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SAPIENZA
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Jet substructure and jet quenching in heavy-ion collisions

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Workshop on High Luminosity LHC and hadron colliders
Frascati, 3 October 2024

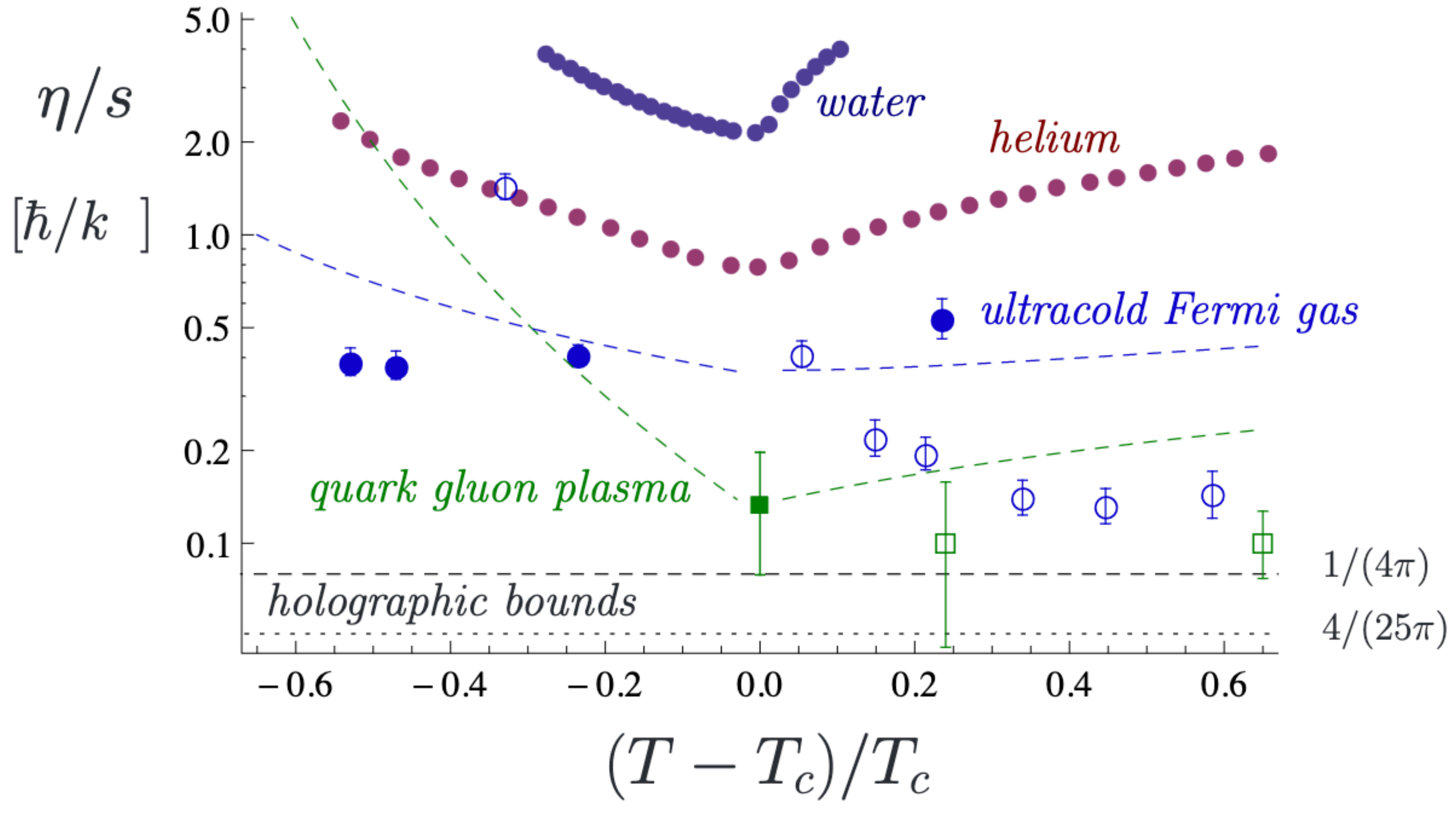
The quark gluon plasma (QGP)

Heavy ion collisions form a droplet of quark gluon plasma

This plasma is measured to be a liquid (not a gas, strongly coupled fluid) with a remarkably low viscosity

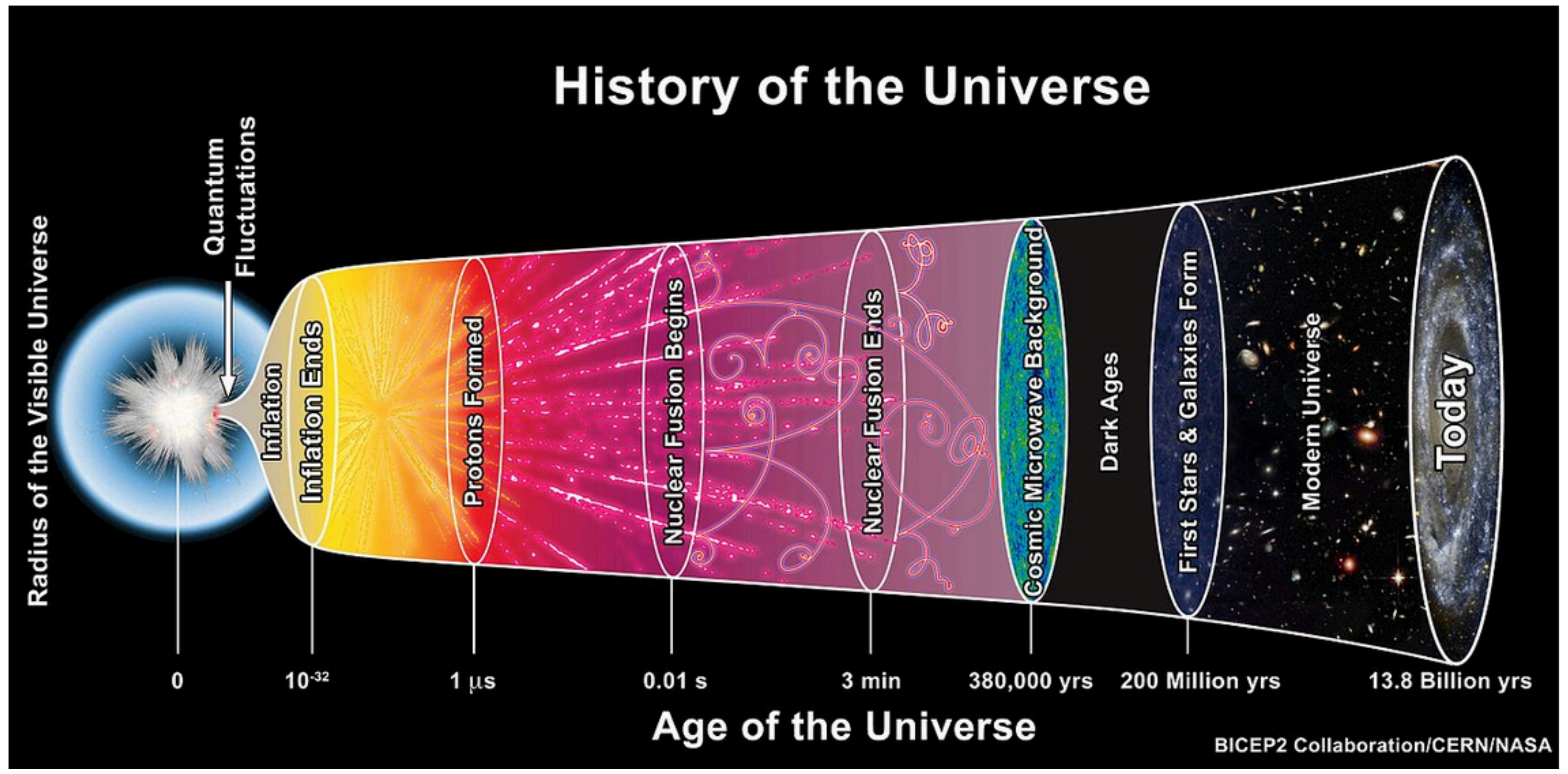
Smallest and hottest droplet of liquid made on earth

Probably the simplest form of complex quantum matter that we know of



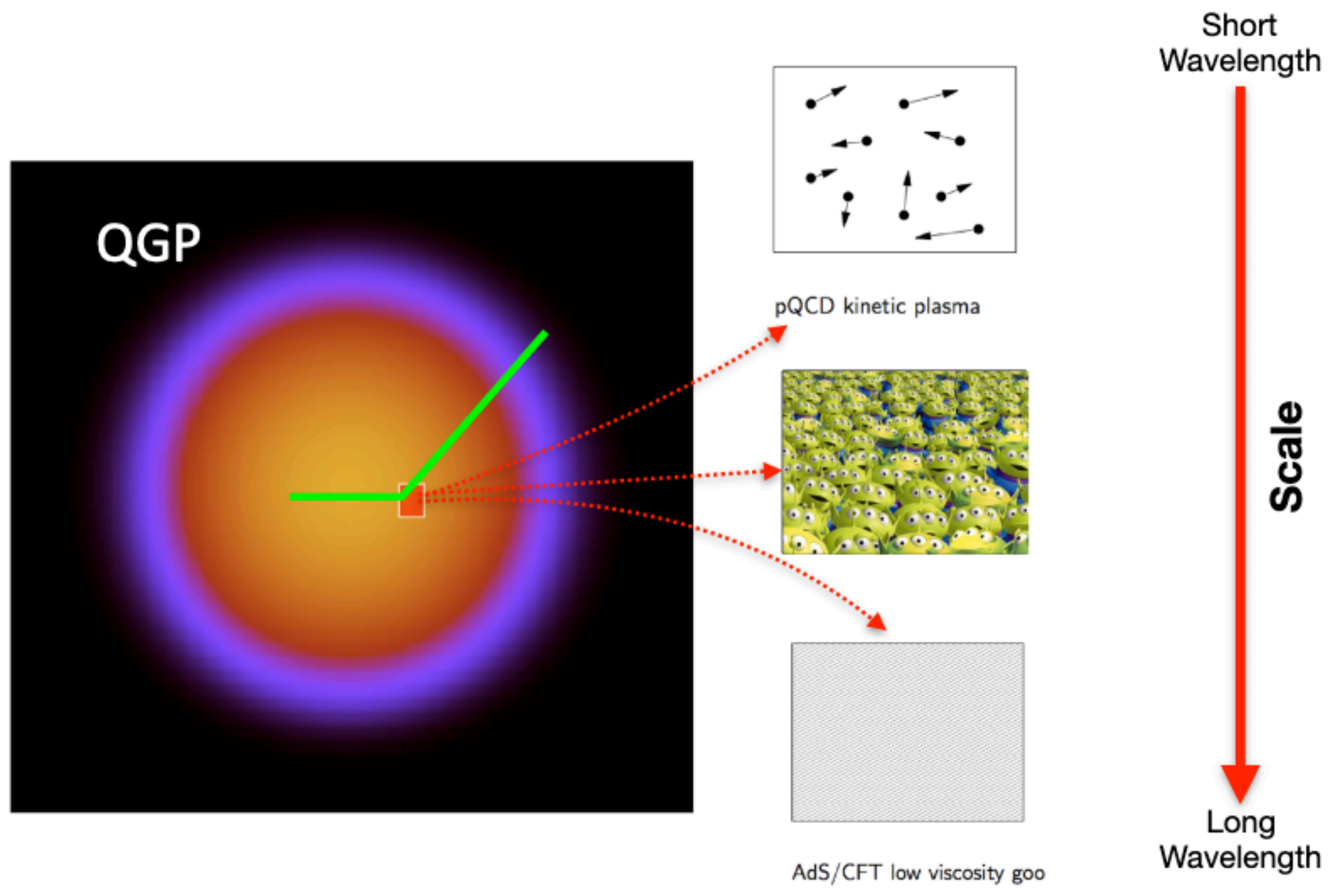
Why is this interesting?

- Cosmology
- Phase diagram of nuclear matter
- Emergence of collectivity



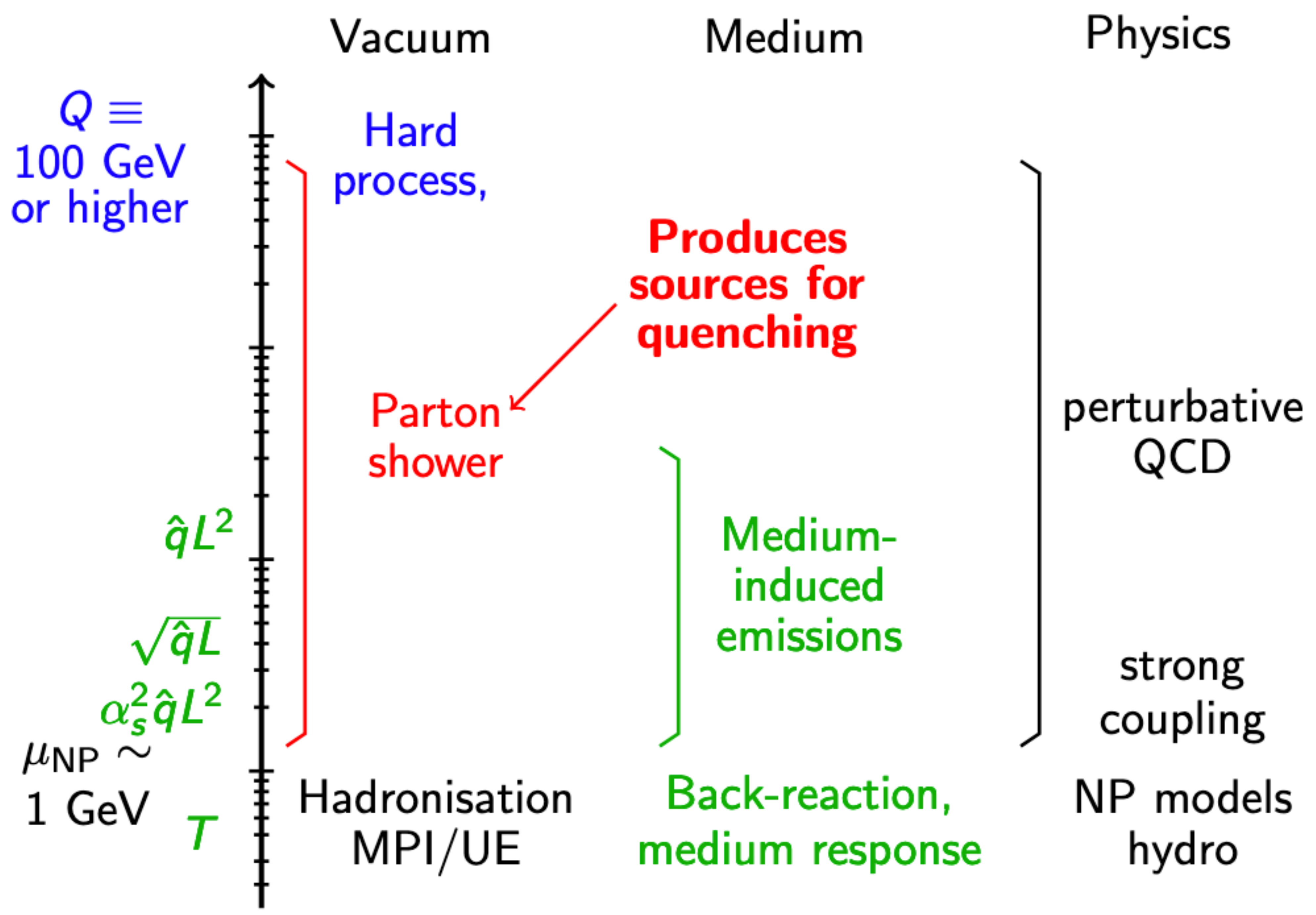
Probing the QGP at varying length scales

What is the microscopic structure of QGP?



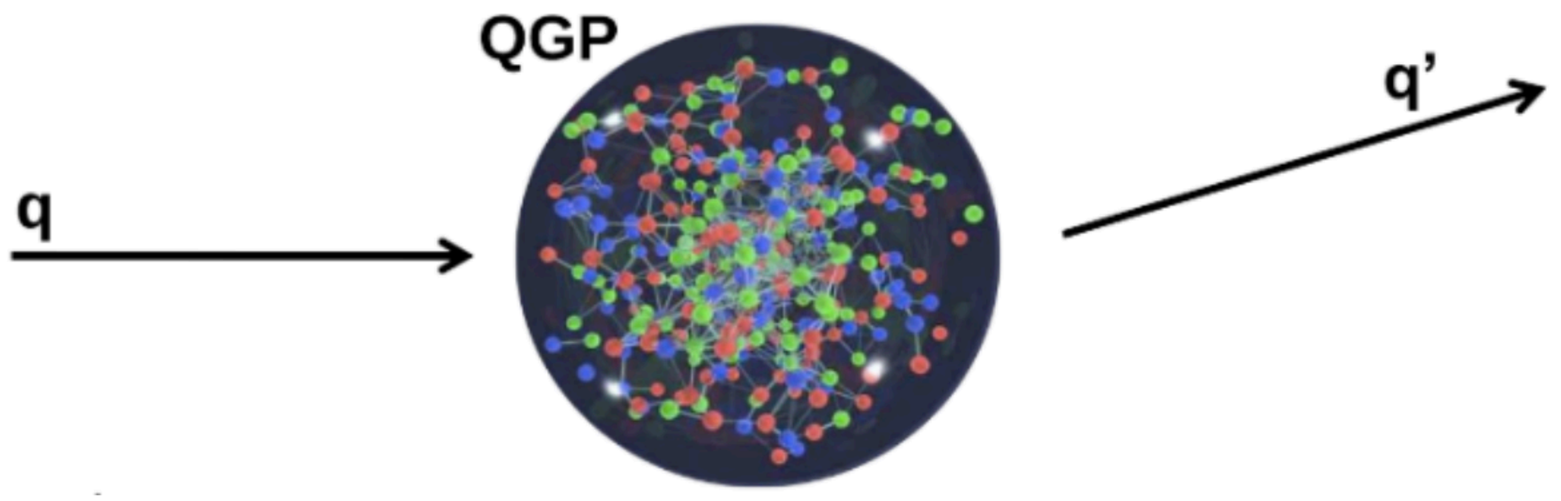
Sketch from Gunter Roland

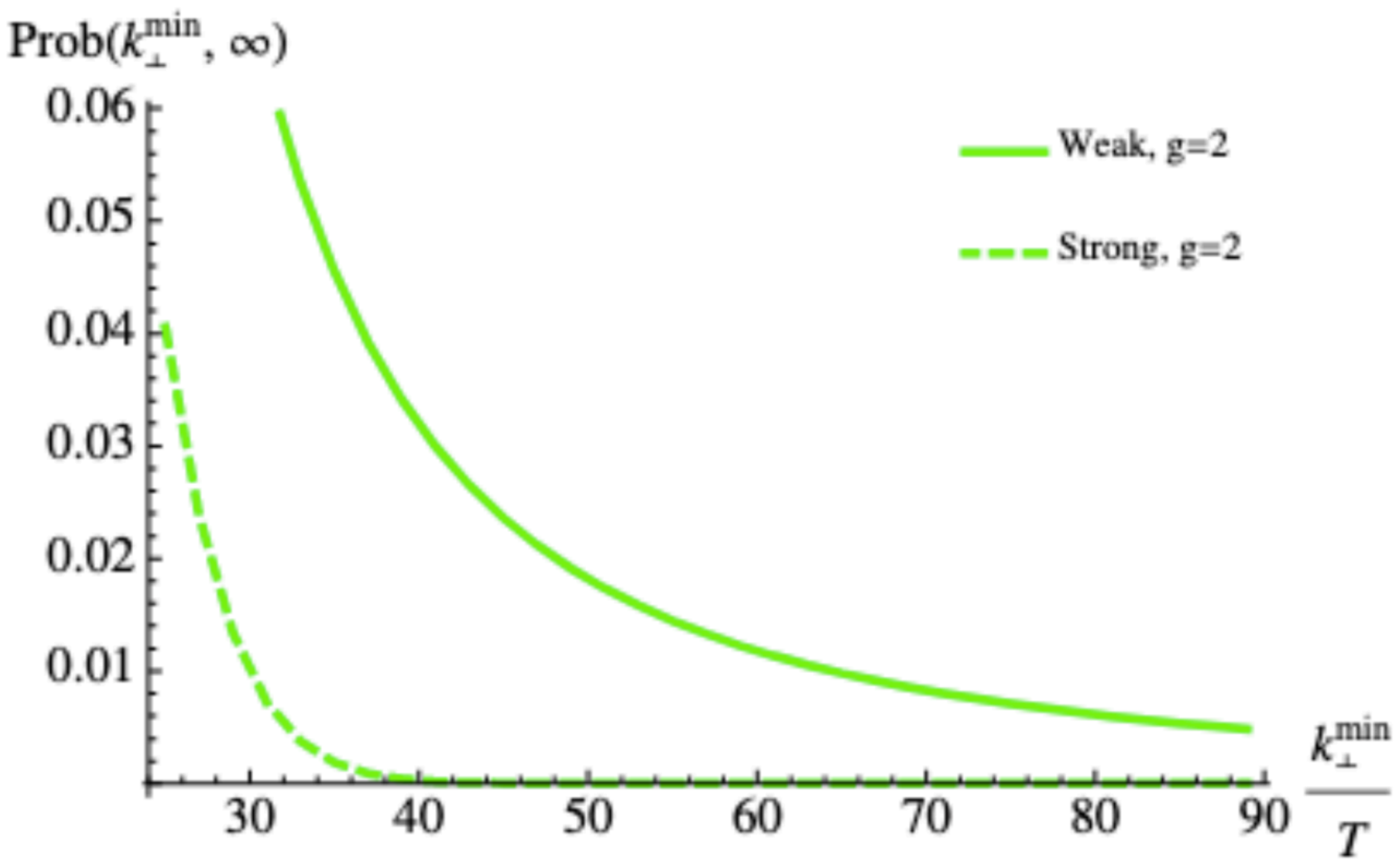
Jet scales interwound with the medium scales



sketch from G.Soyez

Probing the QGP with jets I





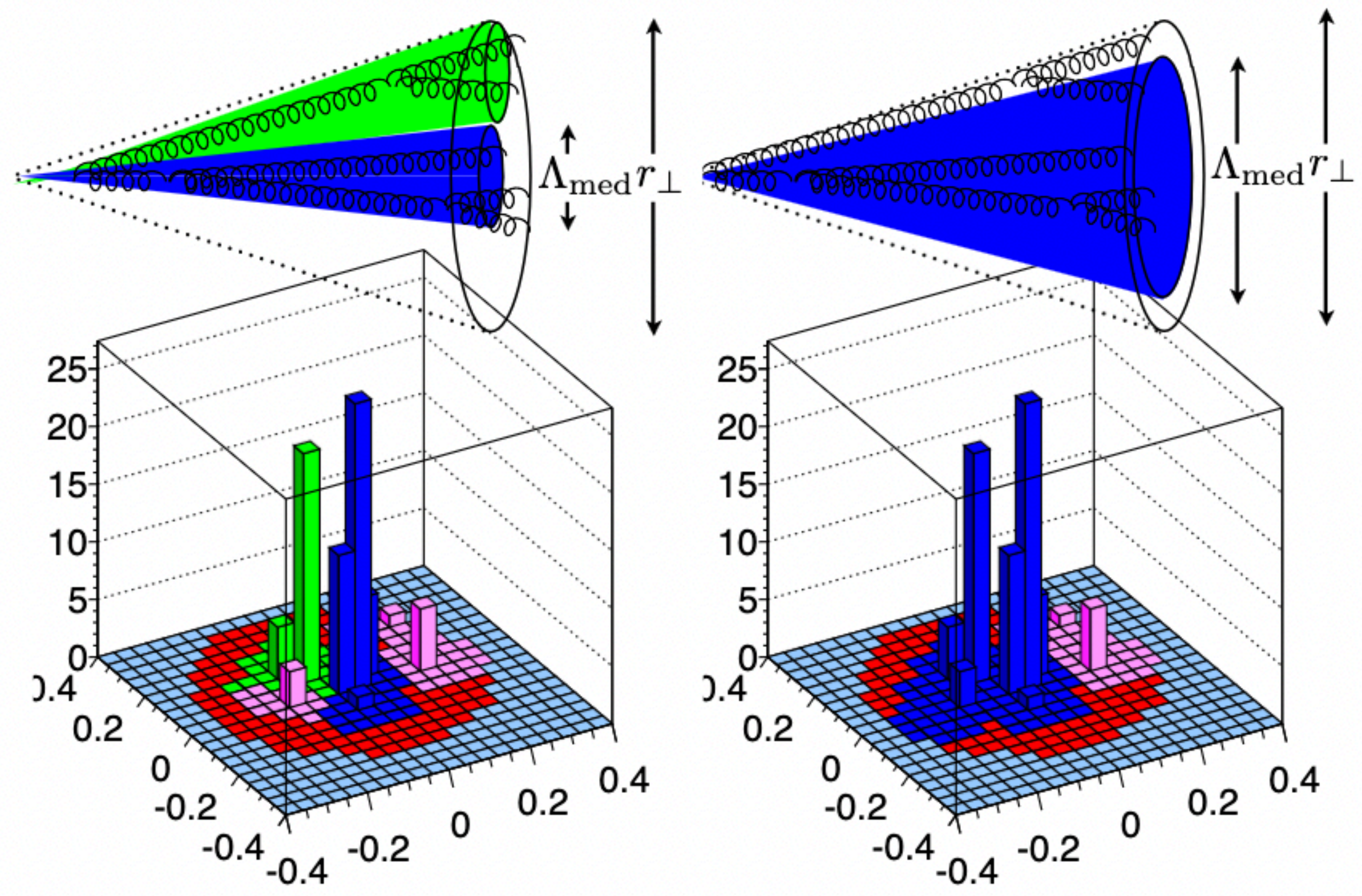
D'Eramo et al, JHEP 05 (2013) 031

When an energetic jet constituent interacts with the QGP:

if the QGP is strongly coupled at all distances, one expects a gaussian distribution for the transverse momentum of the scattered parton

However the underlying rules are QCD's, so if the QGP is probed at sufficiently short distances, the q and g degrees of freedom should emerge and one expects a $1/k_T^4$ tail, typical from point-like scatterers

Probing the QGP with jets II



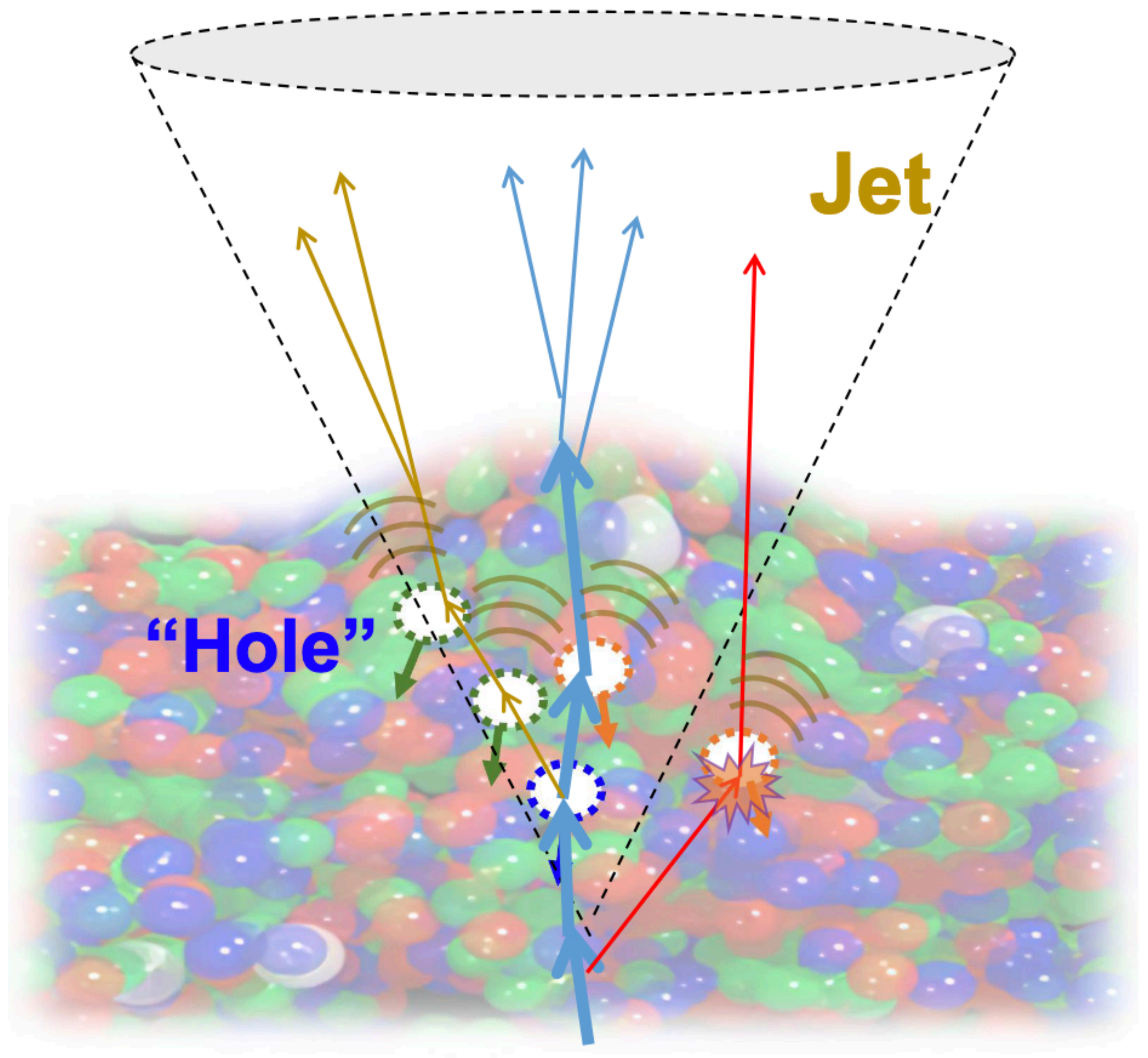
New scales in medium: emissions with $\theta < \theta_C$ are not resolved by the medium

