SAPIENZA
UNIVERSITÀ DI ROMA

The Lund plane, what (I think) we've learned so far

Leticia Cunqueiro

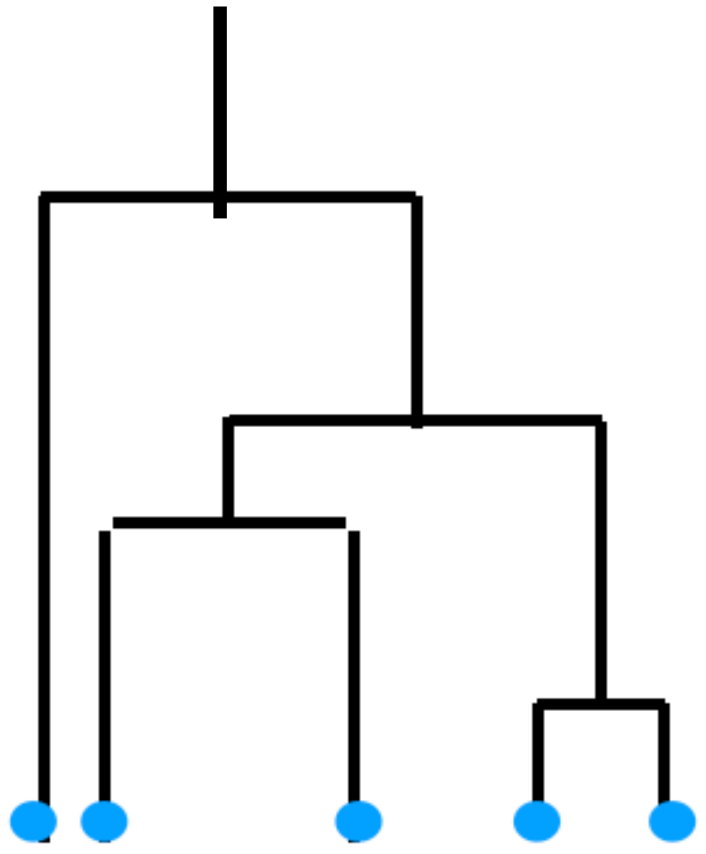
European Research Council
Established by the European Commission

New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions
12-16 February, ECT Trento*

Jet substructure to probe the internal dynamics of jets

Essentially, two ways of looking inside jets:

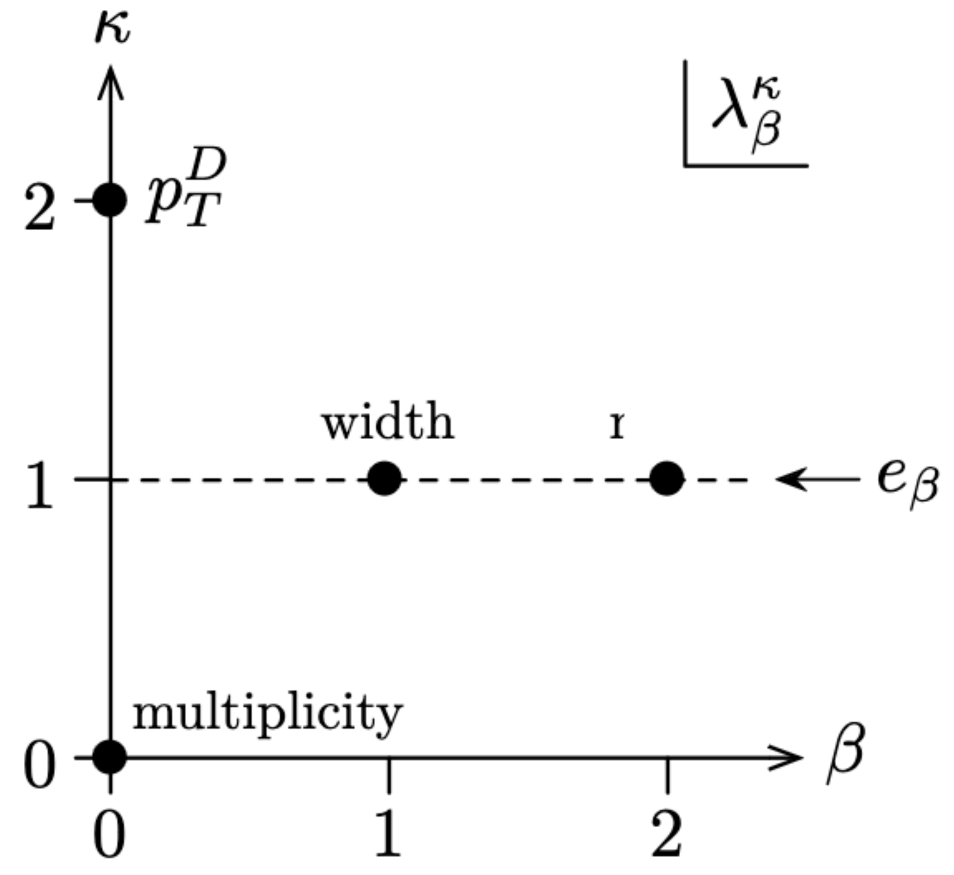
Use the jet tree:
hierarchical structure of jet constituents using the clustering history of a “physical” clustering algorithm



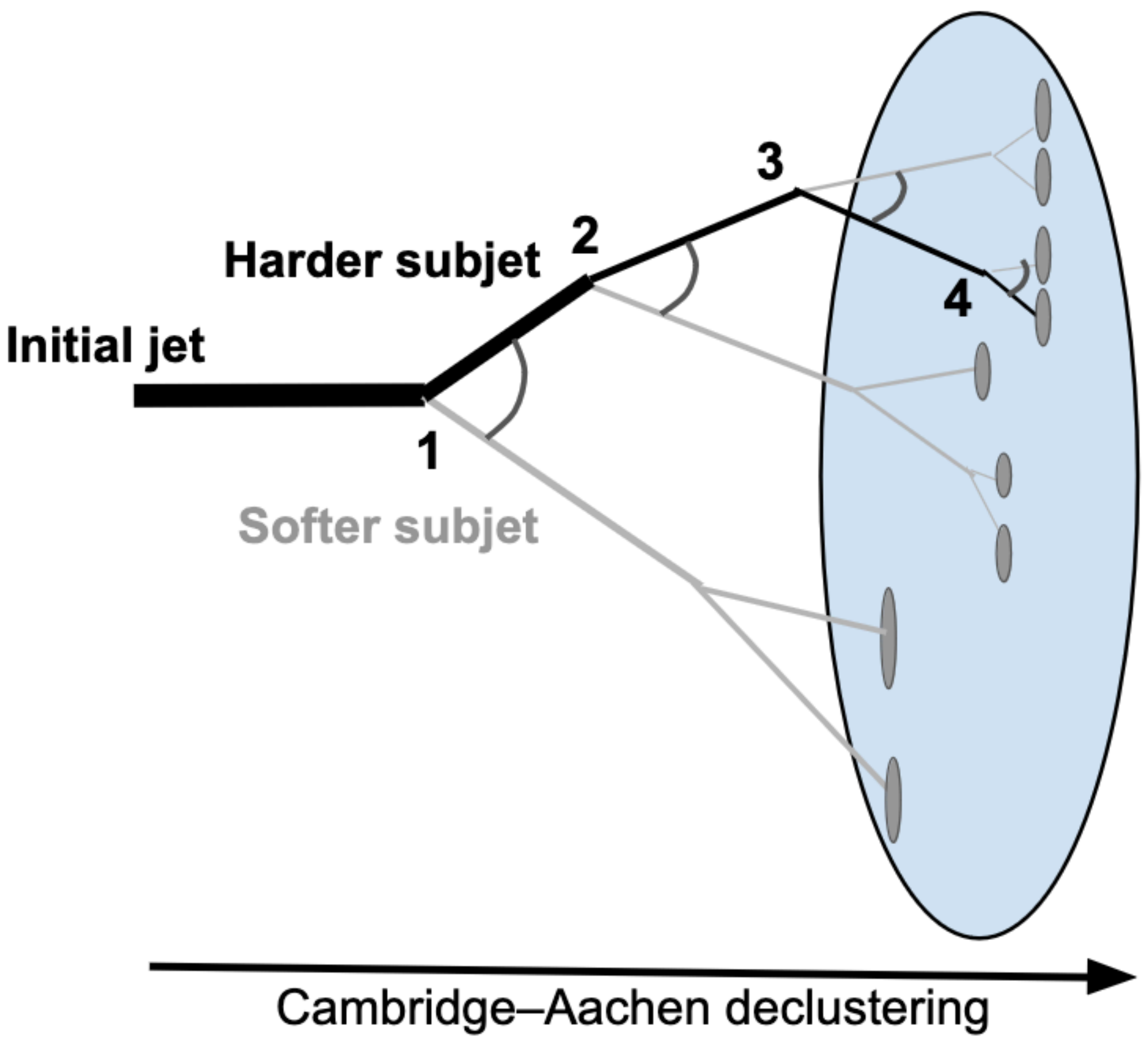
Use energy flows:
build jet-shape observables using energies and angles of jet constituents

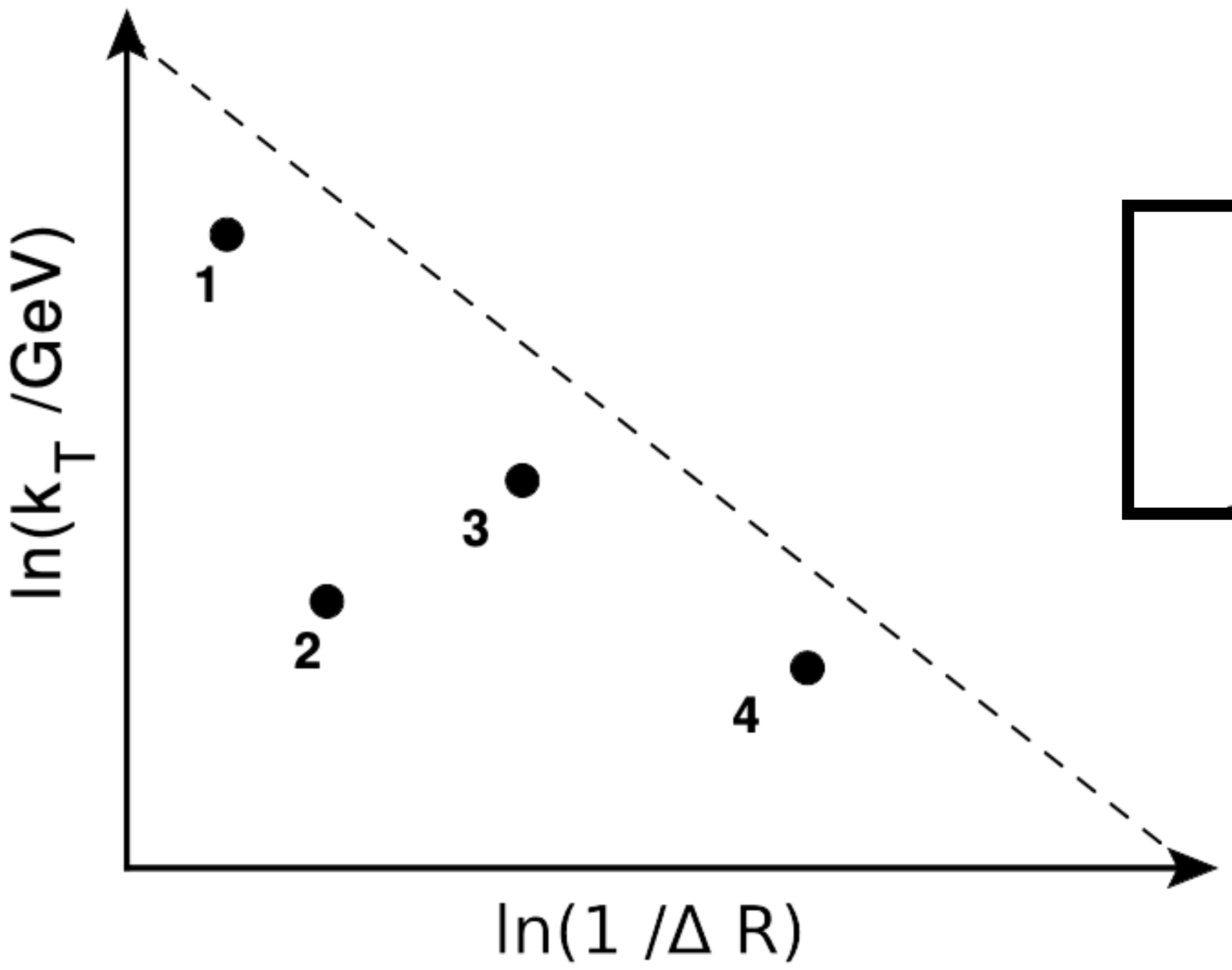
example, generalised angularities—>

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{R_i}{R_0} \right)^\beta$$



The primary Lund jet plane density





$$\rho(k_{\mathrm{T}}, \Delta R) \equiv \frac{1}{N_{\mathrm{jets}}} \frac{\mathrm{d}^2 N_{\mathrm{emissions}}}{\mathrm{d}\ln(k_{\mathrm{T}}/\,\mathrm{GeV})\,\mathrm{d}\ln(R/\Delta R)}$$

Dreyer et al, JHEP 12 (2018) 064

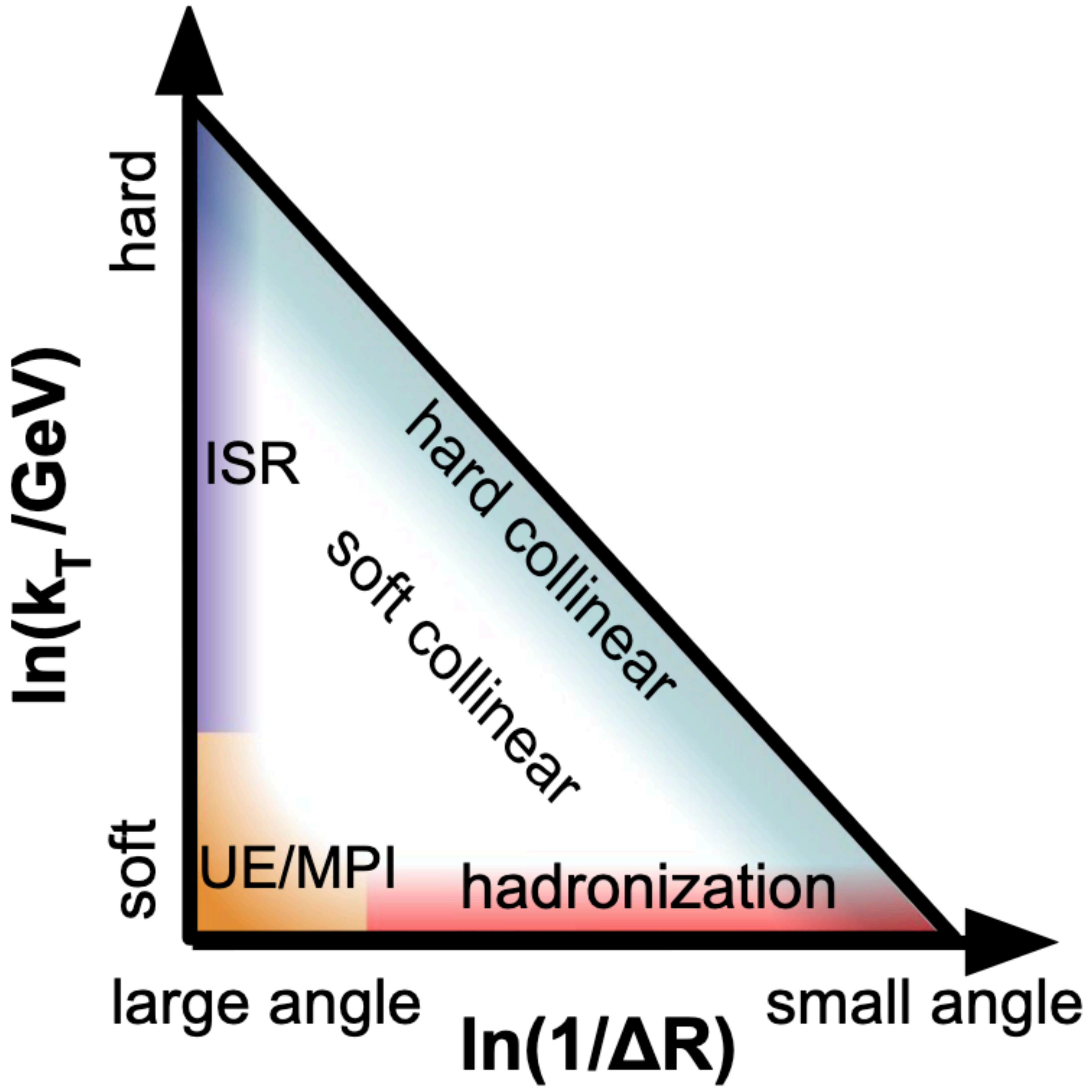
The jet tree is built using CA algorithm

The subleading prong kinematics are registered onto the lund plane for every node following the leading branch at each step

The density is expressed double-differentially in $ln(k_T)ln(R/\Delta R)$, approx the momentum and angular scaling of QCD radiation

In the soft and collinear limit: $\rho(k_{\mathrm{T}}, \Delta R) \approx \frac{2}{\pi} C_{\mathrm{R}} \alpha_{\mathrm{S}}(k_{\mathrm{T}})$

The primary Lund jet plane density in pp



$$\rho(k_\mathrm{T}, \Delta R) \equiv \frac{1}{N_\mathrm{jets}} \frac{\mathrm{d}^2 N_\mathrm{emissions}}{\mathrm{d}\ln(k_\mathrm{T}/\,\mathrm{GeV})\,\mathrm{d}\ln(R/\Delta R)}$$

