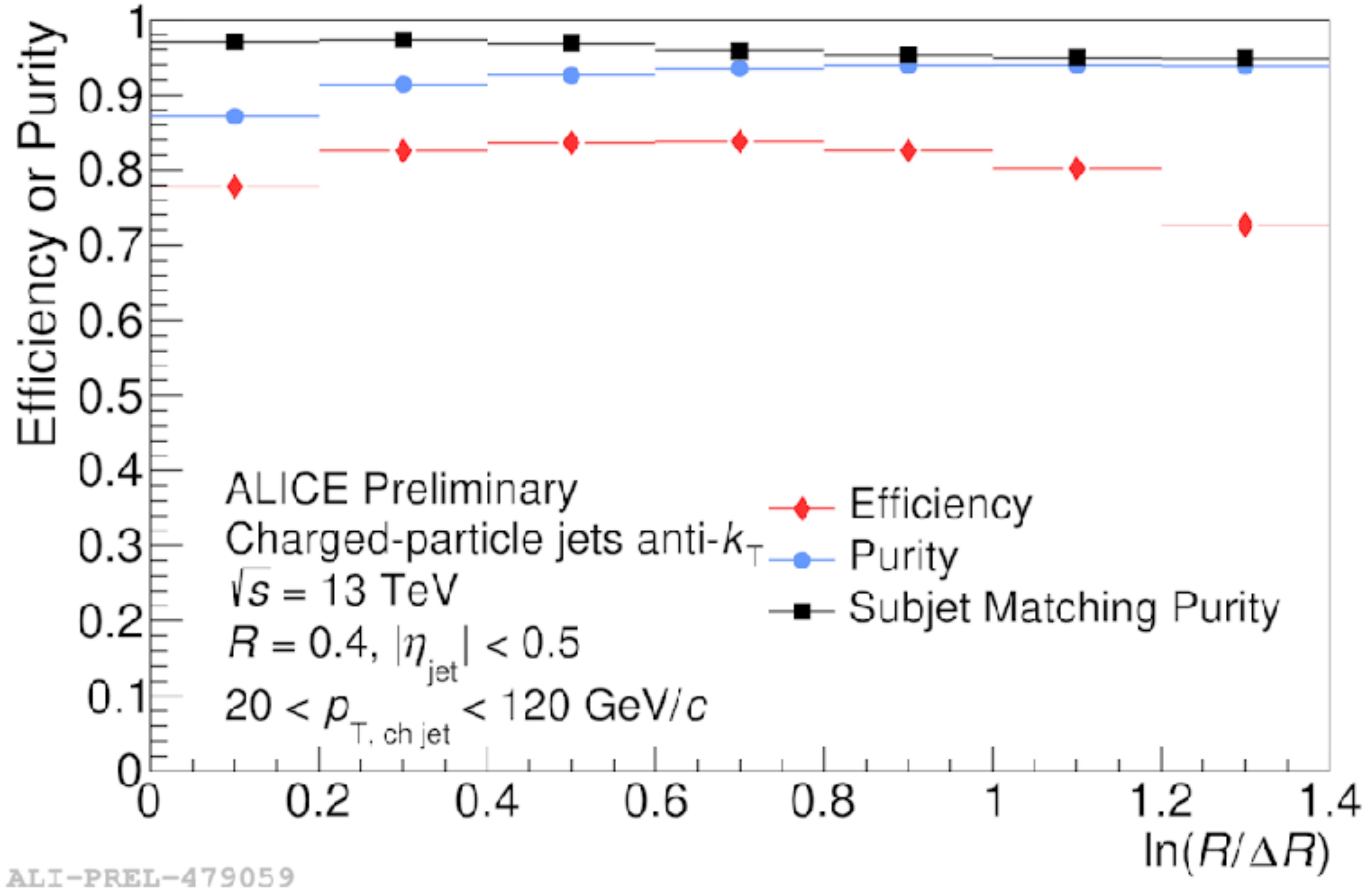
Analysis procedure

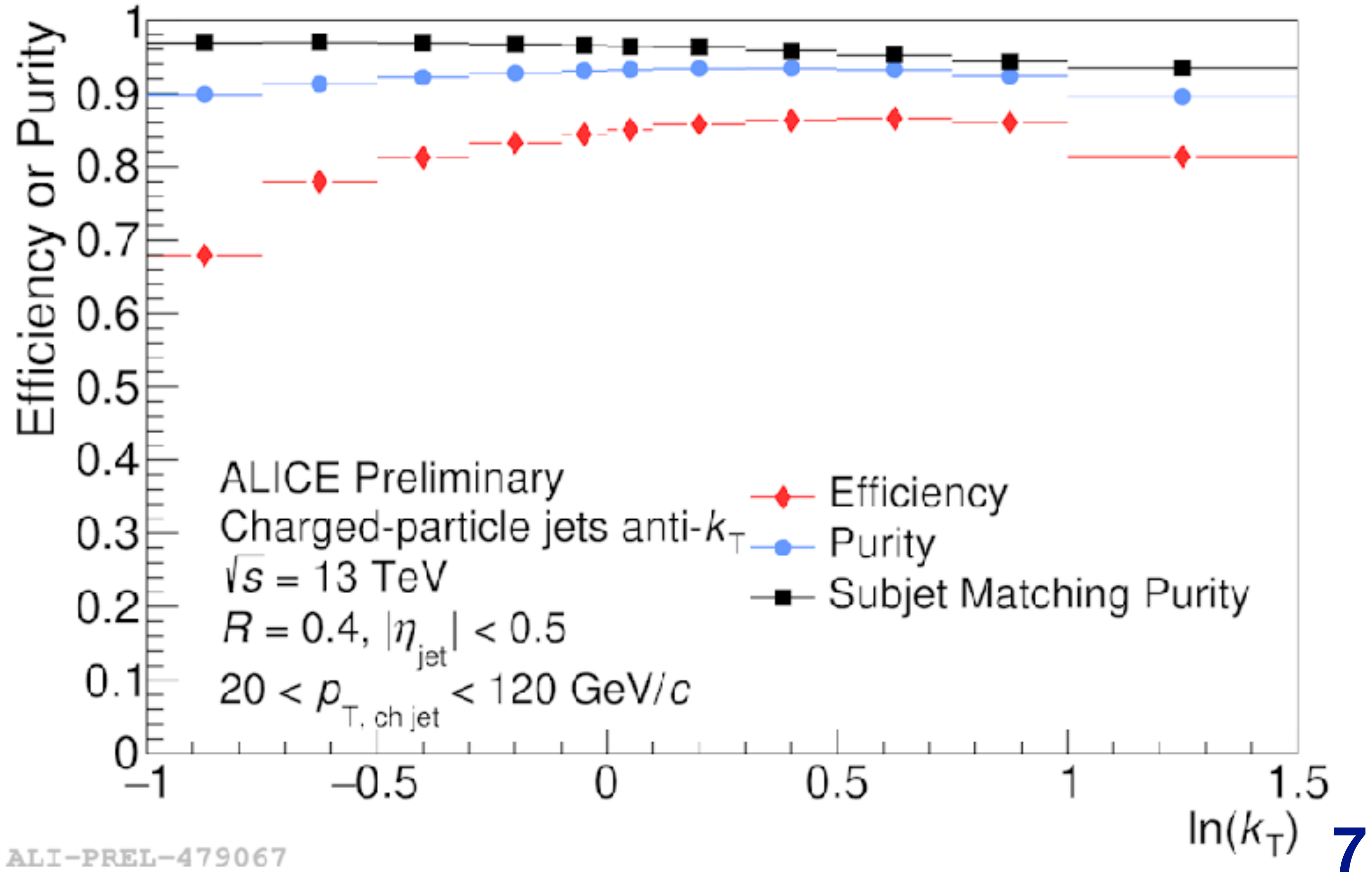
- Calculate the efficiency and purity:

$$e = \frac{N_{\text{true}}^{\text{match}}}{N_{\text{true}}} \qquad p = \frac{N_{\text{reco}}^{\text{match}}}{N_{\text{reco}}}$$

- Correct the raw data for the purity $N_{\text{raw,corr}} = p * N_{\text{raw}}$
- Unfold using response and correct unfolded result for the efficiency $N_{\text{tot}} = (1/e) * N_{\text{unf}}$
- Normalize with 1D unfolded spectra
- Subjet matching purity: did the true splittings end up in the correct reconstructed splittings?

Subjet matching purity is very high!