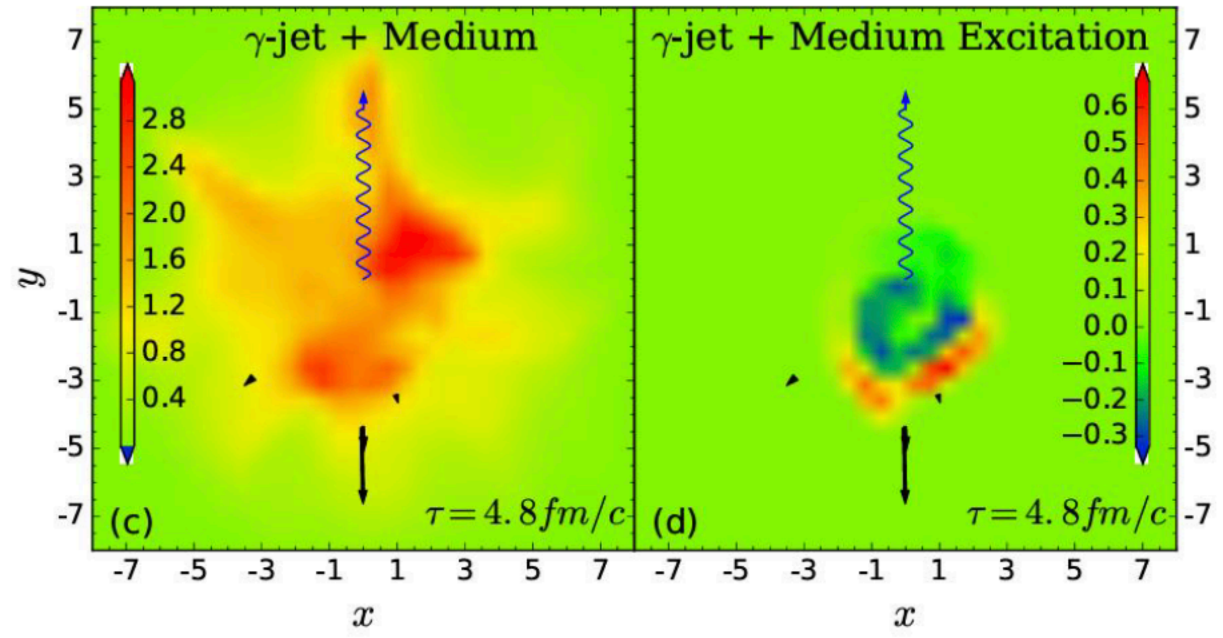
Consequence: jet-QGP interaction depends on the jet internal structure

θ_C not yet unambigously measured

Casalderrey et al, Phys.Lett.B725 (2013)

Probing the QGP with jets III





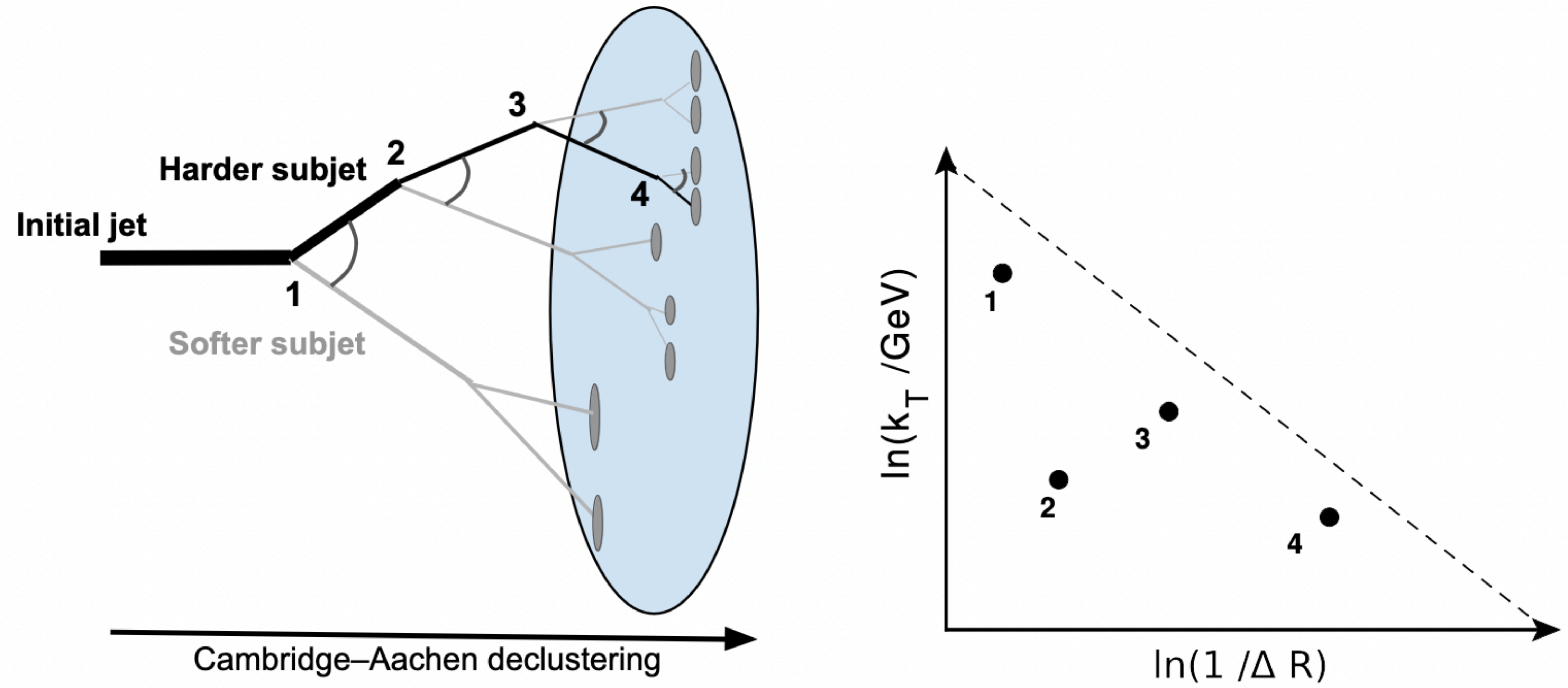
CoLBT Chen, Cao, Luo, Pang, Wang
PLB 777 (2018) 86-90

More water going on the duck direction

Jets drag the QGP
Experimentally, correlated background

Two recent languages for jet substructure

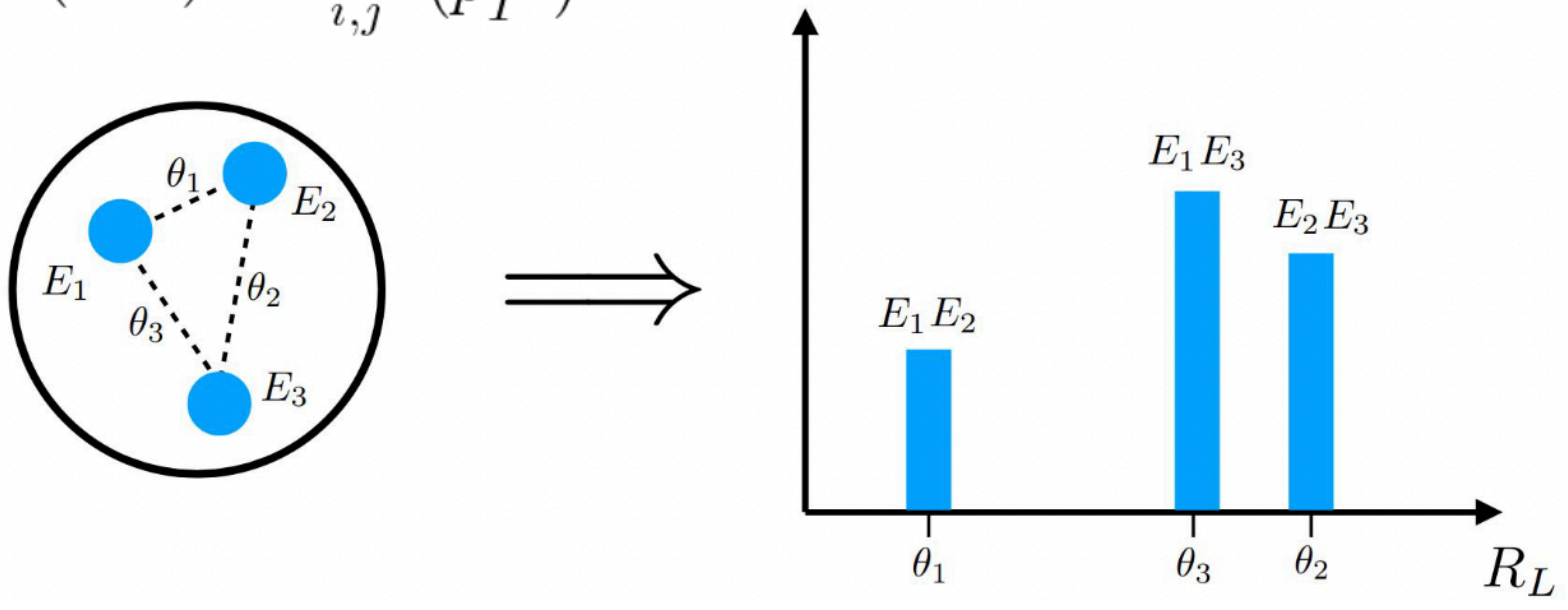
Using the jet tree



Hierarchical structure of jet constituents by undoing the clustering history

Using the energy flow

$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \frac{p_T^i p_T^j}{(p_T^{jet})^2} \delta(\Delta R_{ij} - \Delta R)$$

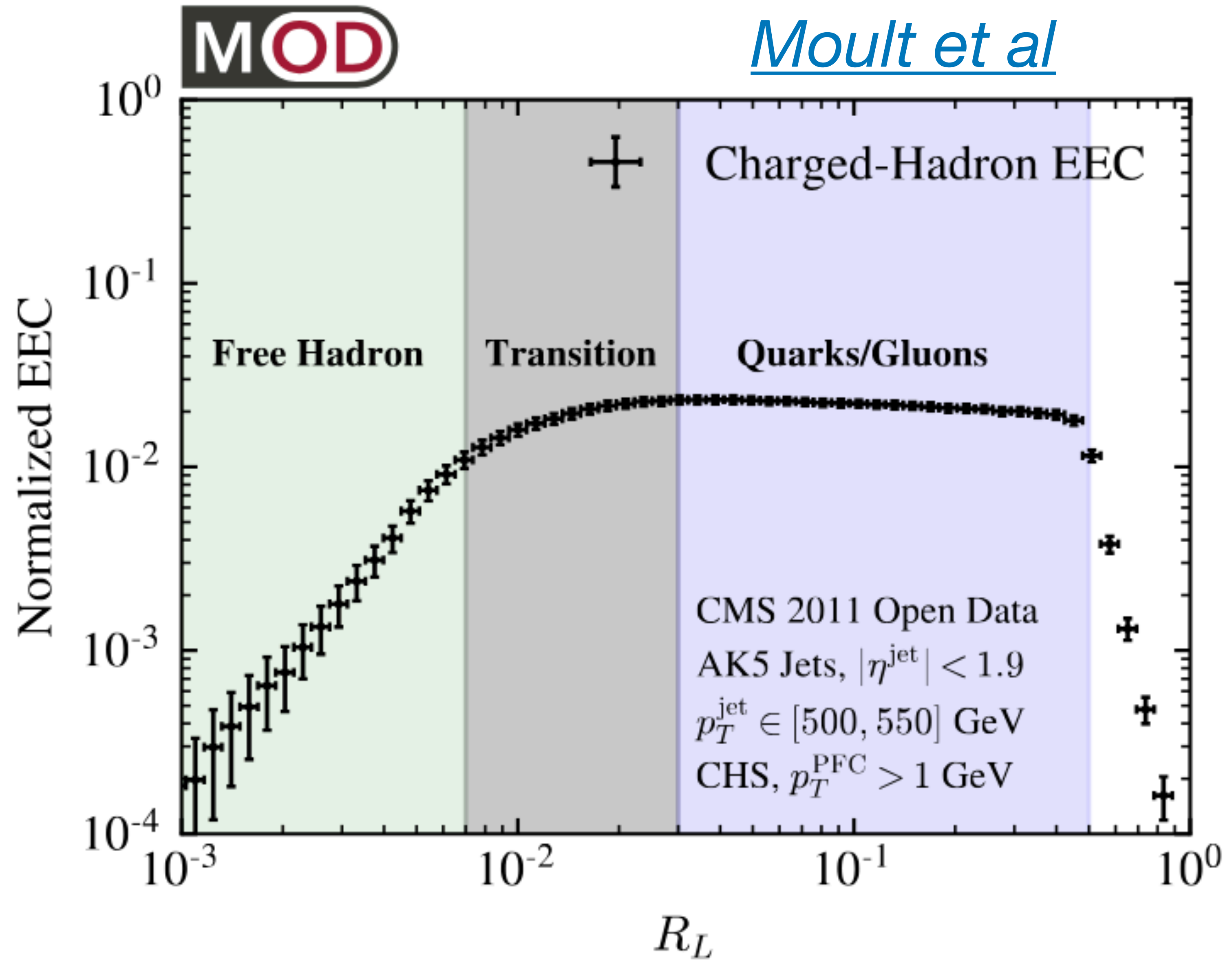


N-point correlation function measured as energy-weighted N-way correlation between configurations of particles

Two recent languages for jet substructure

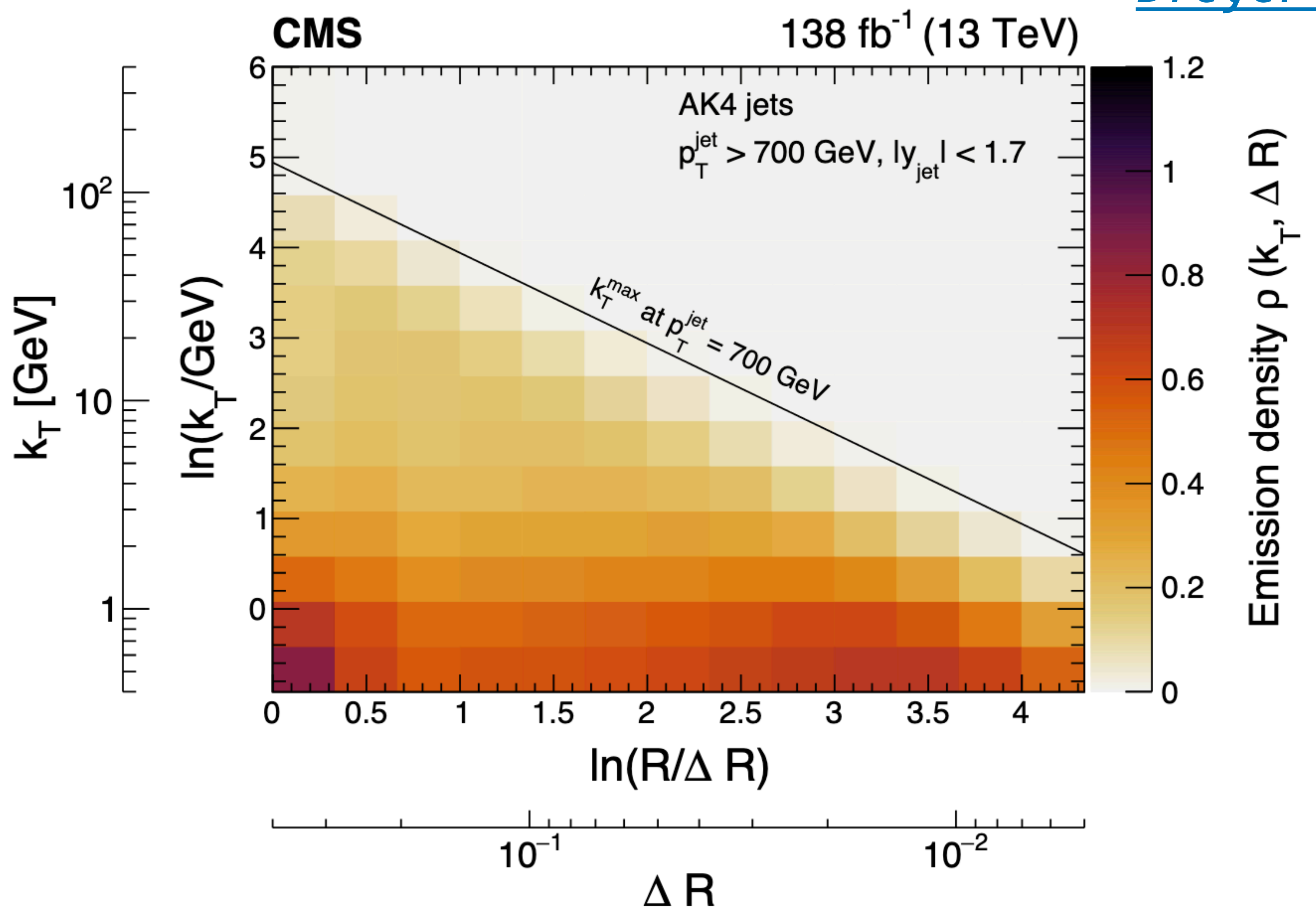
Energy Energy Correlators

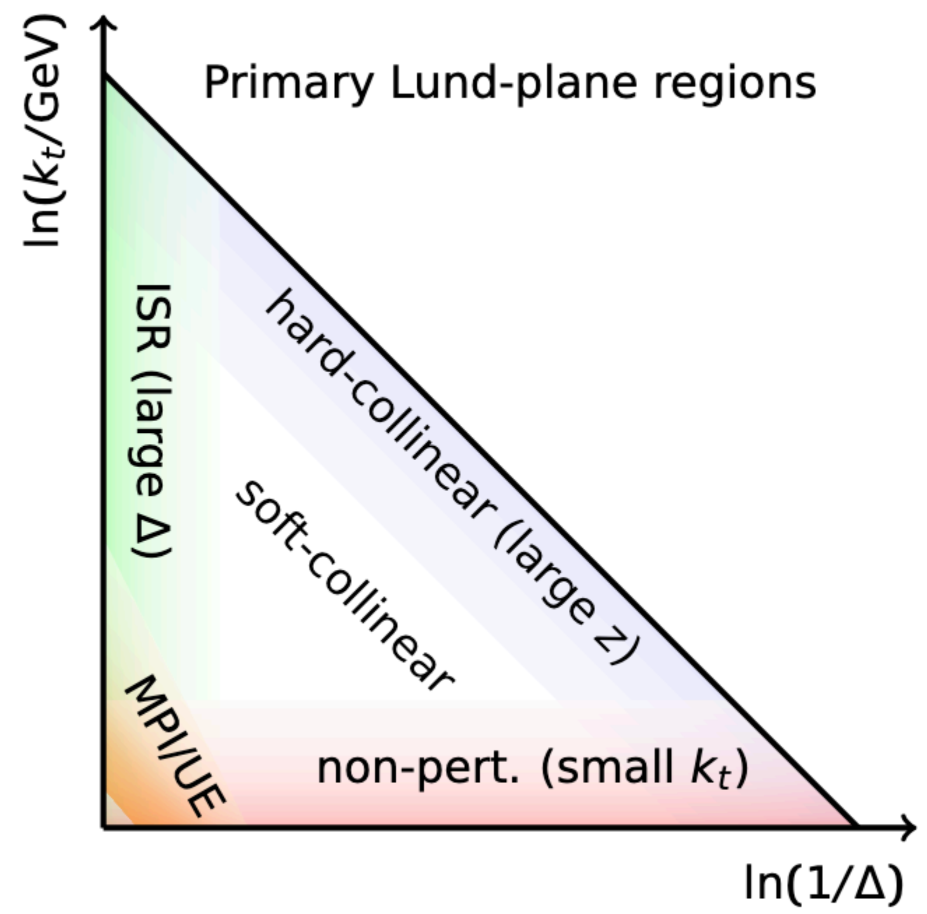
Moult et al



The Lund jet plane

Dreyer et al, JHEP 12 (2018) 064





EEC: p_T-weighted particle correlations
Lund jet Plane: proxy for parton shower via Cambridge-Aachen declustering

Separation large angle/small angle and soft/hard modes
Calculable in pp

Two languages for jet substructure

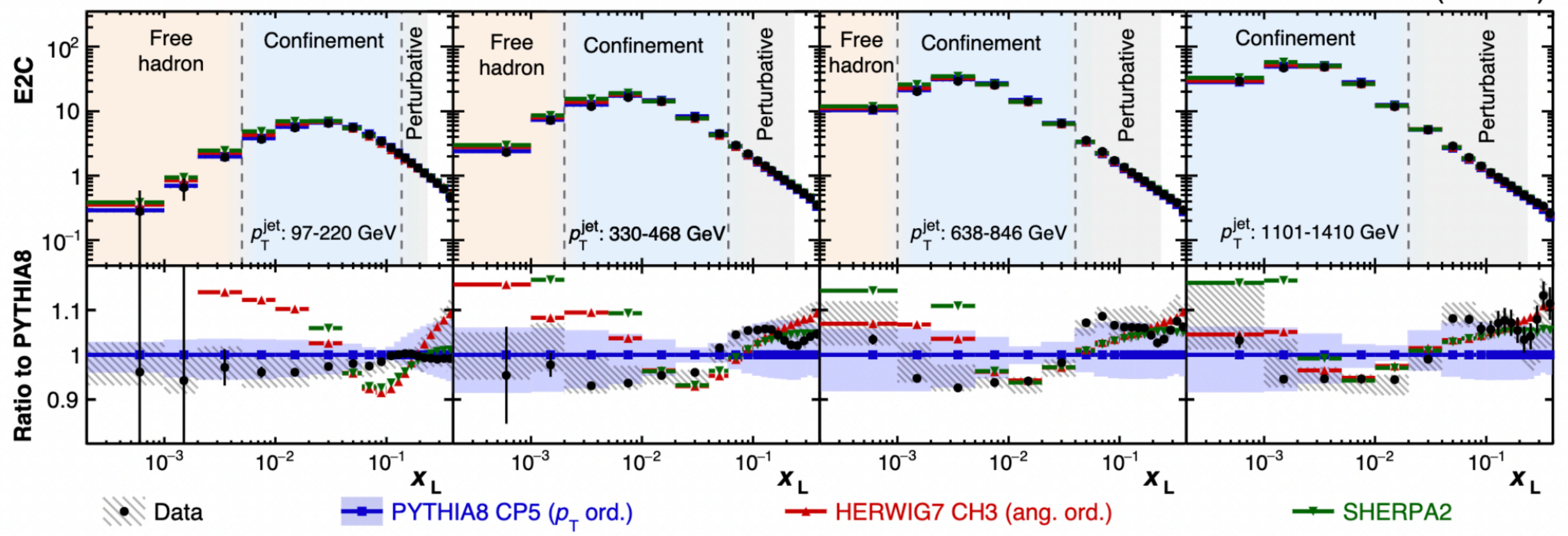
See talk by Ian Moult

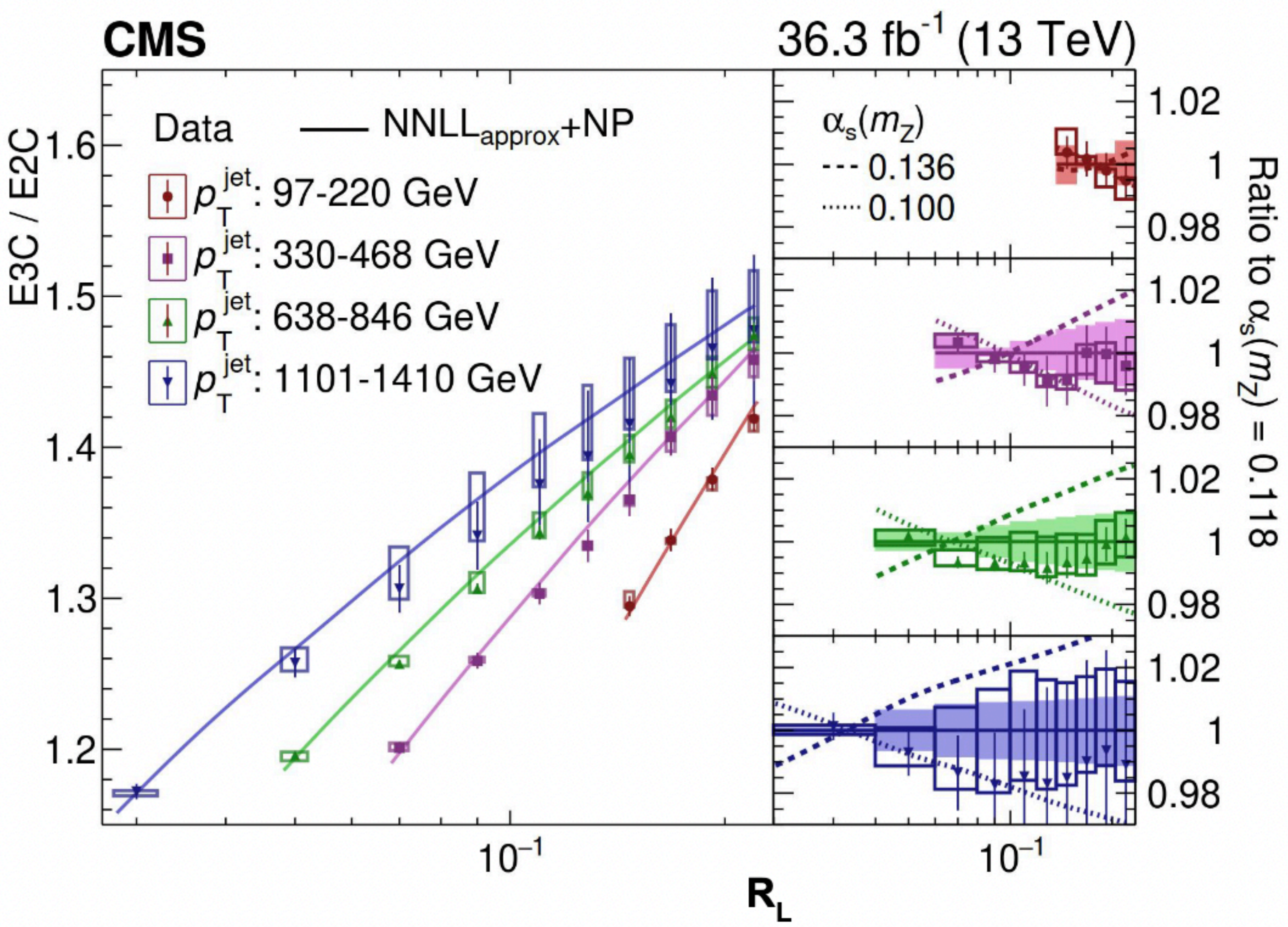
Systematics cancel out in the ratio E3C to E2C

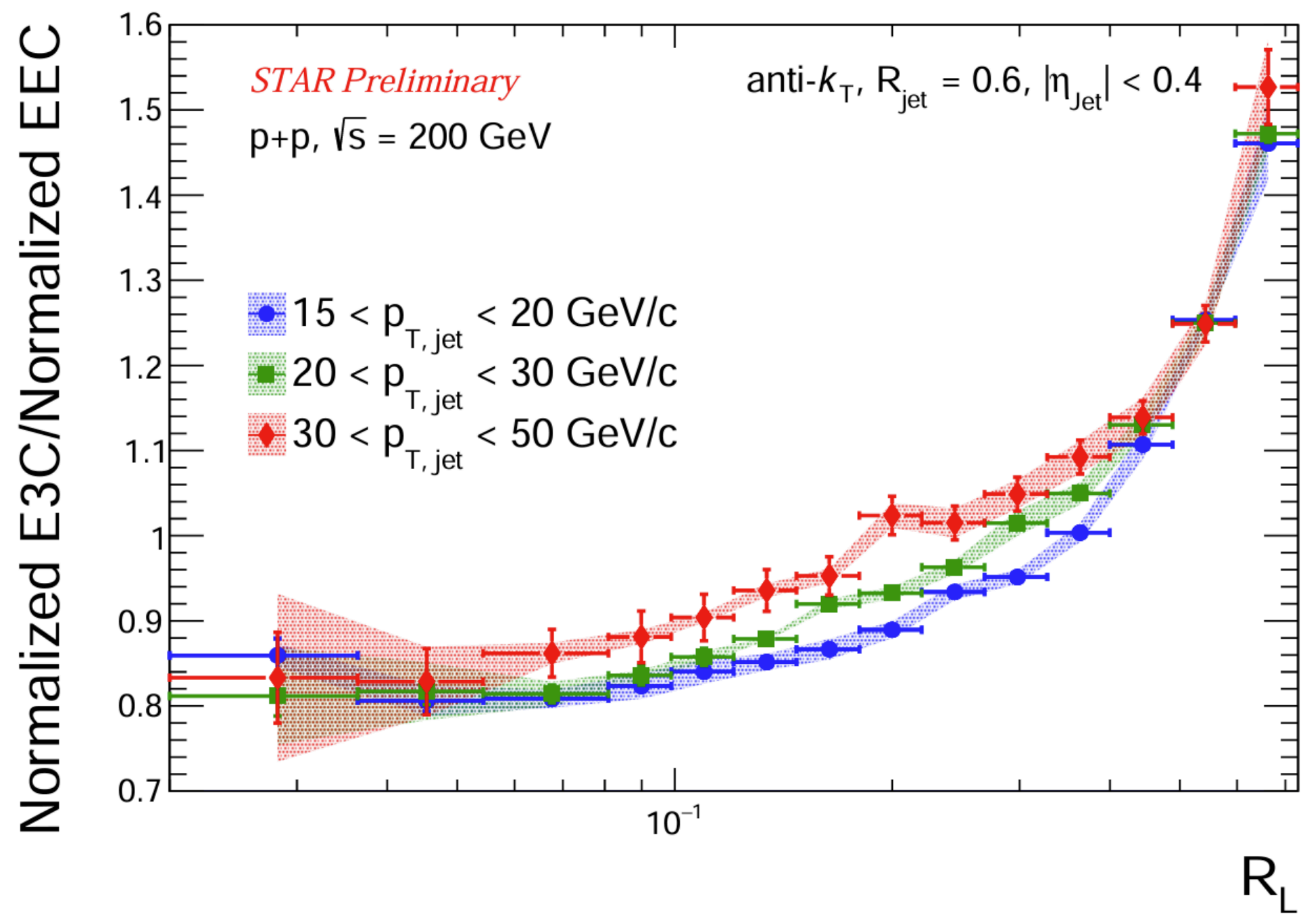
Ratio in the perturbative region proportional to α_S

Comparisons to NLO+ NNLL +NP allow for the most precise value of the strong coupling constant using jet substructure today

[CMS, 2402.13864 [hep-ex]]