Detailed information about the jet radiation pattern

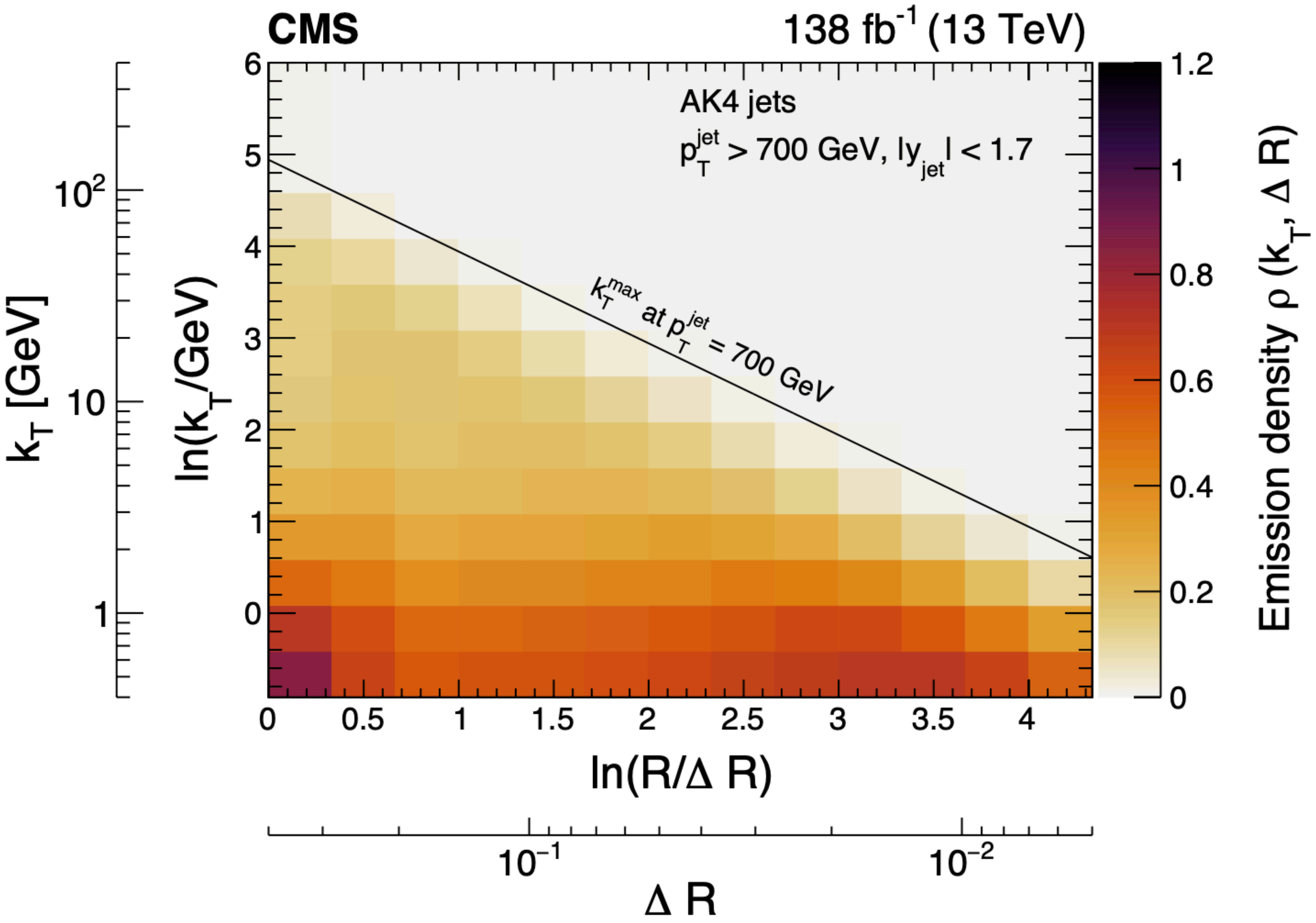
Constrain to different aspects of the parton shower in a modular fashion:
separation of hard/soft and large/small angle physics

Analytically calculable ***Lifson et al, JHEP 10 (2020) 170***

All groomed observables are subsamples of the Lund plane

The Lund jet plane density in pp

Fully corrected Lund jet plane for R=0.4 jets using charged particles



The analysis requires a 3D unfolding of the emissions (plus the 1D unfolding of the normalization, N_{jets})

To build a response matrix:

-match det-level and part-level jets

-match det-level and part-level splittings
unique geometrical matching:
det-level splitting is the closest
to part-level splitting and viceversa

Correct for the matching purity and efficiency

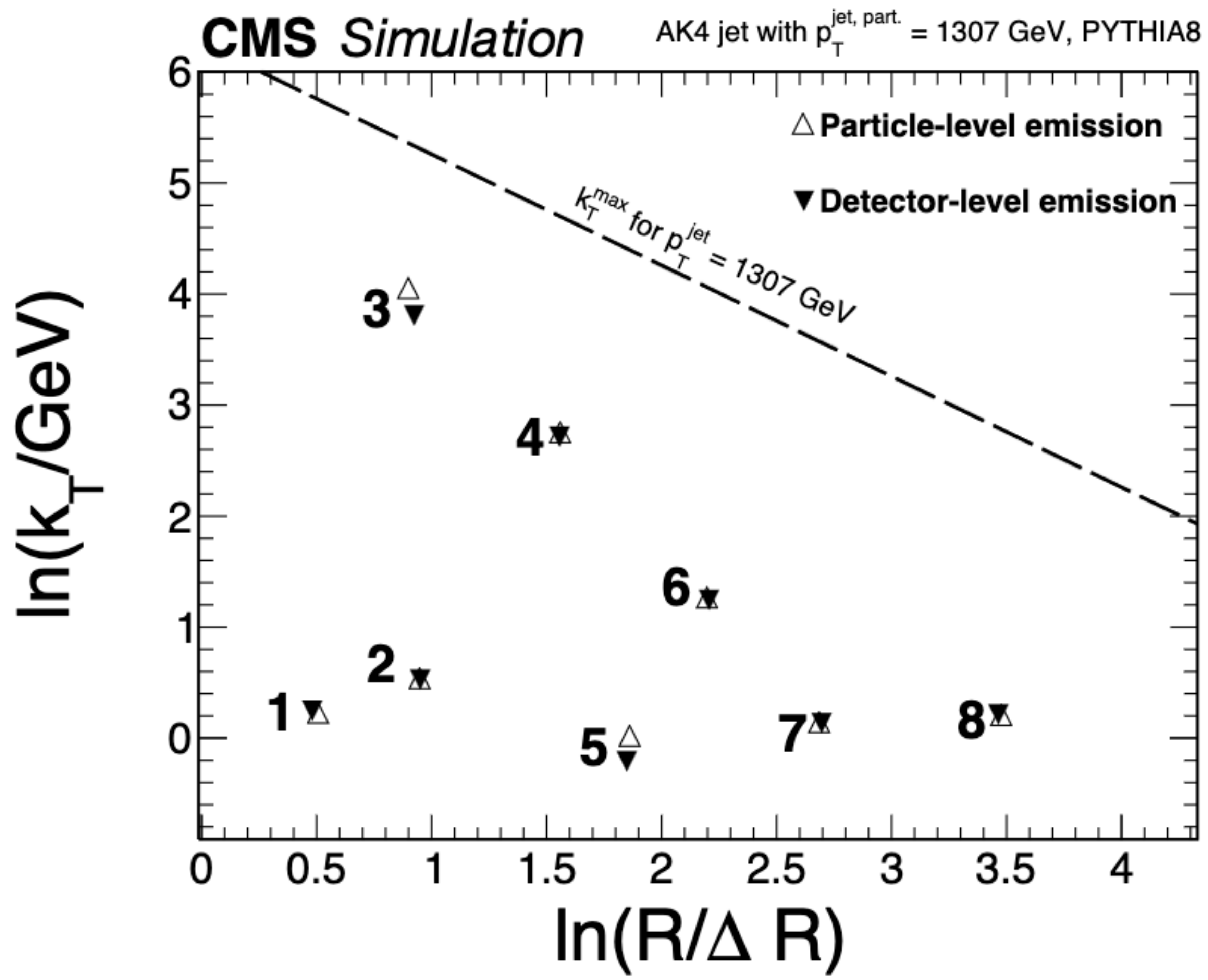
(see also ATLAS and ALICE's measurements)

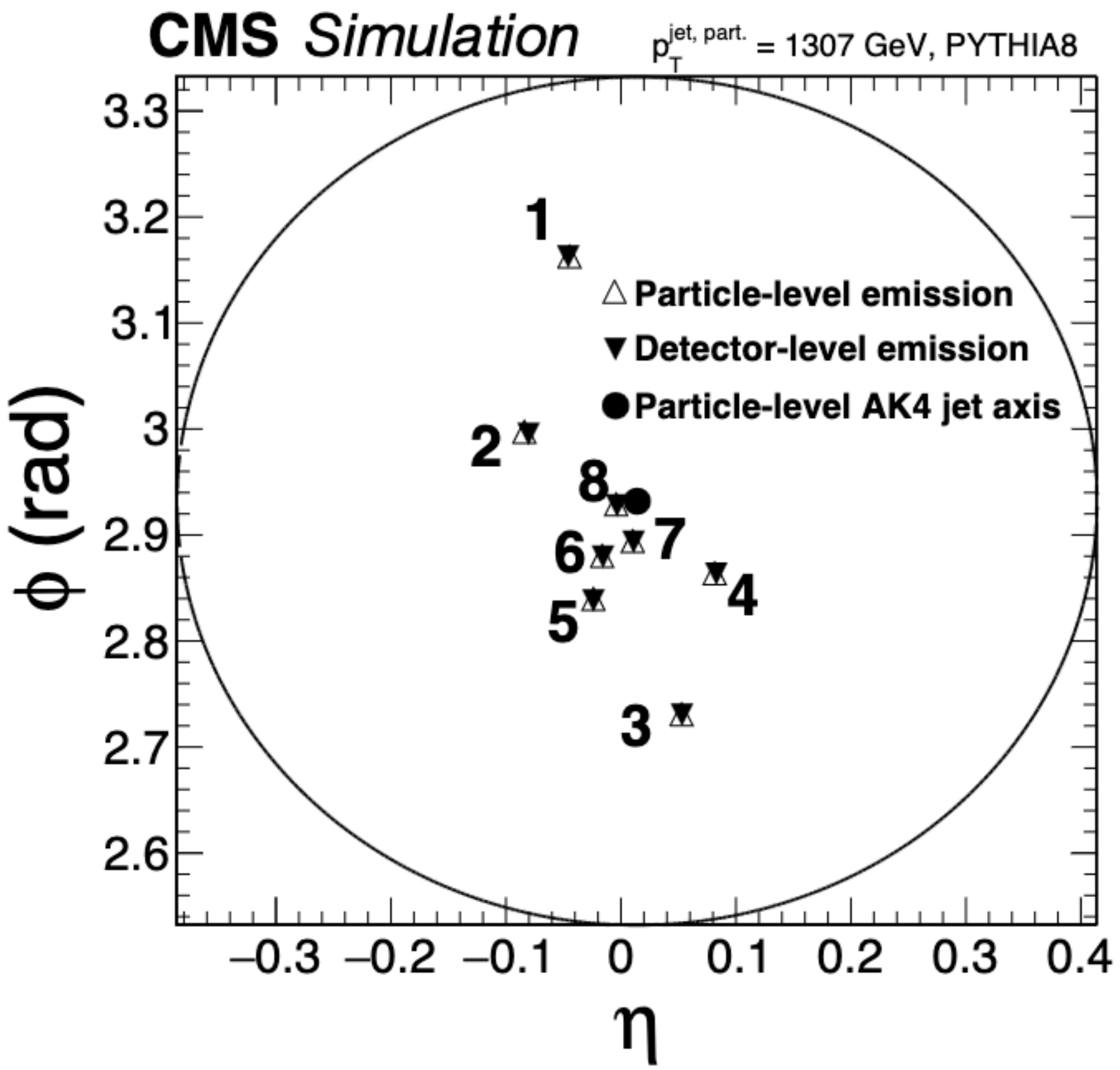
CMS-PAS-SMP-22-007, arXiv: 2312.16343

The Lund jet plane density in pp: geometrical matchig of splittings

Flat geometrical matching

CMS-PAS-SMP-22-007





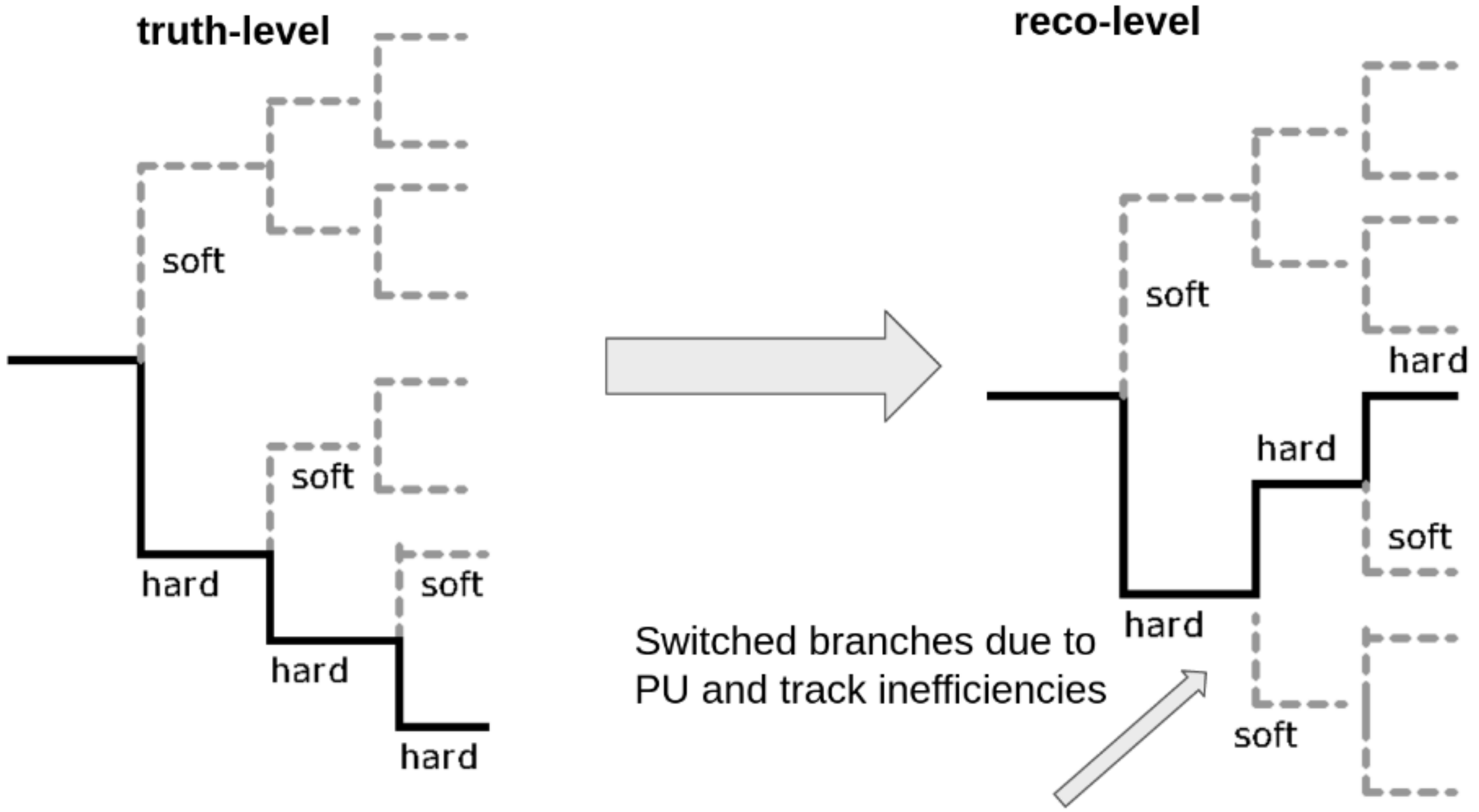
In general there is good correspondence between detector and particle level spittings, matching eff and purities ~90%

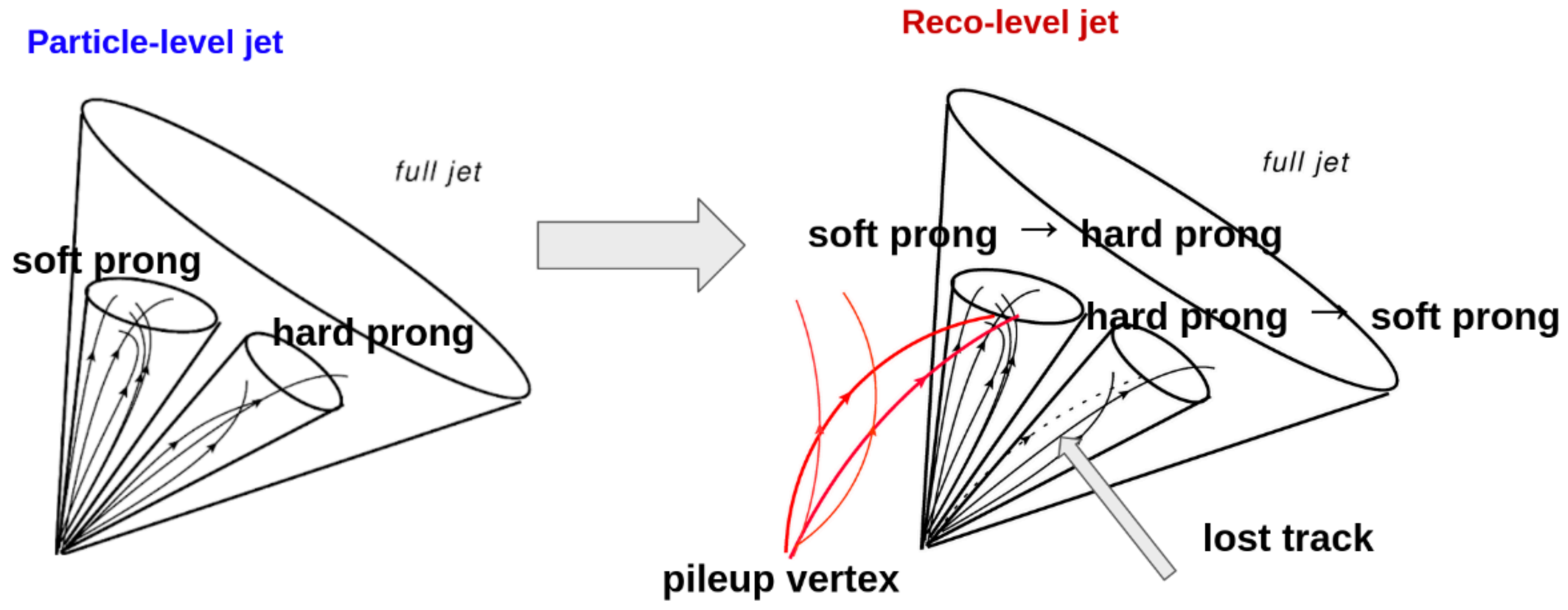
Detector effects such as tracking efficiency and momentum smearing can worsen the correspondence

Large purity correction in the limit of soft and large-angle emissions due to UE and pileup
Large efficiency corrections in the region of small angles and low k_T due to det-level low p_T cutoffs