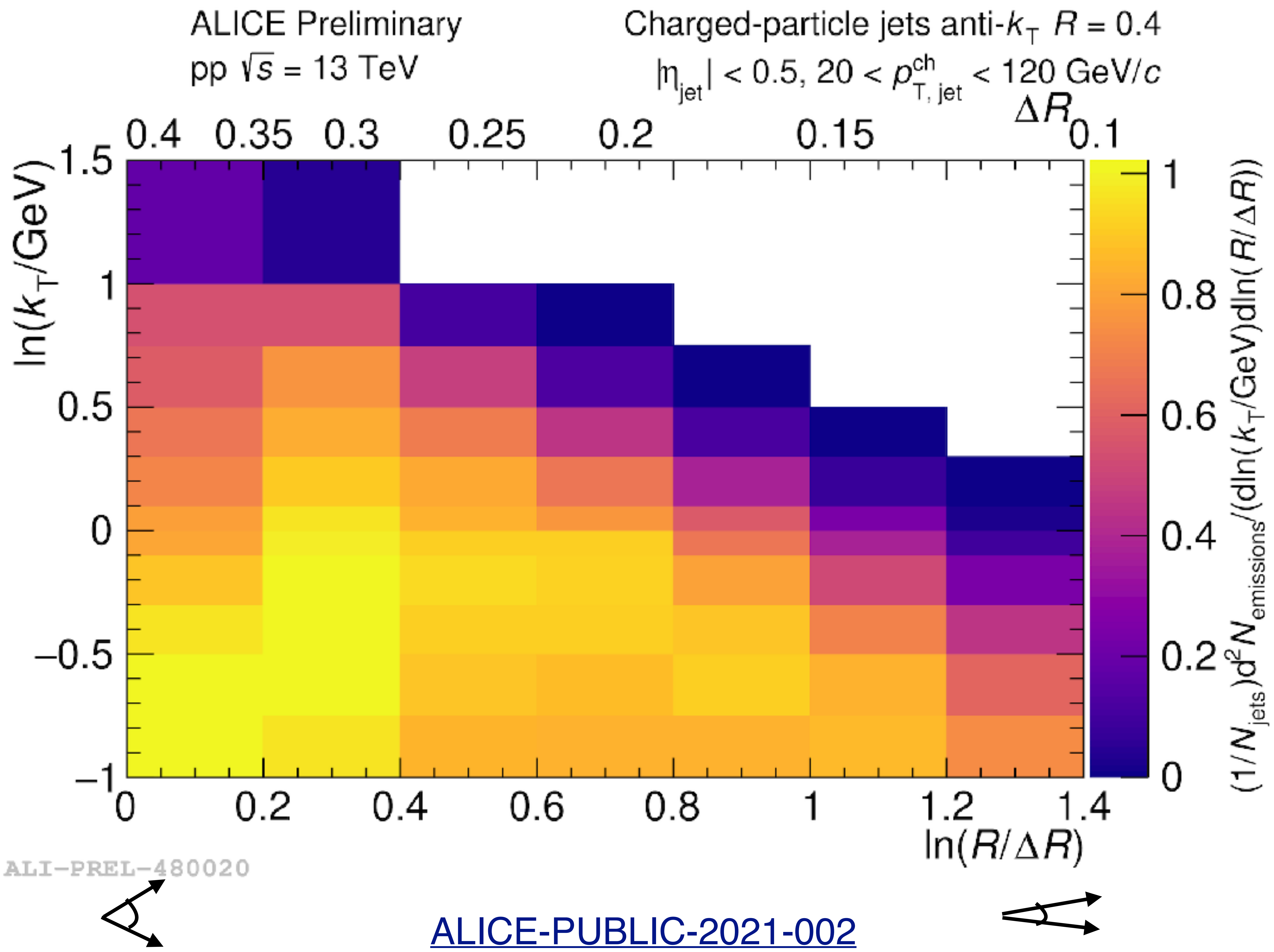


Unfolded Lund plane density

Fully corrected Lund plane in pp collisions for charged-particle jets between 20–120 GeV/*c*

k_T reach out to 5 GeV/*c*

Make projections to isolate regions of phase space and make detailed comparisons to generators



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MC generator comparisons

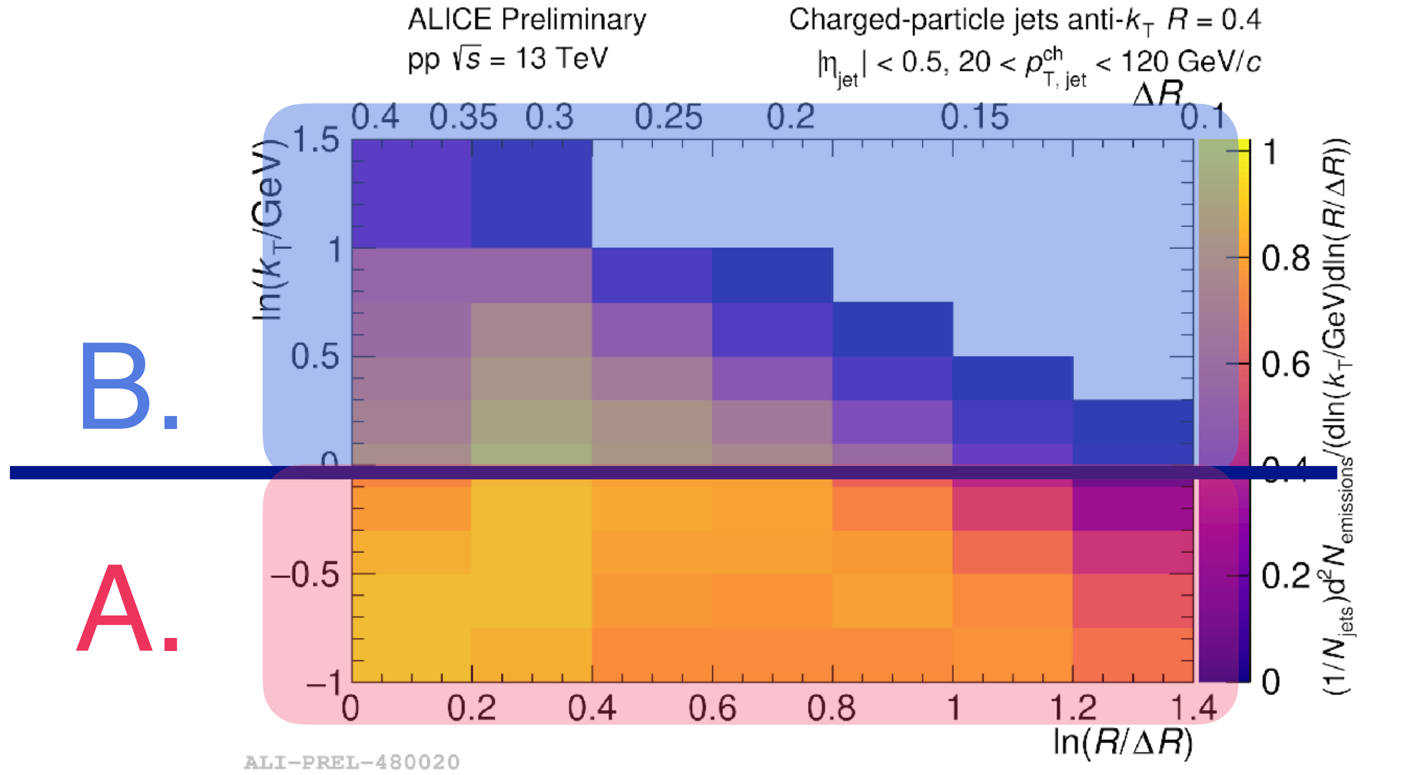
- Different MC generators have different implementations of the parton shower and hadronization

	Parton Shower	Hadronization	
PYTHIA8 Monash	k_T ordered	Lund string	*CPC* 178 (2008) 852-867
Herwig 7	Angular ordered	Cluster	*EPJC* 76 (2016) 4, 196
Sherpa (AHADIC)	Dipole shower	Cluster	*JHEP* 02 (2009) 007
Sherpa (Lund)	Dipole shower	Lund string	

- Dominant systematic is model dependence: unfold with response built from Herwig