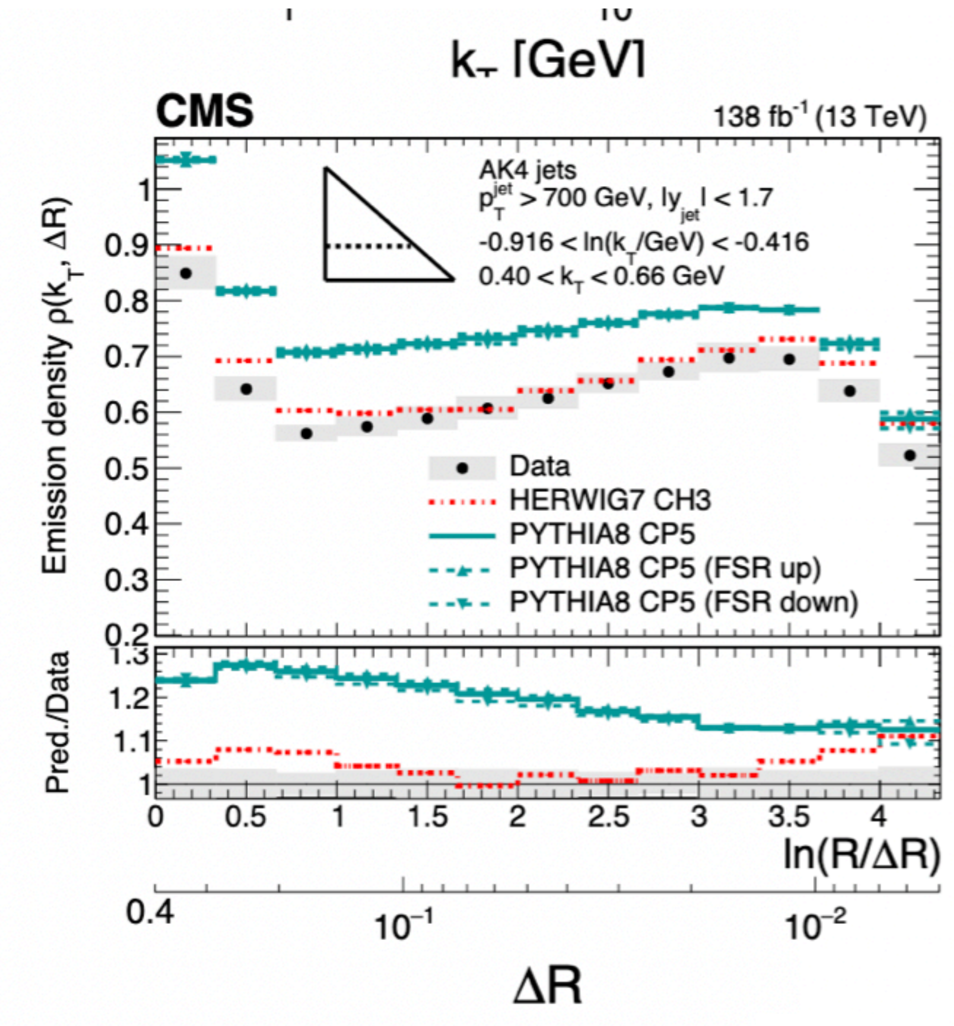


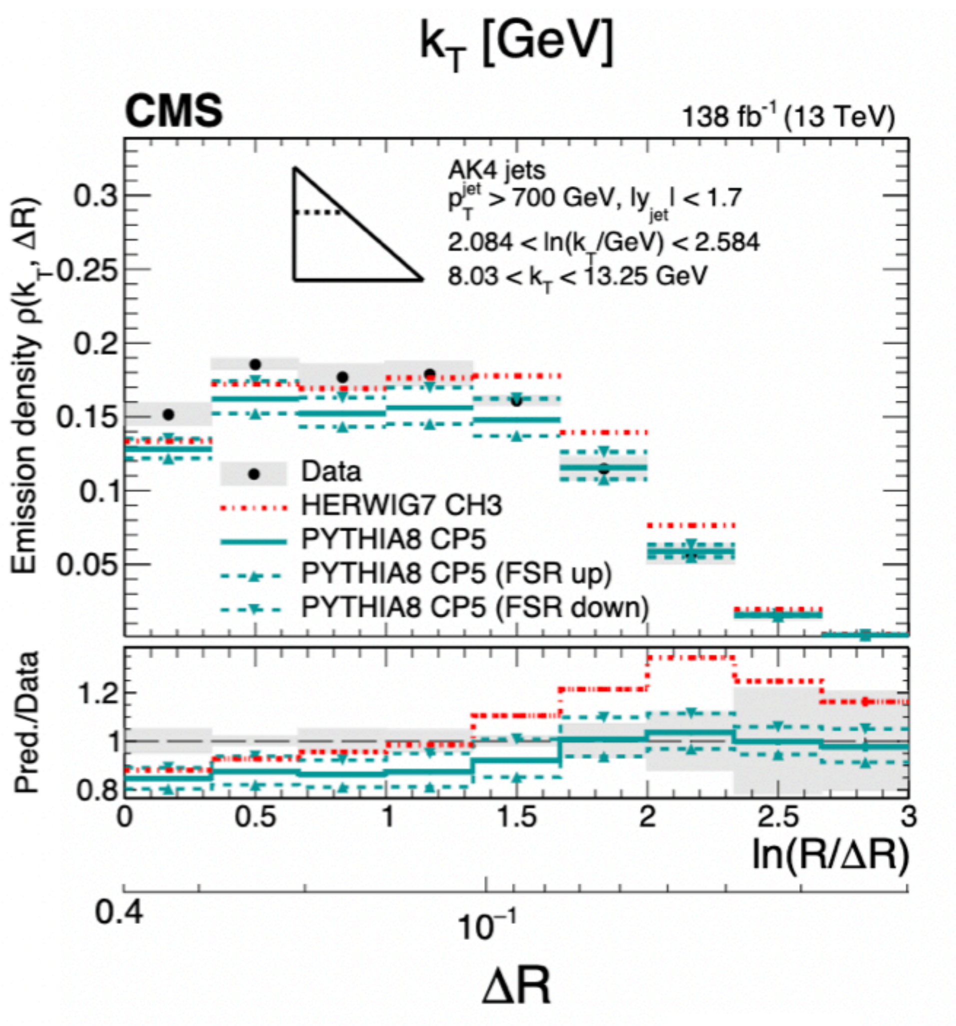




Two languages for jet substructure

[CMS, JHEP 05 (2024) 116](https://doi.org/10.1007/JHEP05(2024)116)

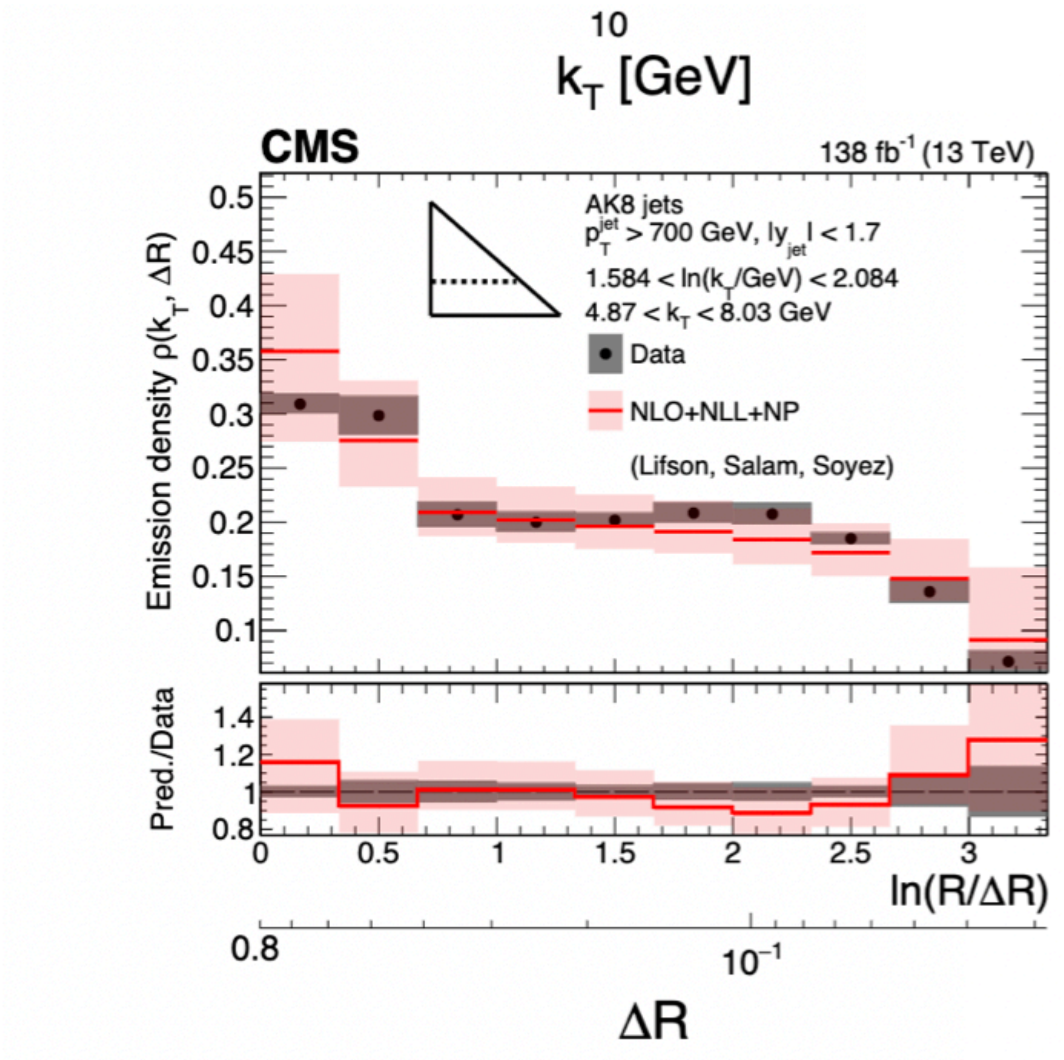


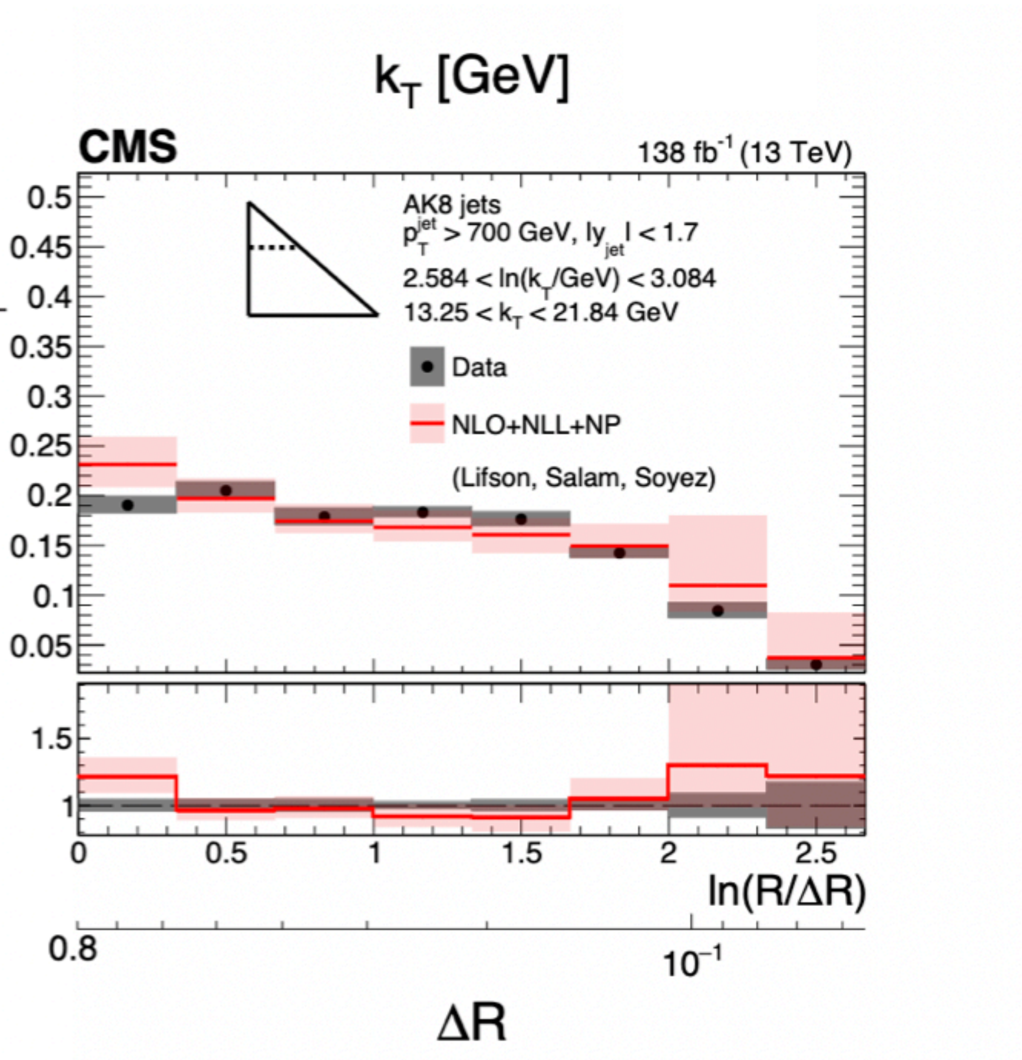


As an example, see comparison between Herwig7 CH3 and Pythia8 CP5 :

In the nonperturbative region, Pythia overestimates the number of emissions and Herwig describes better the data

In the perturbative region, sensitivity to FSR scale variations



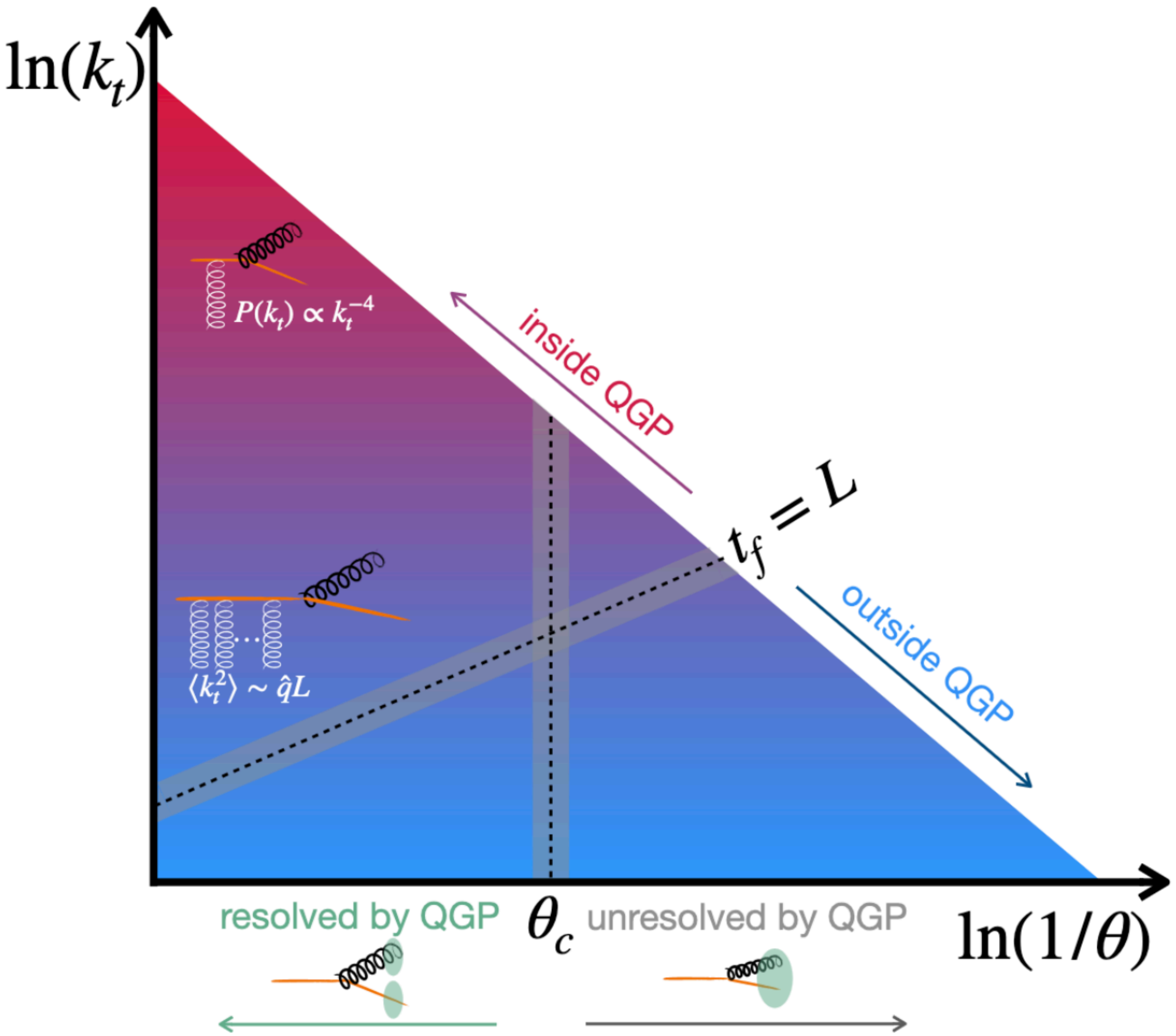


Comparison to NLO+NLL+NP analytical calculations adapted from [Lifson et al, JHEP 10 (2020) 170]()

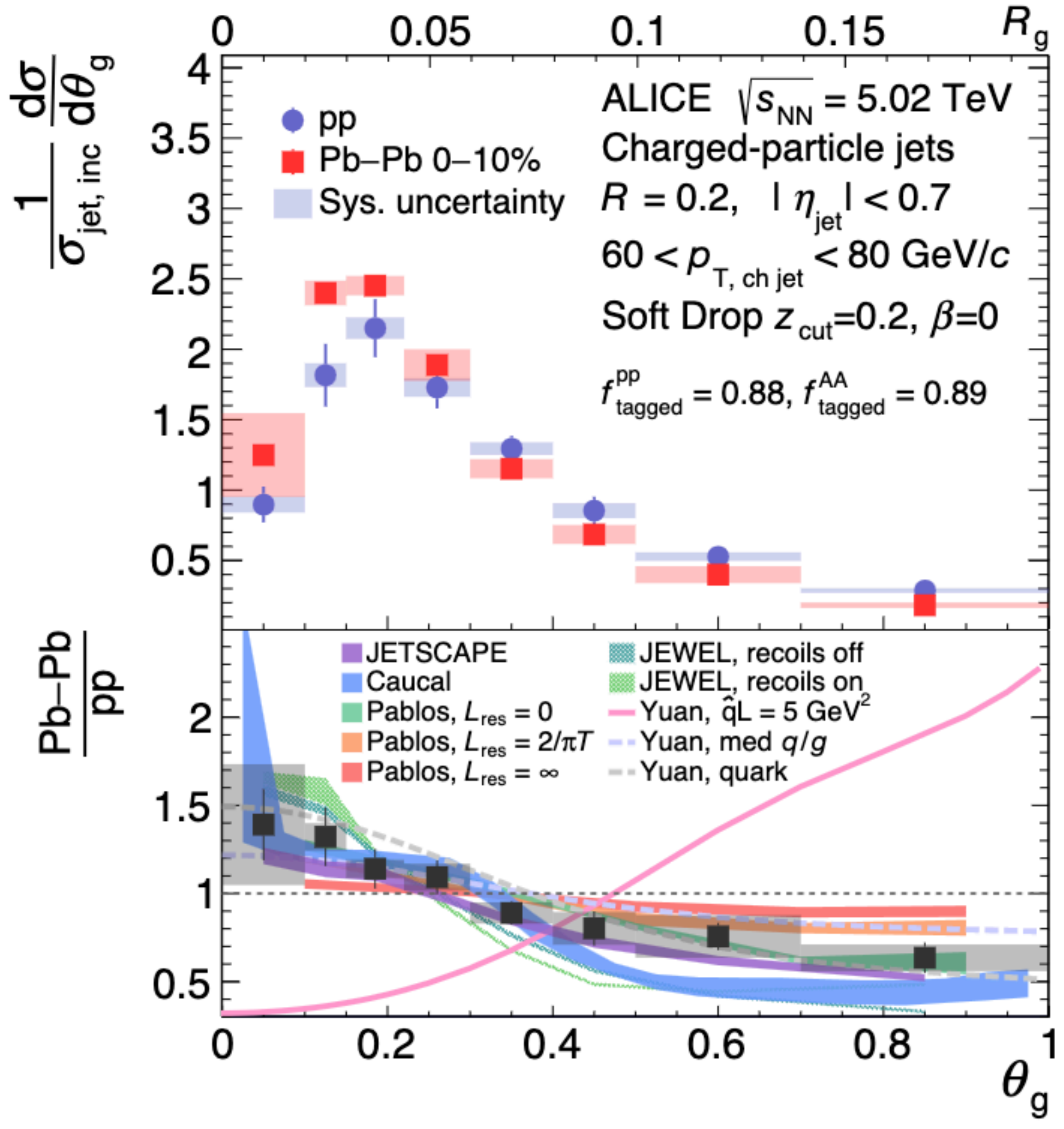
Predictions in agreement with the data within theoretical and experimental uncertainties

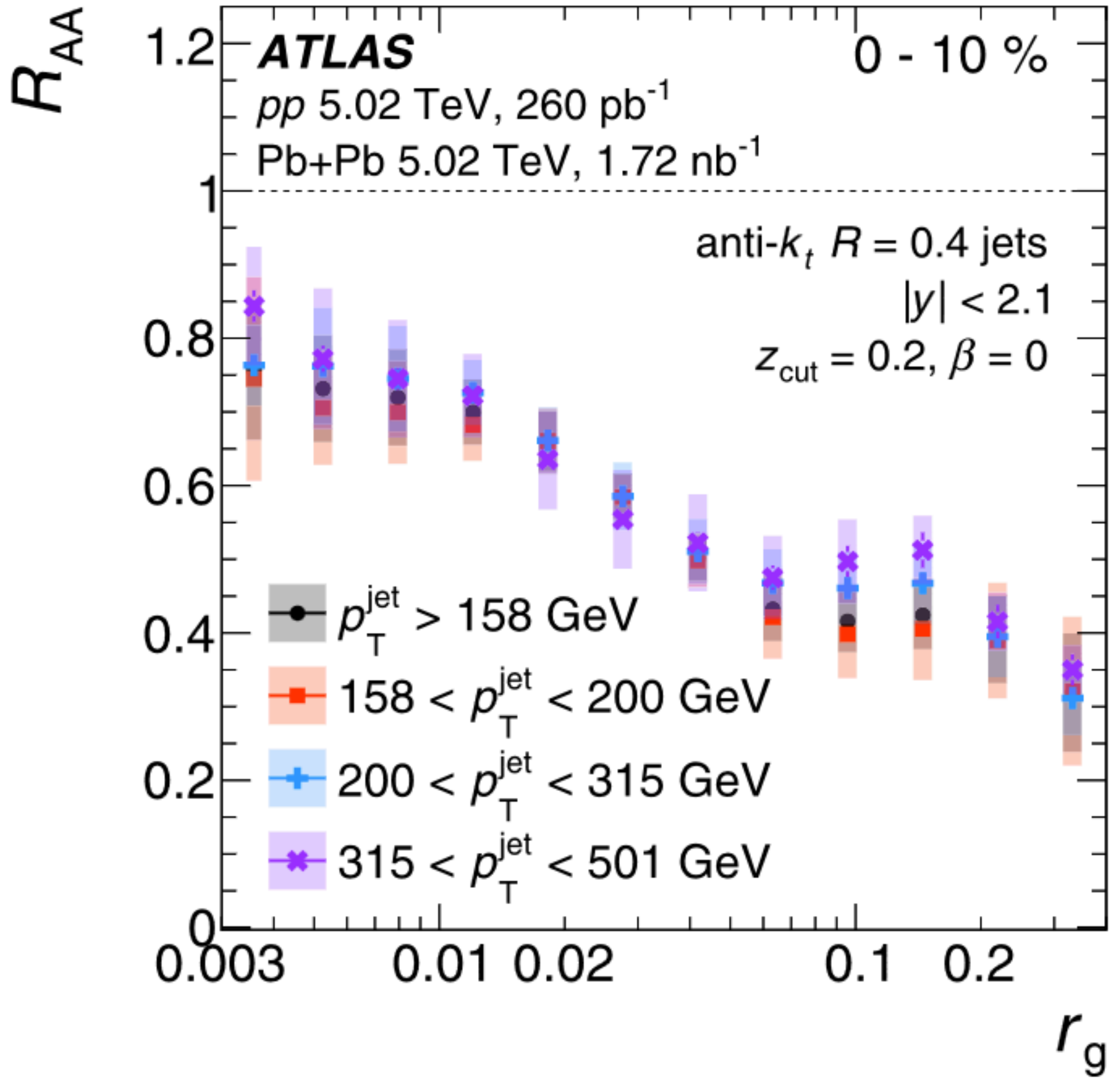
The Lund plane in PbPb collisions

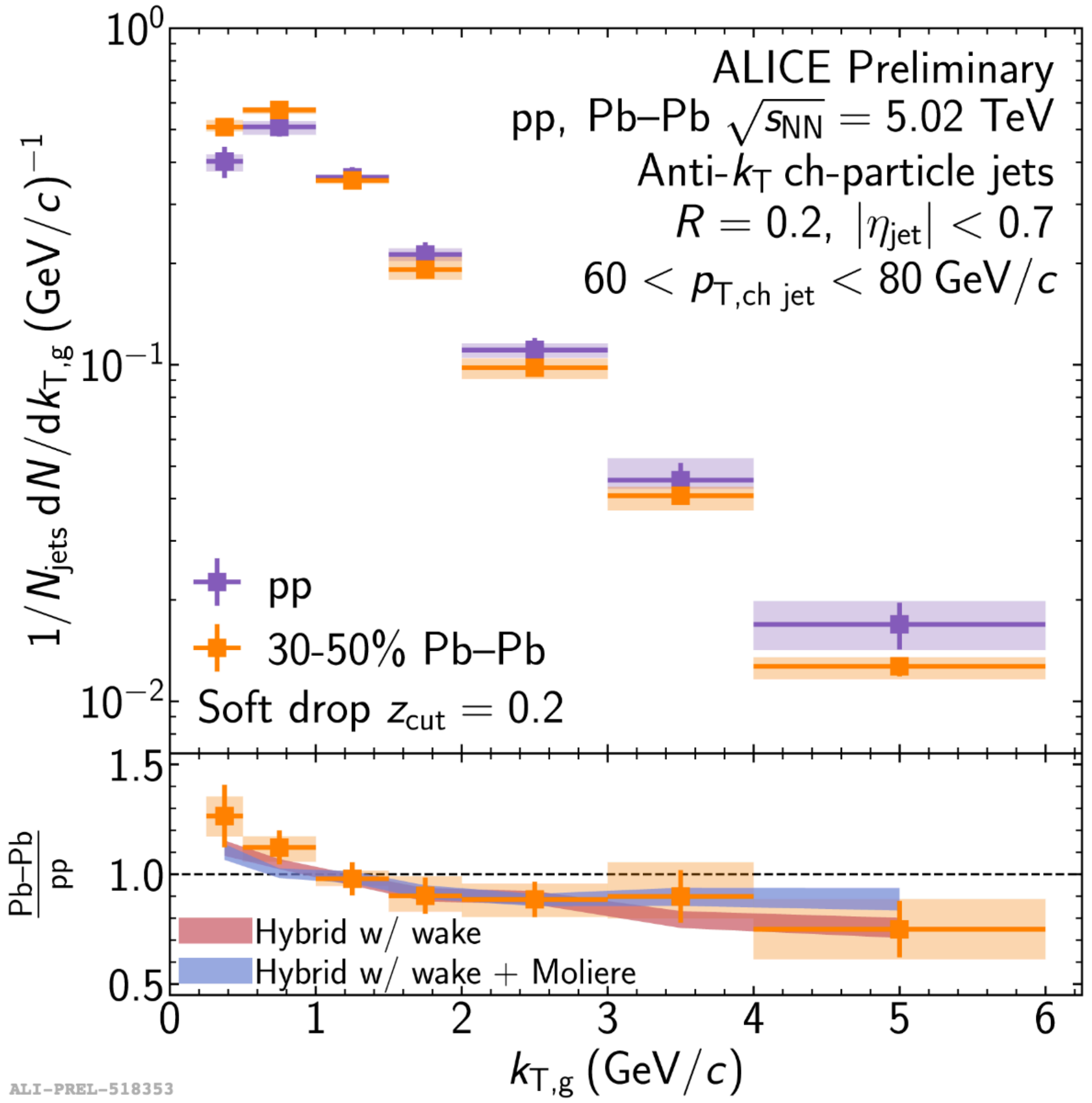
The Lund plane density in PbPb is not expected to be filled uniformly at LO like in vacuum

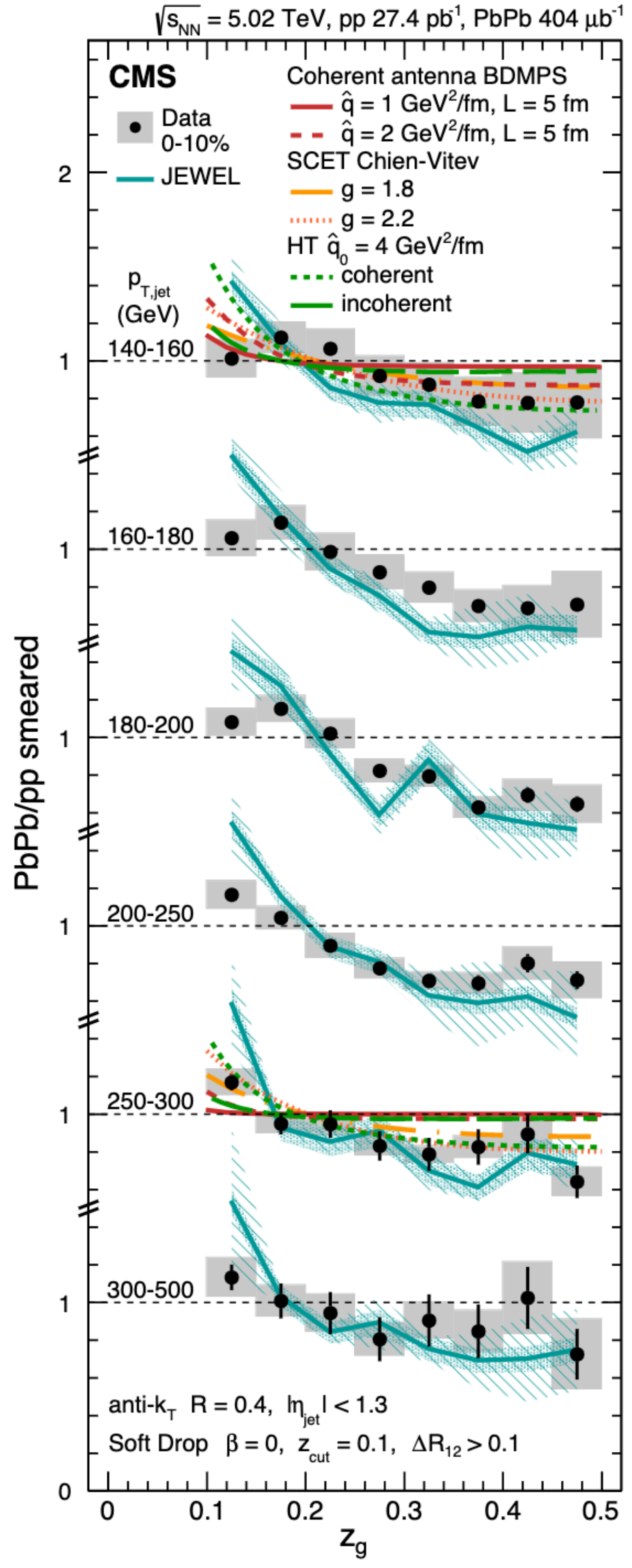


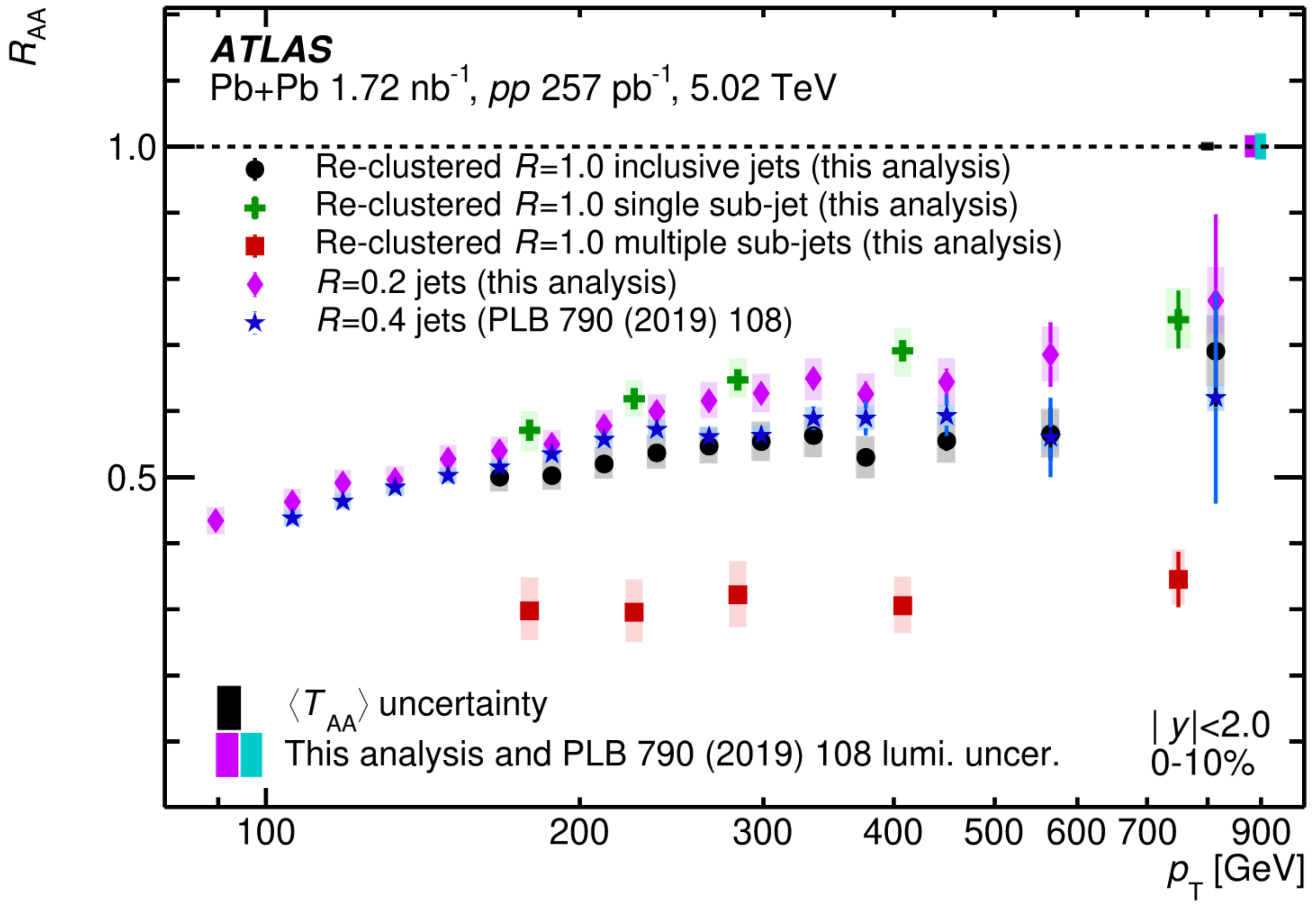
Scans of the Lund plane in PbPb: collage of results