The Lund jet plane density in pp: mismatches

CMS-PAS-SMP-22-007





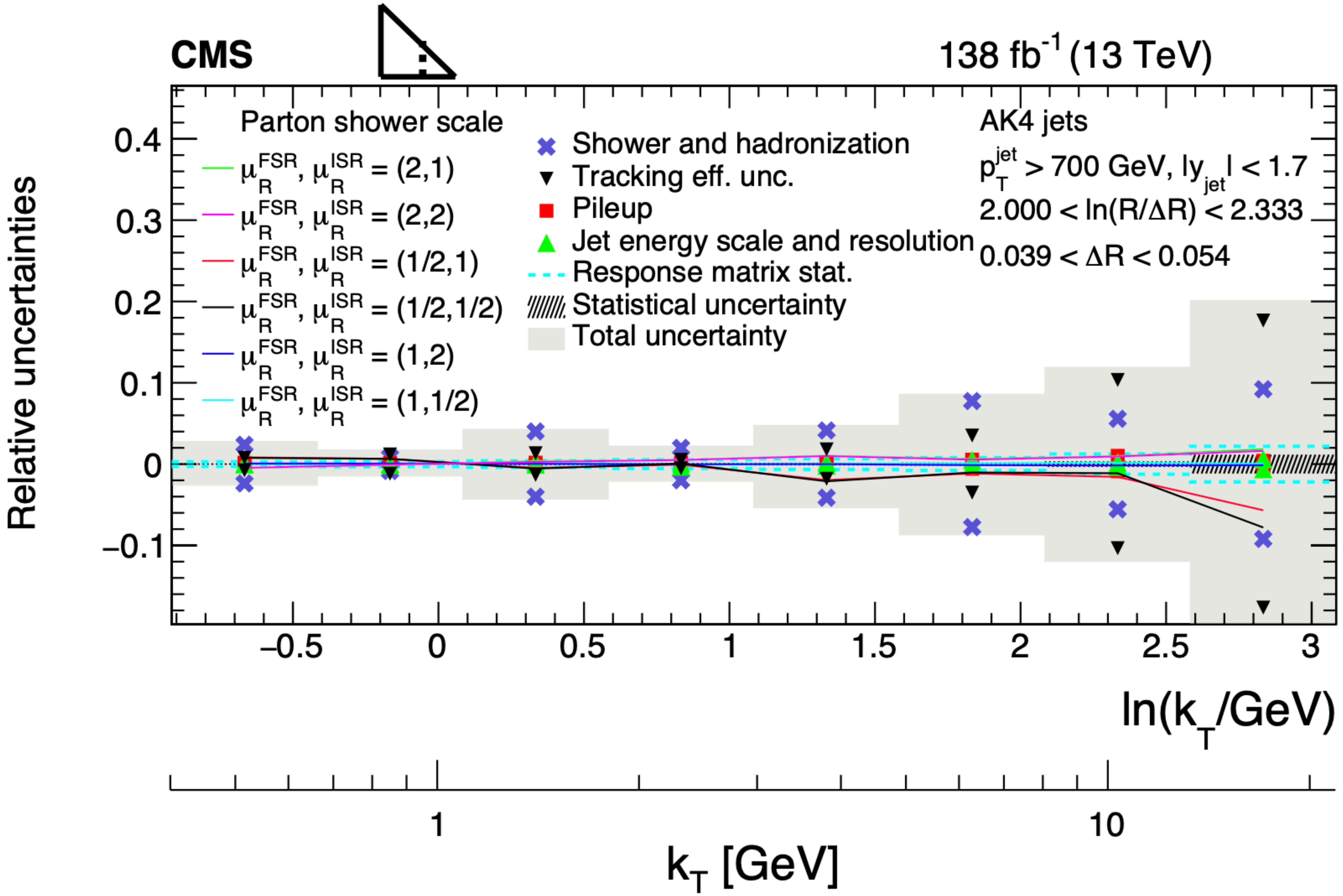
Residual mismatches

Correspondence between particle and det-level splittings is lost

Typically due to swaps between the leading and subleading prongs due to pileup and track loses

Few percent of the matched emissions in simulation that contribute as off-diagonalities in the response matrix

The Lund jet plane density in pp



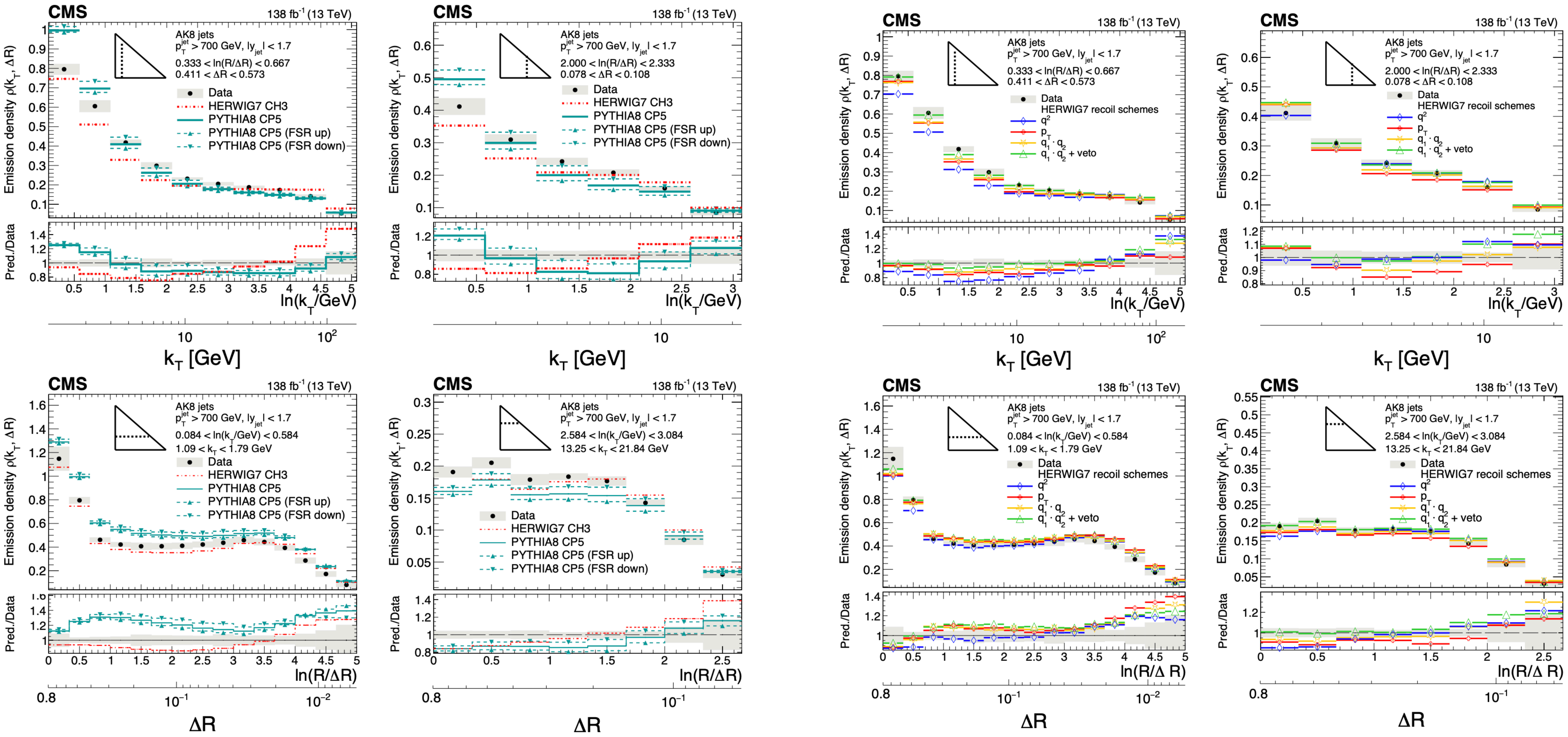
Dominant uncertainties:

track. eff uncertainty, up to ~20%
model dependency, up to ~10%

The track inefficiency uncertainty hits badly the high-kT perturbative domain
Swaps can be mitigated by measuring the full Lund plane, not the primary!

CMS-PAS-SMP-22-007, arXiv: 2312.16343

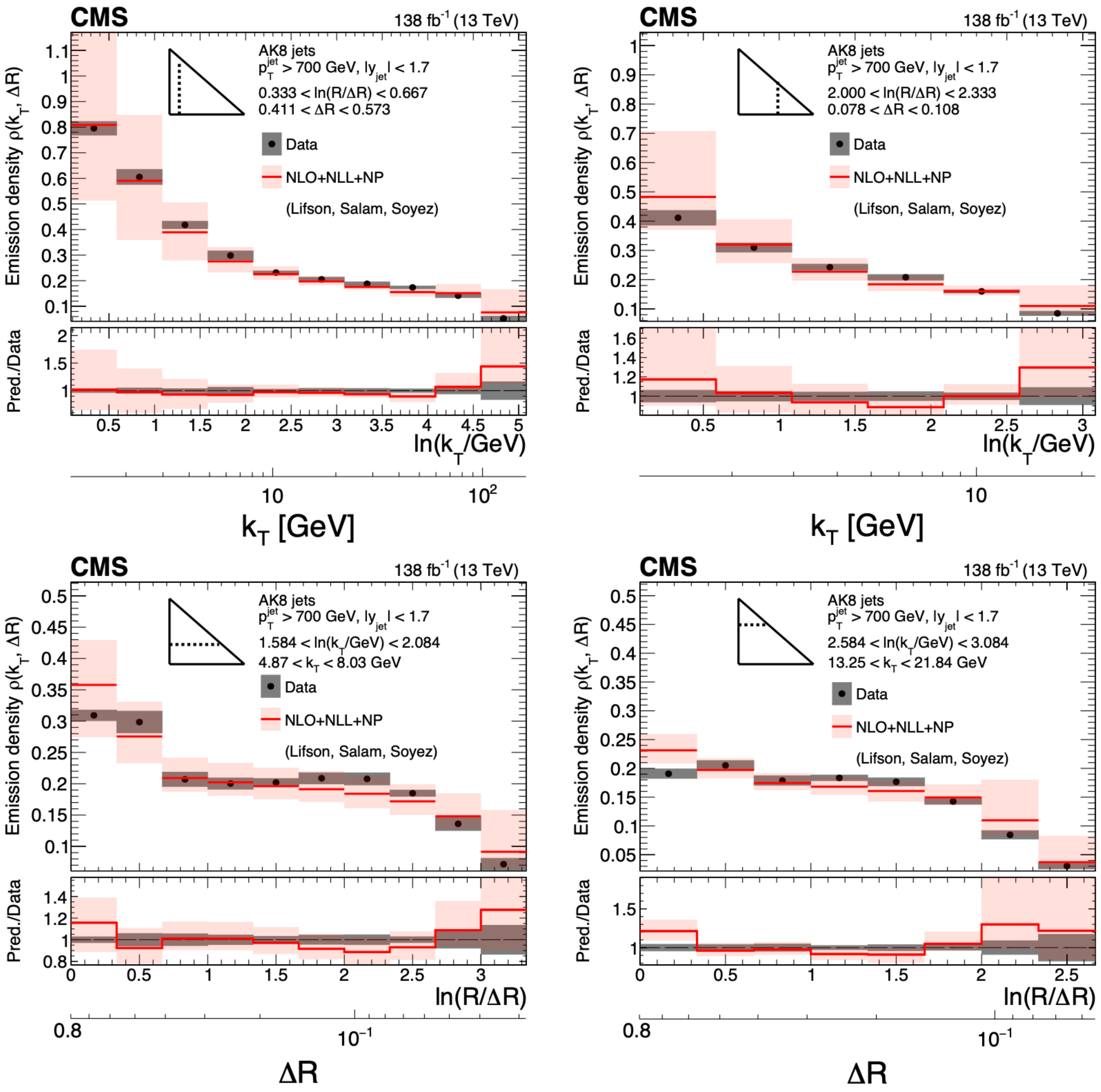
The Lund jet plane density in pp



Examples of comparisons to Pythia tunes and Herwig recoil schemes

CMS-PAS-SMP-22-007, arXiv: 2312.16343

The Lund jet plane density in pp

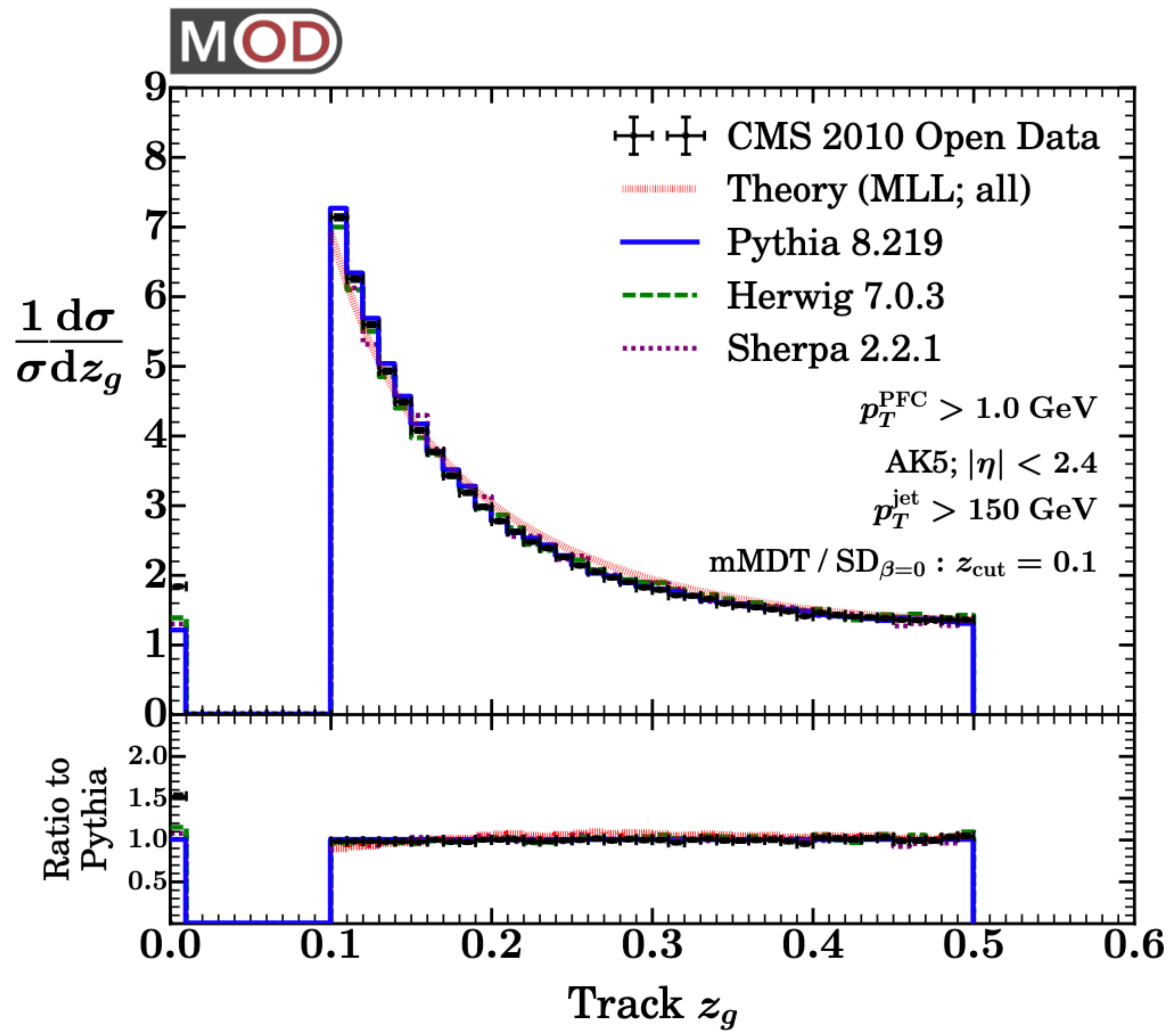


NLO+NLL+NP analytical calculation based on ***Lifson et al, JHEP 10 (2020) 170***

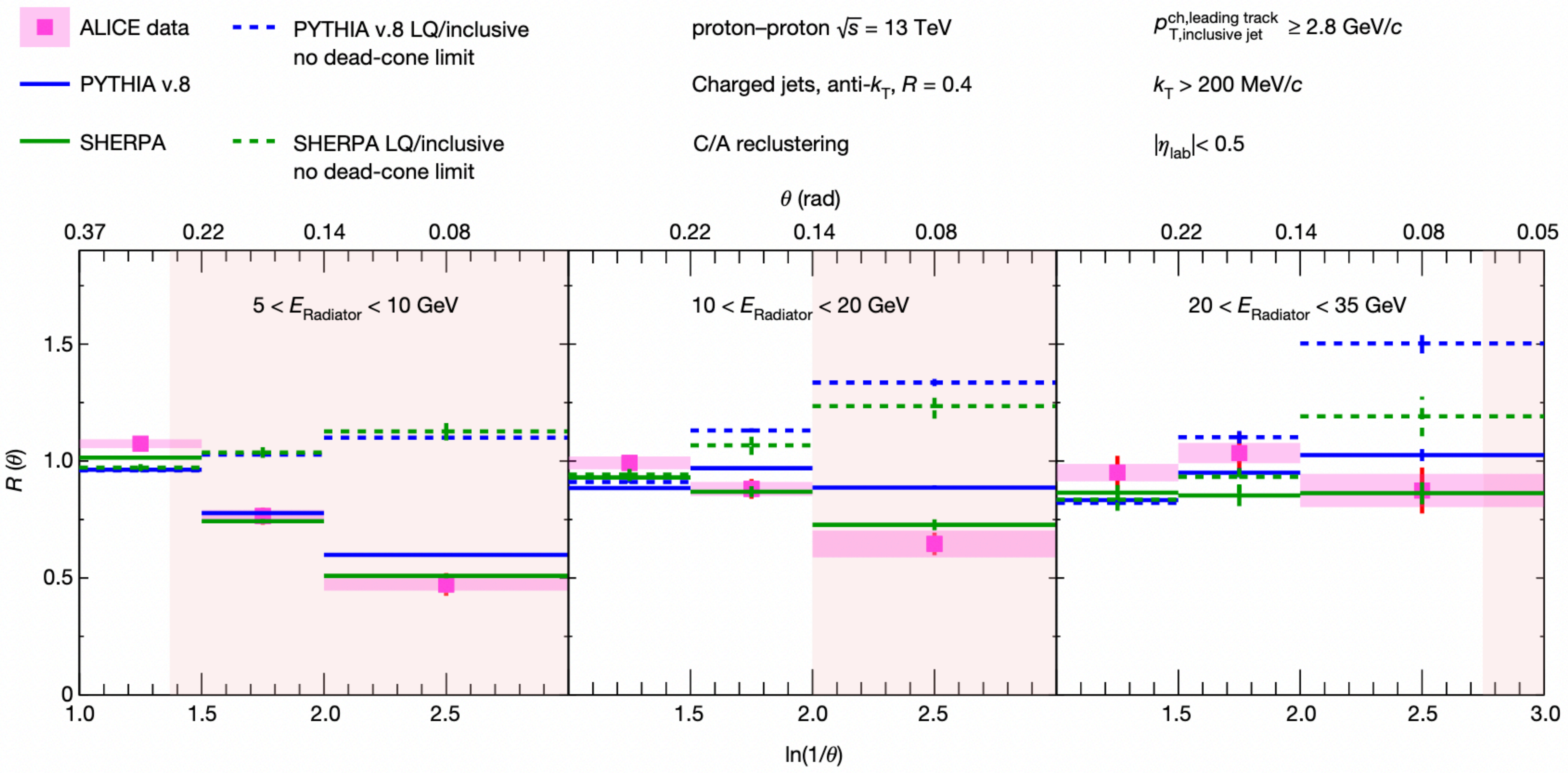
CMS-PAS-SMP-22-007, arXiv: 2312.16343

Exposing building blocks of QCD with the Lund plane, 2 examples

Larkoski et al, Phys. Rev. Lett. 119, 132003 (2017)