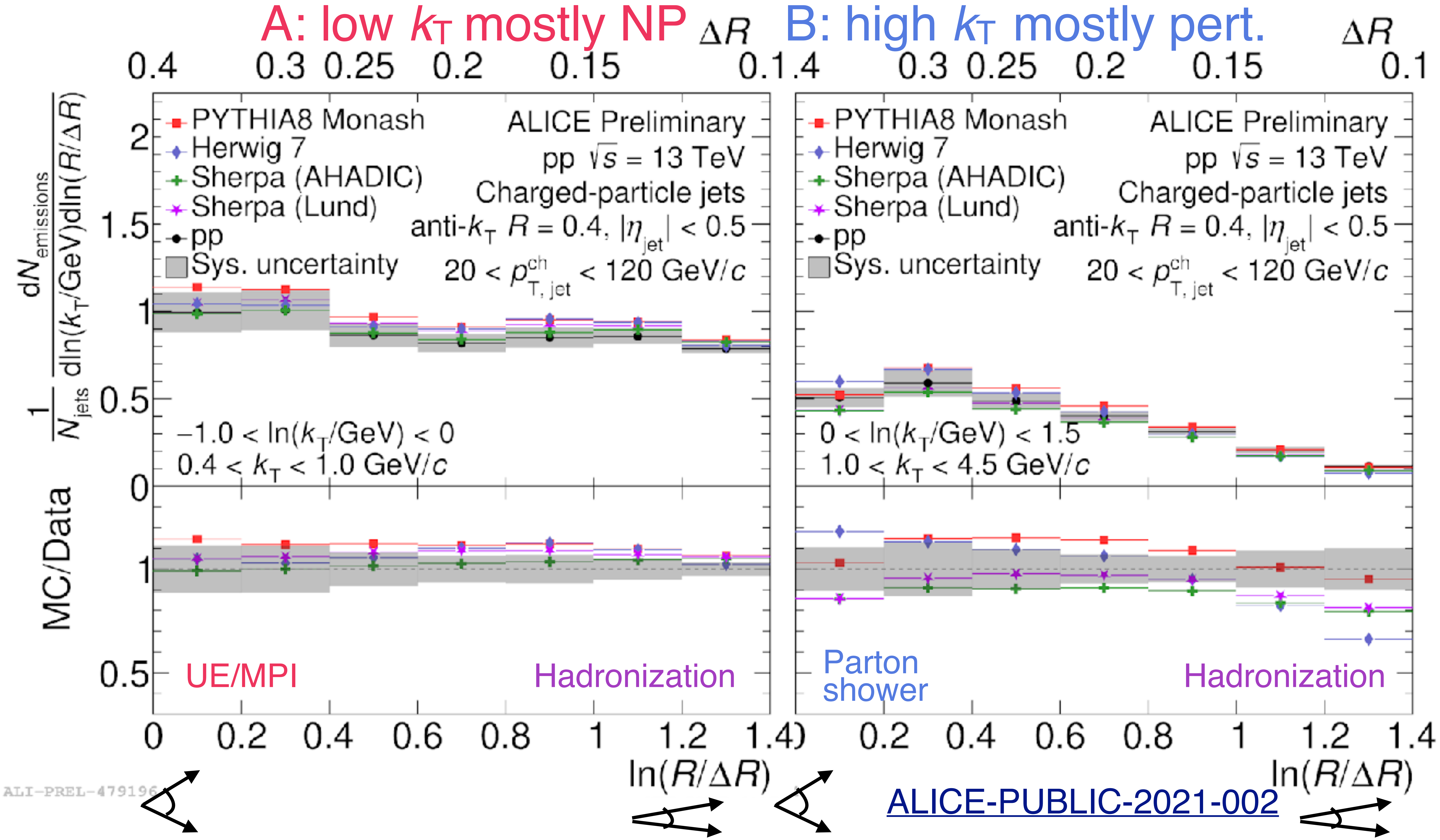
Regions of the Lund plane

Project onto angular axis to separate pert. vs. NP splittings



Agreement with MC ~10% in most cases