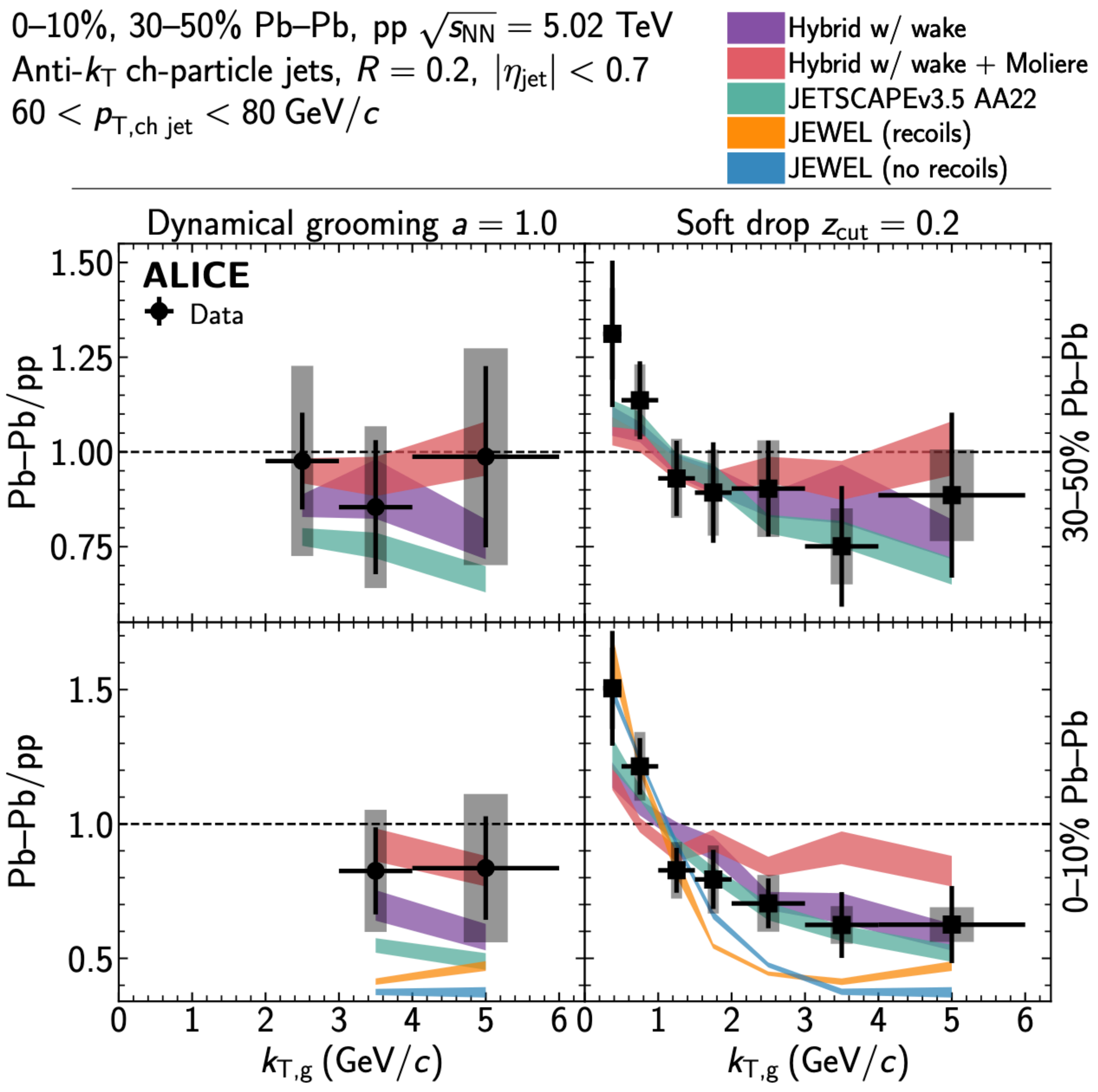






In general all we see is a suppression of broad substructures, also at the level of jet shapes

Scans of the Lund plane in PbPb: collage of results



ALICE, https://arxiv.org/abs/2409.12837

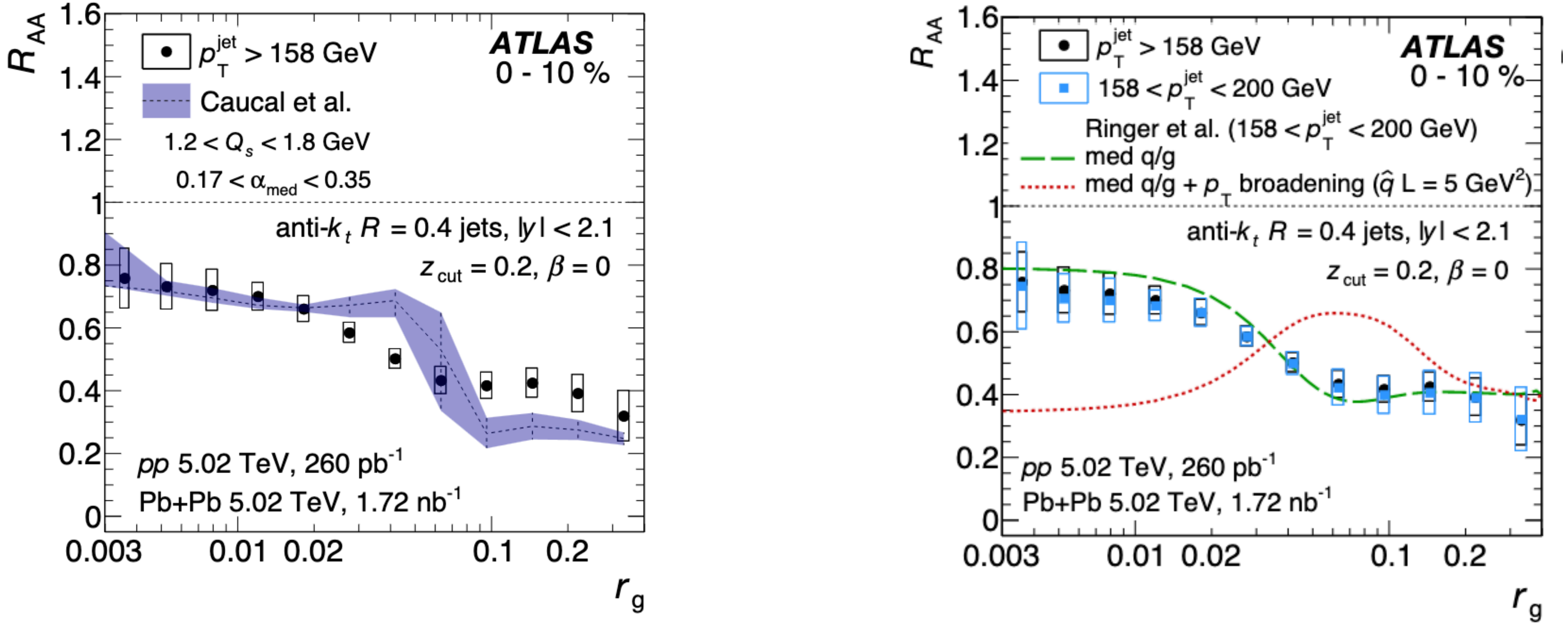
Hardest k_T emission inside the jet

Sensitivity to hard elastic scattering
Suppression of wake effects with small R jets

Sensitivity possibly darkened by the selection bias effect

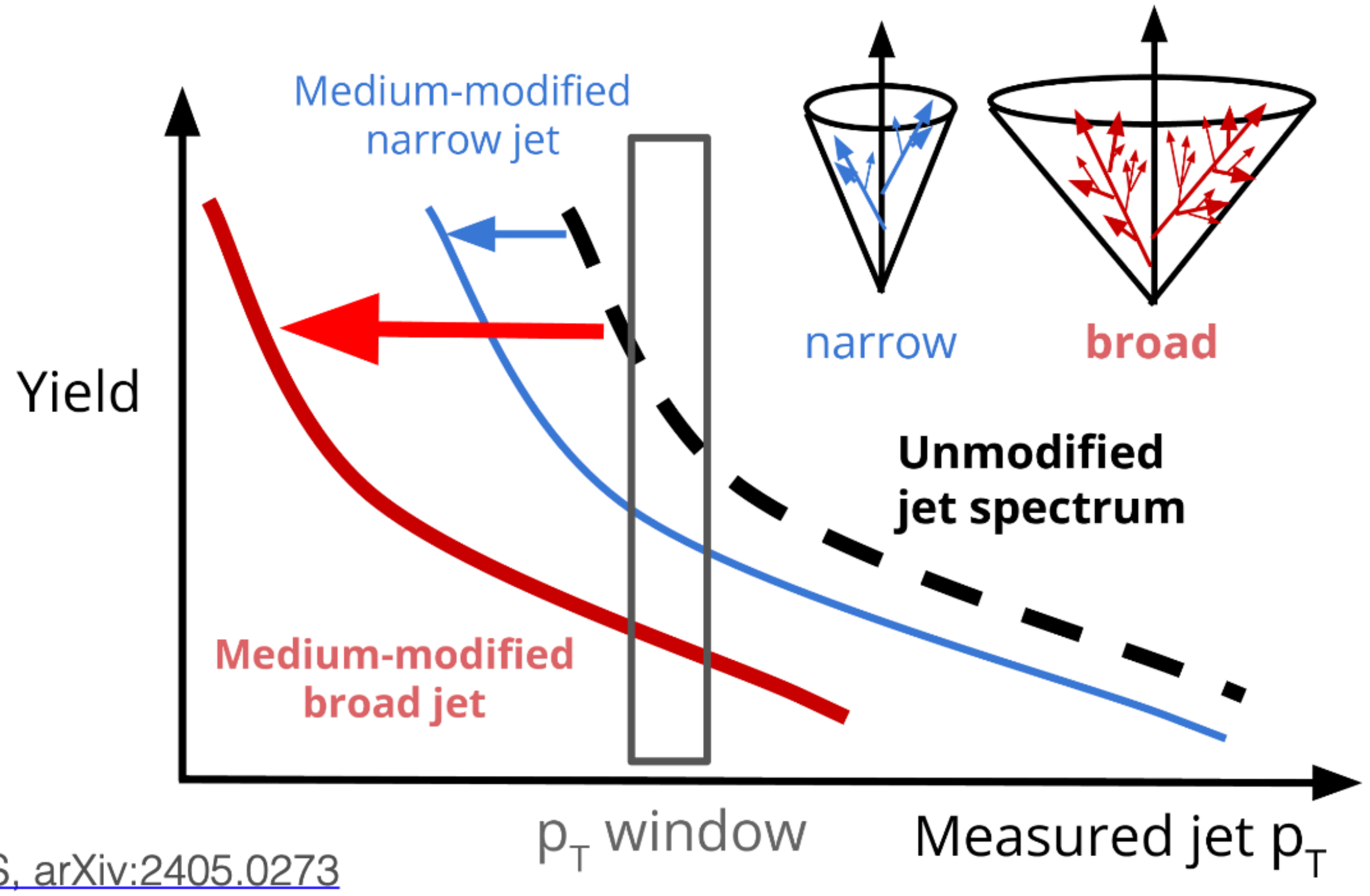
Scans of the Lund plane in PbPb: collage of results

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



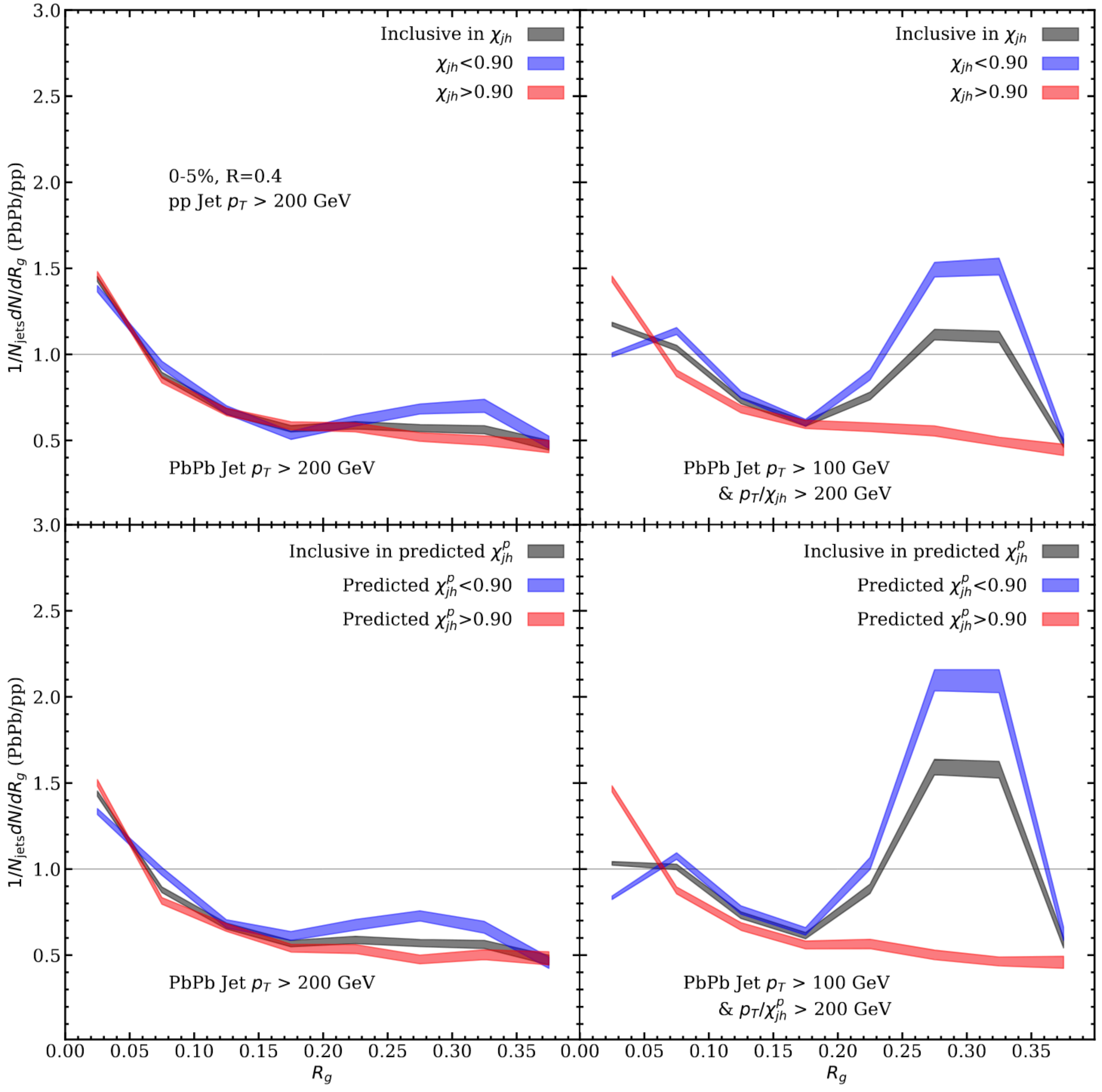
An intriguing step behaviour around the coherence angle in the implementation of Caucal et al
But step function also present in a model with no explicit implementation of coherence angle

The selection bias: comparing pp and PbPb



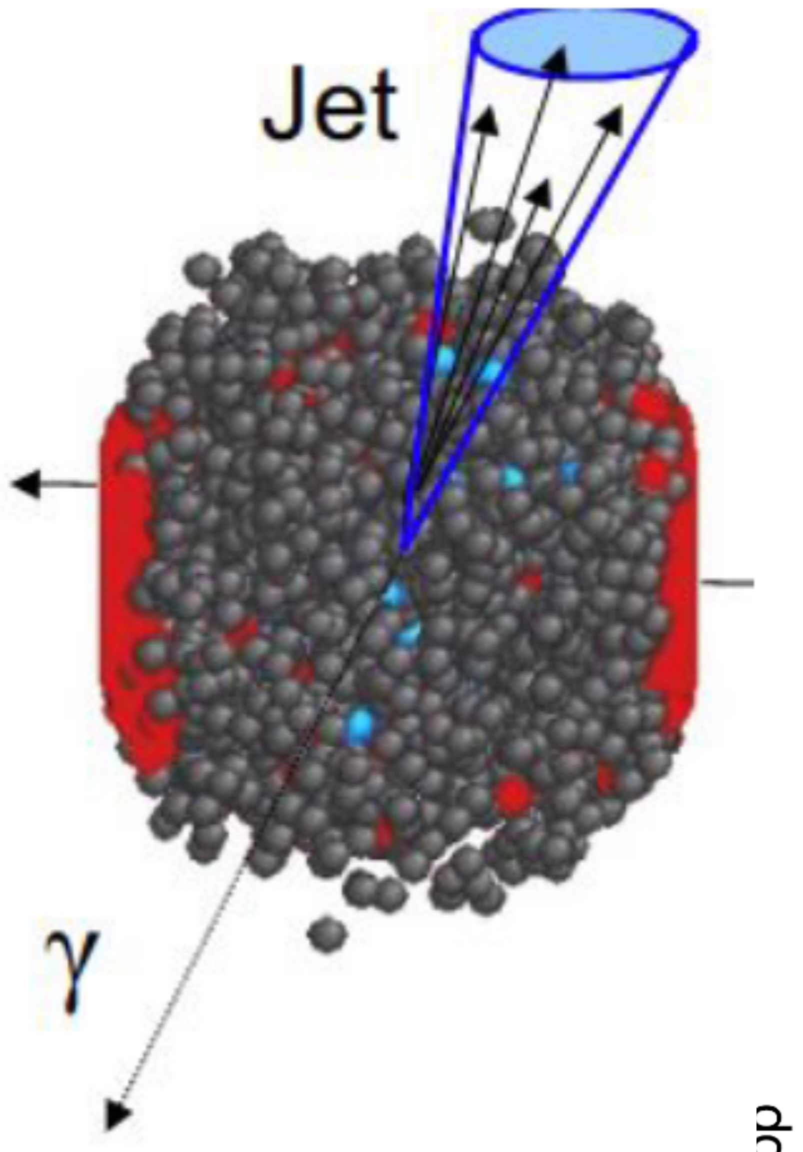
CMS, arXiv:2405.0273

When one compares pp and PbPb at the same reconstructed jet p_T, PbPb biased selection of less quenched jets: stronly quenched jets are filtered out to lower jet p_T



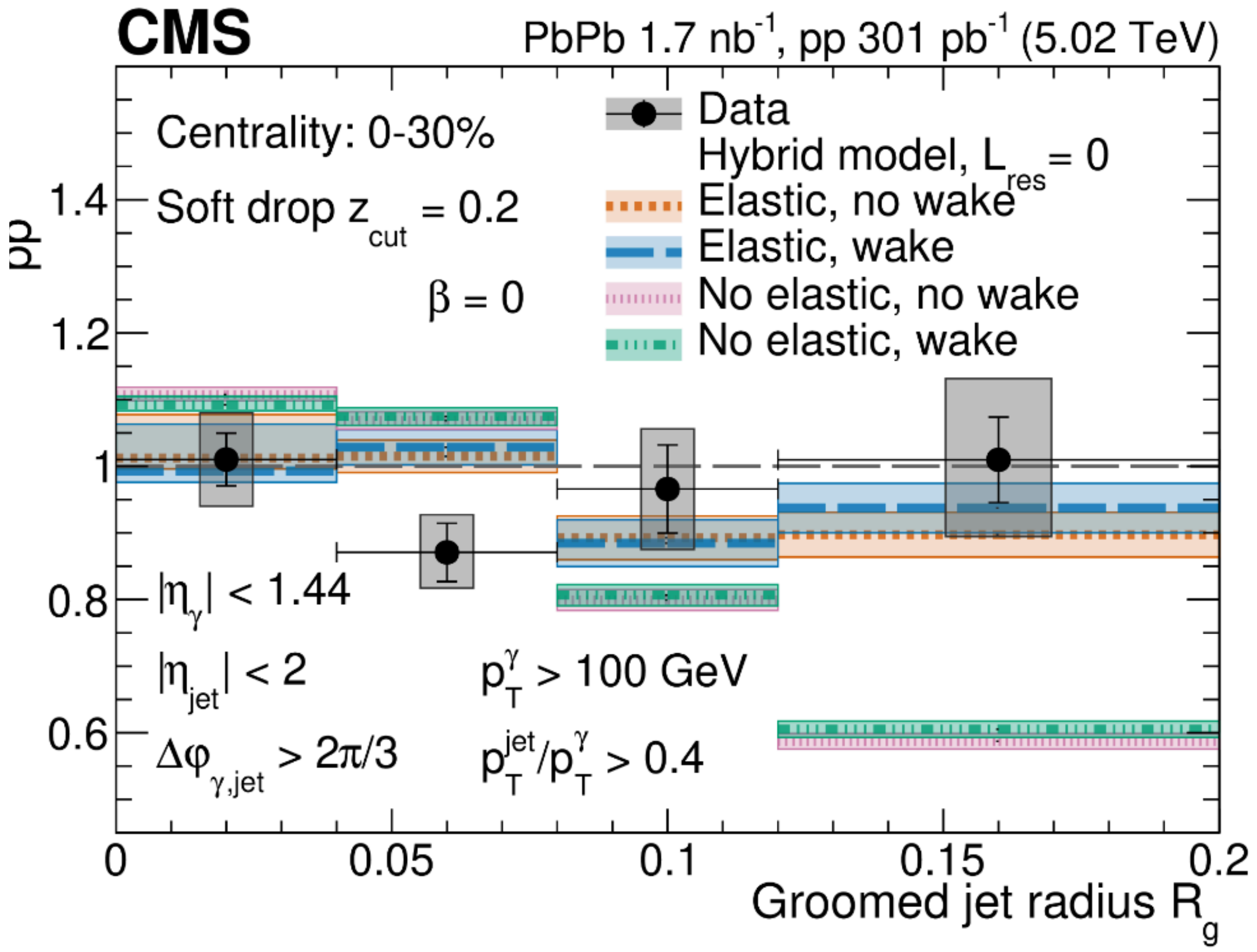
Du et al, 2106.11271, Brewer et al, 2009.03316

Substructure of jets recoiling from an energetic γ



$x_{\gamma j} > 0.4$ (w/ quenched jets):

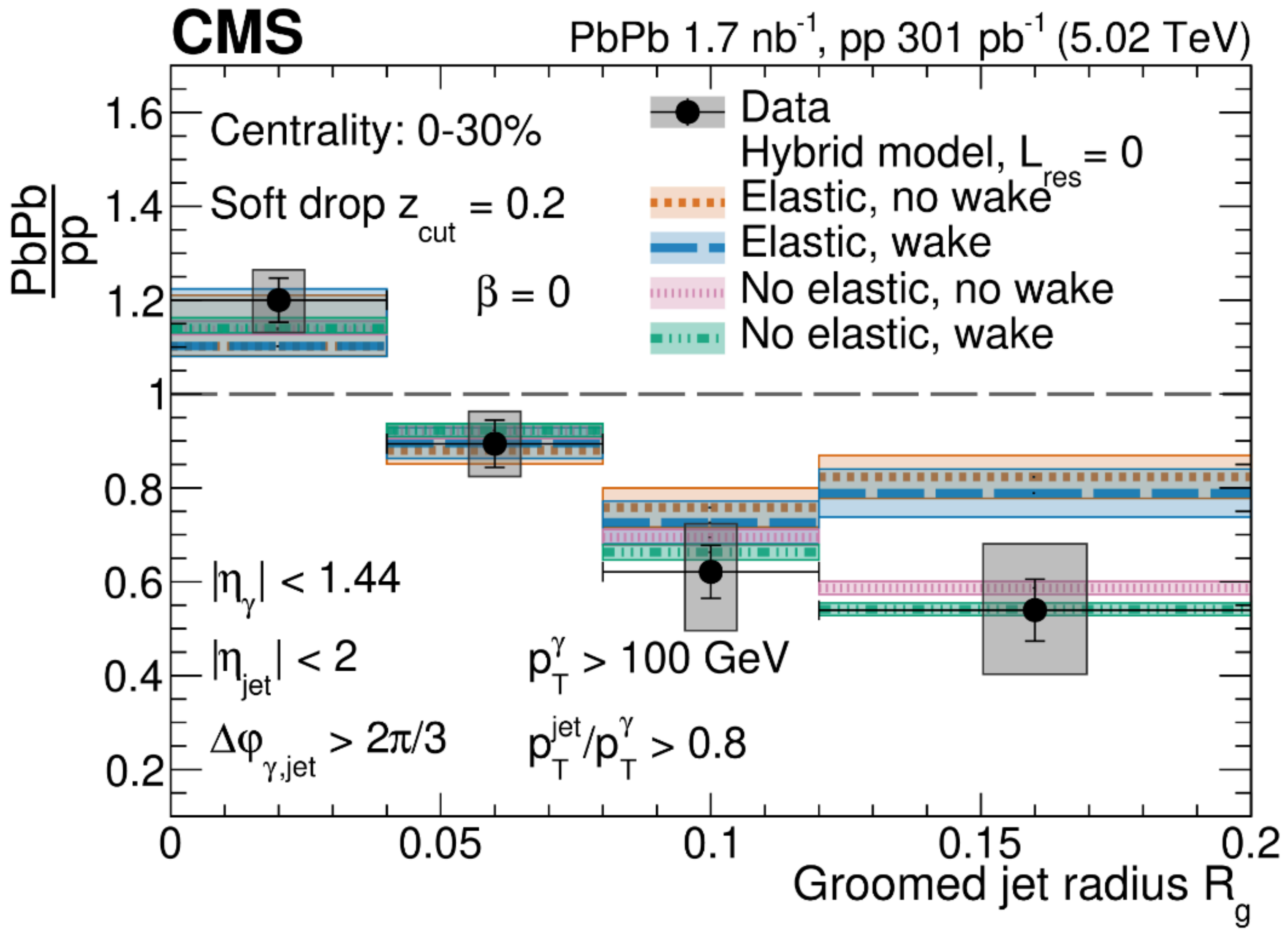
no narrowing observed



CMS, arXiv:2405.0273

$x_{\gamma j} > 0.8$ (less quenched jets):

narrowing is restored

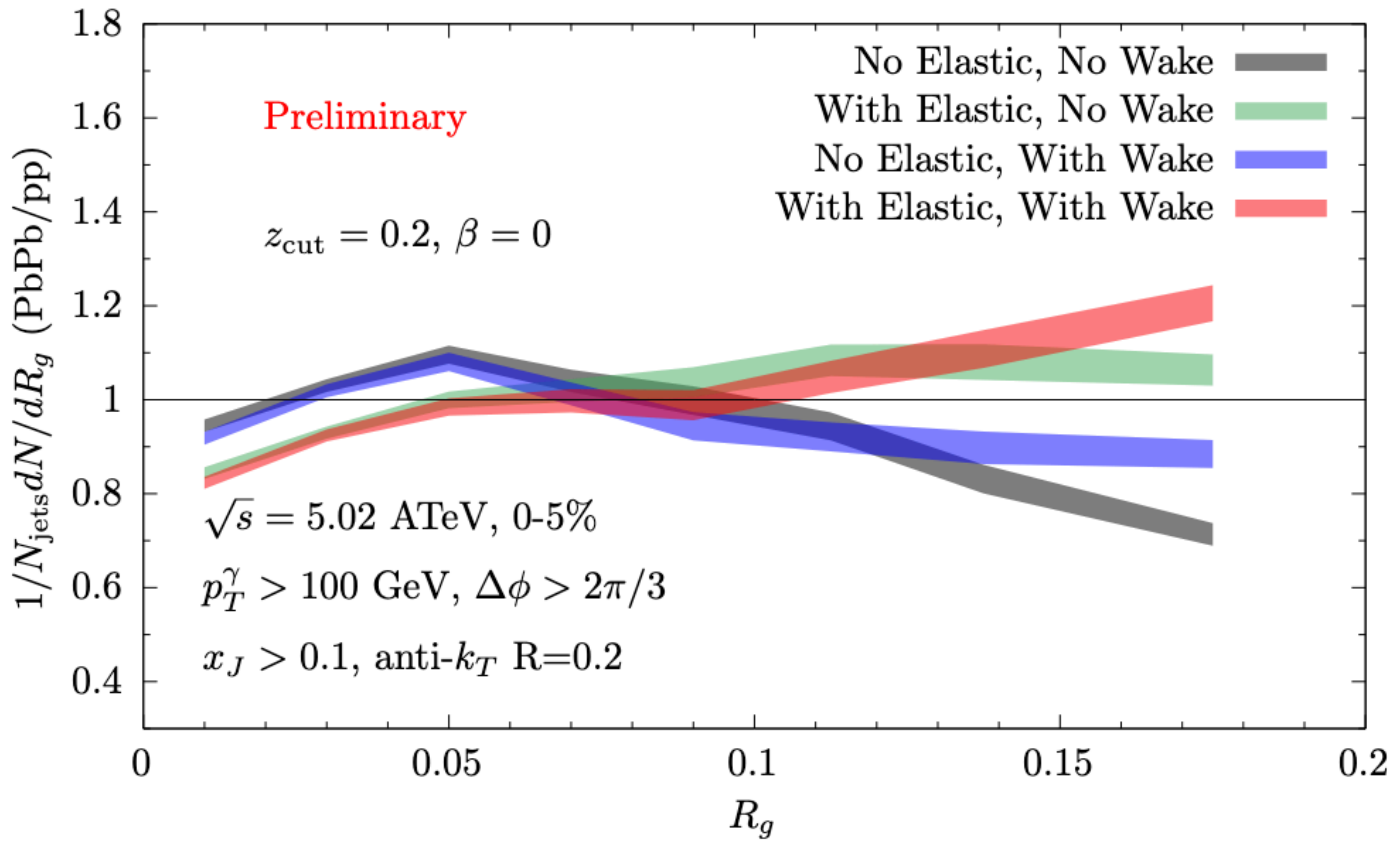


Sensitivity to hard scatterings in the the medium

Sensitivity enhanced when more quenched jets are included in the sample

Selection bias under control!