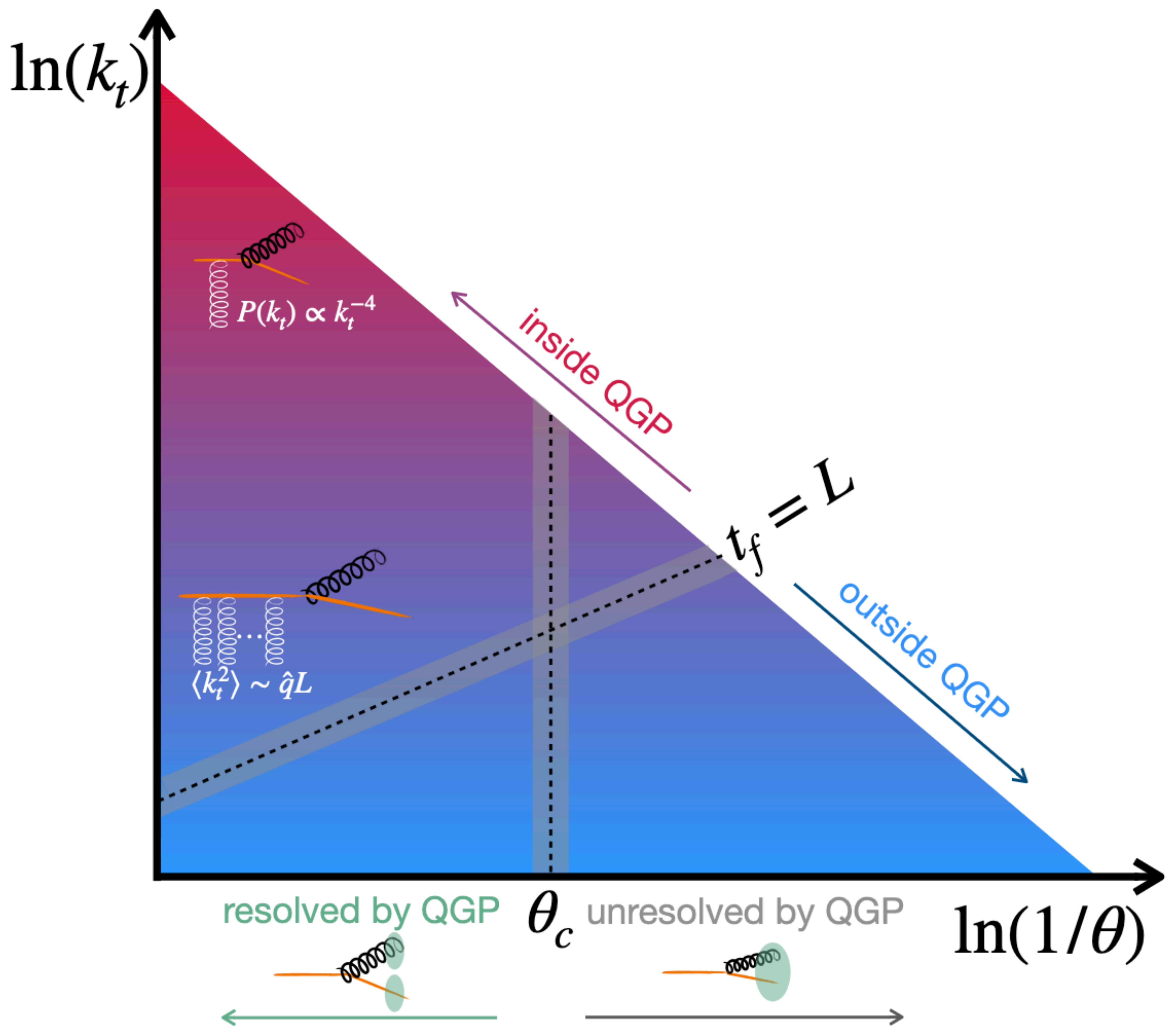
[ALICE, Nature 605, 440-446 (2022)]



SoftDrop momentum balance that asymtotes to the QCD splitting energy at sufficiently hight jet energy

Direct visualization of the dead cone effect in bins of the energy of the radiating prong

The Lund plane in heavy-ion collisions

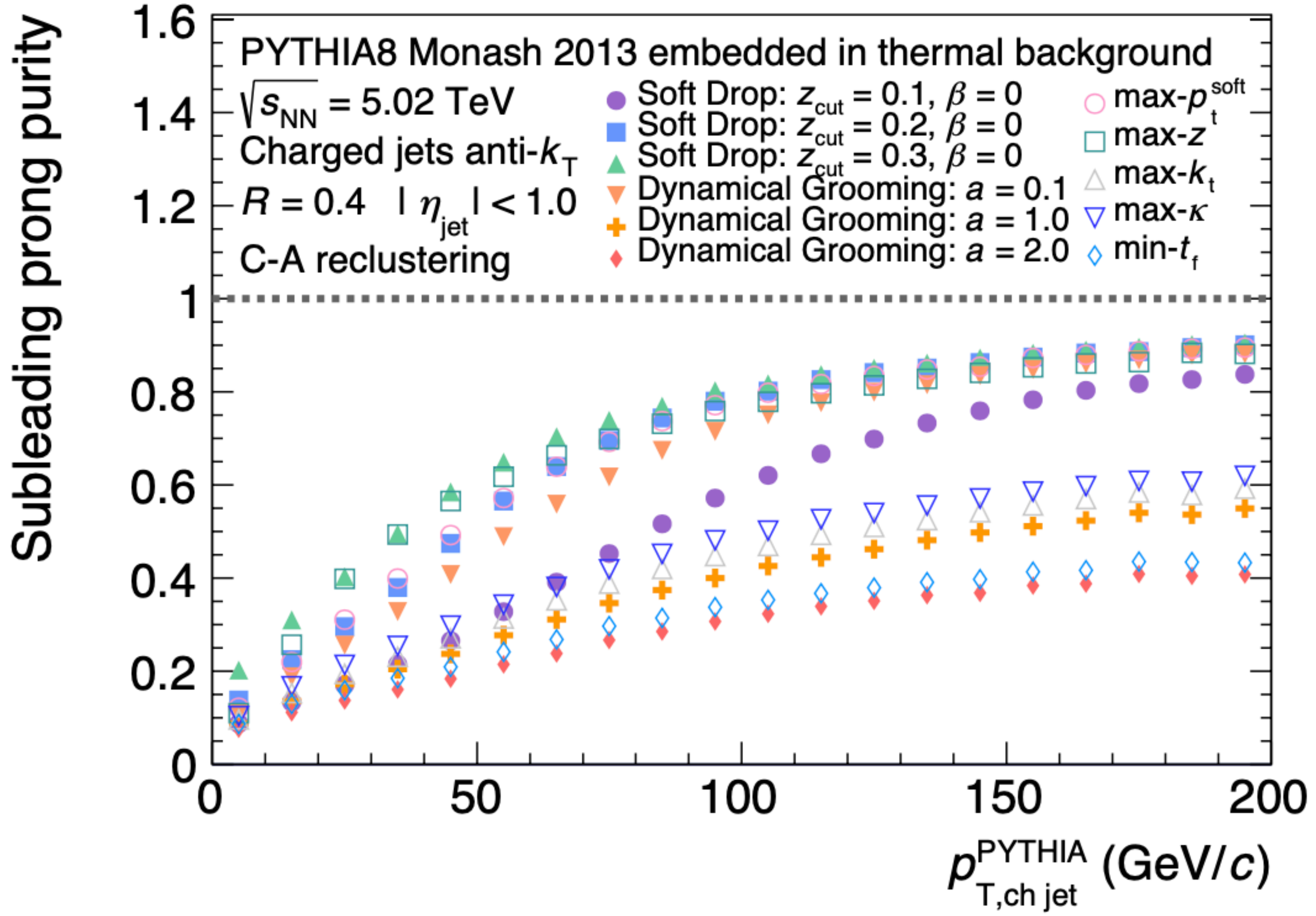


Strategies to isolate and characterize QGP-induced signal and map it to the microscopic properties of the QGP

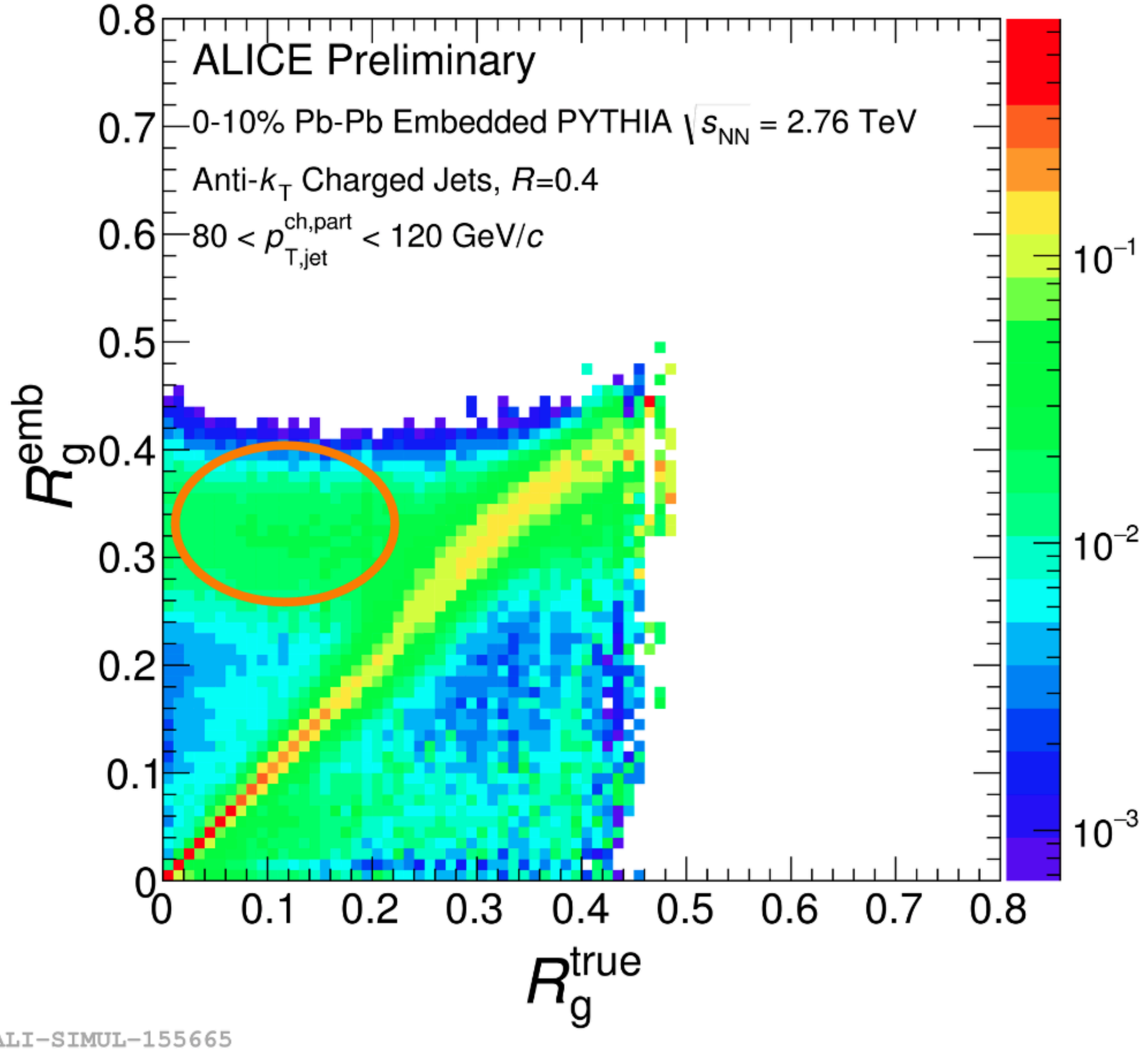
sketch from Cunqueiro et al arXiv:2311.07643

Scans of the Lund plane in PbPb: mismatches

Mulligan,Ploskon, Phs.Rev.C102 (2020)



combinatorial prongs



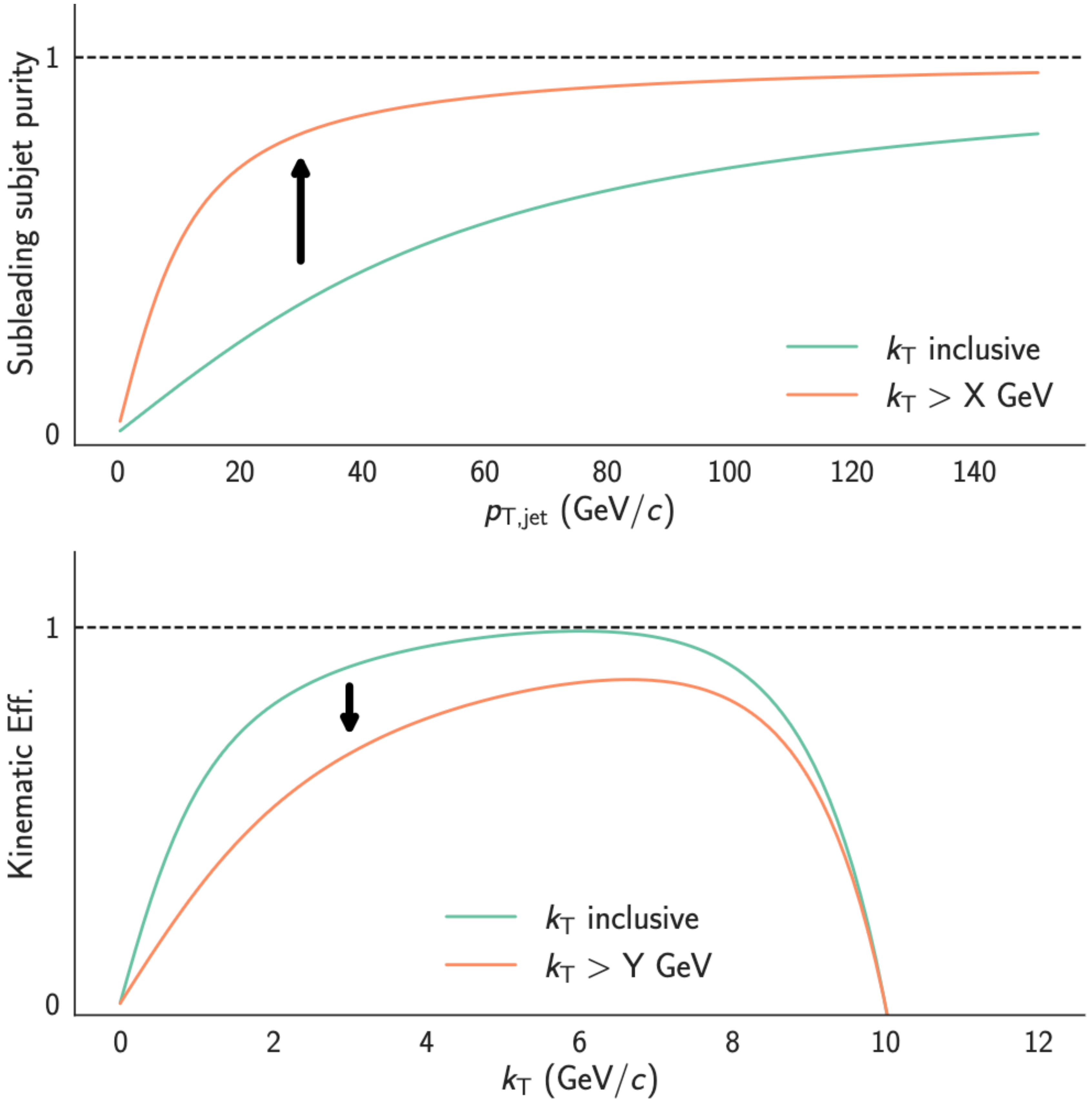
What in pp is just a few percent can become overwhelming in PbPb due to the large UE

Scans of the Lund plane in PbPb: mismatches

- Dynamical Grooming exhibits **reduced subleading subjet purity** in Pb–Pb
- **Off-diagonal mismatched splittings** are major component at low k_T

→ **Problematic for unfolding**

- Caused by **requirement to always select a splitting**
- **Address by minimum measured k_T** requirement
- Trade **improved purity** for **reduced dynamic range** and kinematic efficiency
- **Minimum *z*** has similar impact



Raymond Ehlers, Lund Plane Workshop 23

Slide from Raymond showing a typical trade-off:
you cut on a variable (k_T of the splitting in this case) in order to suppress combinatorial prongs
but then you have to deal with a big purely MC-based correction due to the background smearing of that variable

Scans of the Lund plane in PbPb: uncertainties

Model (prior) uncertainty

in pp is dominant

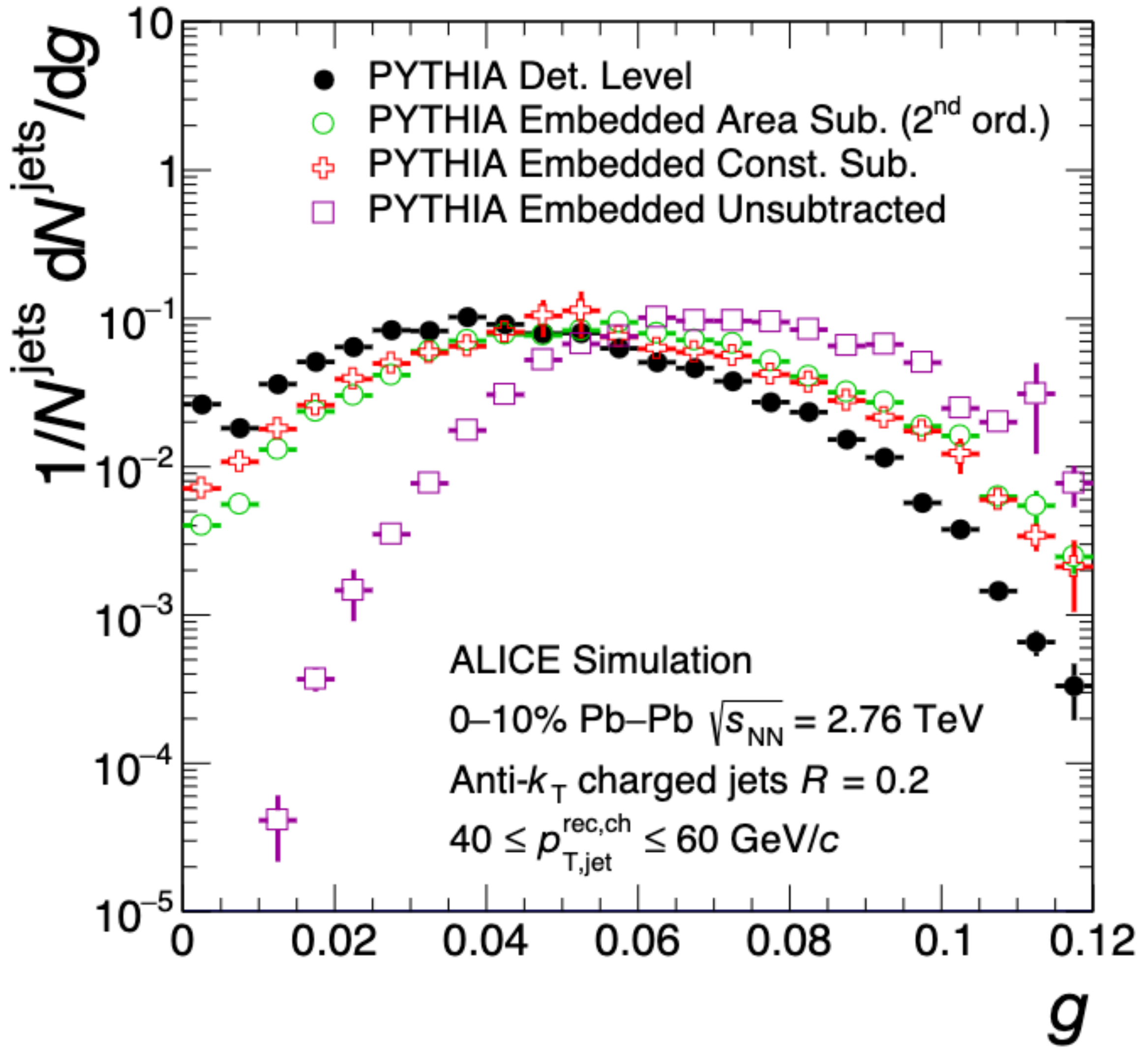
in PbPb, several strategies:
- -nominal is typically pythia/herwig embedded into PbPb
- -variation is a change of the q/g fraction in the vacuum baseline
- -other educated guesses inspired by theory, see for instance ***Phys.Lett.B*** **849 (2024) 138412**