Herwig suppressed relative to data for hard collinear splitting



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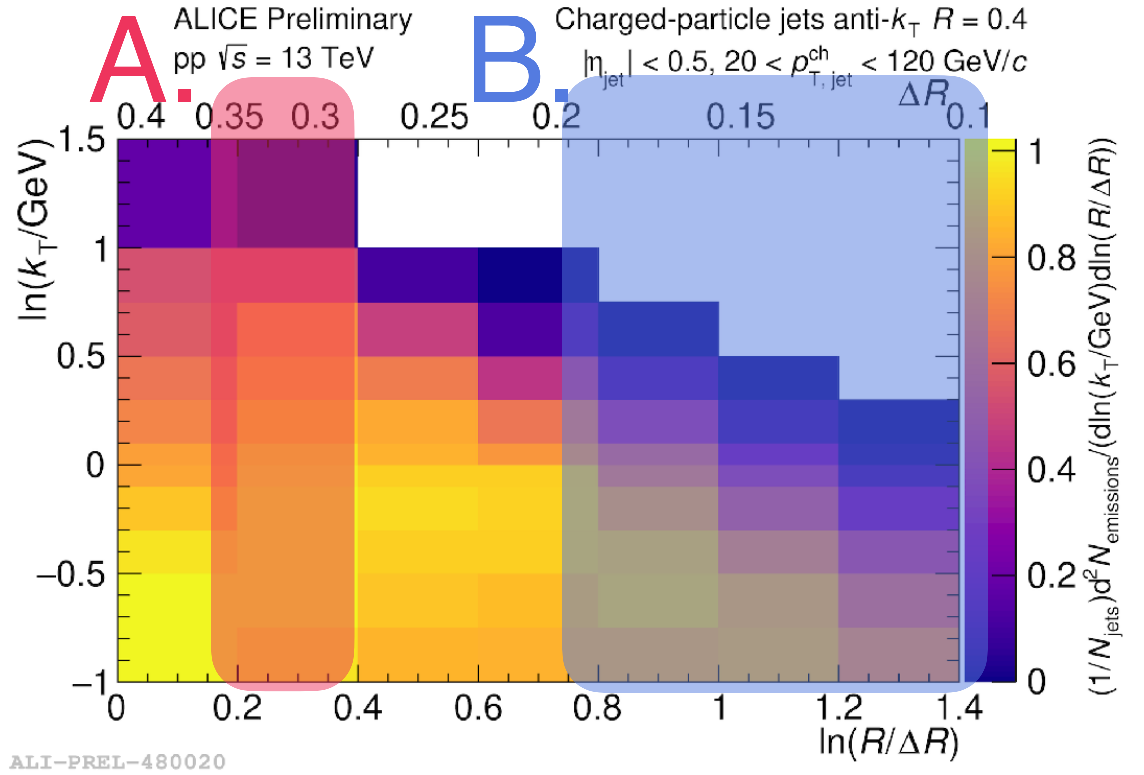
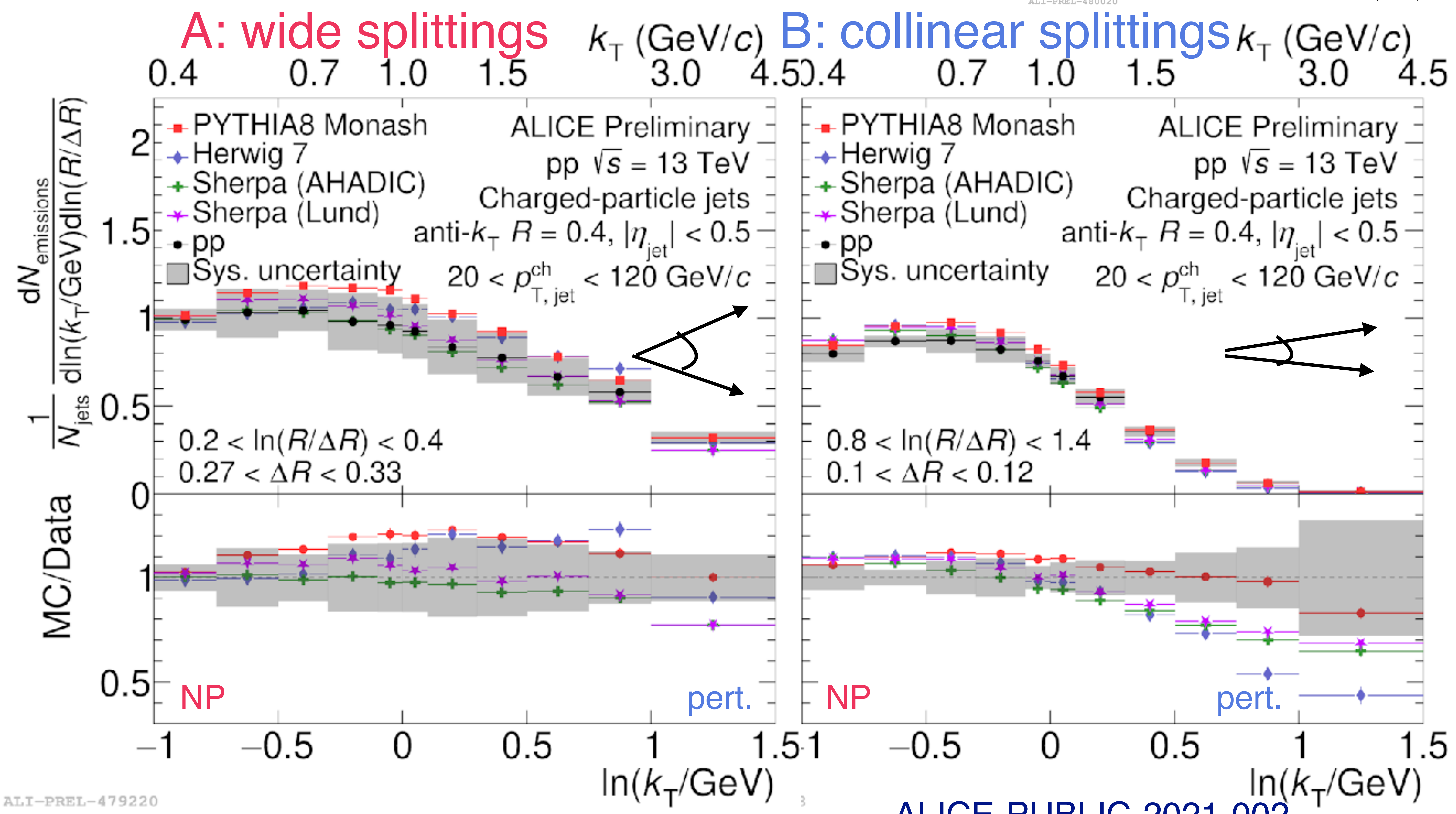
Regions of the Lund plane