Substructure of jets recoiling from an energetic γ



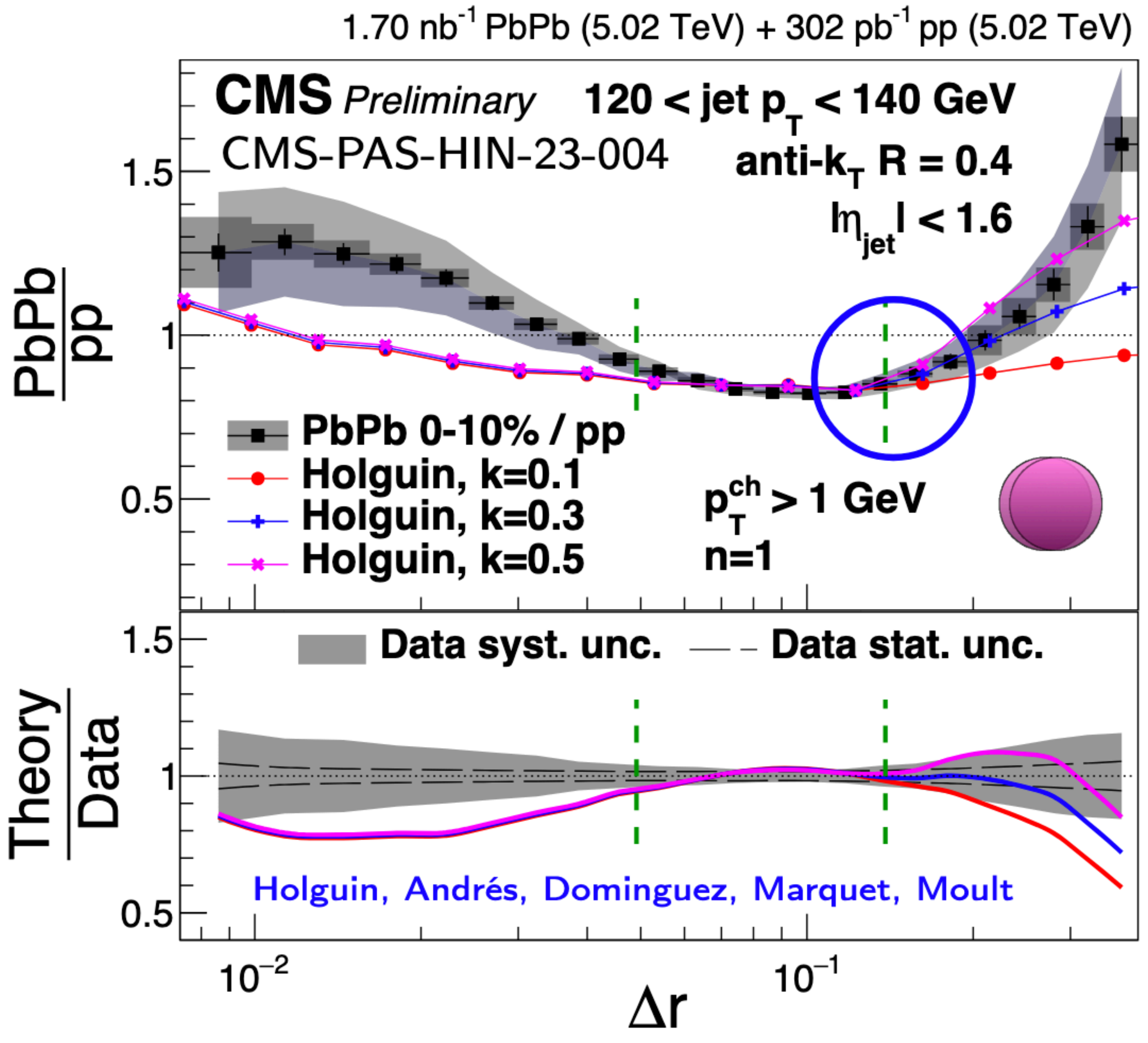
Ideal limit xJ->0 to include the jets that are quenched the strongest

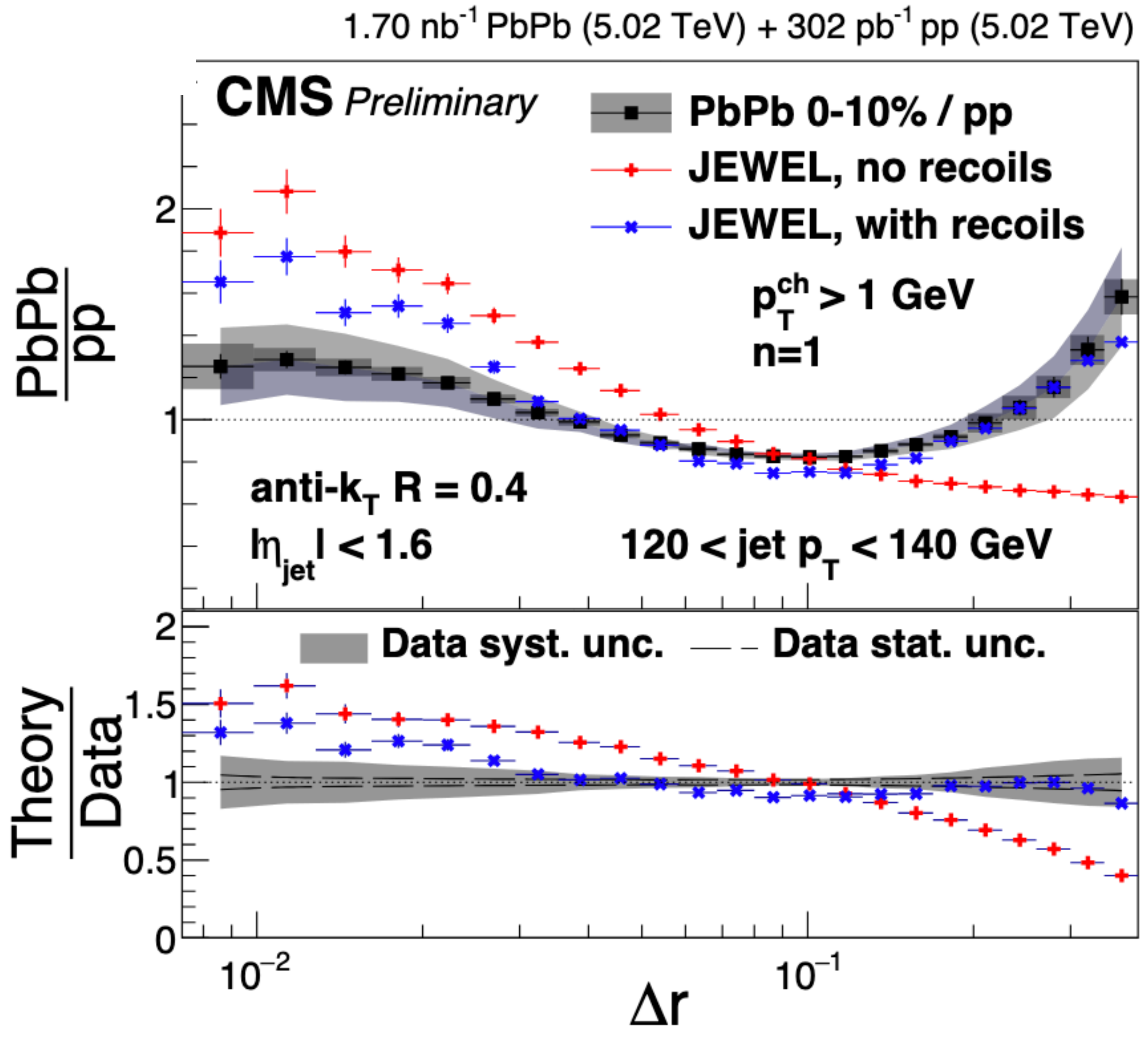
Experimentally, low xJs are achieved via <u>increasing the energy of the photon</u> (there's a lower limit in jet reconstruction)

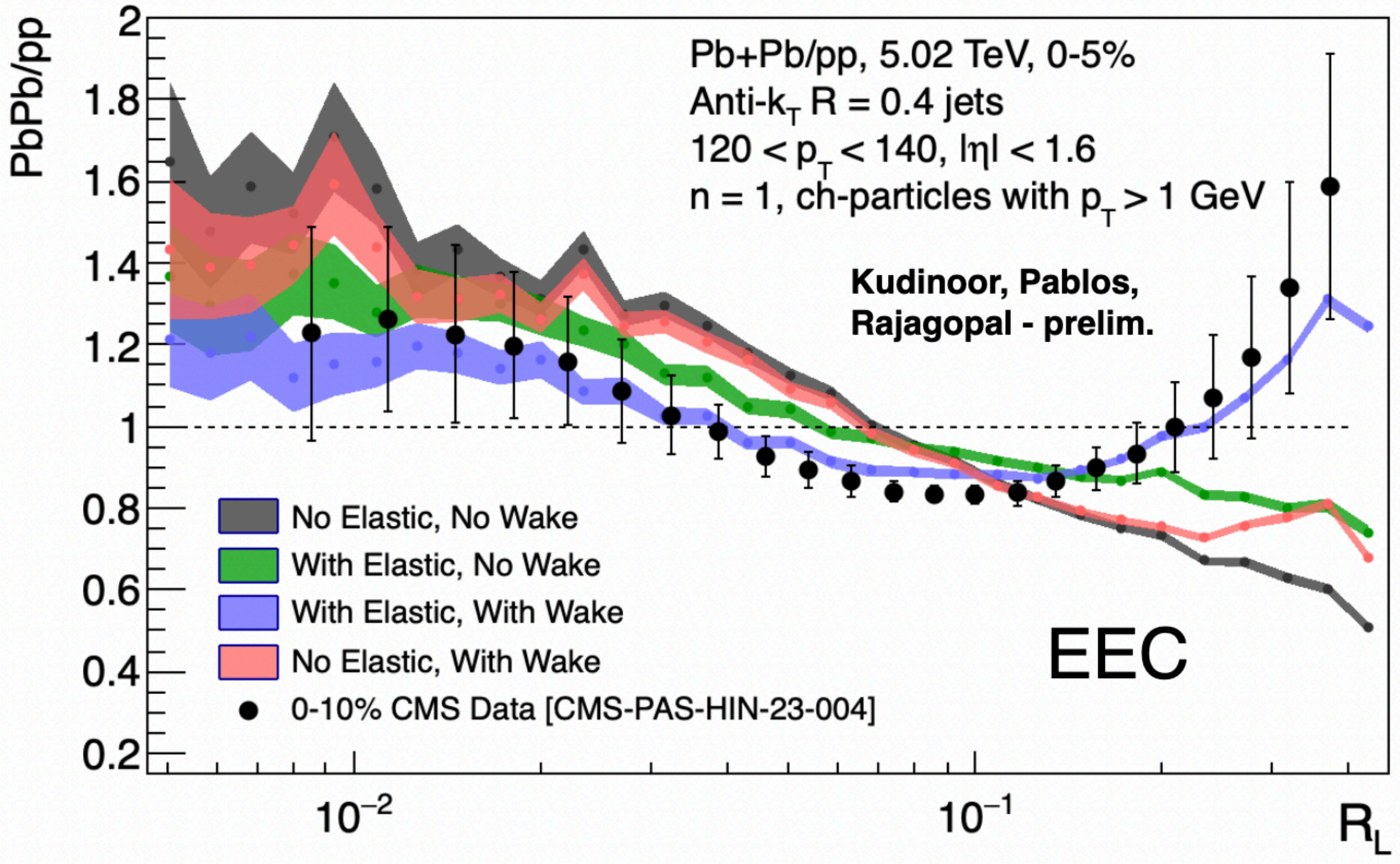
Statistically hungry!

The hybrid model shows a big leak of quenched jets below xJ=0.4

EEC in PbPb



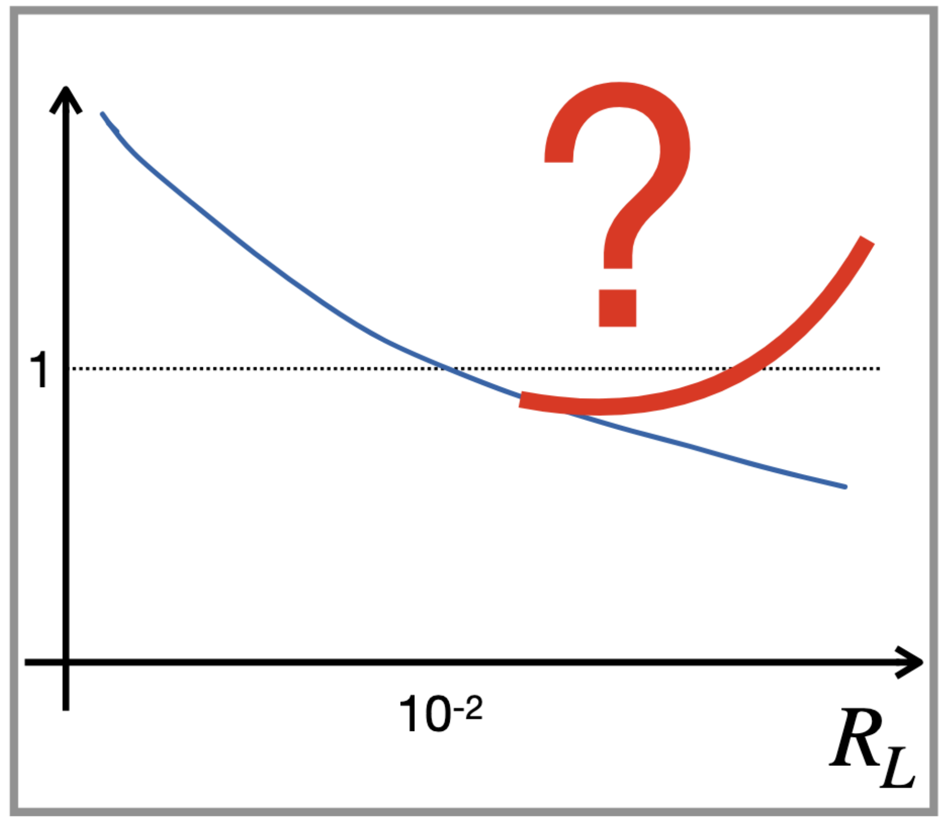




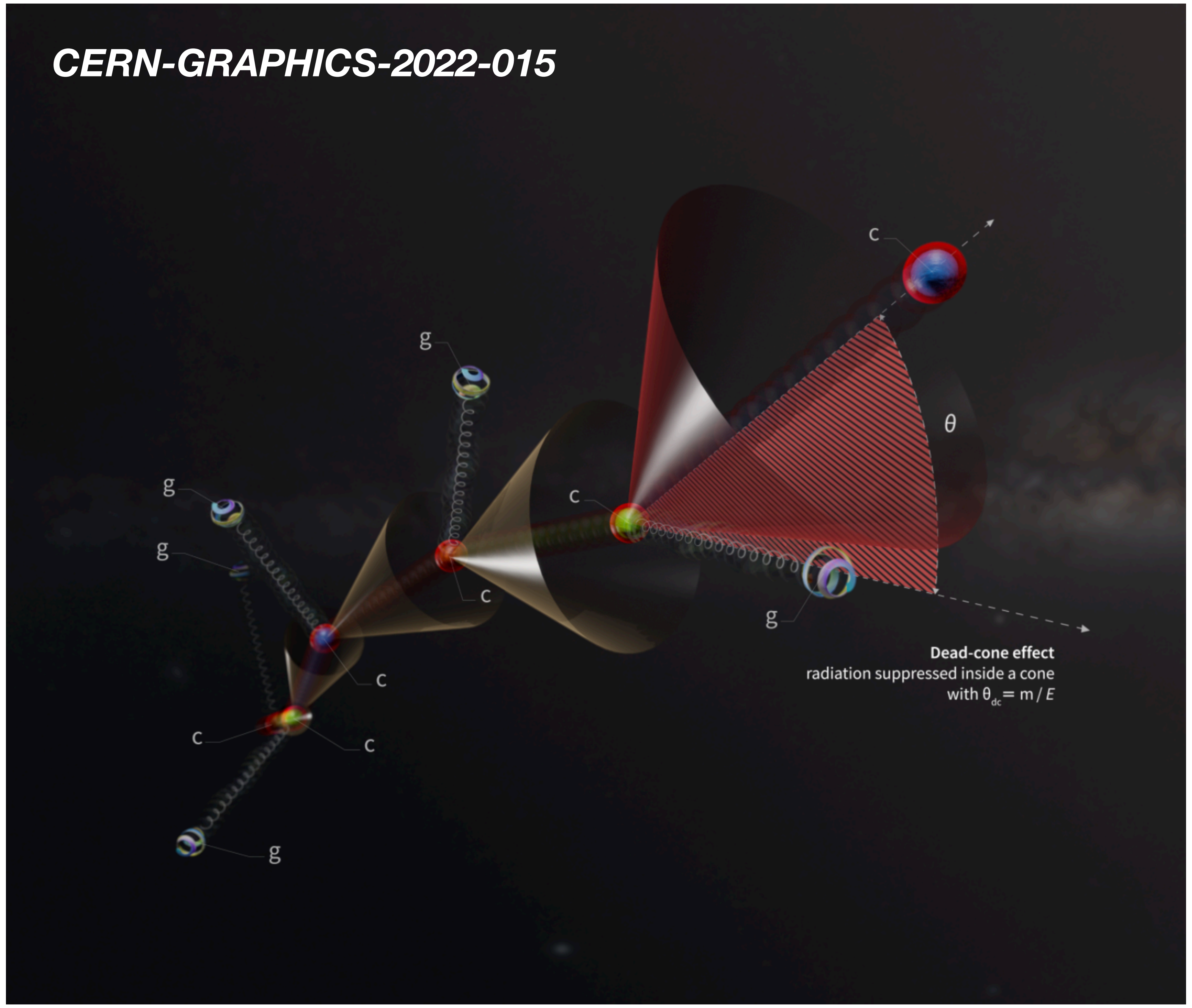
Nice surprise: first substructure observable not showing the narrowing pattern

Several competing mechanisms contributing to large angles, great new opportunity

Selection bias can be corrected at inclusive level using scaling properties of the observable *Carlota Andres et al, arXiv:2409.07514*



Heavy flavours and the Lund plane

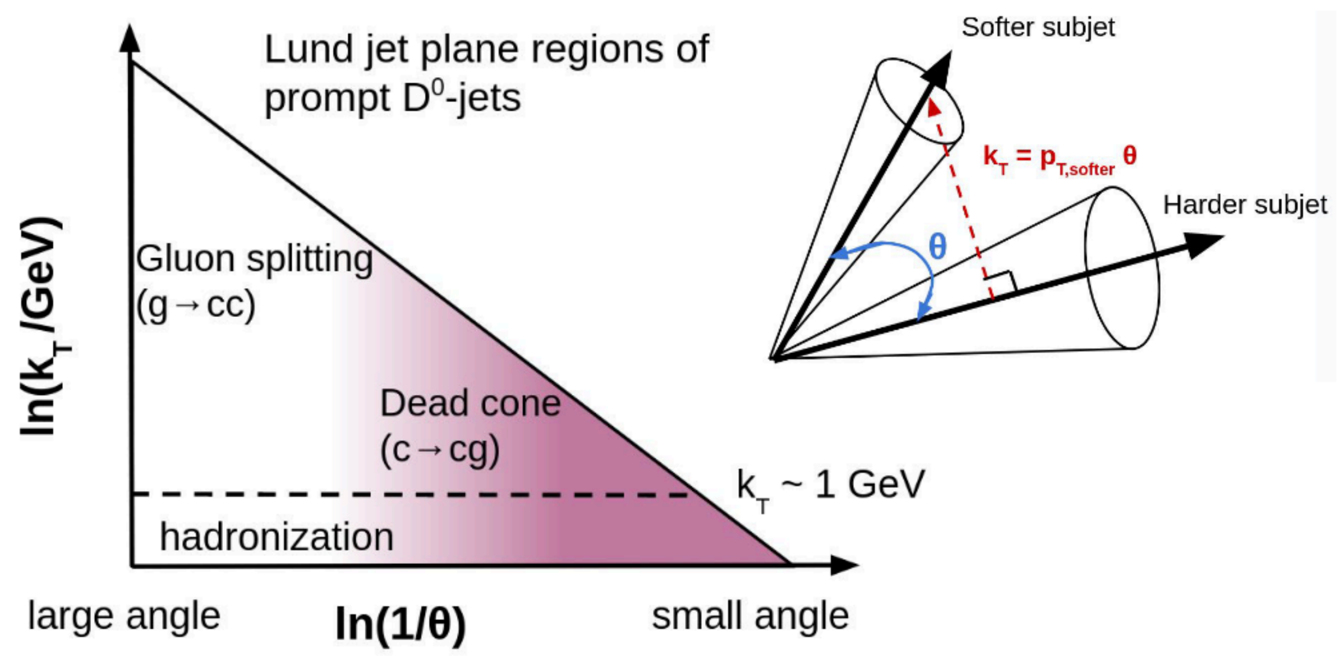


CA jet tree for heavy flavour hadrons

m_Q/p_{Tjet} sets the scale of the minimum
dead cone angle in the jet tree, ie that of the first emission

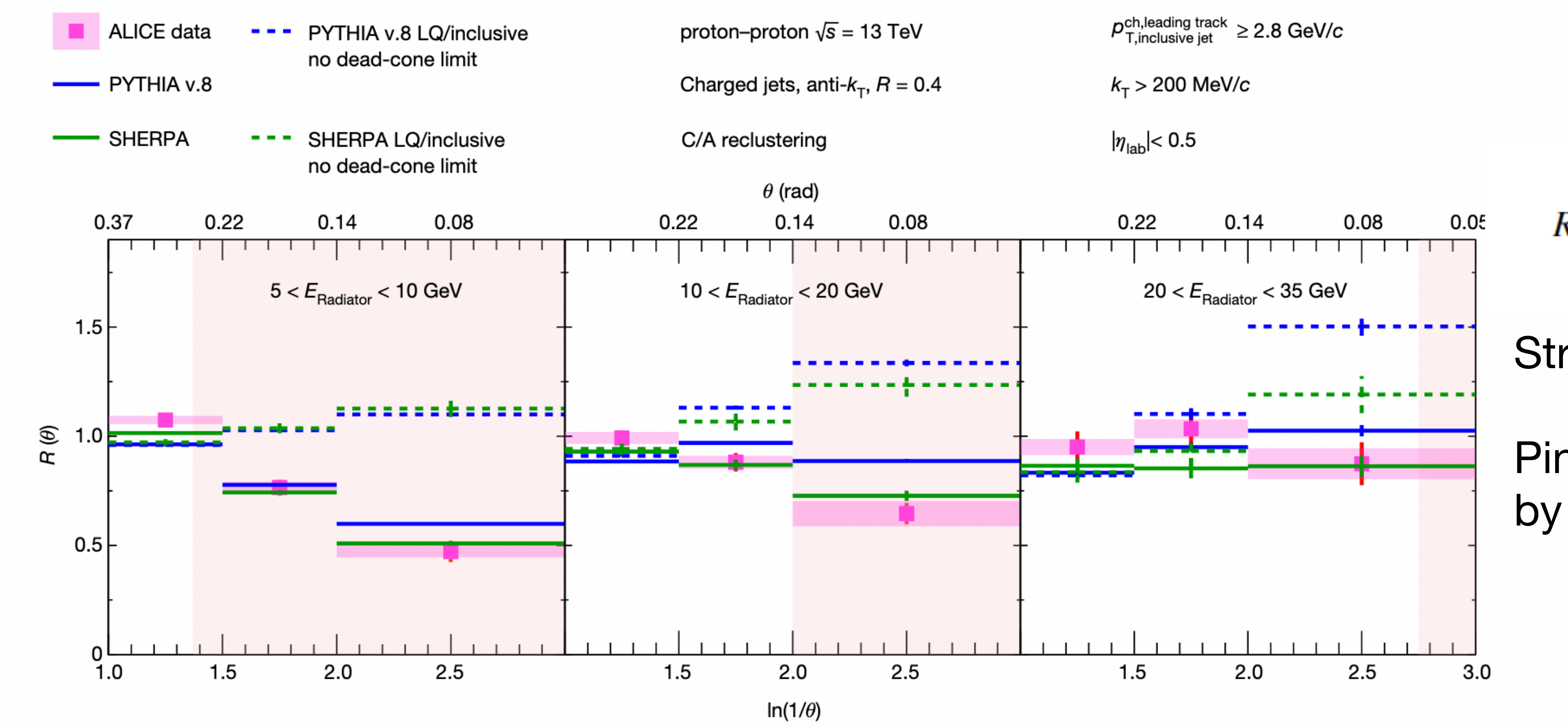
Nodes deeper in the tree ($E_{emitter} << p_{Tjet}$) have bigger dead cones

Sensitivity to quark mass ->access hard&collinear emissions



Seeing the dead cone

ALICE, Nature 605, 440-446 (2022)



$$R(\theta) = \frac{1}{n^{\mathrm{D^0 jets}}} \frac{\mathrm{d}n^{\mathrm{D^0 jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{n^{\mathrm{inclusive\ jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\ jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}} > x\Lambda_{QCD}} .$$

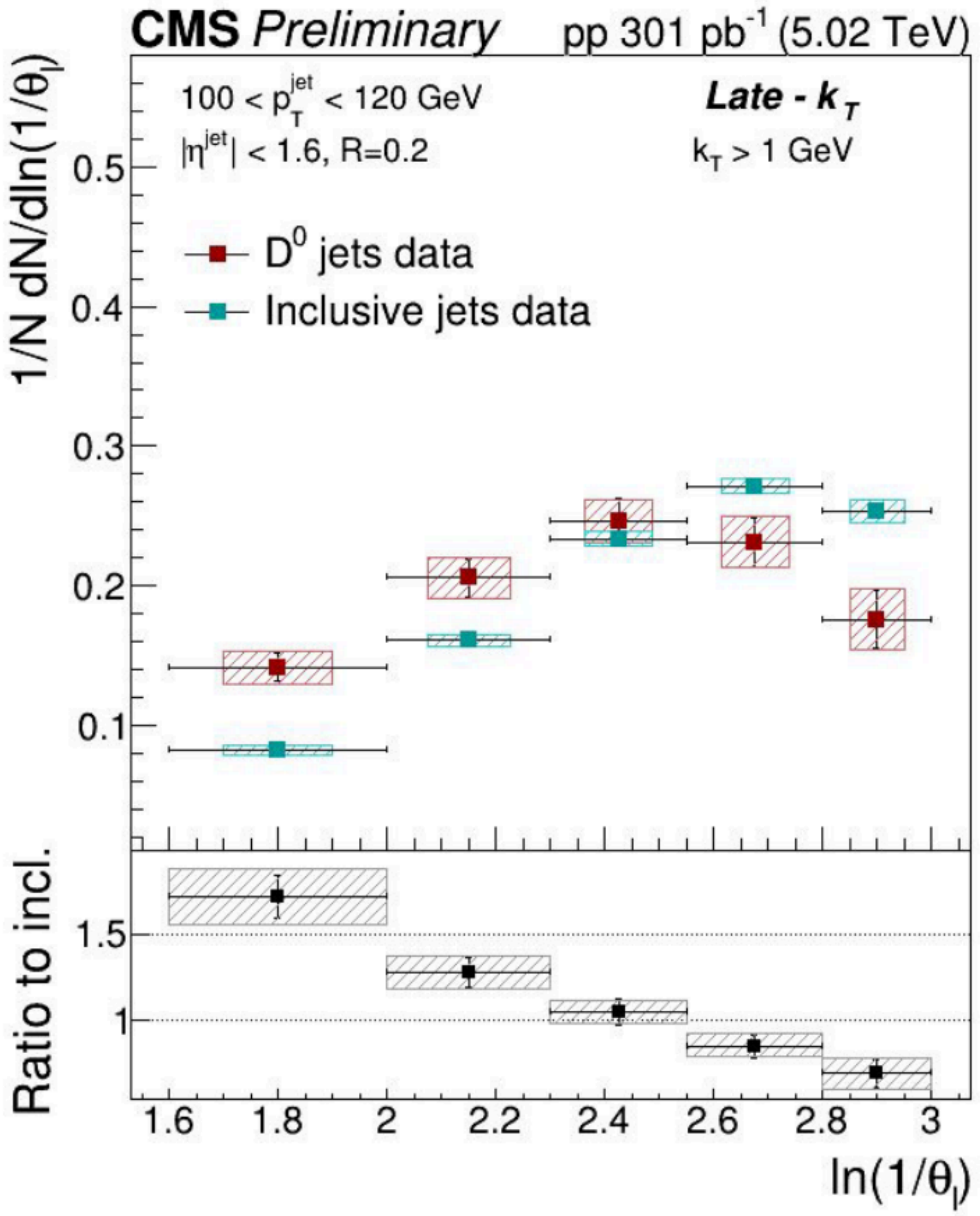
Strong suppression in the lowest $E_{radiator}$ bin

Pink areas represent the vetoed regions given by m_C/E

Accesing the Q->Qg splitting and testing its mass dependence requires:

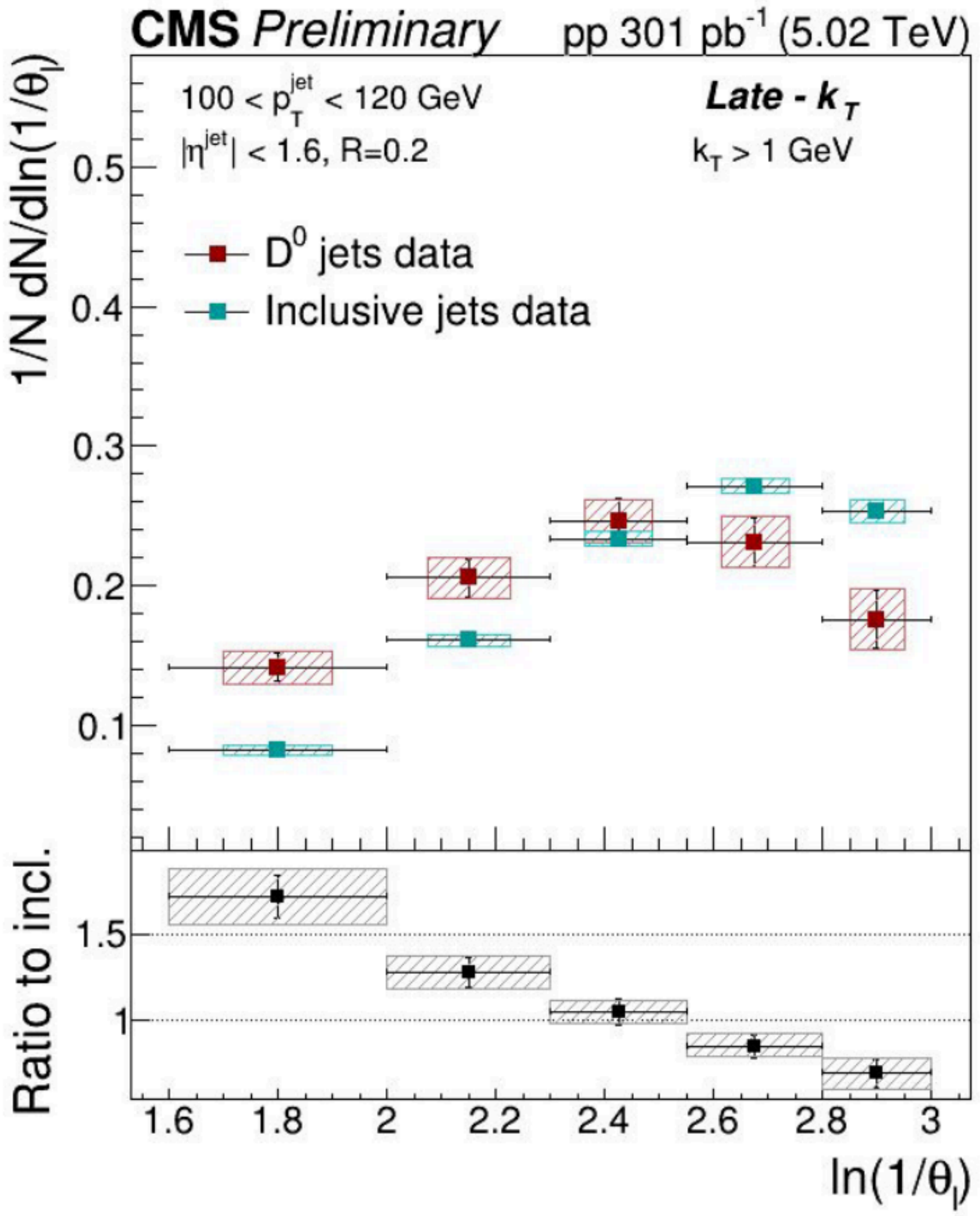
1. To penetrate the jet tree down to the splittings at the smallest angles
2. To suppress hadronisation effects, by imposing a cut on the hardness of the splittings -on k_T
3. To fully reconstruct the heavy flavour hadron: decay products interfere with the jet tree and create extra splittings at small angles that darken the dead cone

Seeing the dead cone at high jet p_T



New algorithms designed to select hard&collinear emissions
Charm quark mass effects for energetic jets
No impact of gluon splittings, contrary to SoftDrop

Seeing the dead cone at high jet p_T



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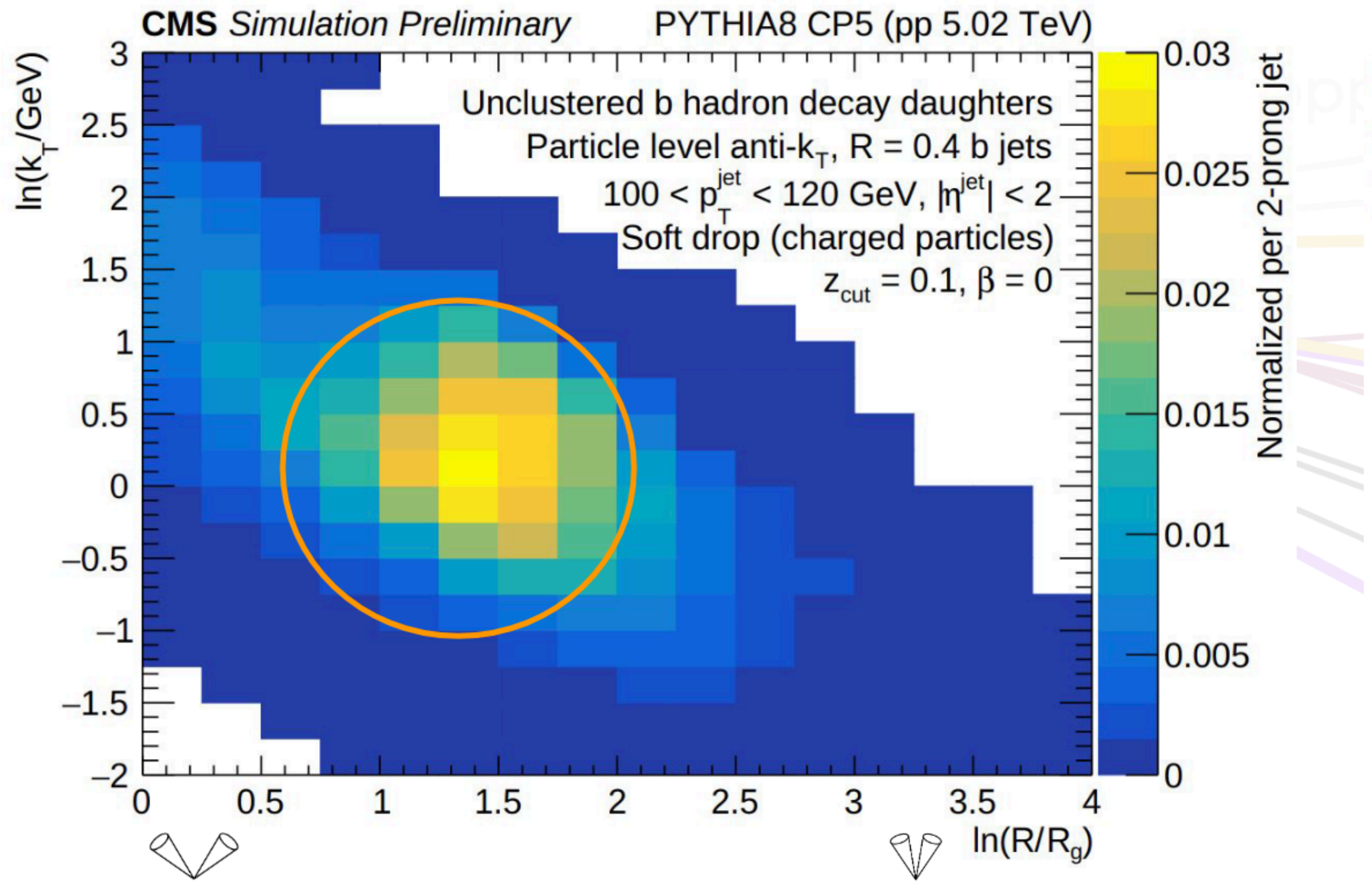
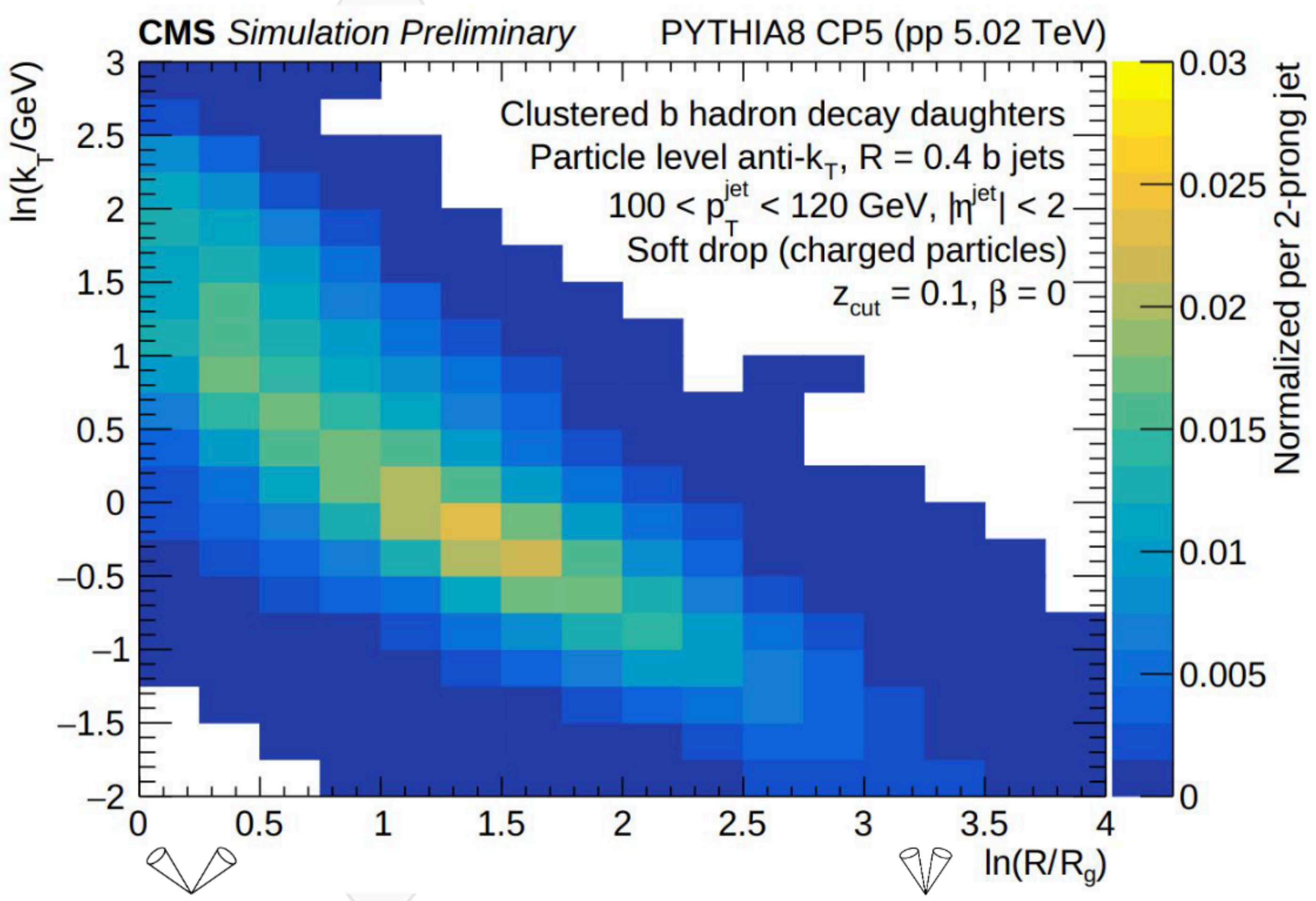
The decay problem in the Lund plane



b decay daughters present

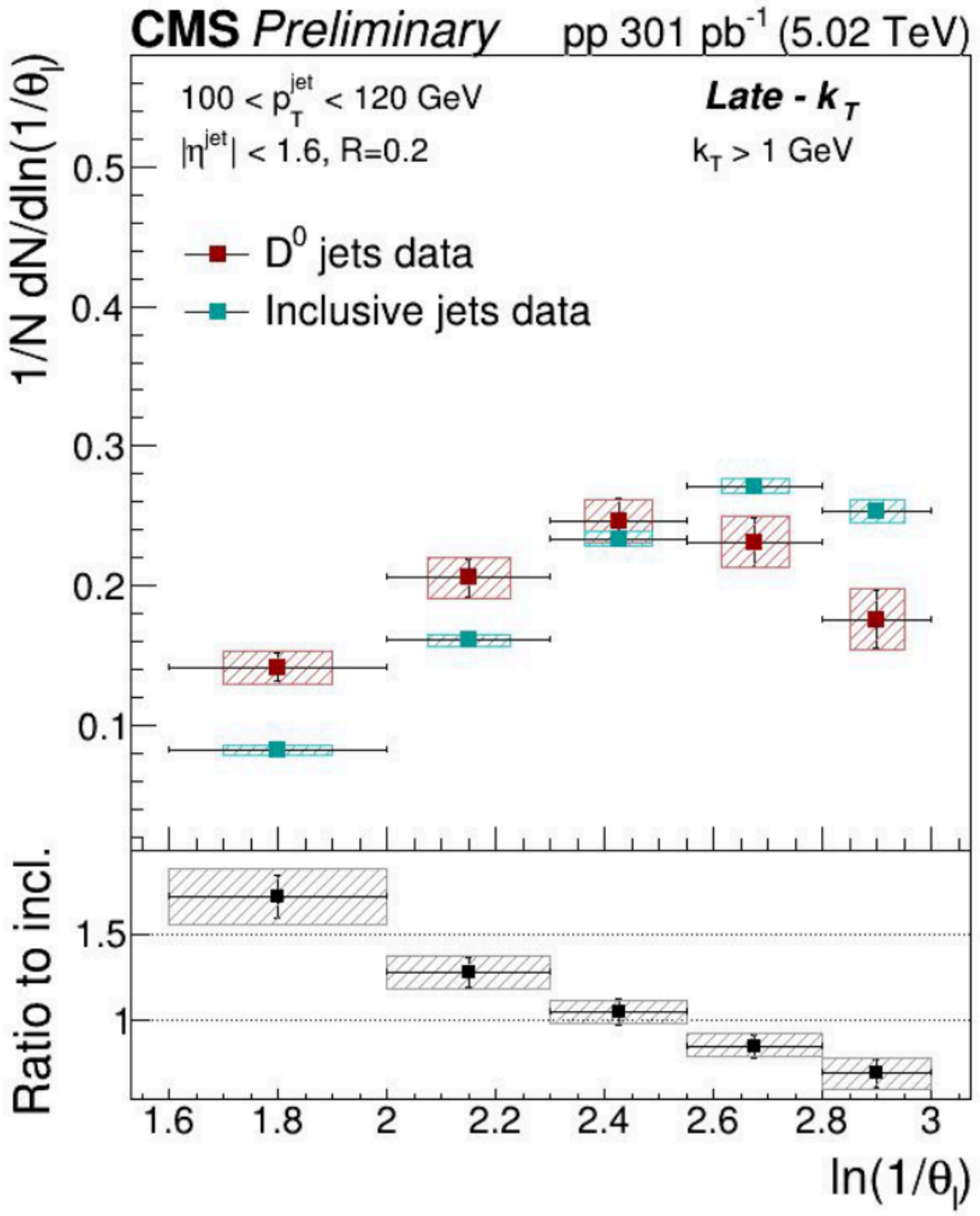


b decay daughters clustered

New method to aggregate the particles from the secondary vertex into a B pseudohadron

Allows to exploit the high statistics of b-tagging as compared to full B hadron reconstruction

Seeing the dead cone at high jet p_T



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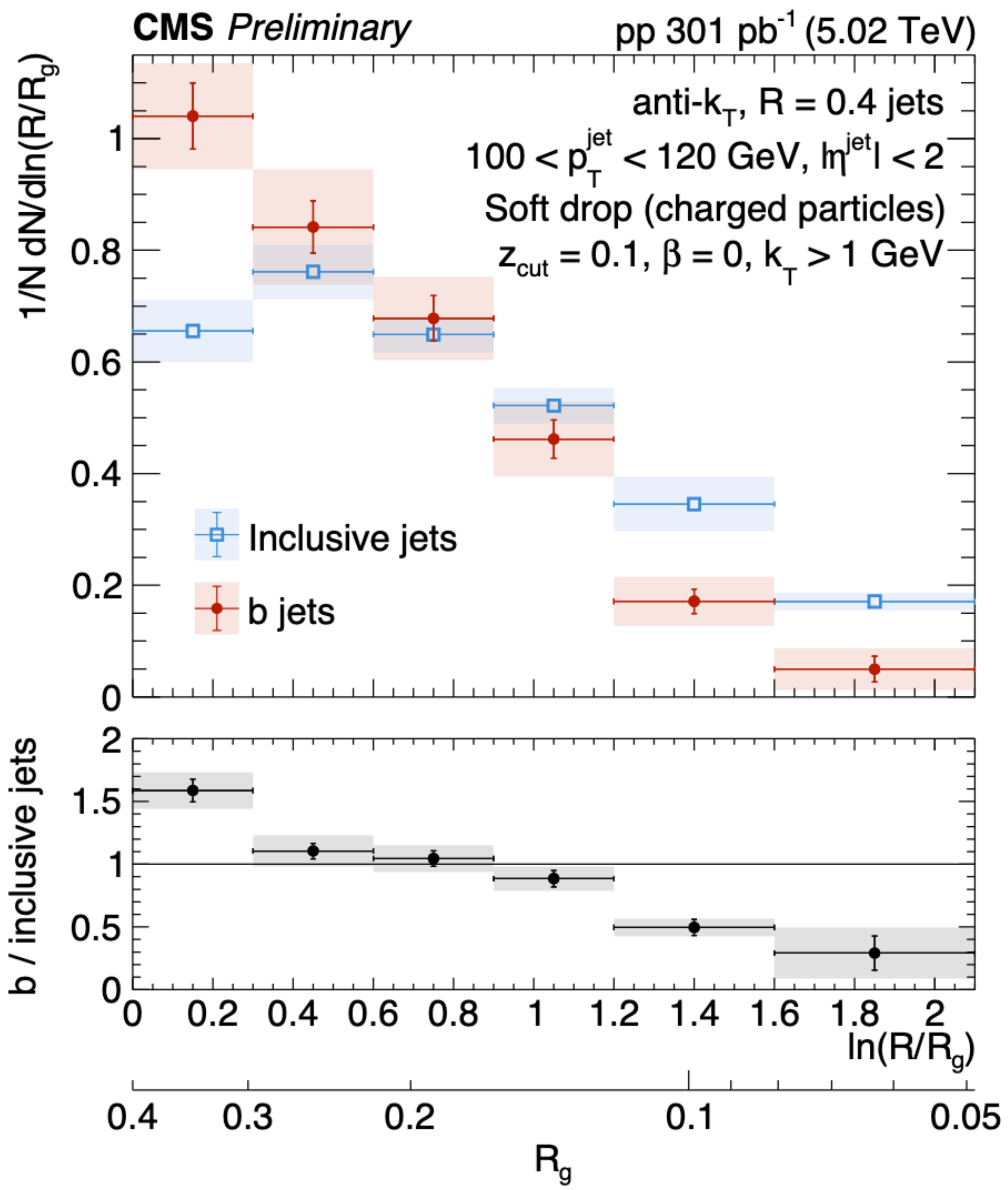
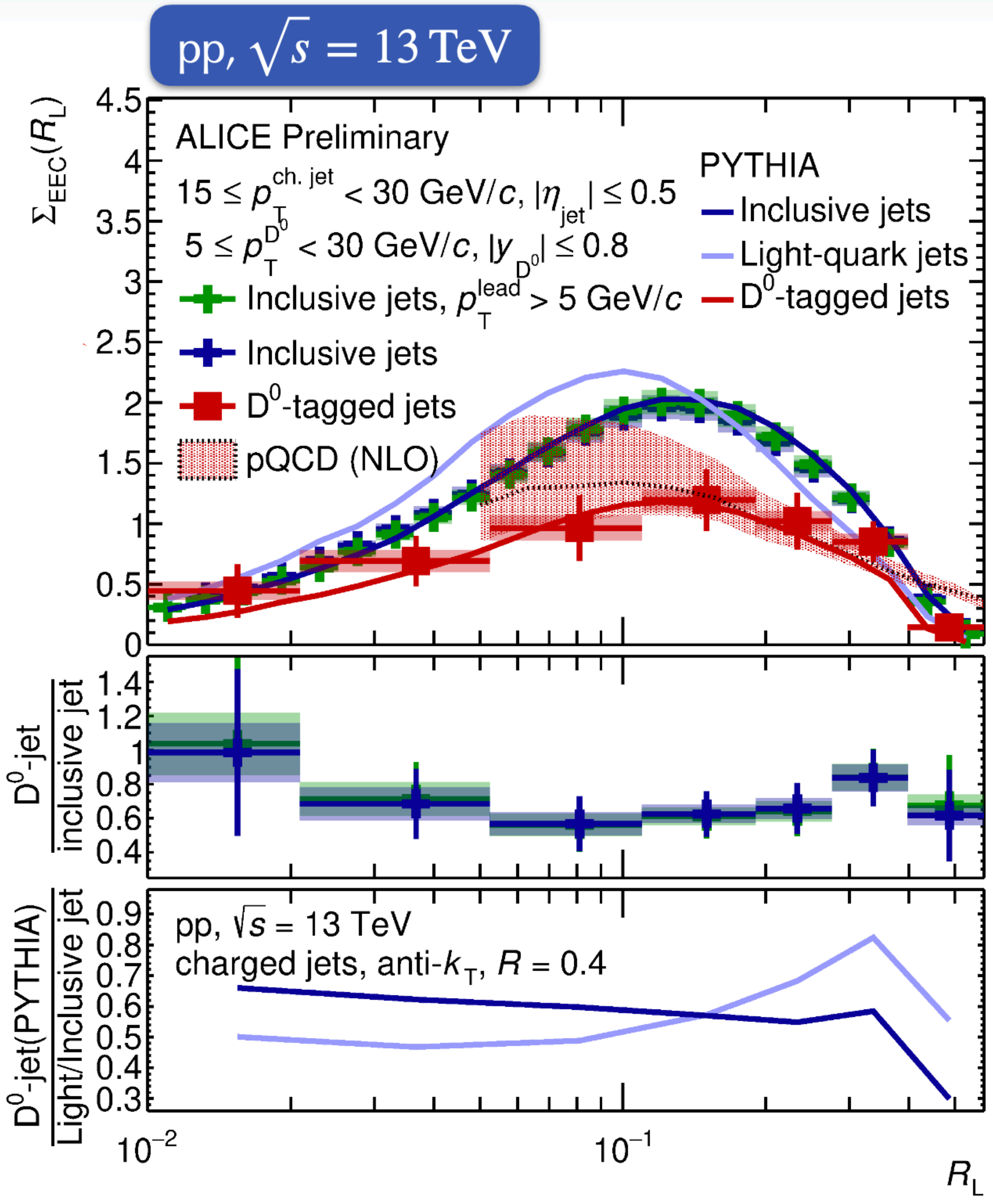
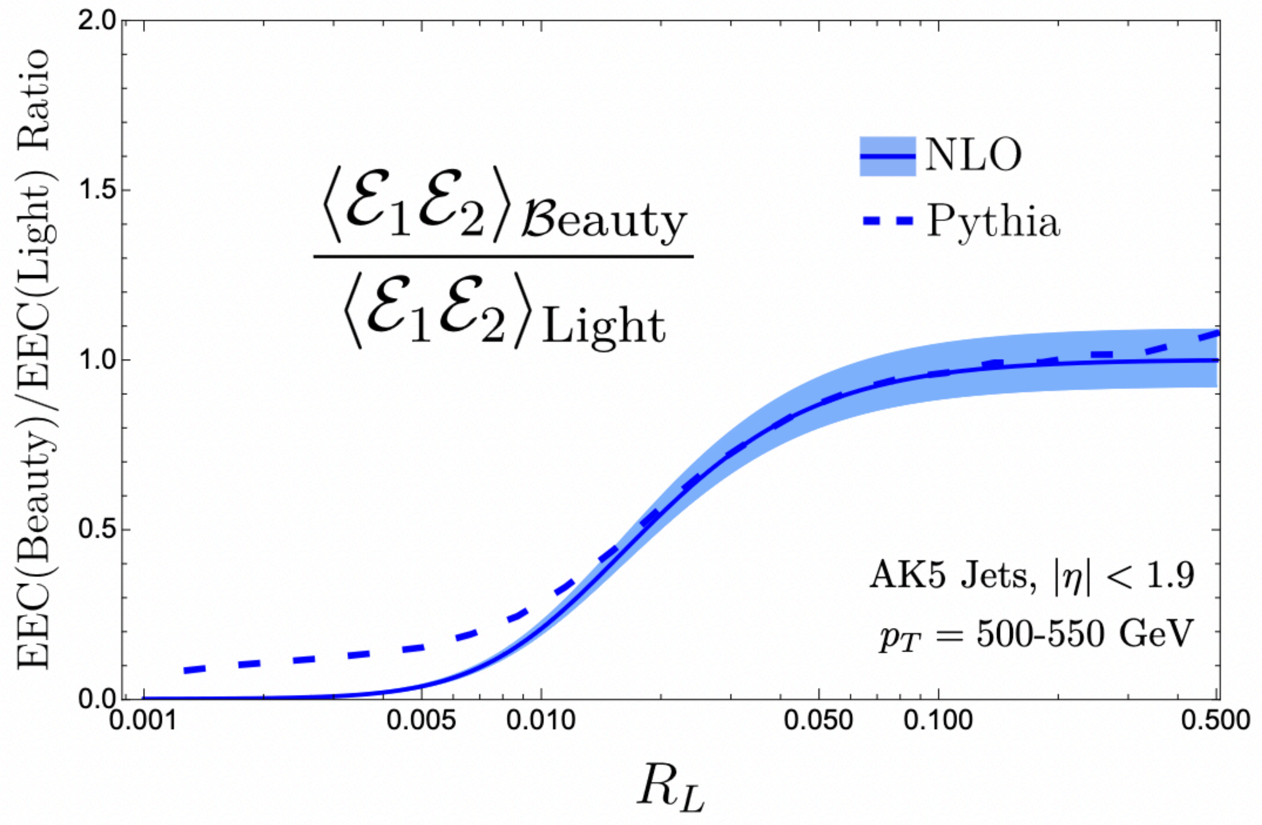


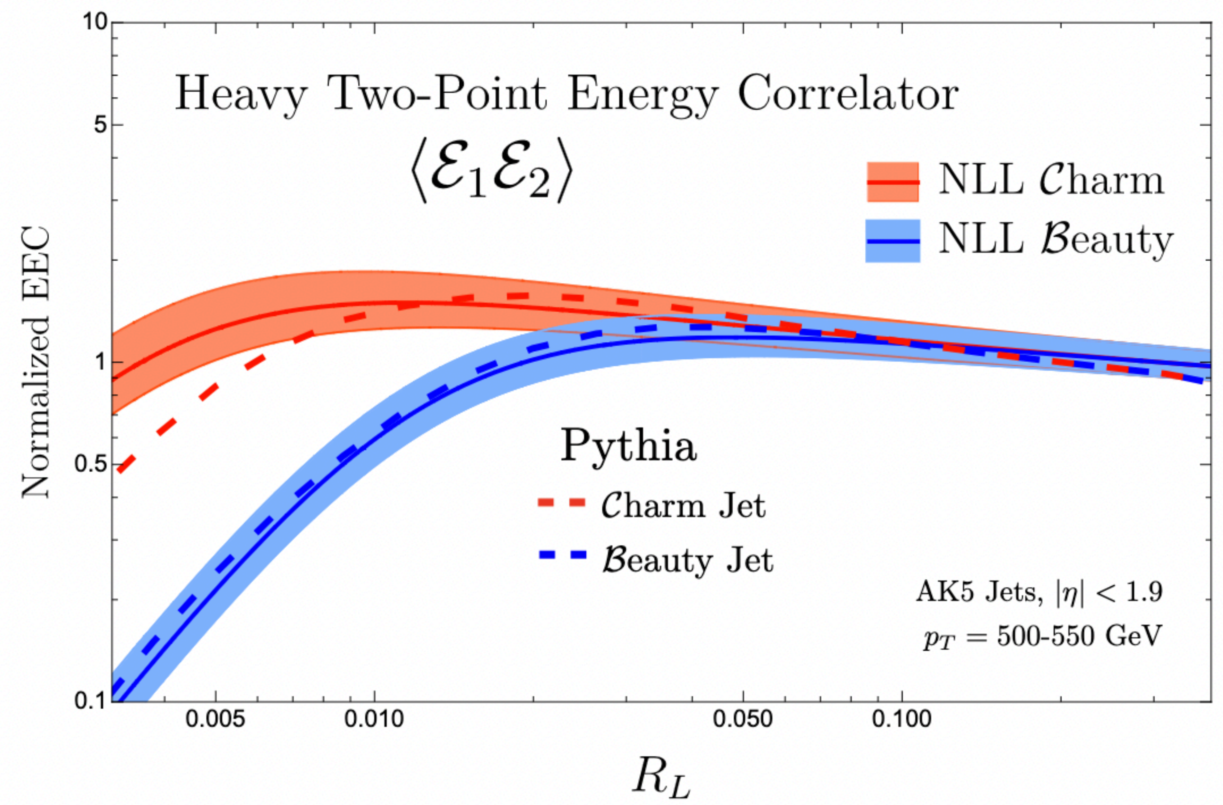
Suppression of collinear emissions for both D-jets and b-jets due to quark masses

Heavy flavours and the EEC

Craft, Lee, Mecca, Moult, [2210.09311]







Strong suppression of the yield of emissions
Reference is currently PYTHIA

First NLL calculation of a heavy-flavoured jet substructure observable in pp collisions
Clear suppression of small angles for b-jets, same scaling behaviour as massless for large angles

Heavy flavour jet substructure prospects for HIN

In medium, an interesting interplay of scales appears:

Salgado et al, Phys.Rev.D 69 (2004) 114003
Cunqueiro et al, Phys.Rev.D 107 (2023) 9, 094008
Andres et al, Phys.Rev.D 110 (2024) 3, L031503

$$\theta_C < \theta < \theta_{dead}$$

To be filled by medium-induced radiation, the dead cone angle needs to be larger than the decoherence angle θ_C

Strong enhancement of collinear splittings is expected for b-jets while c-jets dead cone remains intact

Predictions from both the Lund Plane and EEC languages

No notion of Dead Cone in strongly coupled description. Observing it, would it be a validation of weakly coupled approaches?