Background subtraction uncertainty

in pp we do not subtract the UE contribution

in PbPb, different strategies:

Constituent subtraction vs unbiased area subtraction



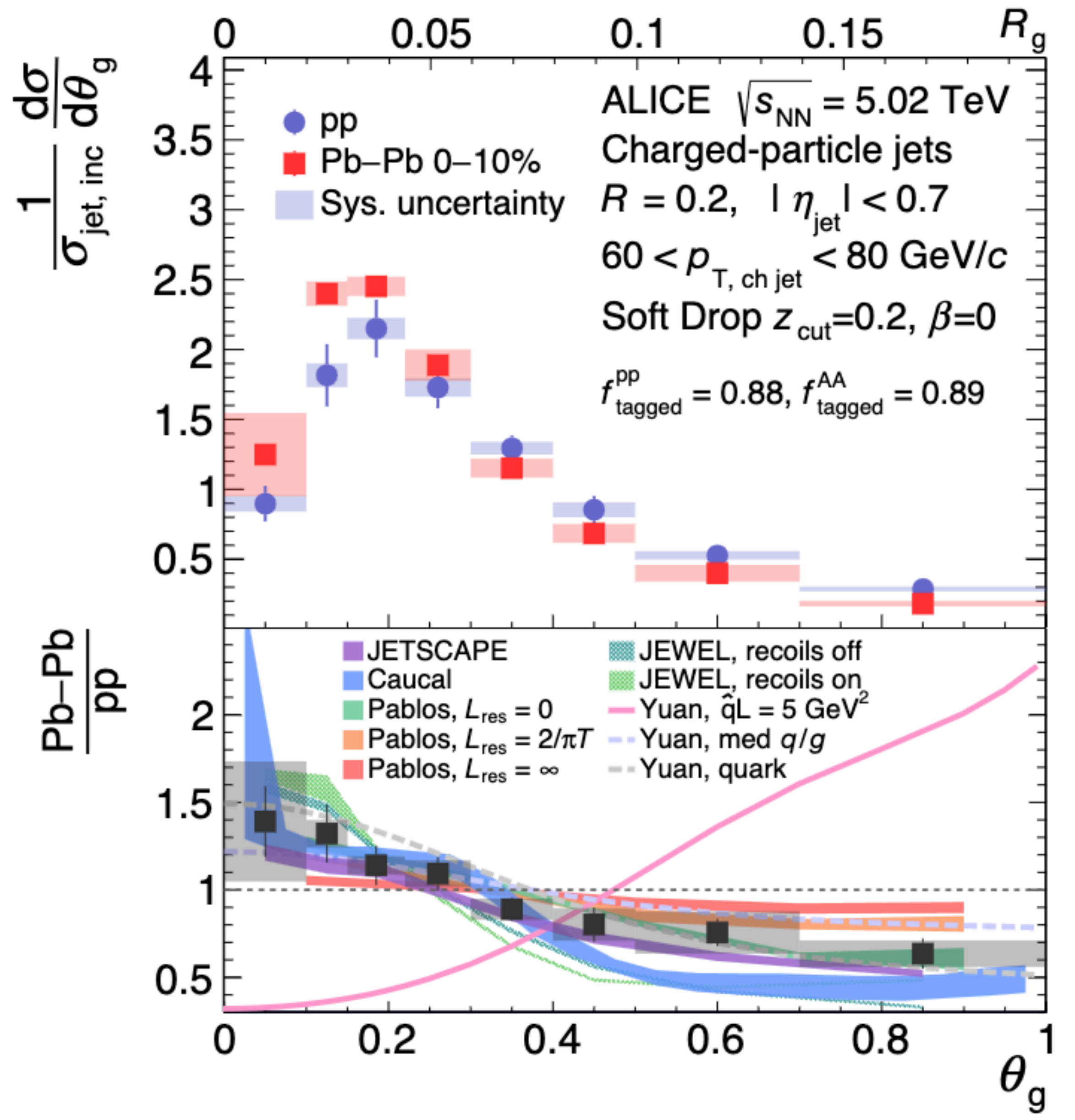
Pb–Pb	Relative uncertainty (%)					
	Trk. eff.	Unfolding	Generator	Tagging	Bkgd. sub.	Total
z_g						
0–10% $R = 0.2$	1–4%	1–4%	1–7%	1–2%	1–6%	4–10%
0–10% $R = 0.4$	1–13%	1–4%	1–7%	2–26%	4–28%	9–41%
30–50% $R = 0.4$	0–2%	0–5%	1–7%	1–6%	2–5%	5–9%
θ_g						
0–10% $R = 0.2$	1–8%	1–4%	1–5%	1–19%	1–14%	3–24%
30–50% $R = 0.4$	3–6%	1–7%	1–5%	0–4%	2–15%	6–15%
30–50% $R = 0.4$ $z_{cut} = 0.4$	4–11%	2–11%	1–5%	1–5%	1–13%	4–20%

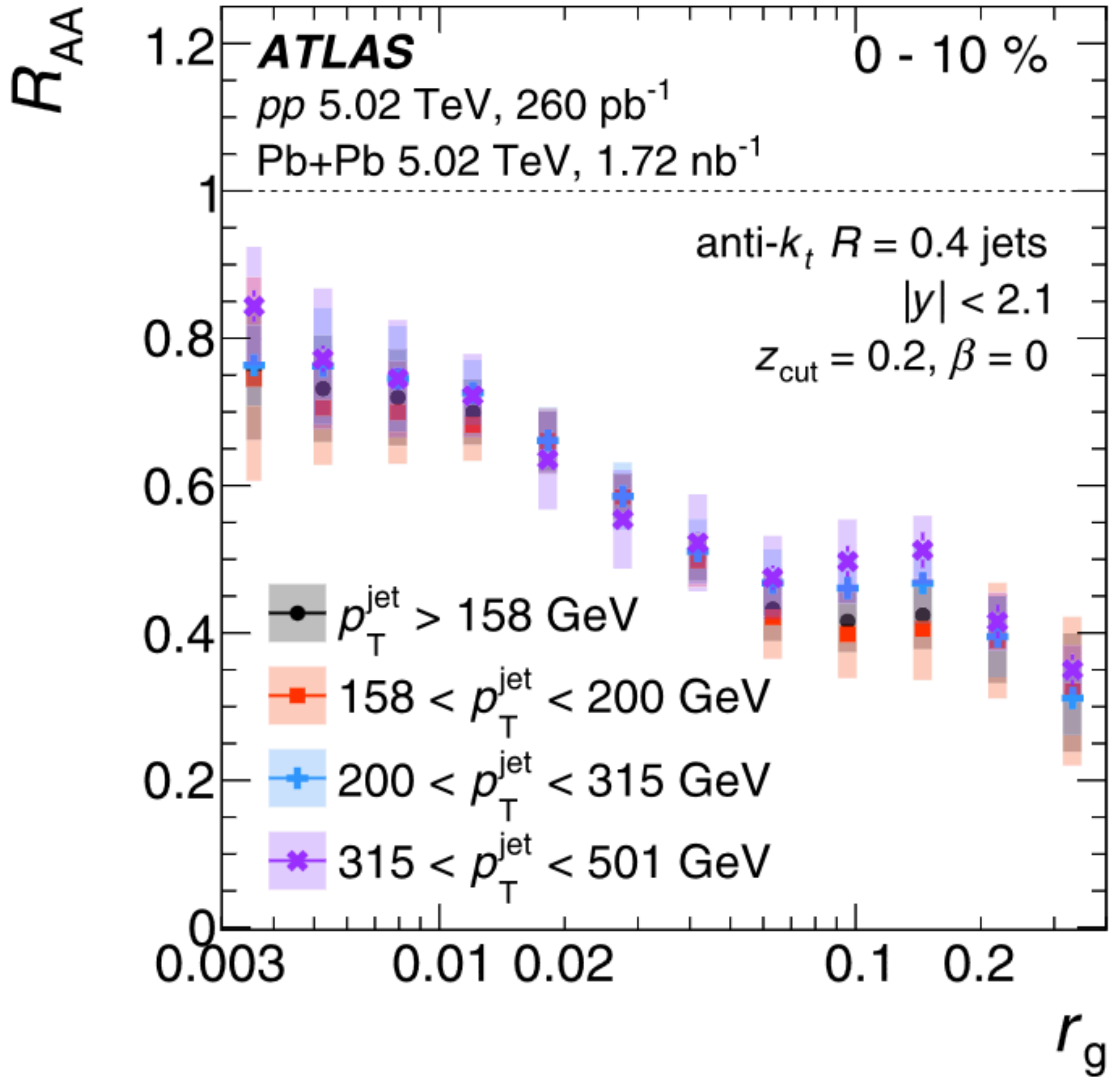
Table 1: Summary of systematic uncertainties on the Pb–Pb measurements. The ranges correspond to the minimum and maximum systematic uncertainties obtained. All values correspond to $z_{cut} = 0.2$ unless otherwise noted.

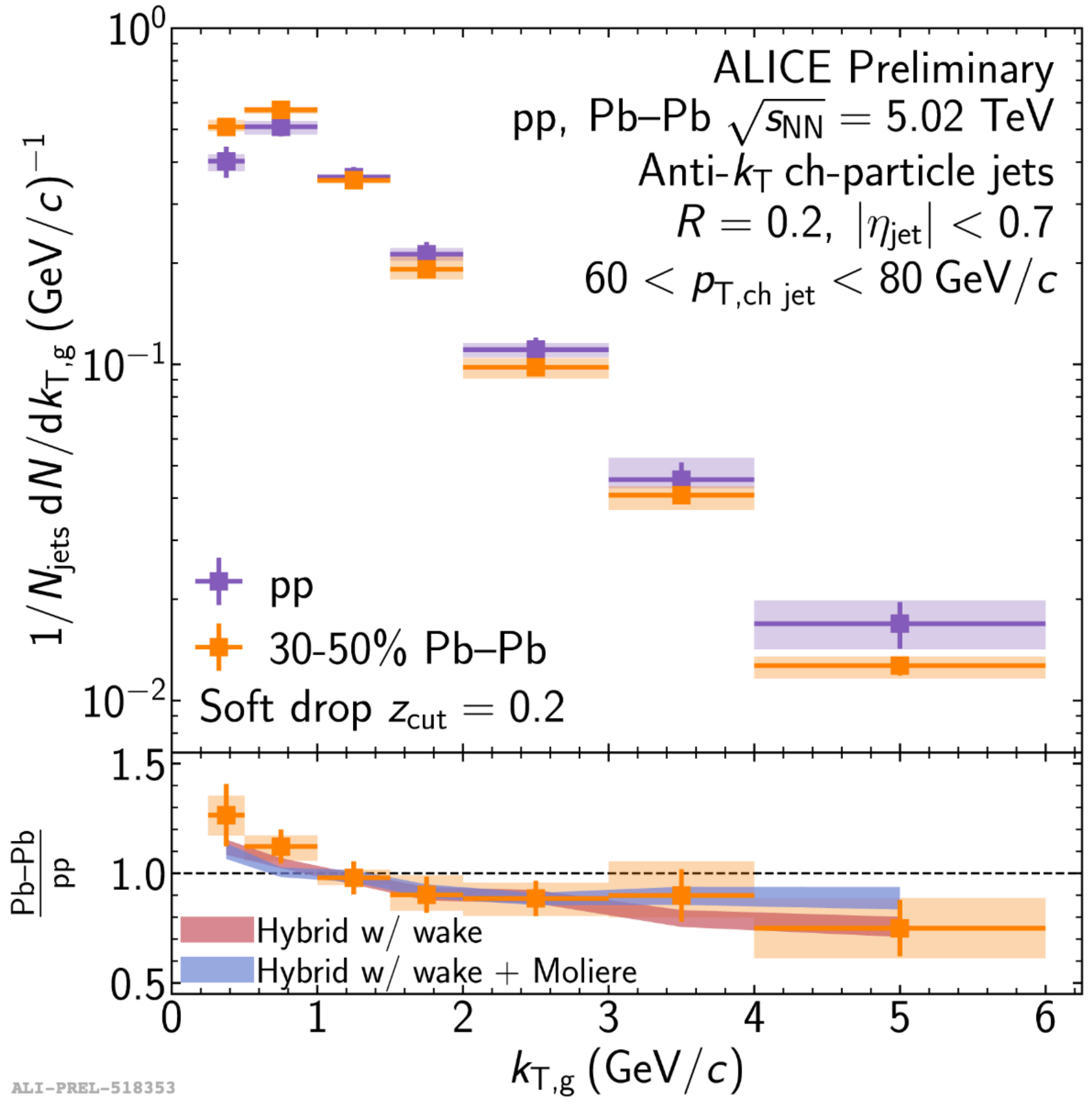
Different R_{max} parameter in the event-wise constituent subtraction method were explored

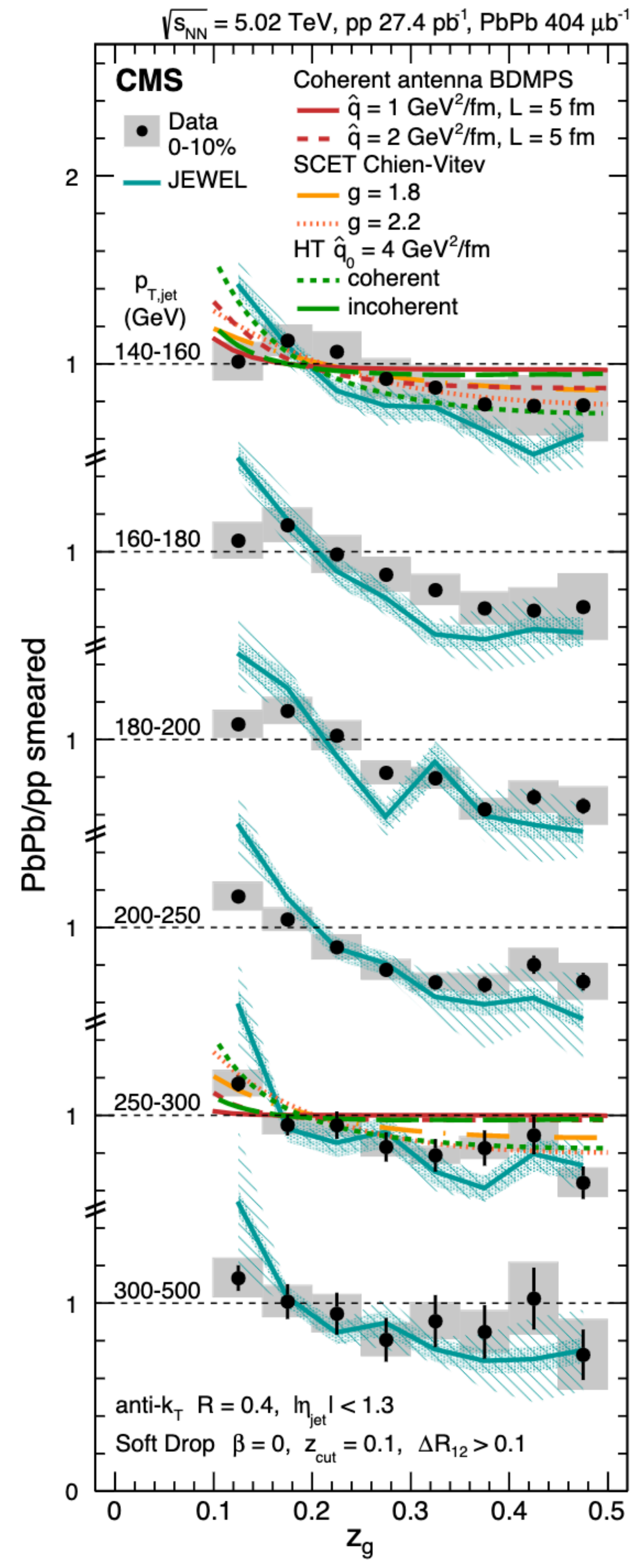
JHEP10(2018)139
JHEP 1406 (2014) 092
Phys.Rev.Lett. 110 (2013) 16

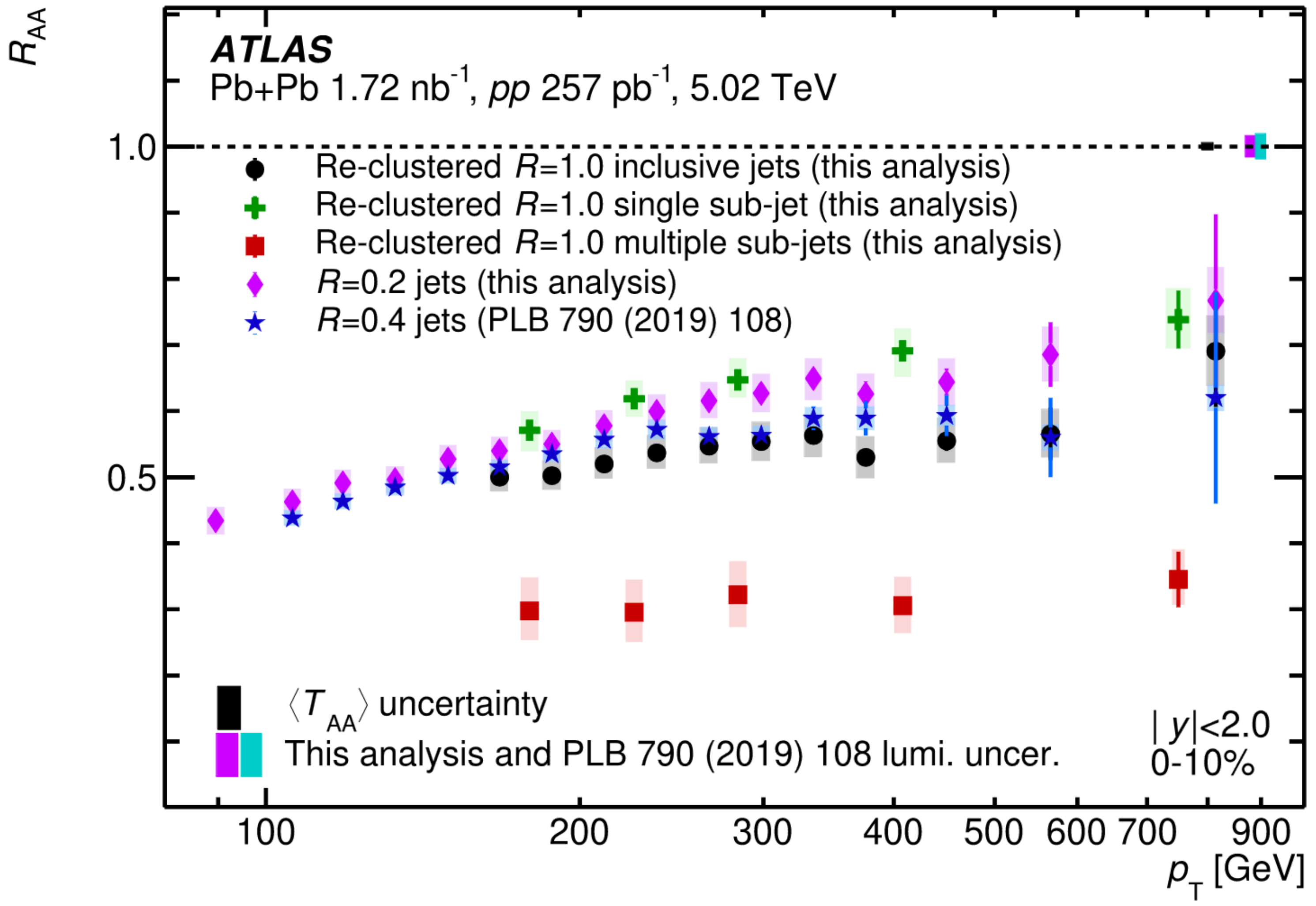
Scans of the Lund plane in PbPb: collage of results