Project onto momentum axis to separate wide vs. narrow splittings



Agreement with MC ~10% in most cases

Significant suppression of MC compared to data for hard collinear splitting



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Summary

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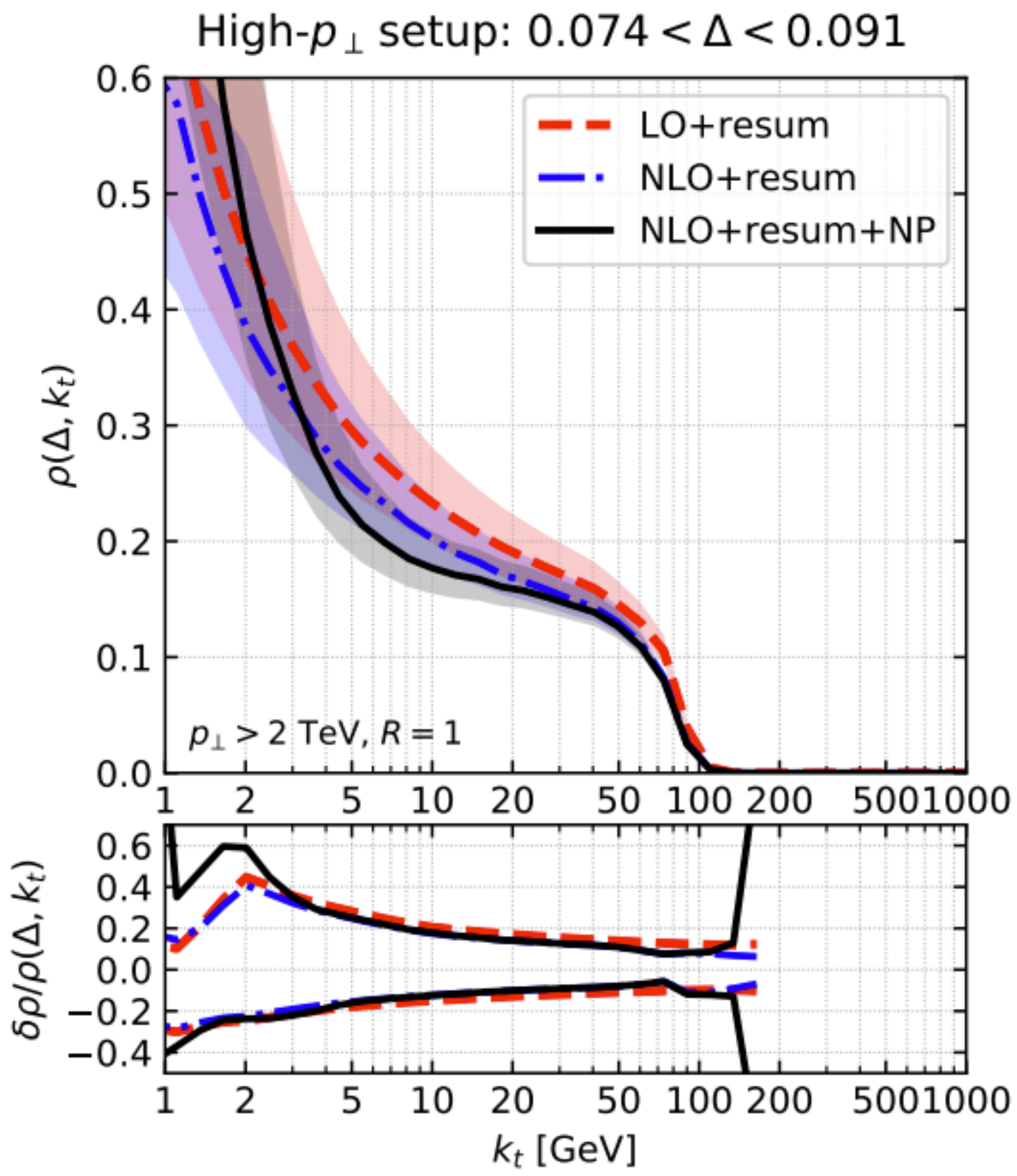
- Fully corrected Lund plane density measured at 13 TeV with ALICE in an intermediate p_T range
  - Isolate regions of the QCD phase space!
  - Generators describe data fairly well (~10%) except for hard collinear splittings, useful for tuning models

- Next steps:
  - Extend measurement to full (charged+neutral) jets in order to reach a more perturbative region at higher jet p_T and higher k_T
  - Compare to analytical all-order single log calculations