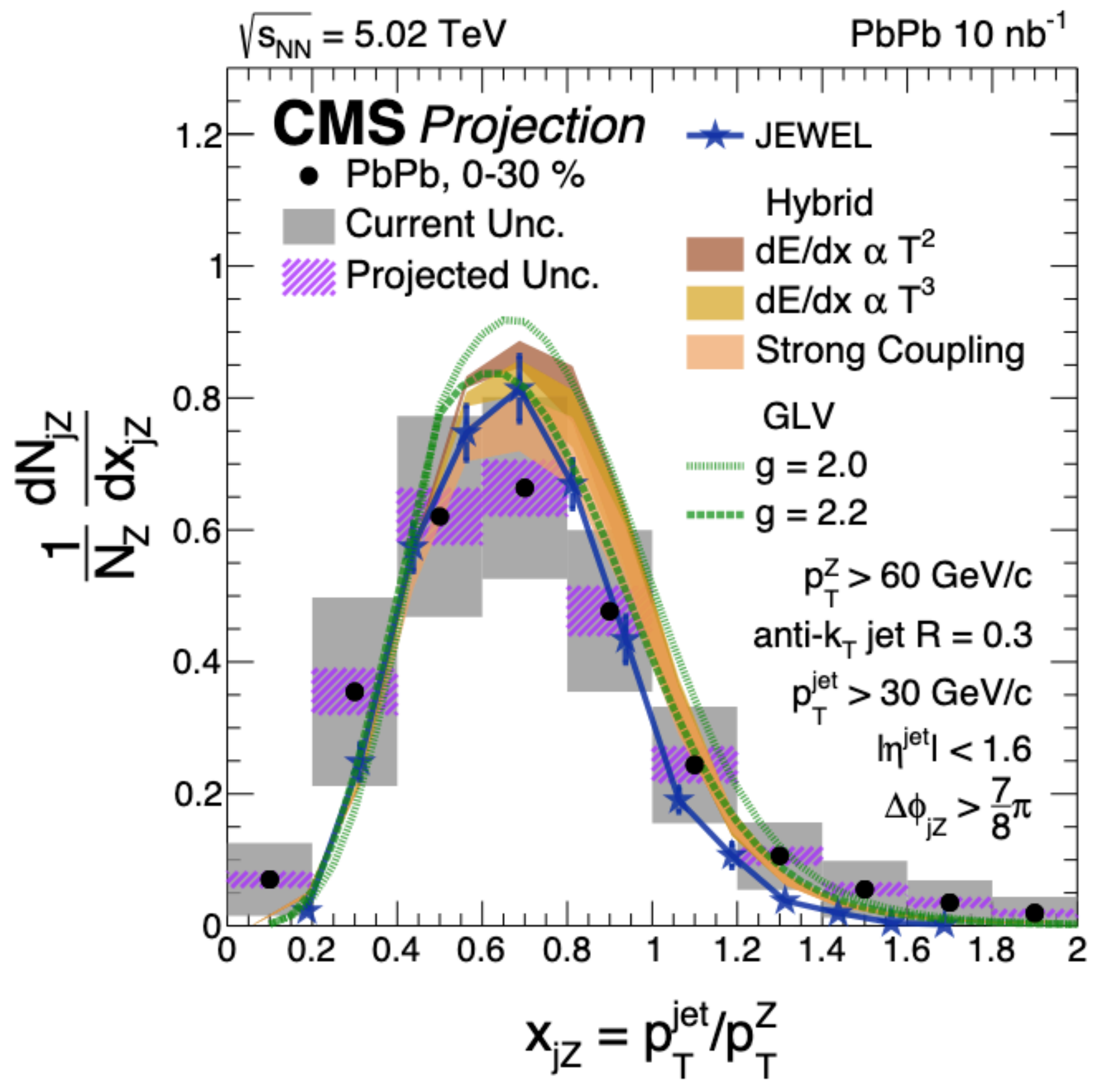
Summary: what HL-LHC brings to jet substructure in HIN

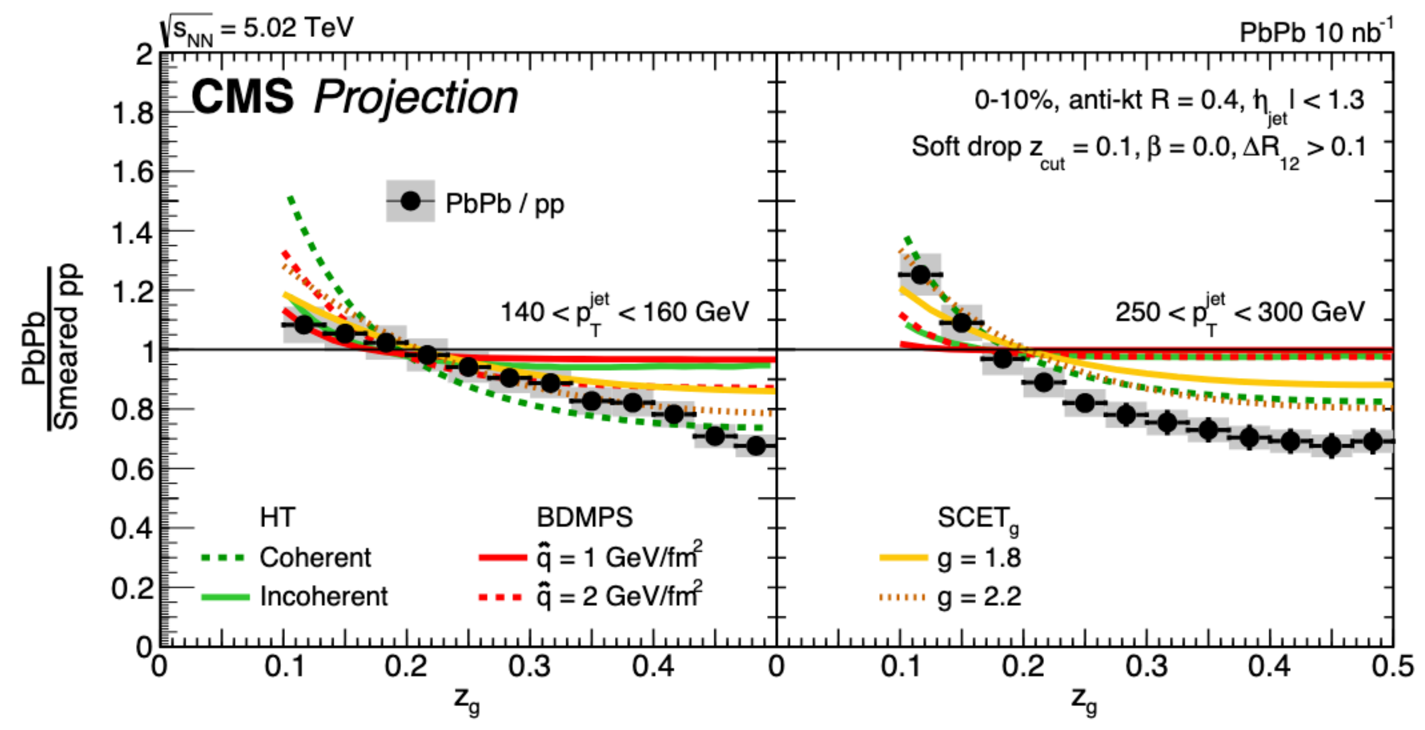
Harder probes

Possibility to go down to xJ->0 to explore the most strongly quenched jets
Possibility to perform jet substructure recoiling from Z bosons too. Zs are cleaner proxies of the energy loss of recoiling jets than γs (no fragmentation component)
New access to the upper corner of the Lund plane of very energetic jets, potentially dominated by vacuum splittings

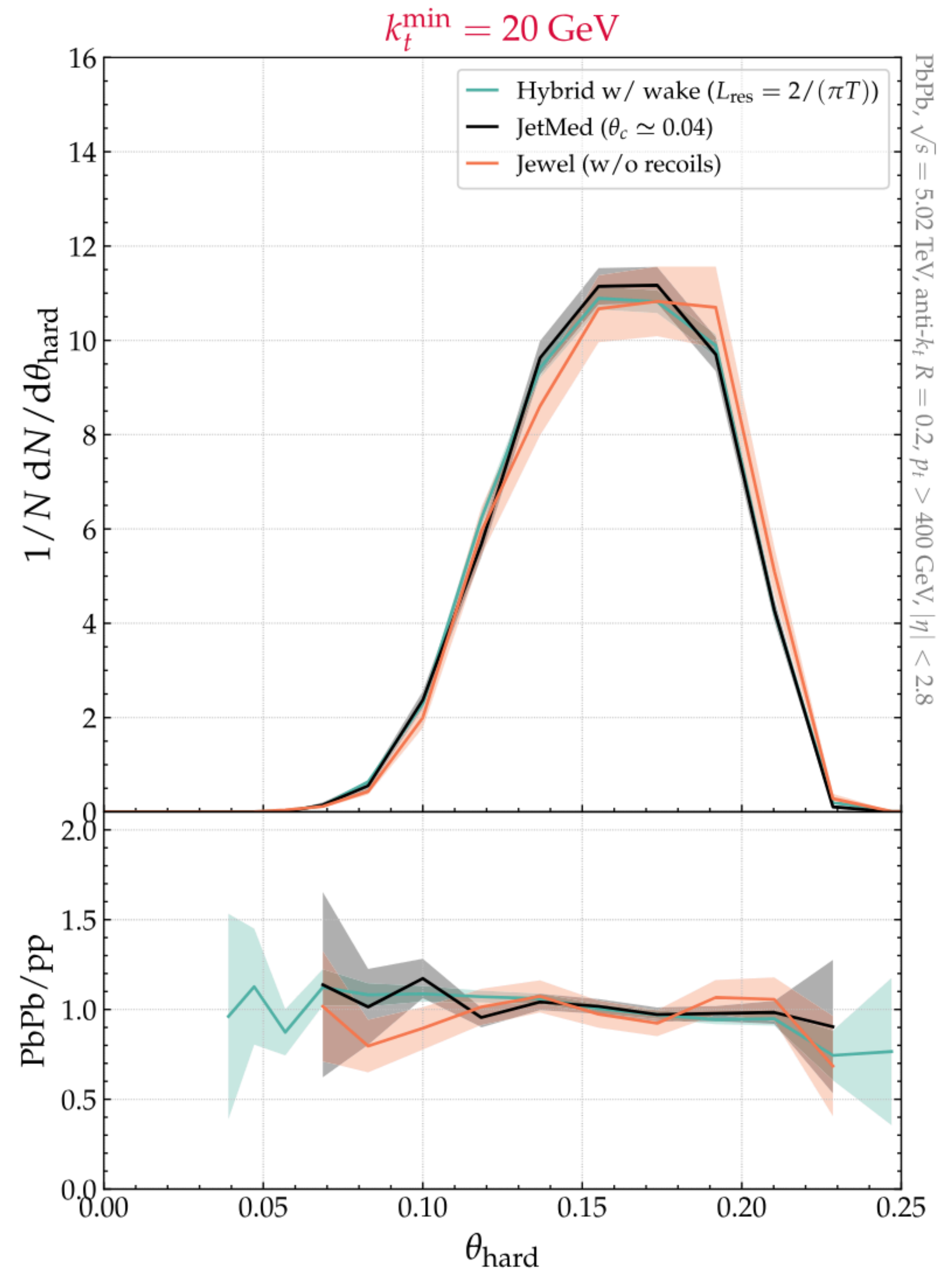
More differential hard probes

Possibility to combine EW bosons and heavy flavour jet substructure





two examples from https://arxiv.org/pdf/1812.06772



Cunqueiro et al, Phys.Rev.D 110 (2024) 1

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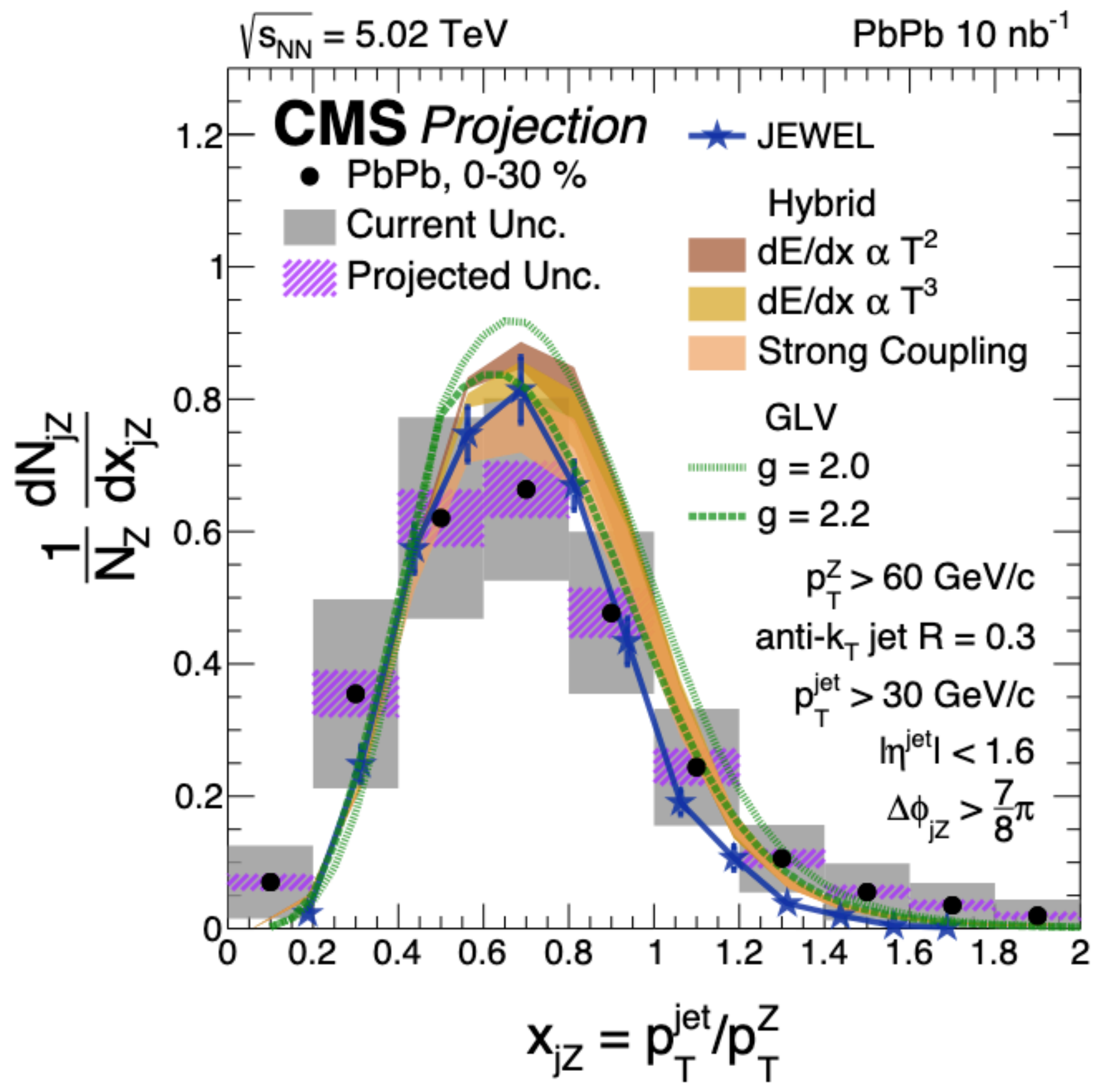
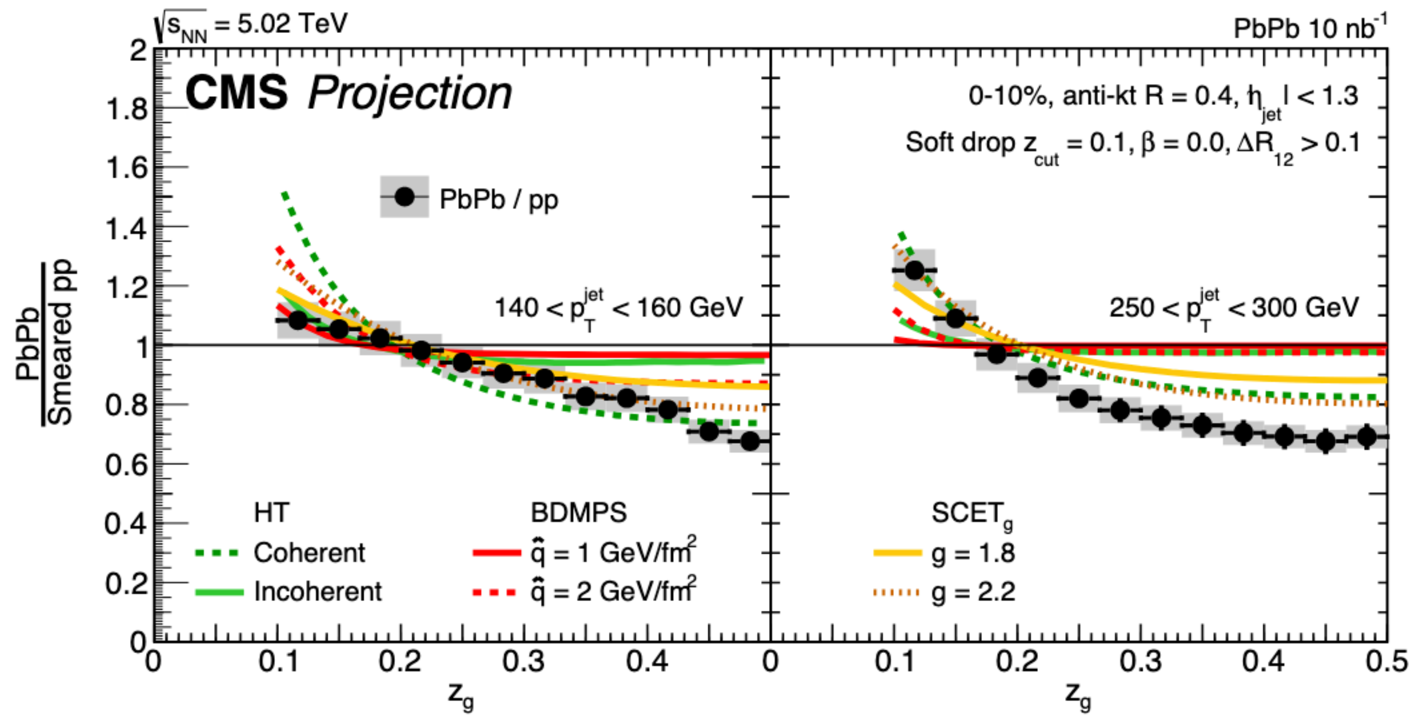
New access to th acuum splittings

More differential hard pr

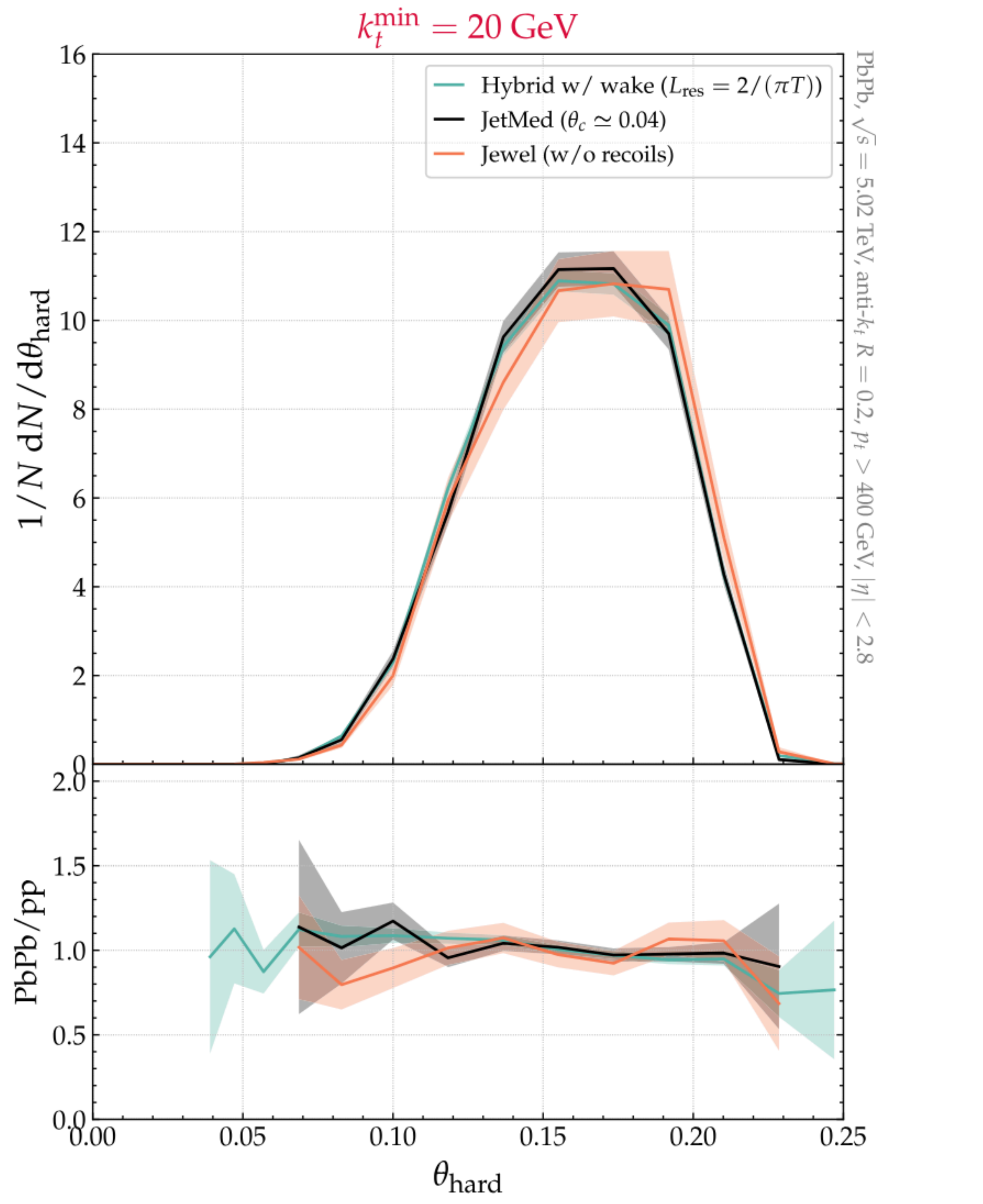
Possibility to com

Probing the microscopic structure of the QGP within reach





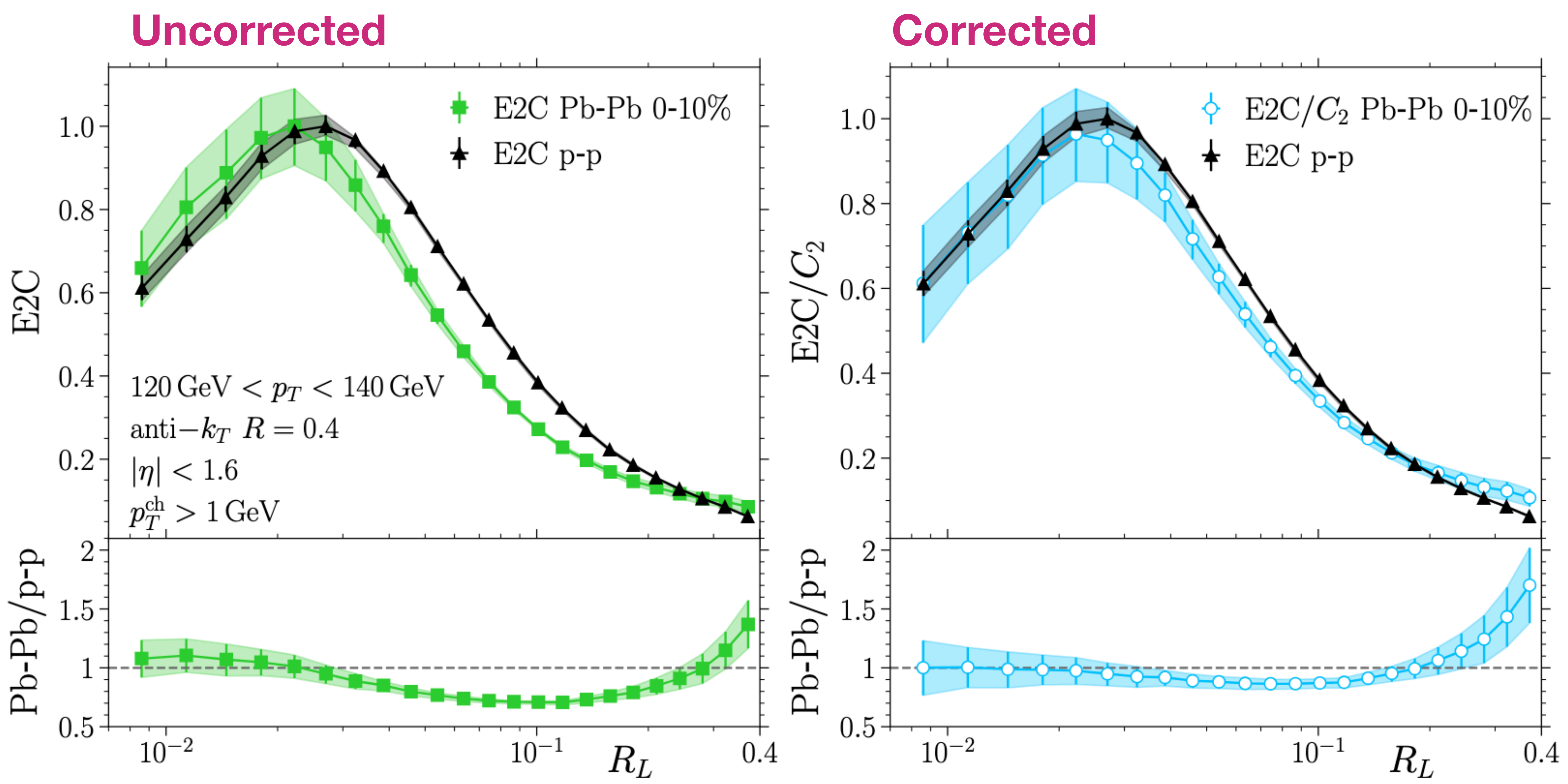
two examples from https://arxiv.org/pdf/1812.06772



Cunqueiro et al, Phys.Rev.D 110 (2024) 1

end

Mitigation of selection bias for inclusive jets



Carlota Andres, Holguin, Kunnawalkam Elayavalli, Viinikainen arXiv:2409.07514

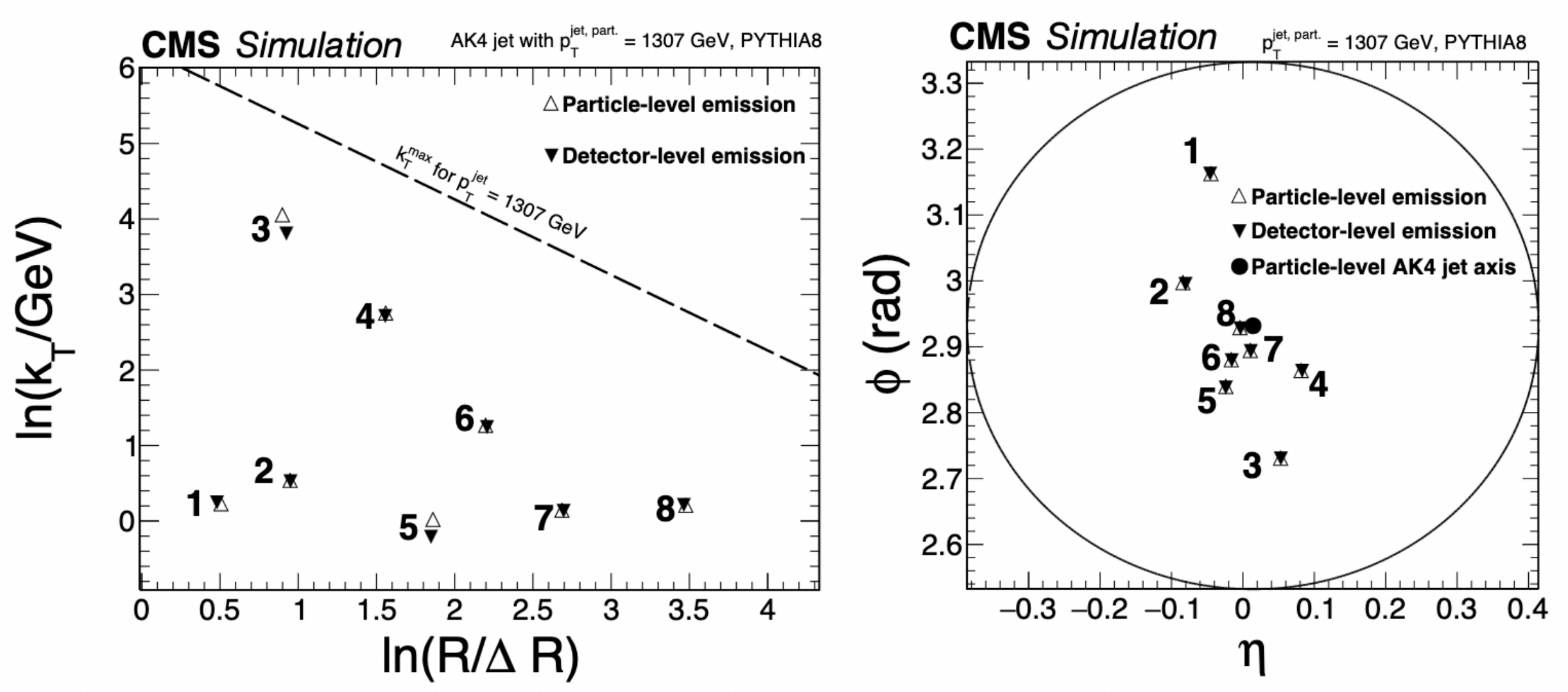
Exploit scaling properties of the observable to suppress the effect of energy loss