In general all we see is a suppression of broad substructures, also at the level of jet shapes *lesson 4: it seems all we see is survivor bias*

A standard? factorized picture

Due to formation time arguments, the shower is expected to factorize into an early, high-energy vacuum shower and a subsequent medium-modified shower

—>there is no experimental confirmation yet of factorization   see Alba's talk

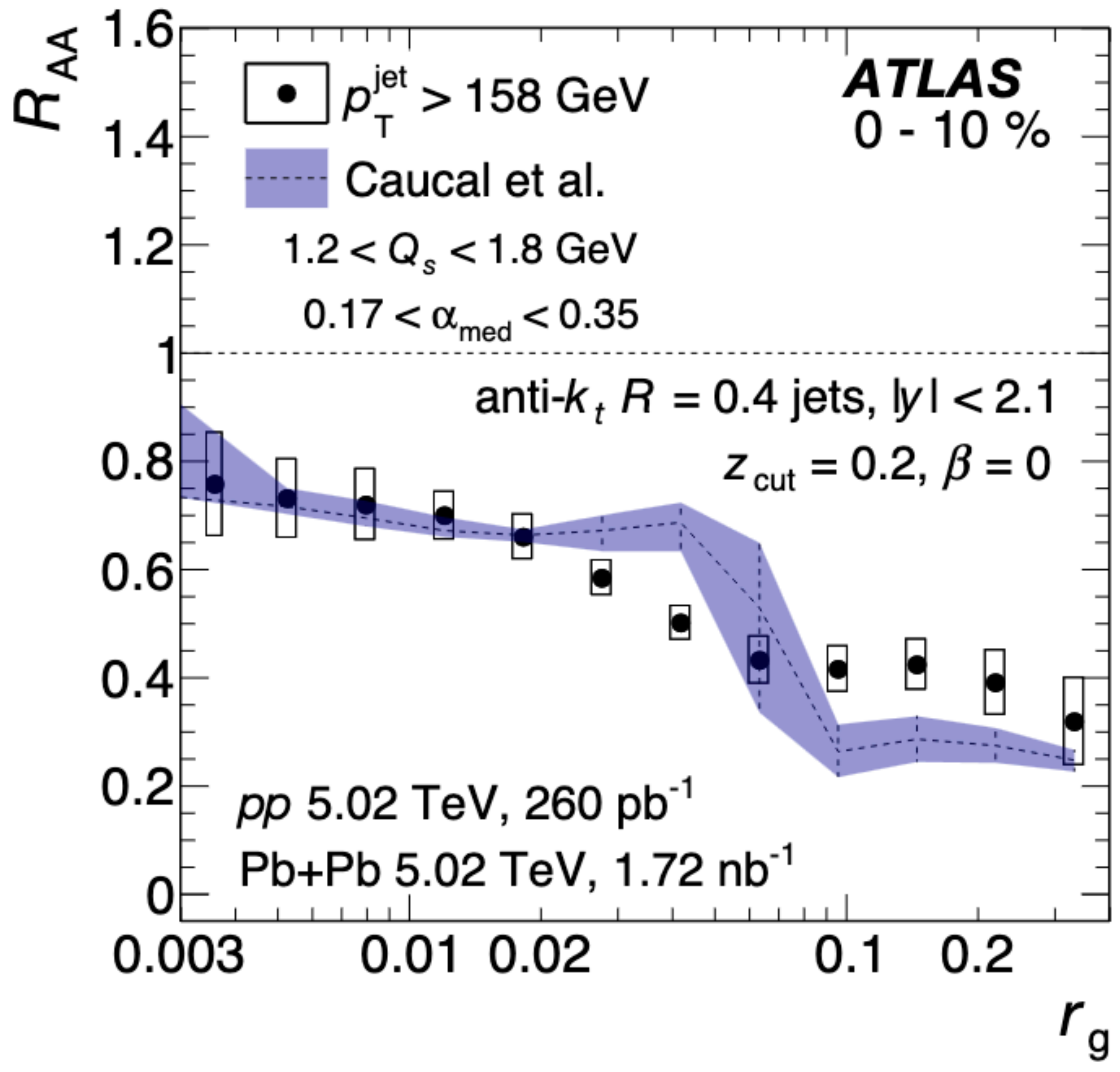
In this picture, early broad vacuum showers result into more quenched jets because they contain more in-medium emitters

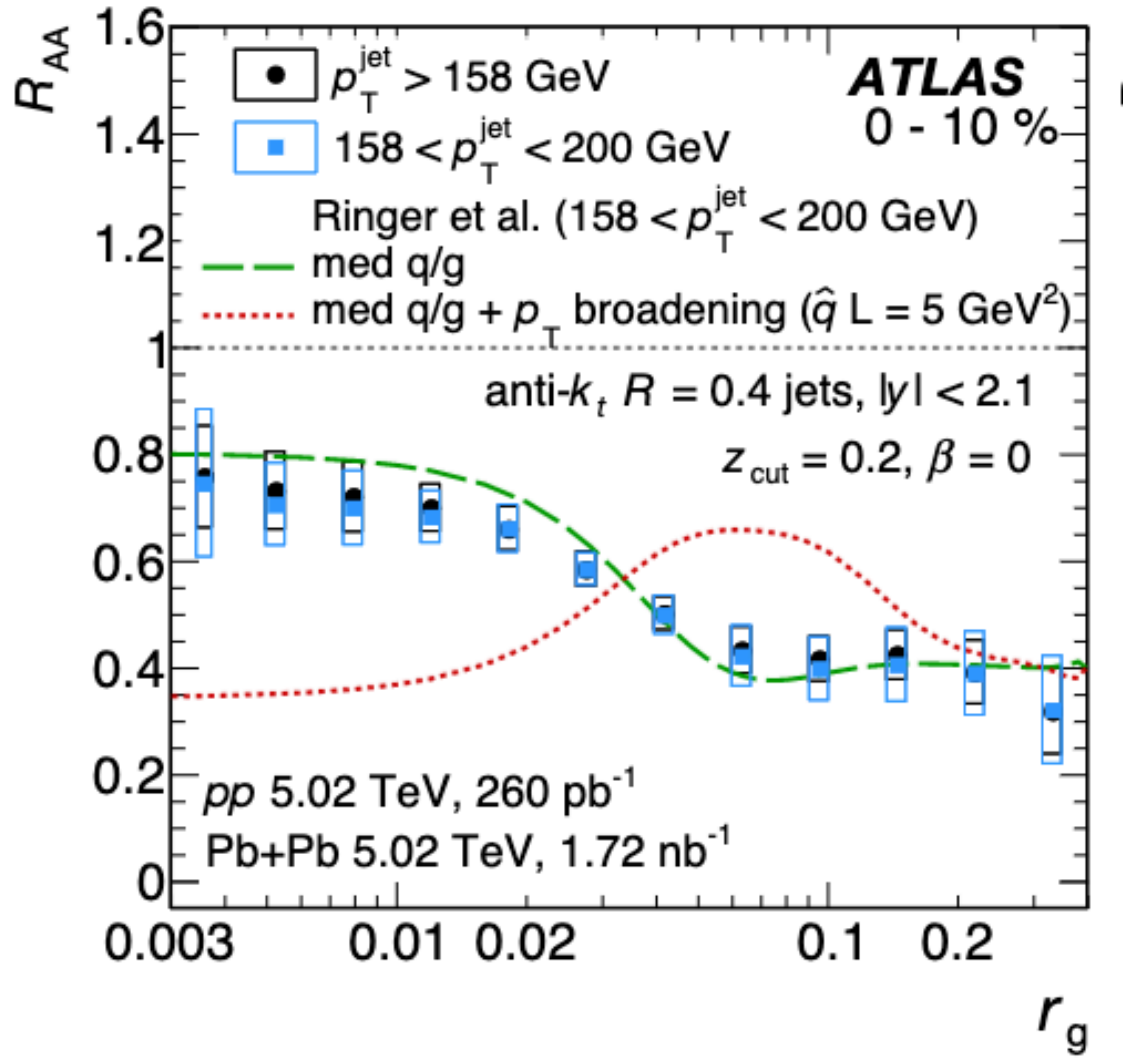
Broad structures are more quenched and thus filtered out to other jet momentum bins, resulting in an effective narrowing of the jet substructure

In this picture color coherence regulates the amount of survivor bias by further reducing the amount of in-medium emitters

Scans of the Lund plane in PbPb: collage of results

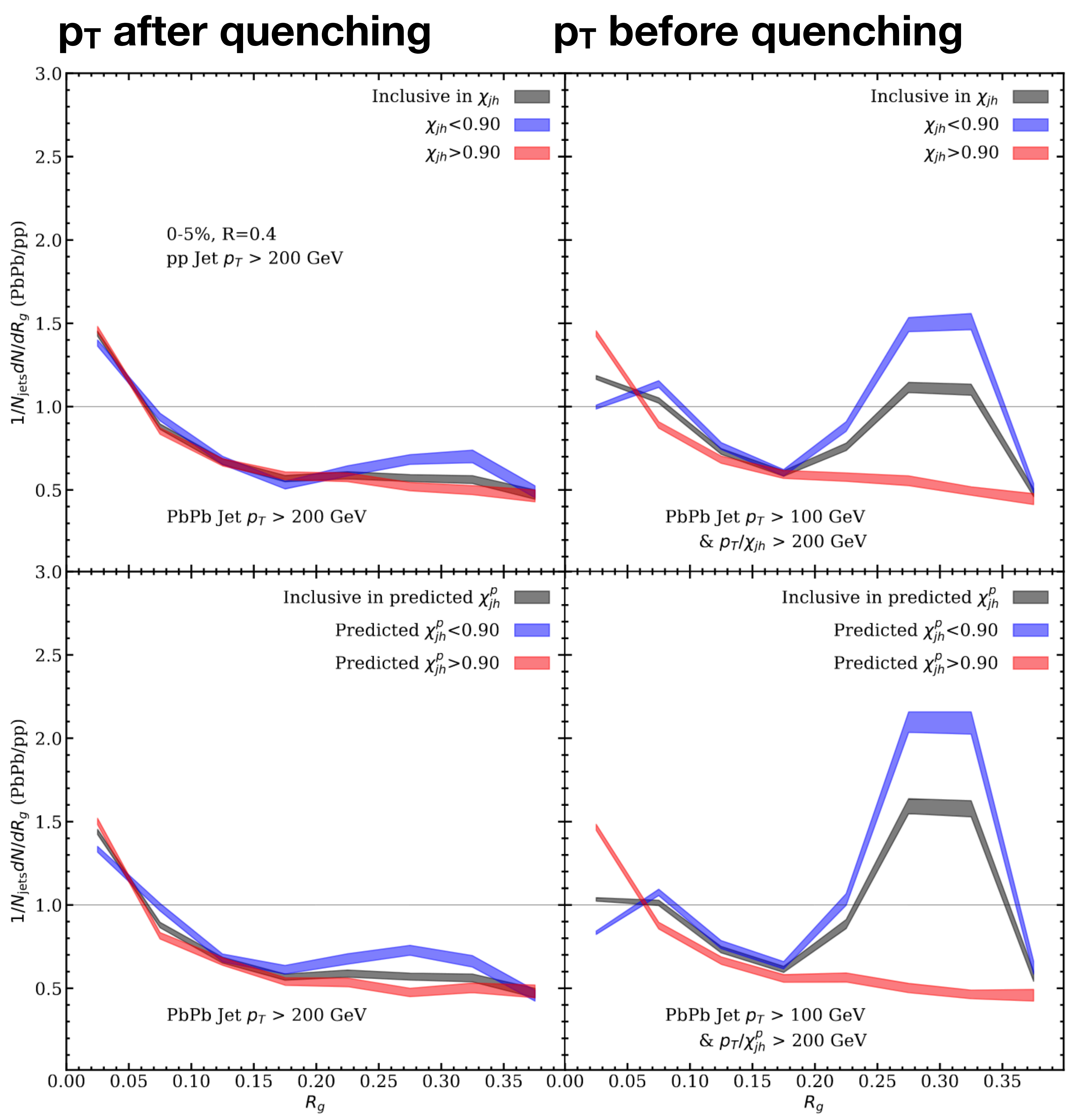
ATLAS, Phys. Rev. C 107 (2023) 054909



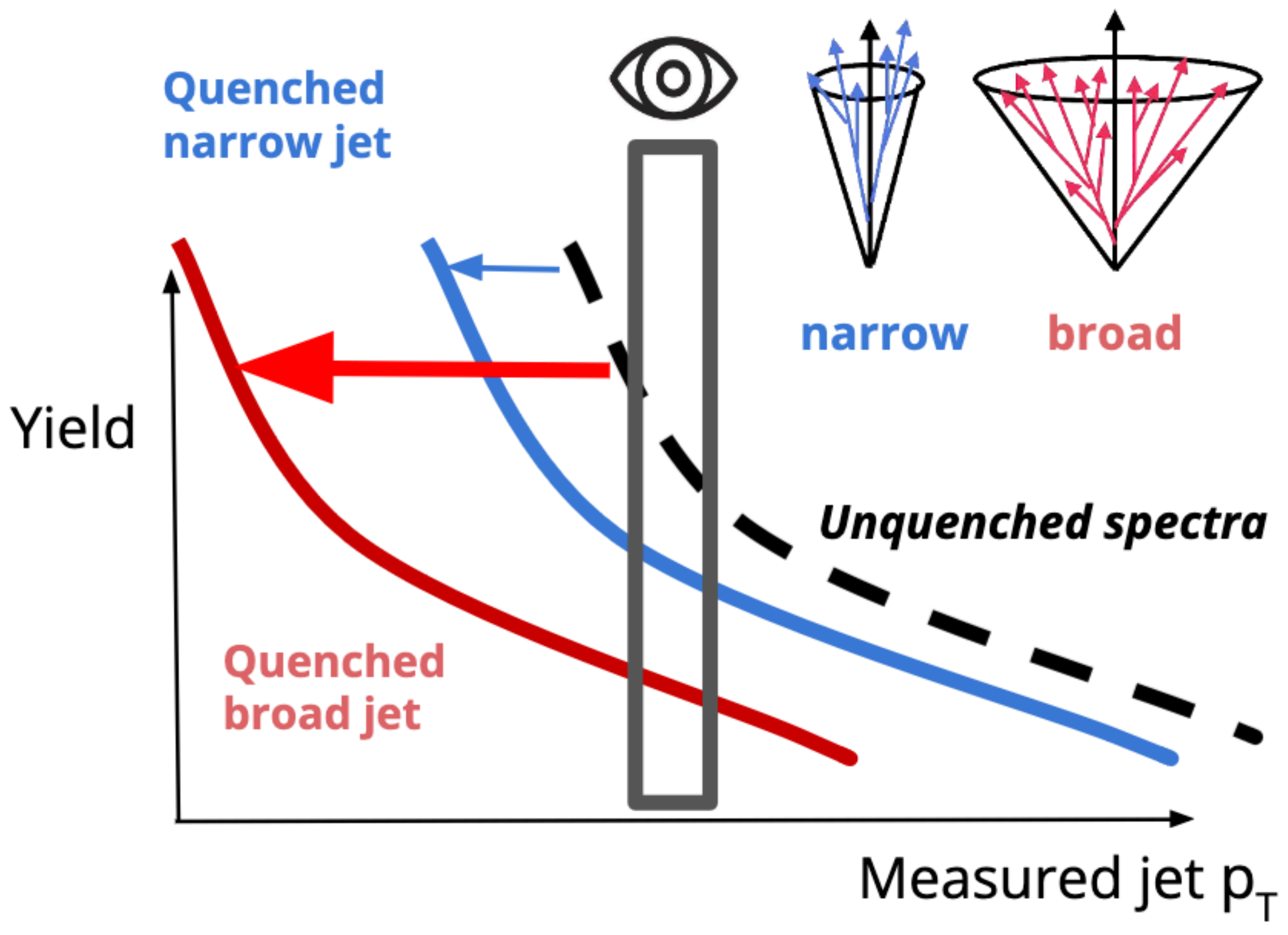


An intriguing step behaviour around the coherence angle in the implementation of Caucal et al
But step function also present in a model with no explicit implementation of coherence angle!