Lifson et al, JHEP 10 (2020) 170

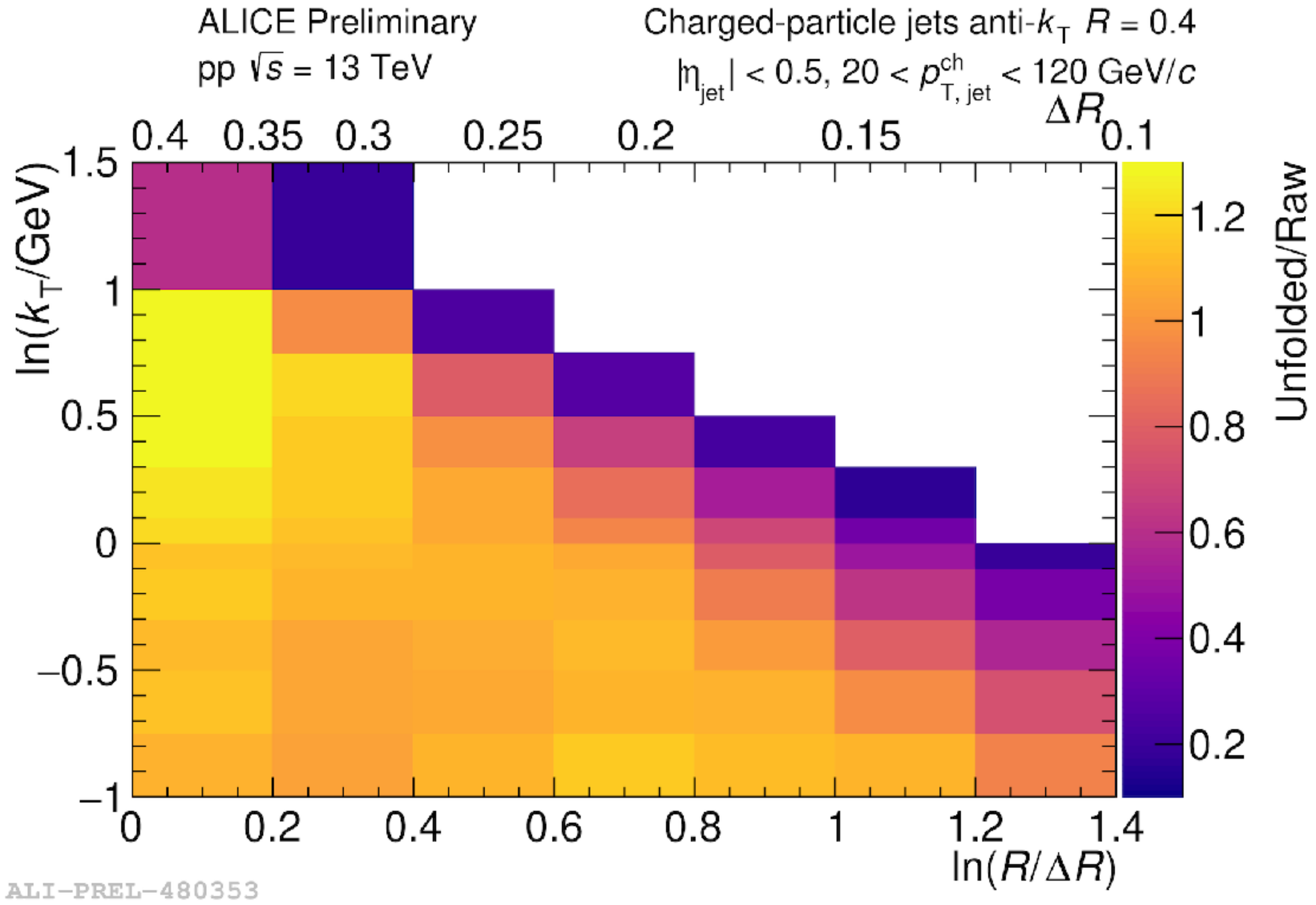


Thank you!