γ-jet substructure: suppression of the survivor bias



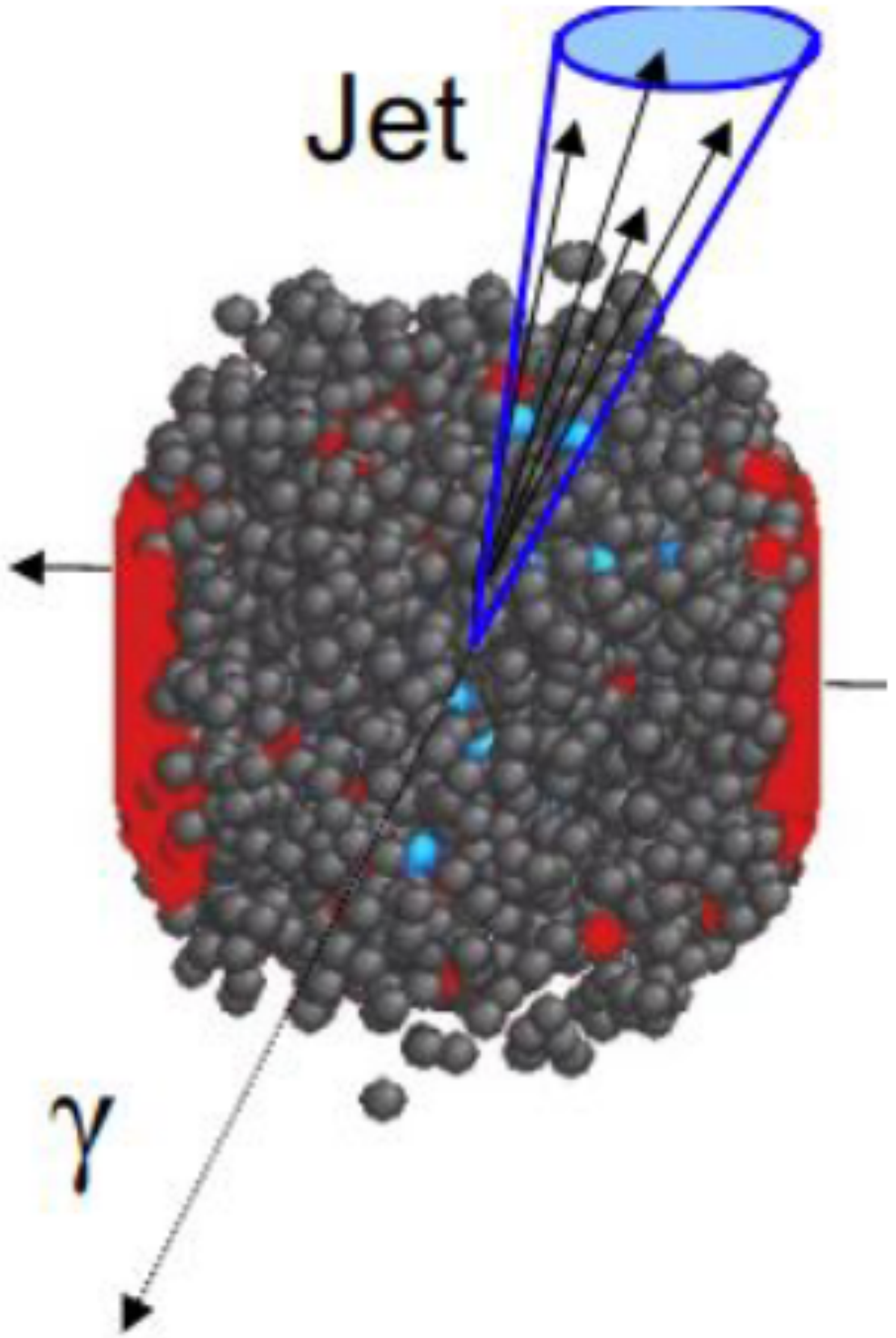
Du et al, 2106.11271, Brewer et al, 2009.03316



Inclusive measurements are limited by selection bias
Effective narrowing: broader jets are more quenched and migrate to lower pt bins

CMS-PAS-HIN-23-001

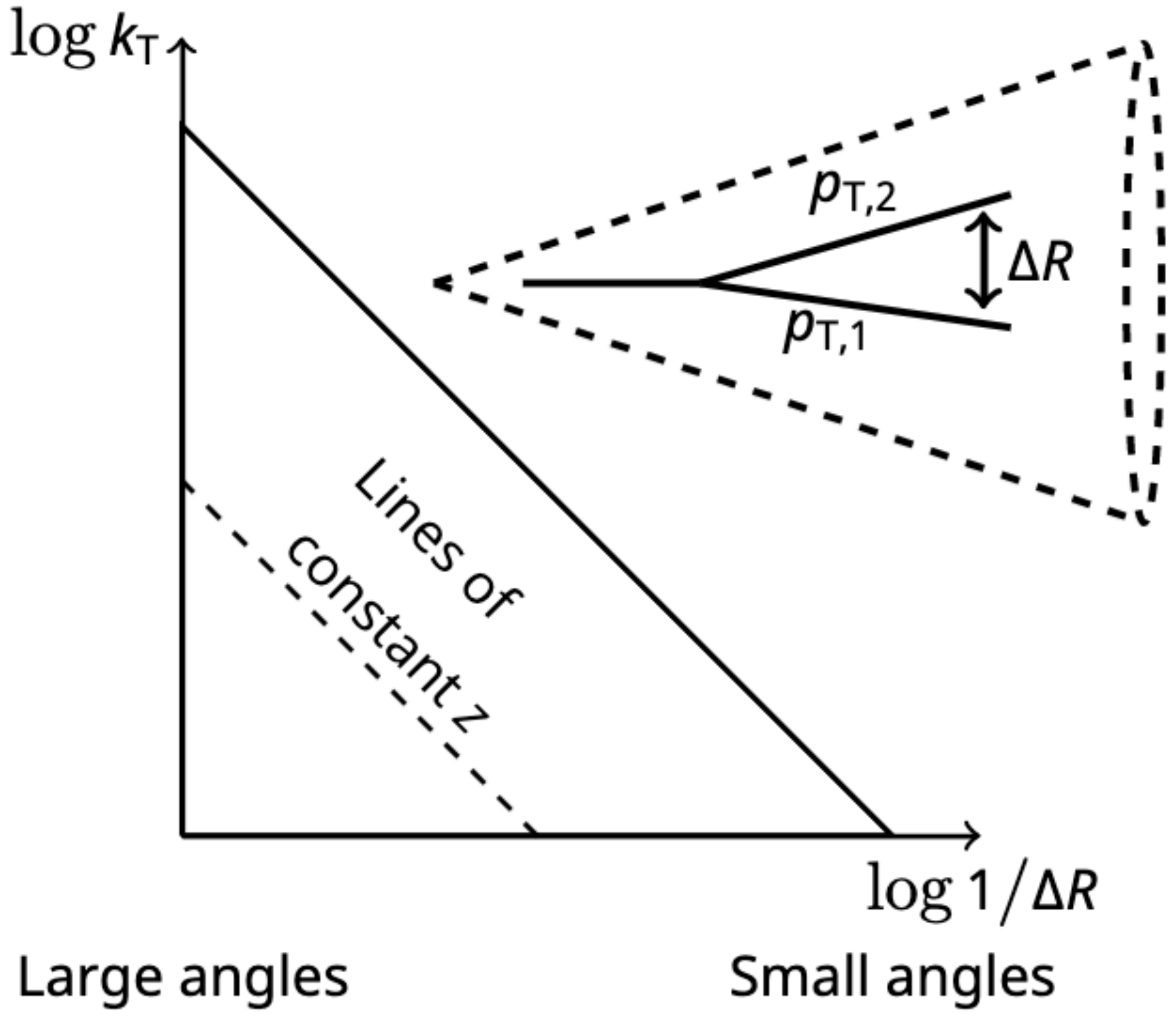
γ-jet substructure: suppression of the survivor bias



The EW boson does not interact strongly with the QGP

The ratio $x_J = p_T^{jet}/p_T^{\gamma}$ can be used as a proxy of the degree of quenching of the recoiling jet

We look at the Lund plane section defined by SoftDrop grooming

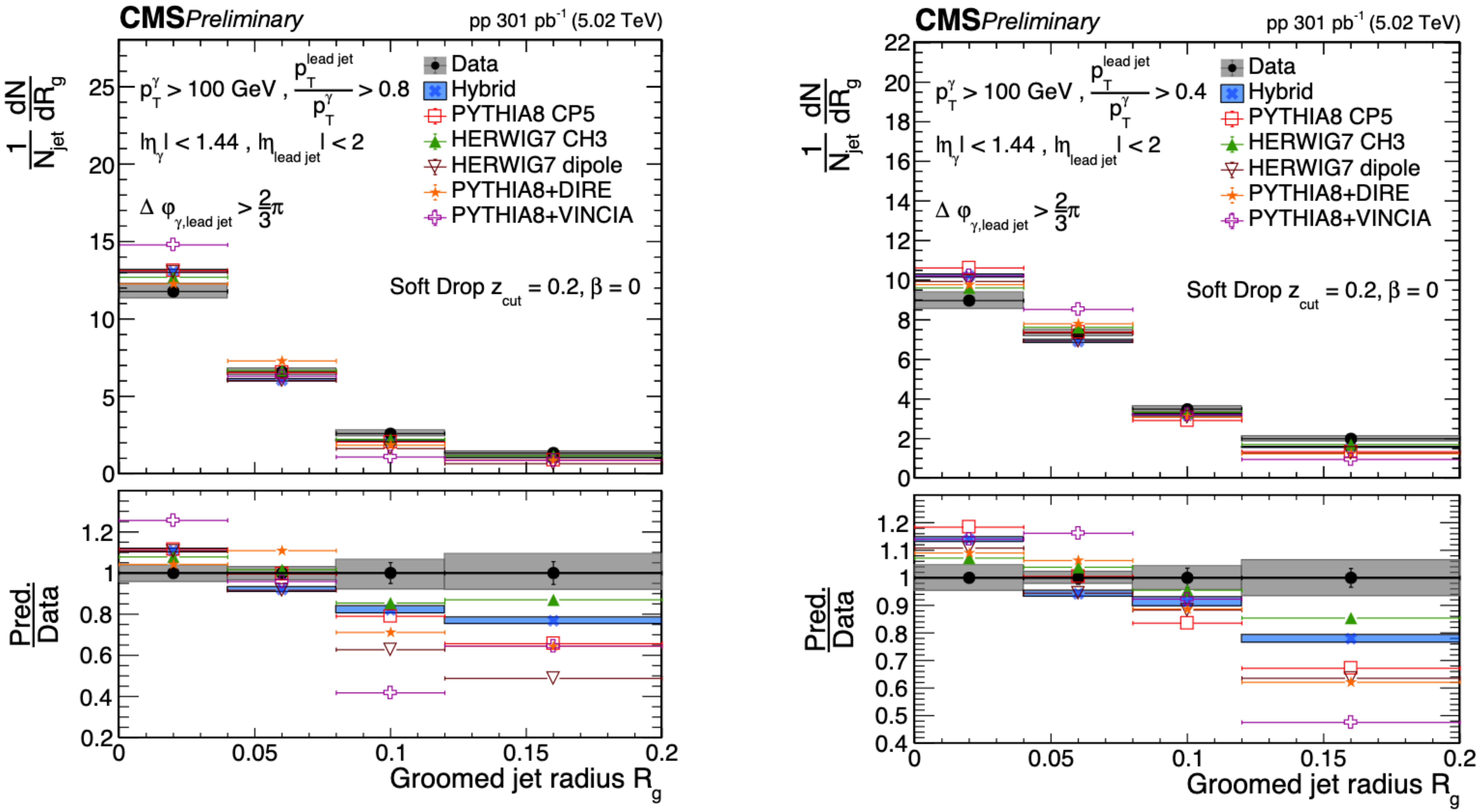


CMS-PAS-HIN-23-001

lesson 4: it seems all we see is survivor bias

γ-jet substructure: suppression of the survivor bias

pp



More $(x_J > 0.8)$ or less $(x_J > 0.4)$ balanced jets due to vacuum out of cone radiation

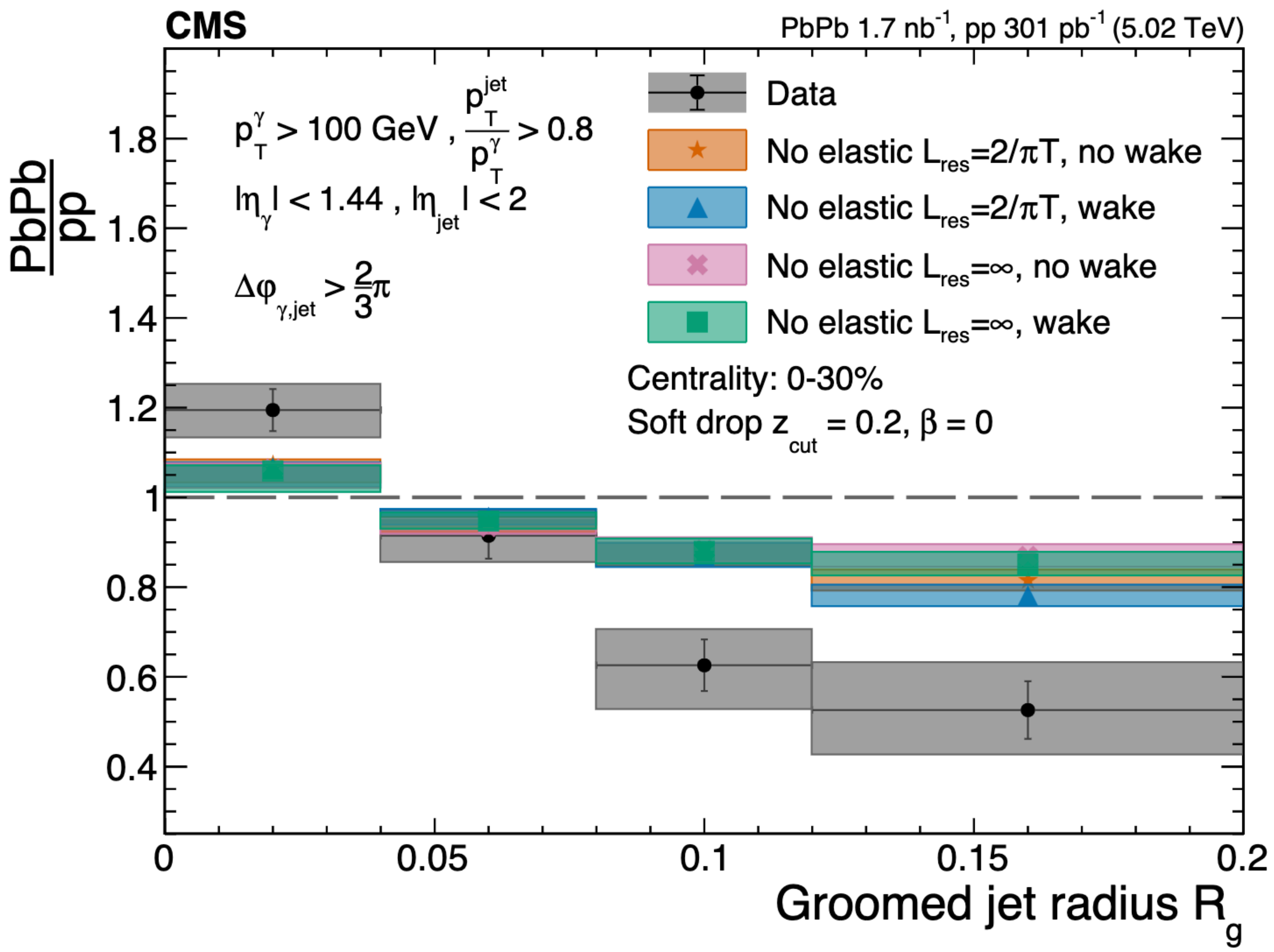
CMS-PAS-HIN-23-001

Worse description by models than in the inclusive case, in particular in the tails of the distribution

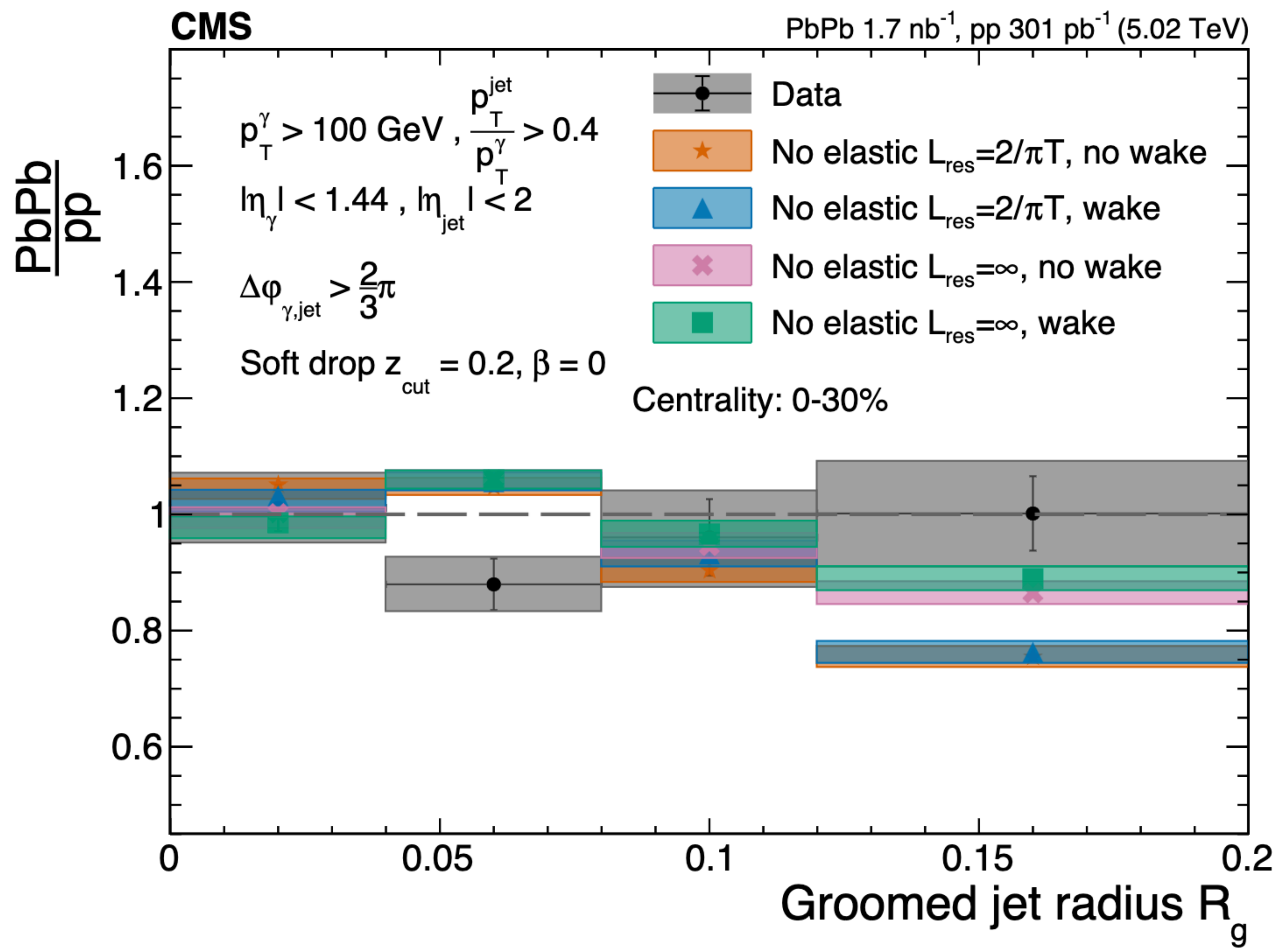
γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



more quenched xJ>0.4



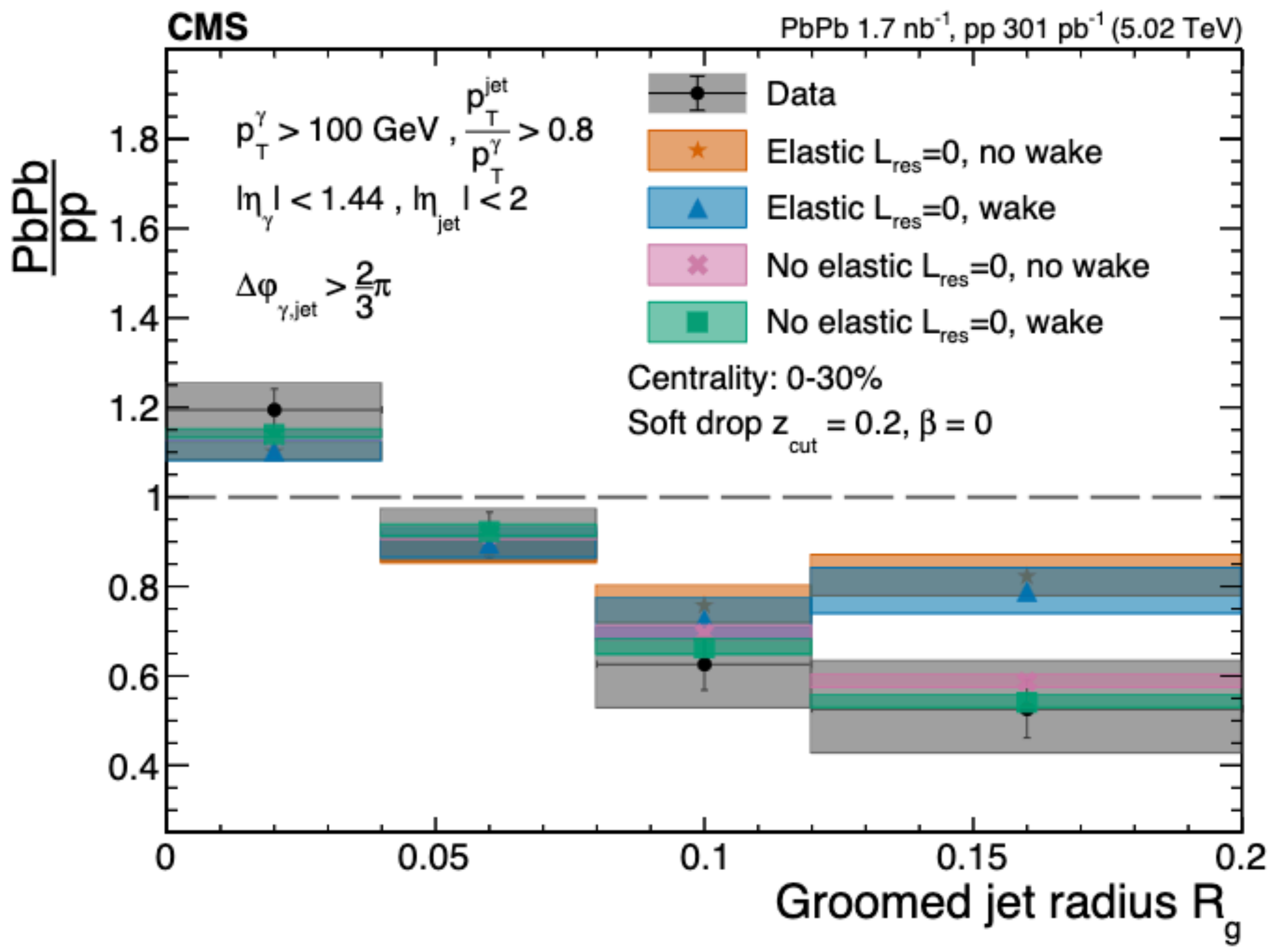
Strong narrowing for jets that are less quenched
No narrowing when including more quenched jets in the recoil sample —>surivor bias!