Backup

Unfolding

- Ratio of the Lund plane density before and after unfolding



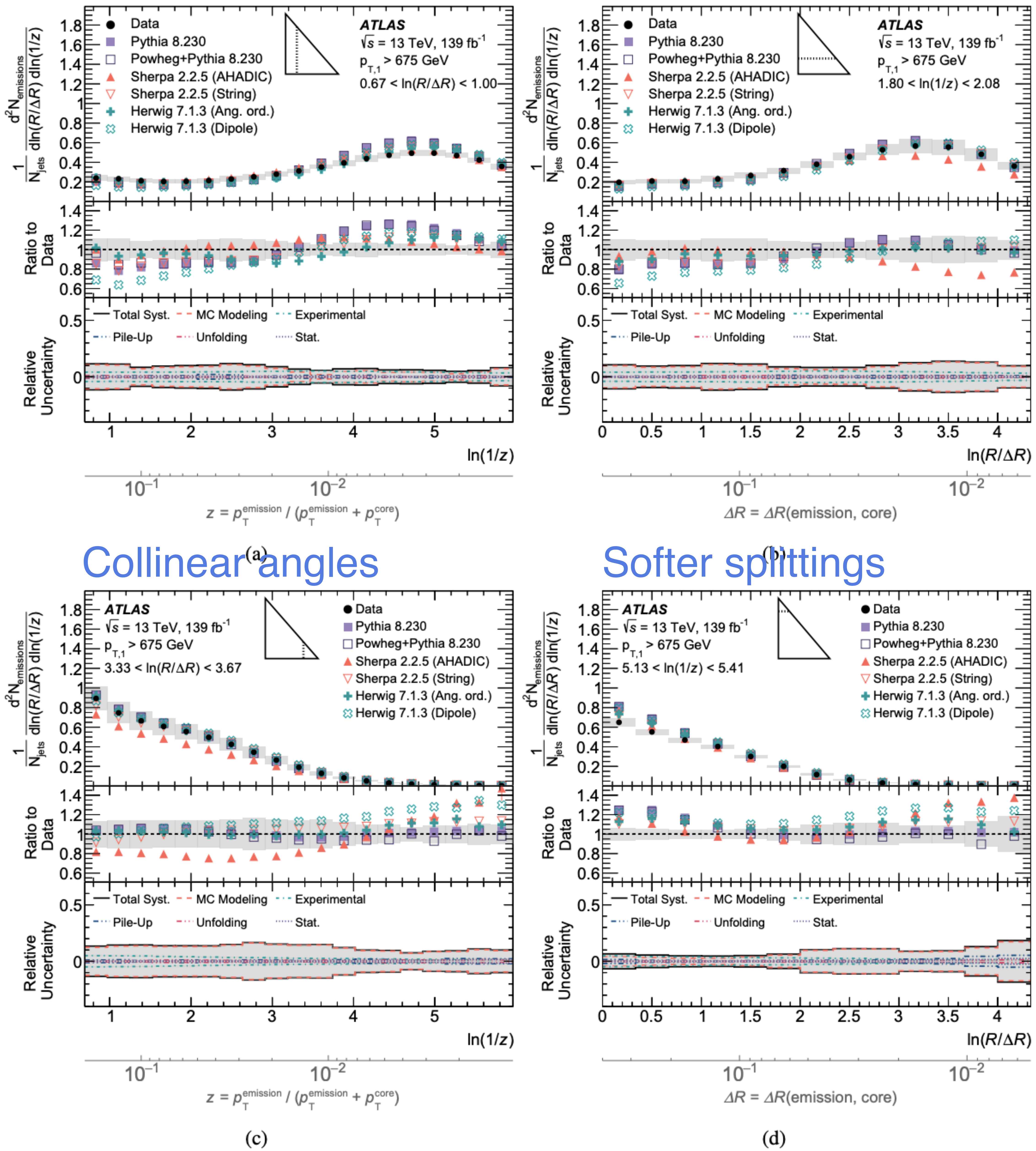
Wider angles

Harder splittings

Collinear angles

Softer splittings

Non-perturbative



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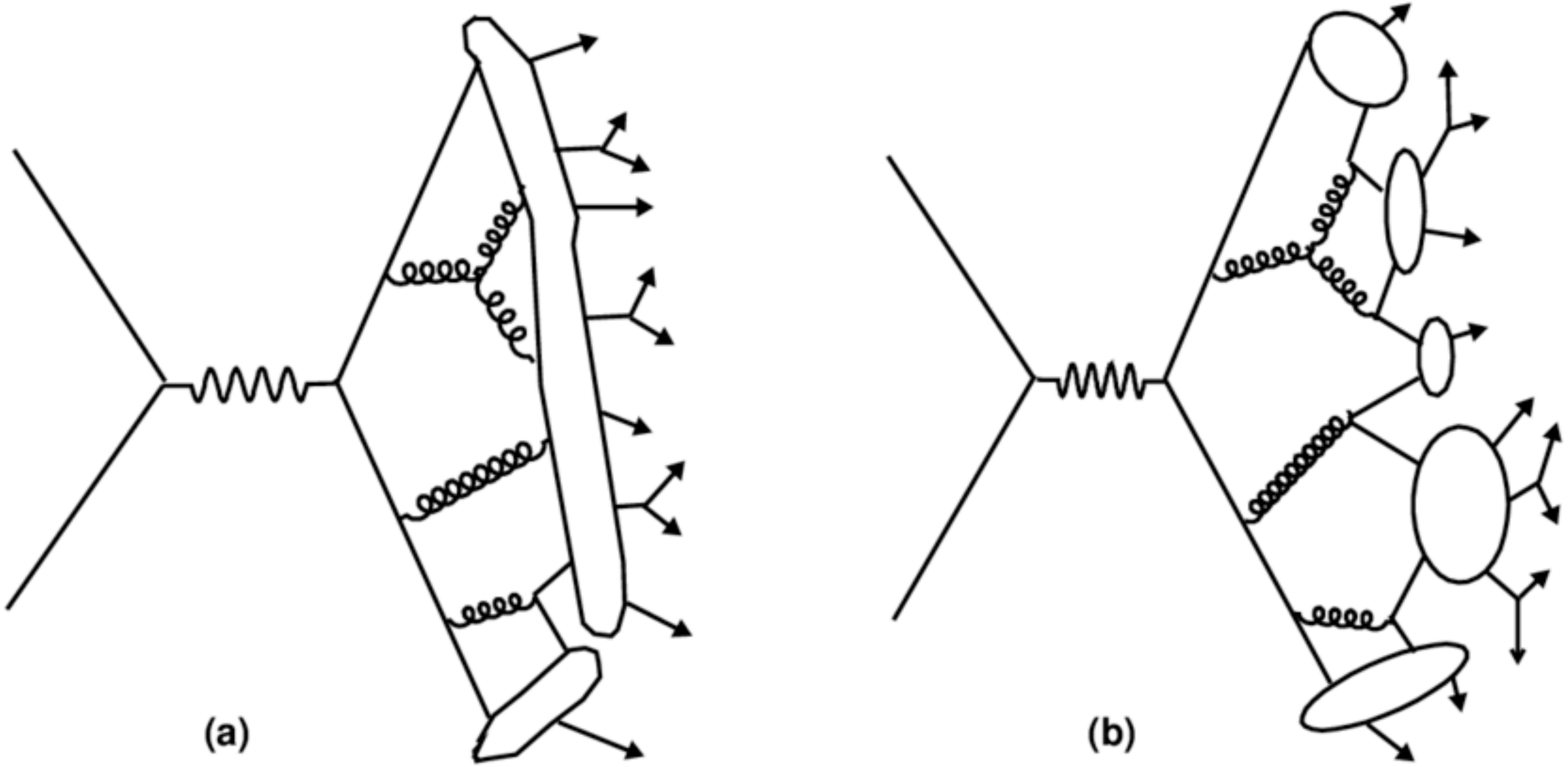
Systematics

- Matching: change the matching distance between the subjets to be tighter (0.05) and loser (0.15)
- Reweighting (prior): unfold with reweighted response by data/MC
- Regularization: -1 and +1 iterations from nominal
- Tracking inefficiency: lower efficiency by 4%
- Non-closure: reweight the pseudo-data and unfold with the nominal response, the difference is taken as a systematic (test 1)
- Model dependence: from Herwig

Hadronization models



Lund string: long distance limit of npQCD where partons are connected by QCD flux tubes, or strings (lattice QCD)

Cluster: perturbative limit where partons that are at energies above hadronization scale are grouped together like in a parton shower in color-neural clusters (pre-confinement)