CMS-PAS-HIN-23-001

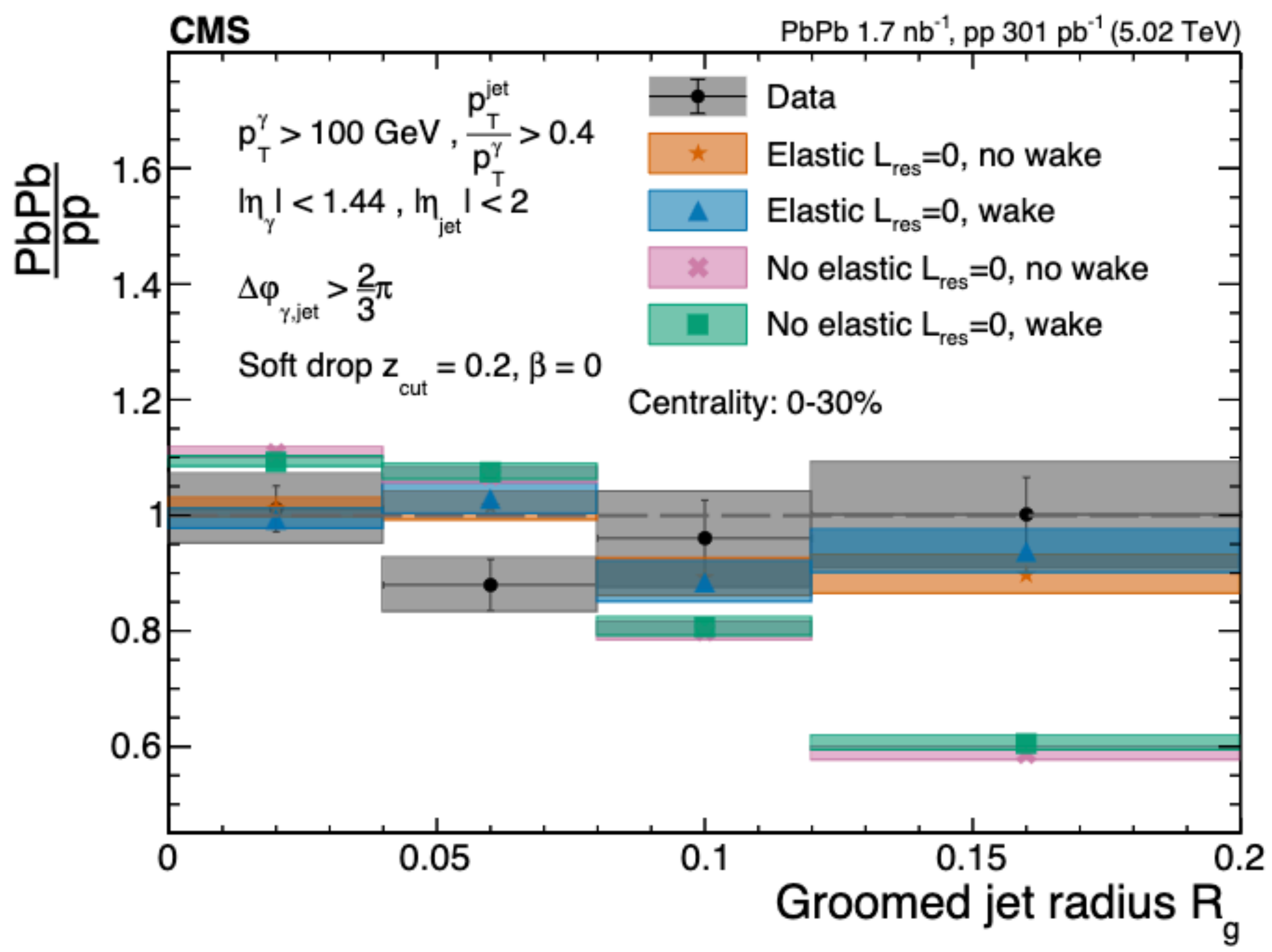
γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



more quenched xJ>0.4



Comparison to the Hybrid model ***(Rajagopal et al, JHEP 10 (2014) 019)***

Factorized by construction

Interplay of several mechanisms:

- Energy loss
- Elastic hard interactions (interaction with free q/g within QGP)
- Resolution length

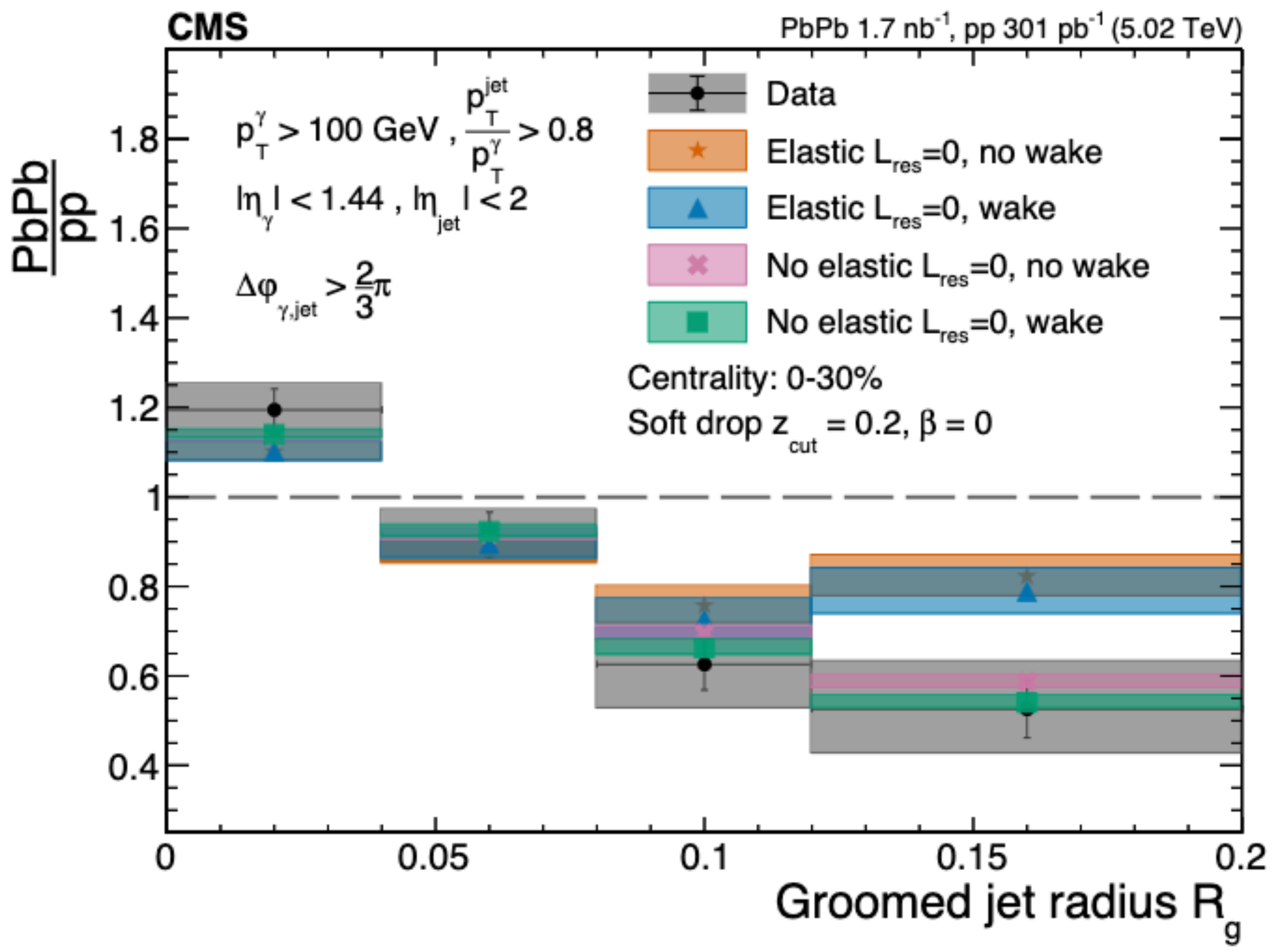
small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

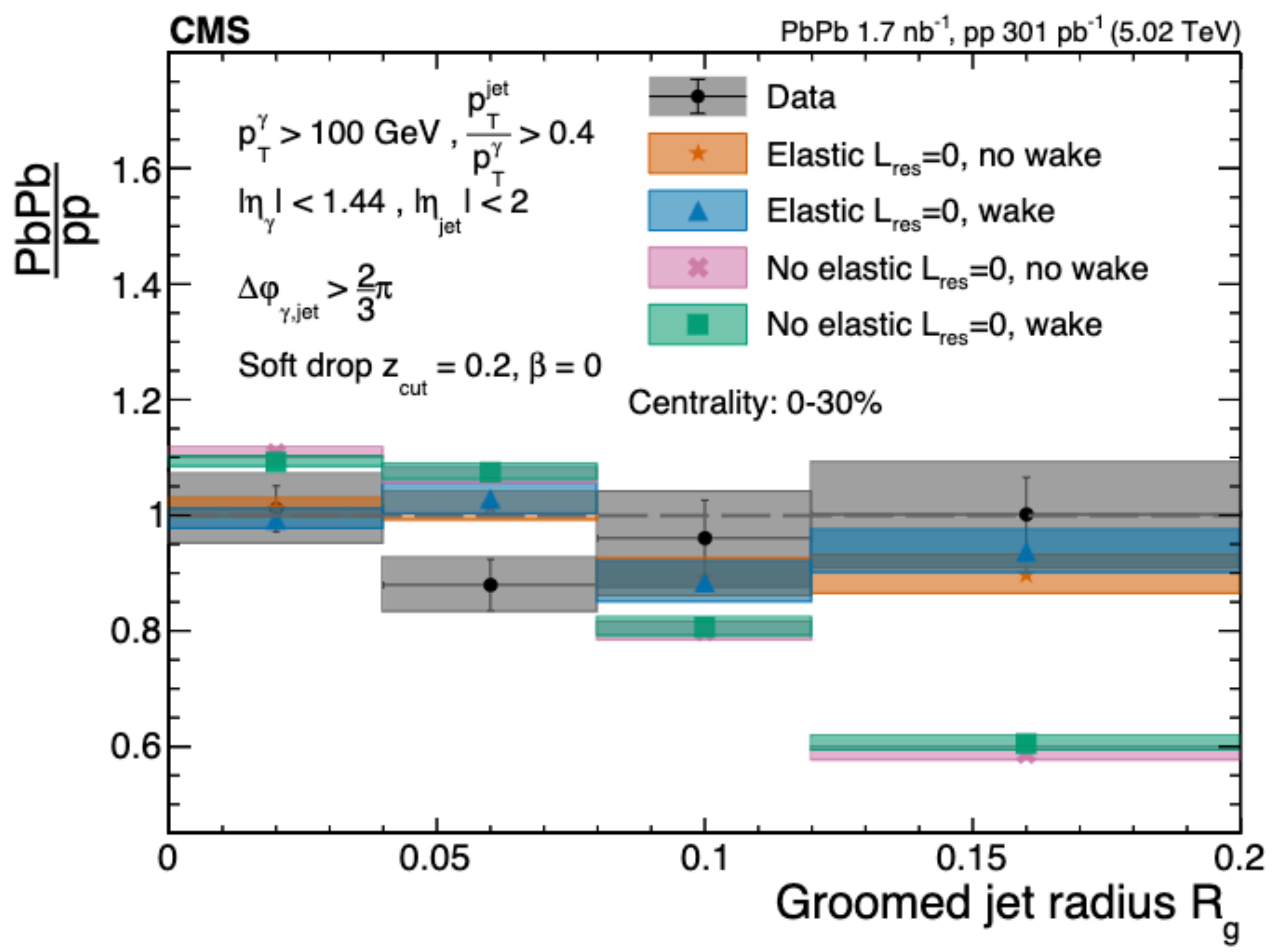
γ-jet substructure: suppression of the survivor bias

PbPb

less quenched xJ>0.8



more quenched xJ>0.4



Comparison to the Hybrid model *(Rajagopal et al, JHEP 10 (2014) 019)*

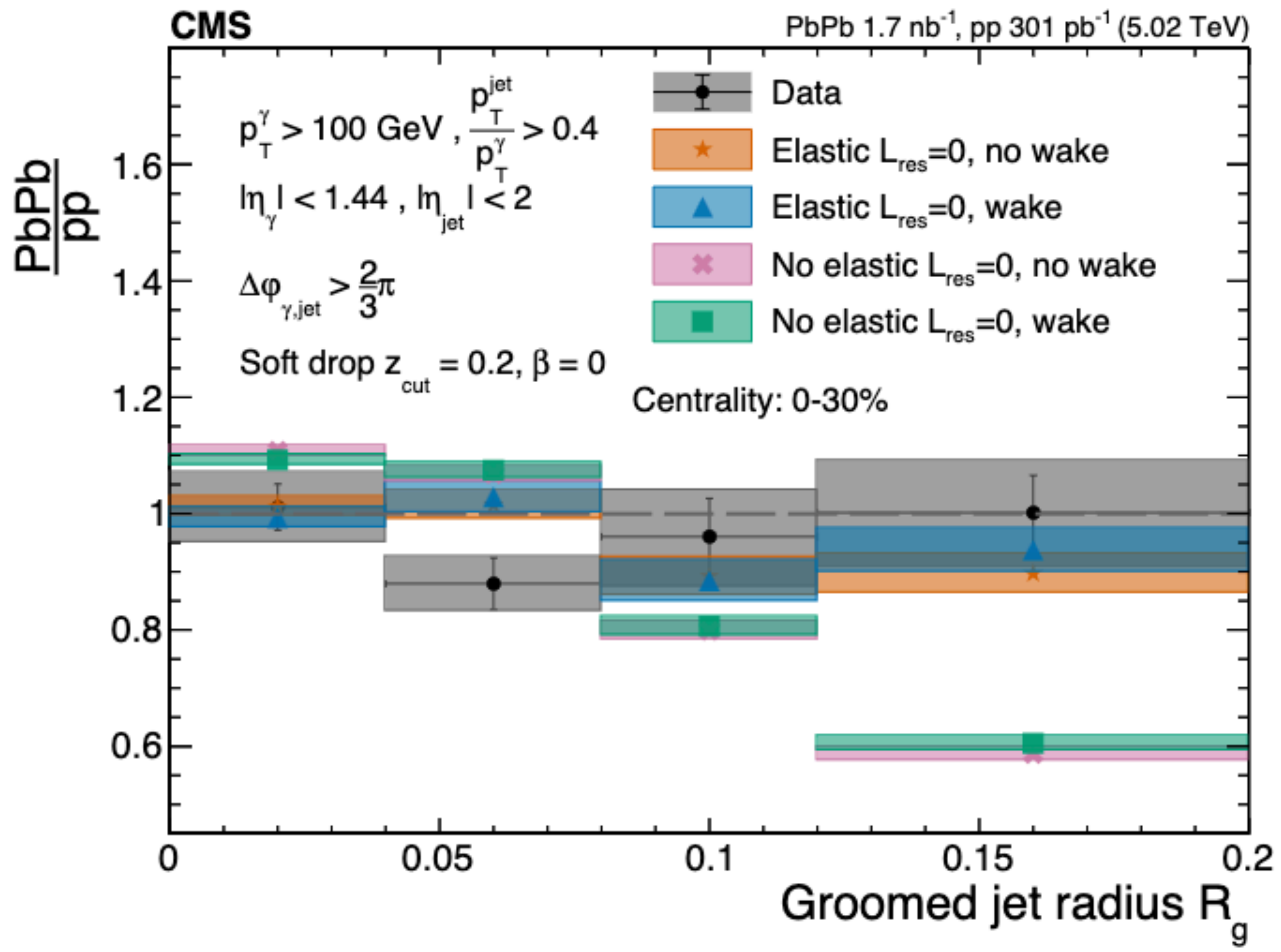
Not a single set of parameters describes the differential data consistently
Great constraining power of the data

small-R suppresses nonperturbative effects like the wake!

CMS-PAS-HIN-23-001

γ-jet substructure, prospects

xJ>0.4



The survivor bias can be fully suppressed when $x_J \to 0$
(the model has a strong survivor bias down to xJ=0.1)

Since low jet p_T is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

Ideally, **simultaneous measurement of x_J and substructure** ,current results are statistically limited

CMS-PAS-HIN-23-001

Summary

The Lund plane density in pp: strong constrain to the parton shower in a “modular” fashion

Building blocks of the parton shower exposed: splitting functions, dead cone.

Inspection of the Lund plane in heavy-ion collisions is an active area of research, fundamental microscopic properties of the QGP at reach

In order to measure the amount of intrajet broadening to link it to fundamental properties, survivor bias needs to be suppressed: new posibilities using EW-boson tagged jet substructure

Interplay between anti angular ordered emissions and CA algorithm for jet quenching needs further study

New interesting possibilities in the domain of heavy flavour jet substructure, but not the scope of this talk