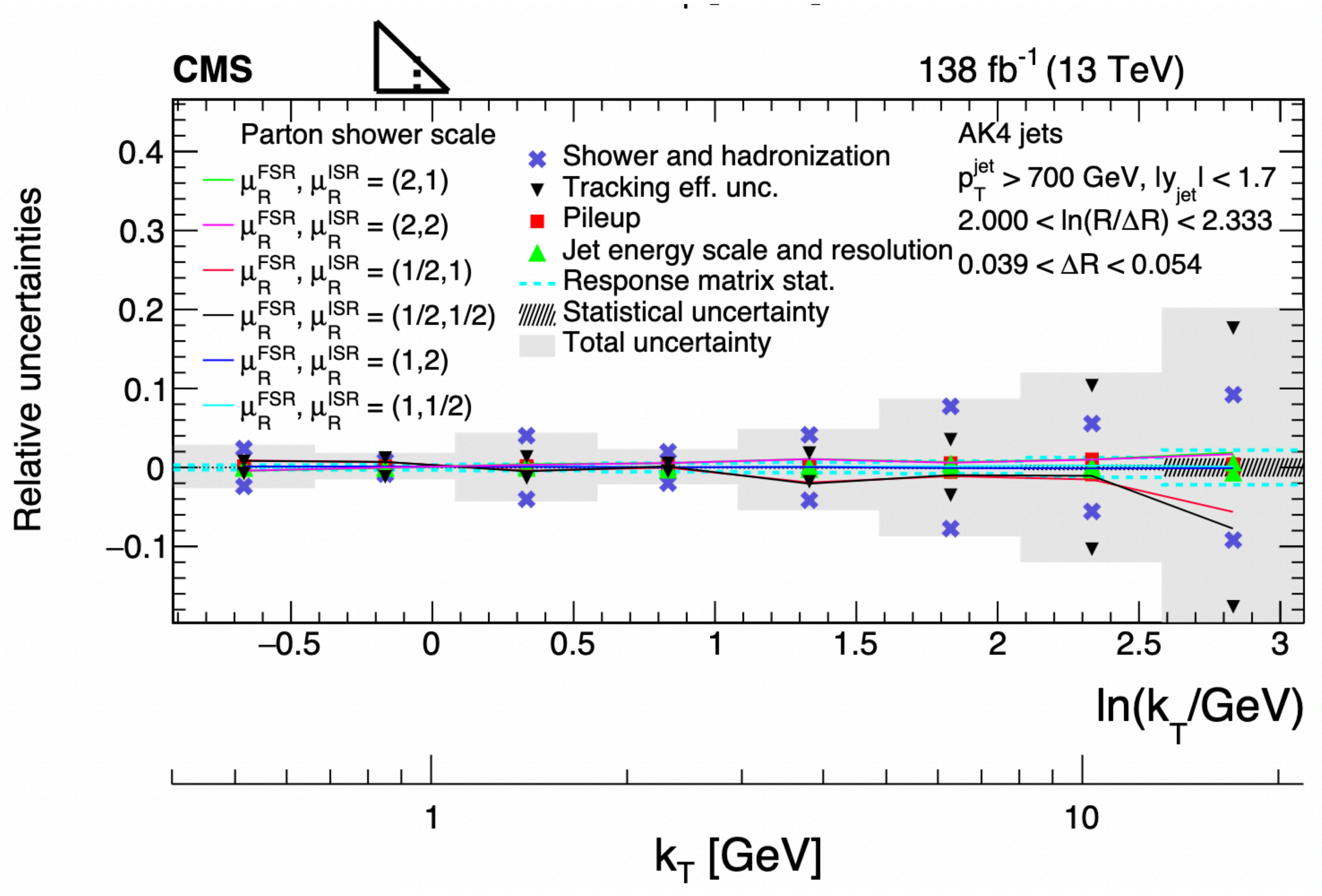
Or one can avoid it completely by measuring the EEC in the full Z-tagged event, see *talk by Yi Chen for the upcoming measurement*

Technical challenges: the Lund Jet Plane in pp

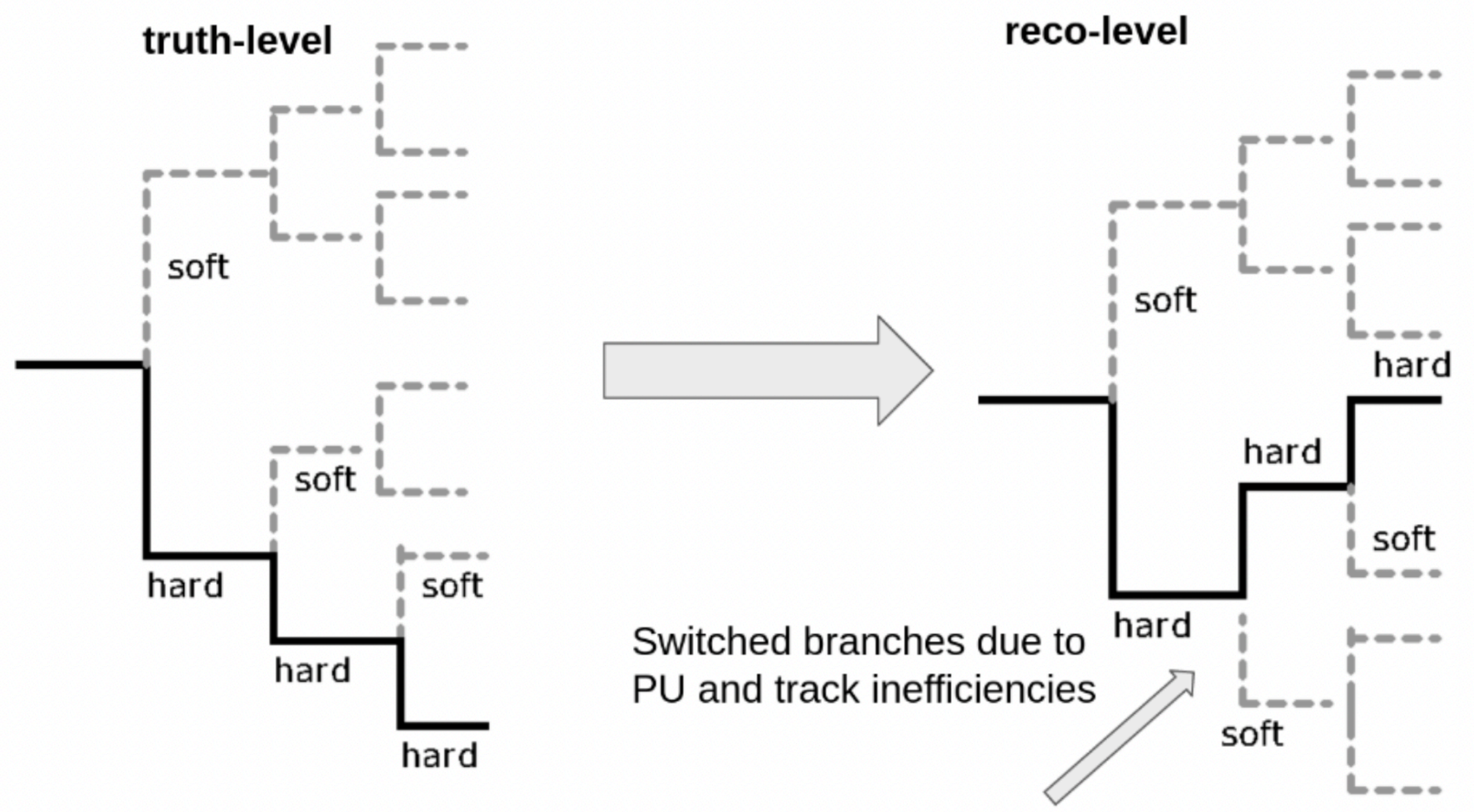
Vangelis Vladimirov

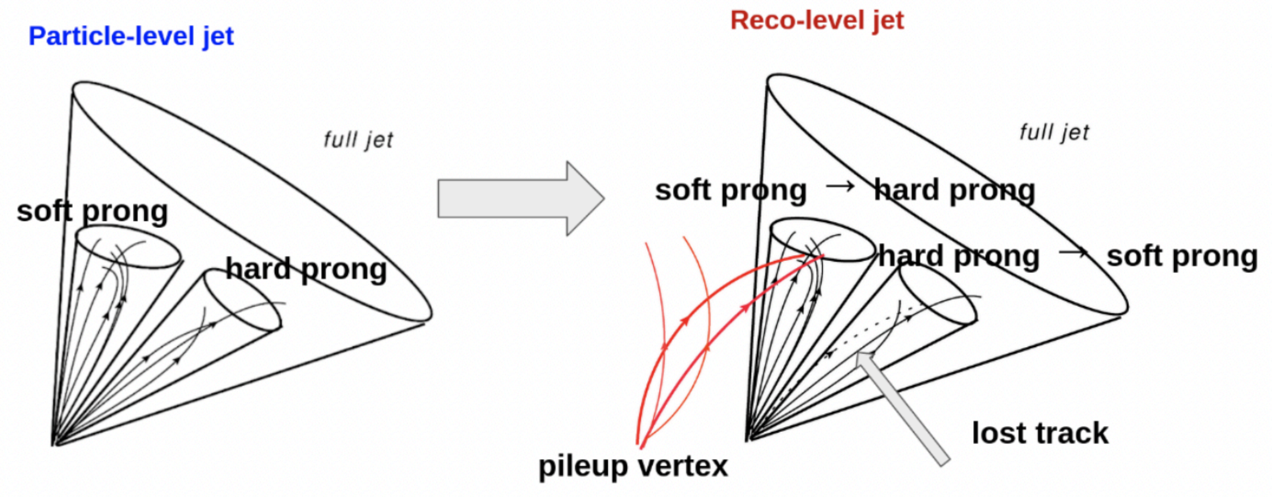
Flat geometrical matching of prongs





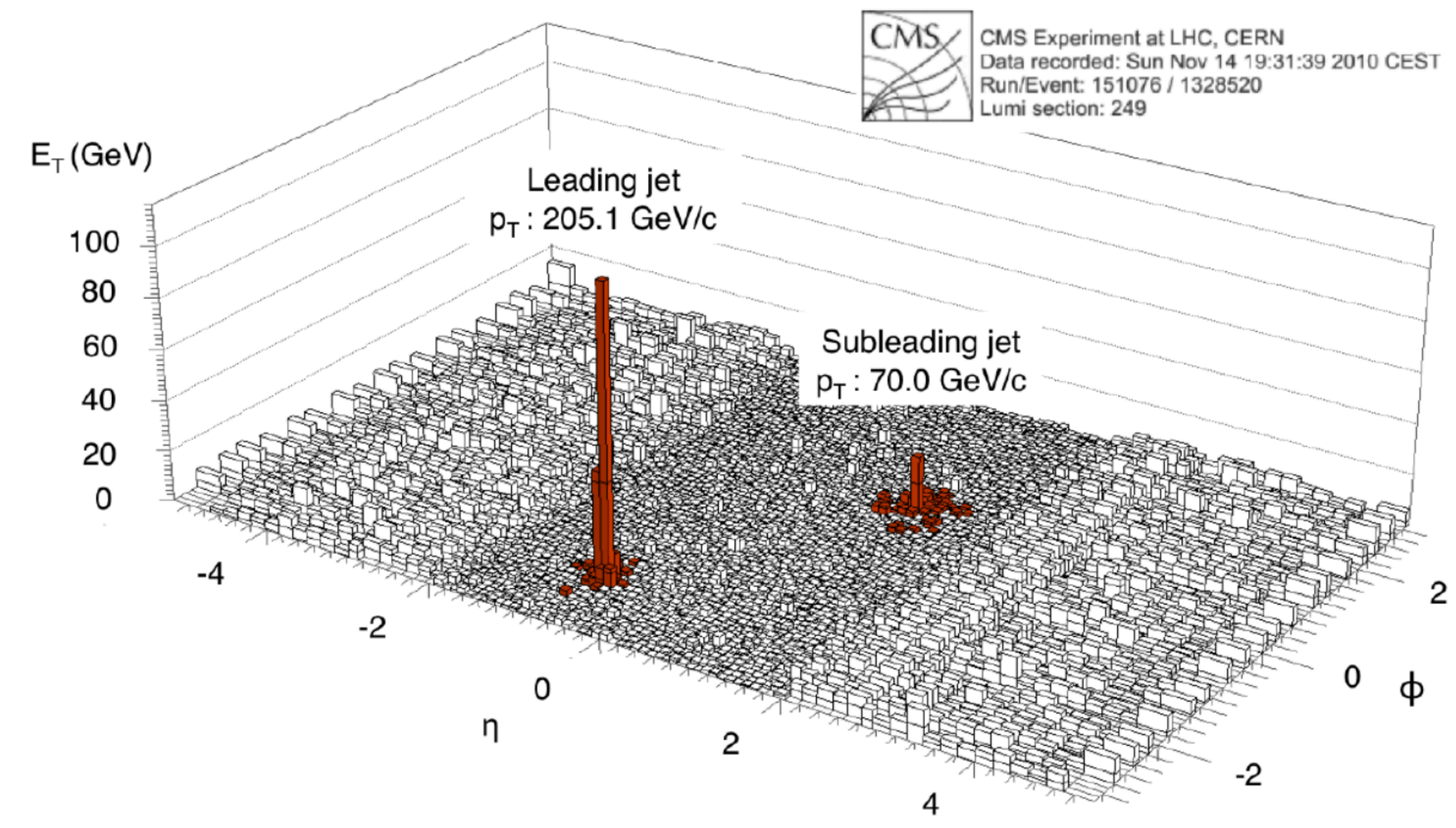
Residual mismatches, induce offdiagonalities in the response



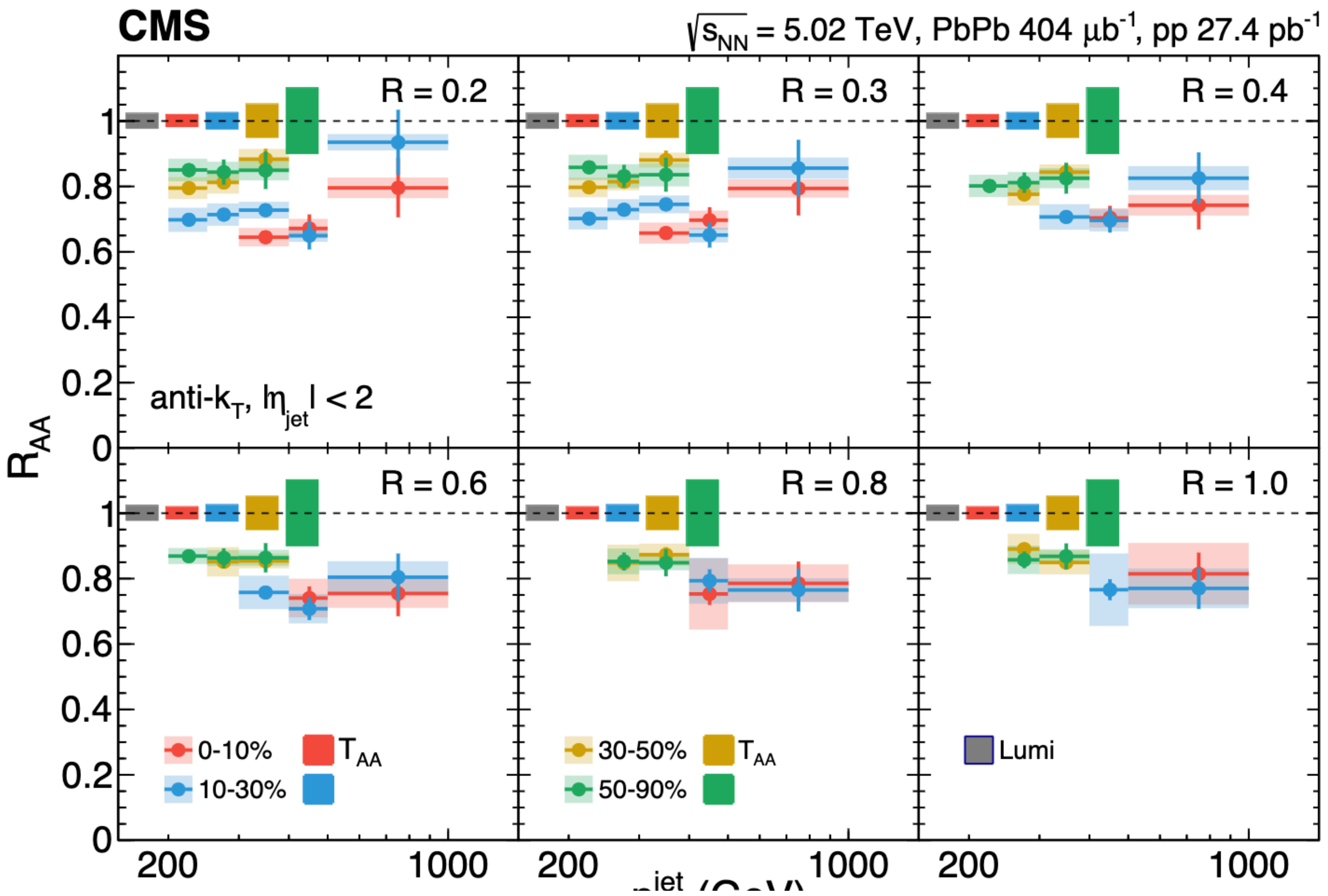


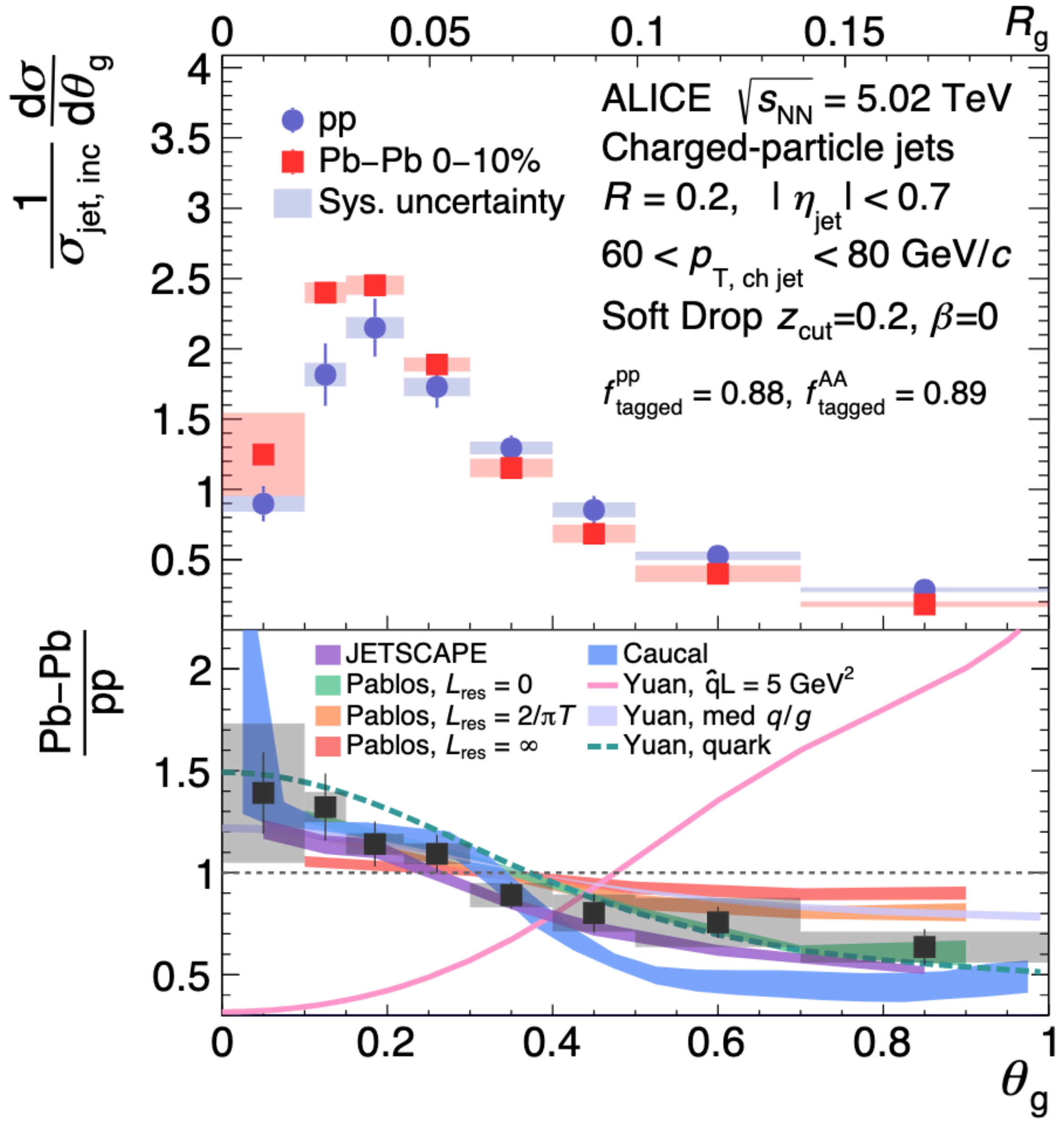
In the high k_T perturbative domain:
track. eff. uncert ~20%
model uncert ~10%

Jets in heavy-ion collisions in three plots



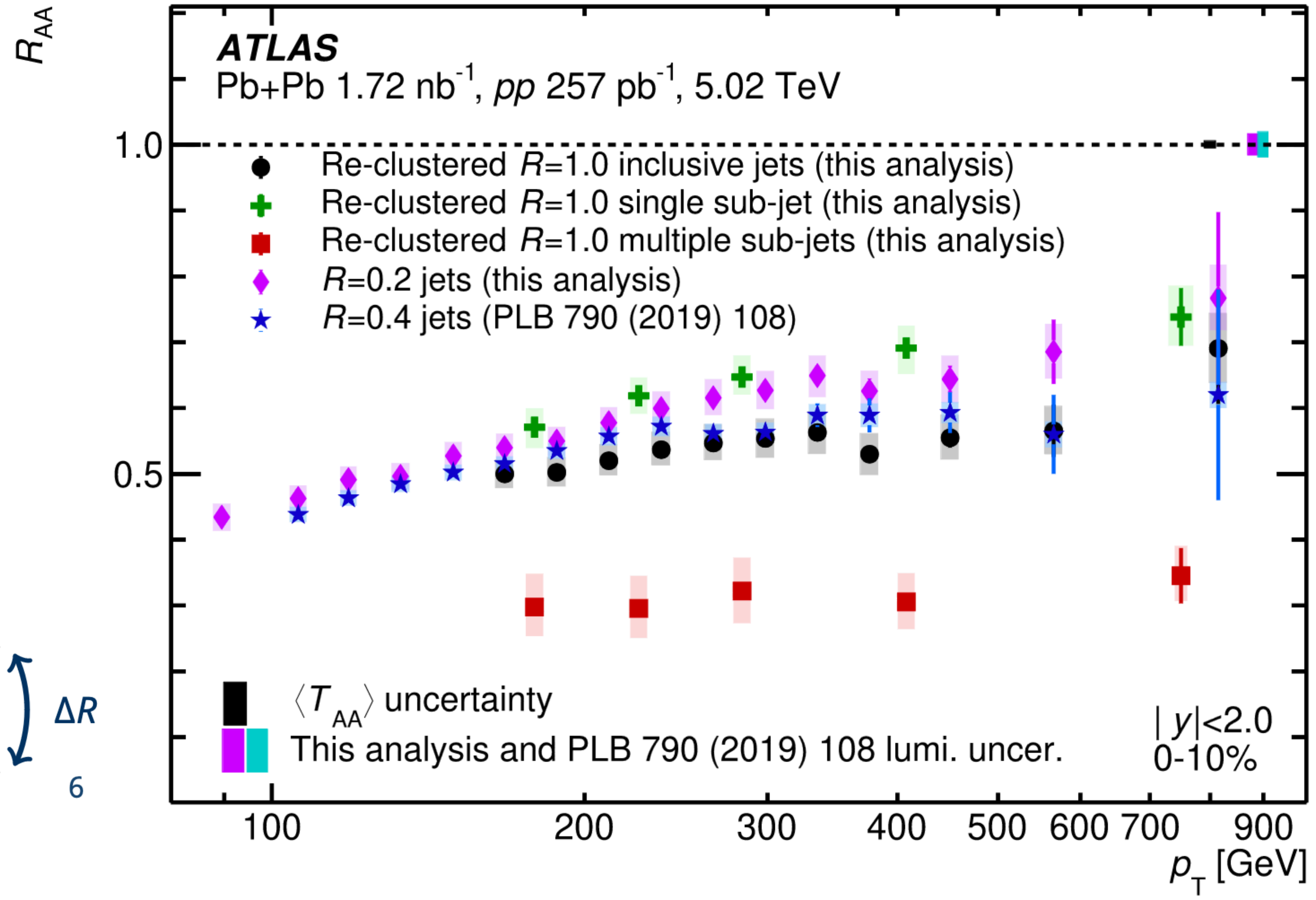
jets are "stopped" in the QGP





broad structures more suppressed

ALICE, PhysRevLett.128.102001

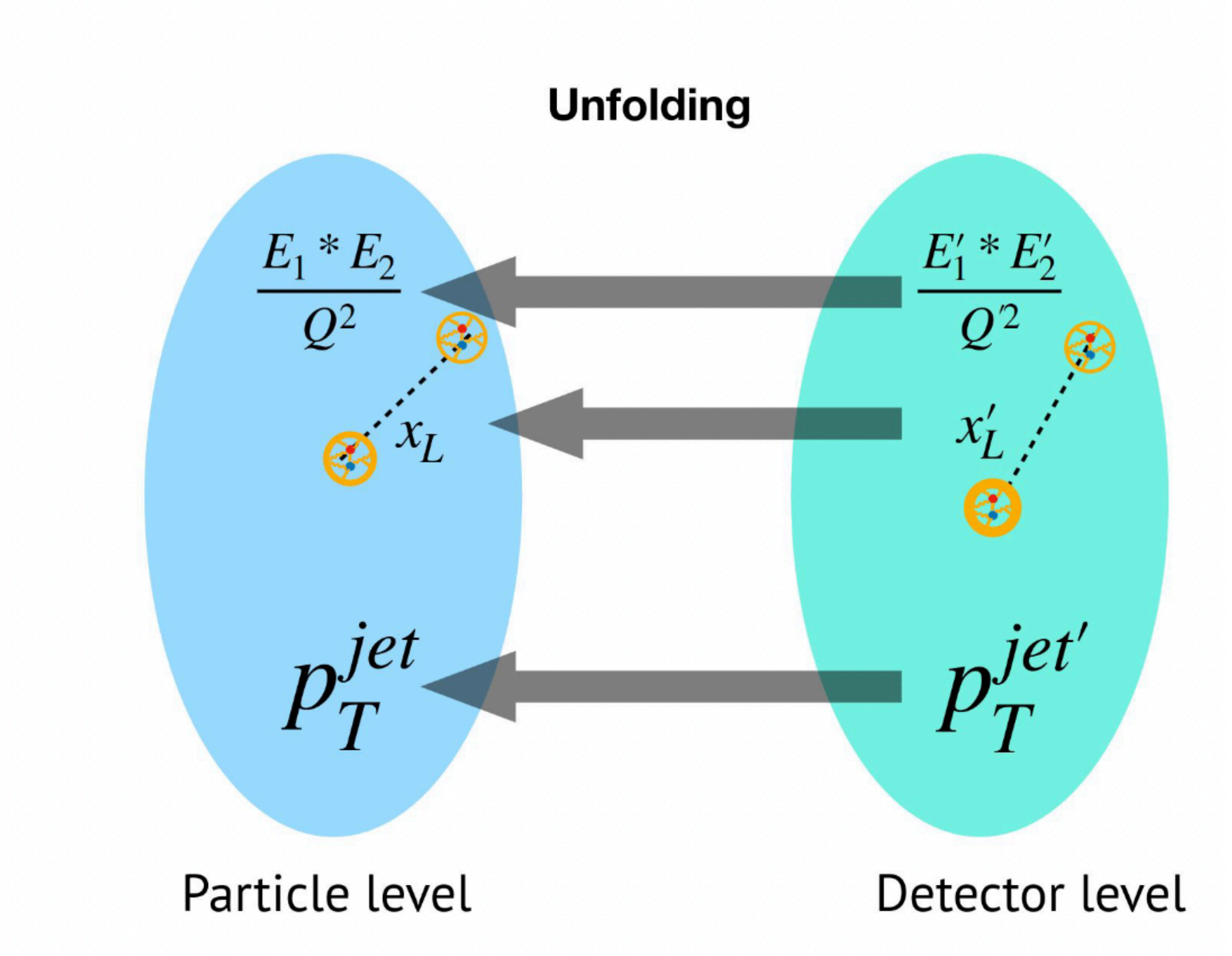


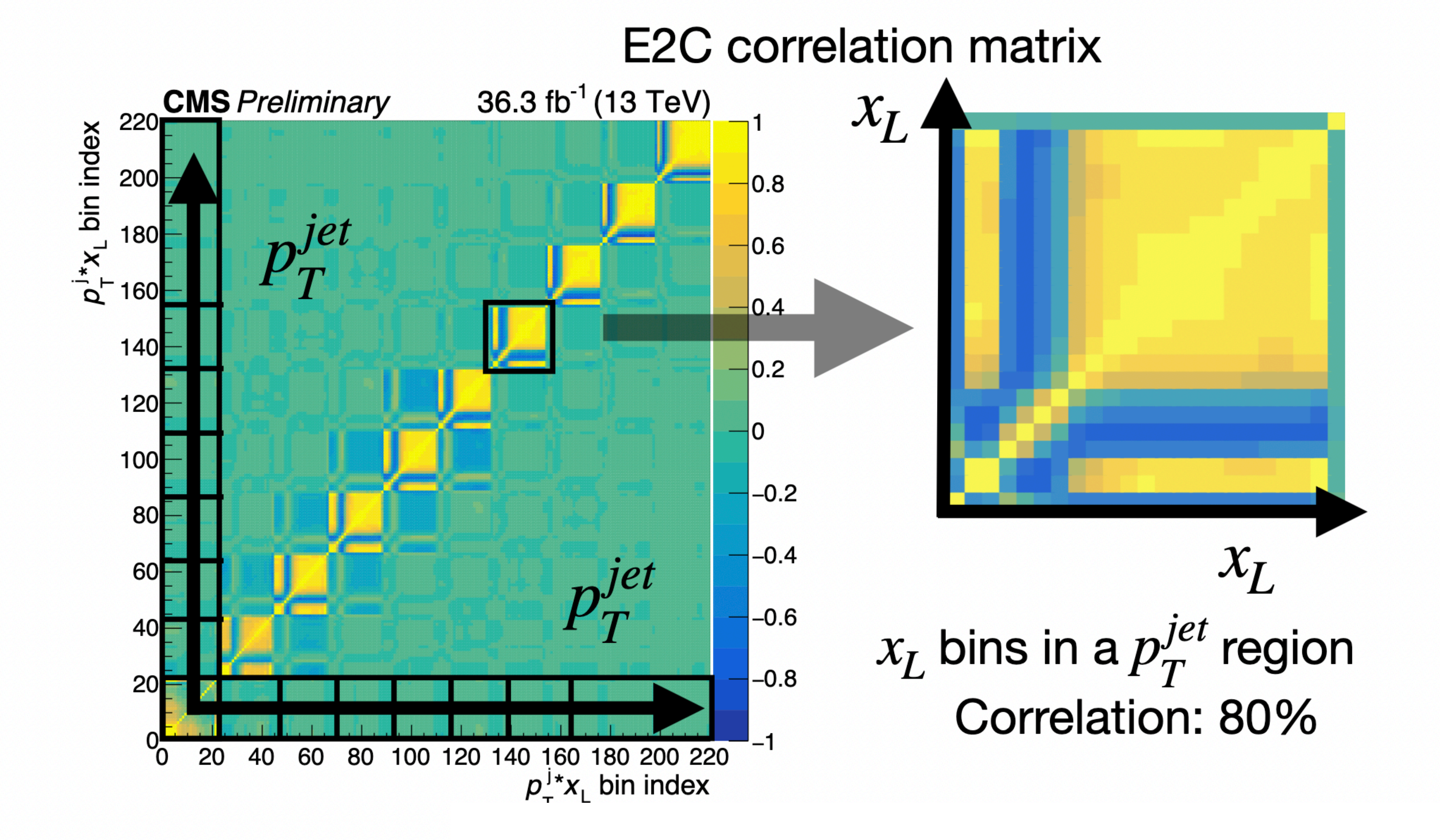
level of suppression depends on internal structure

ATLAS, arXiv:2301.05606

Technical challenges EEC

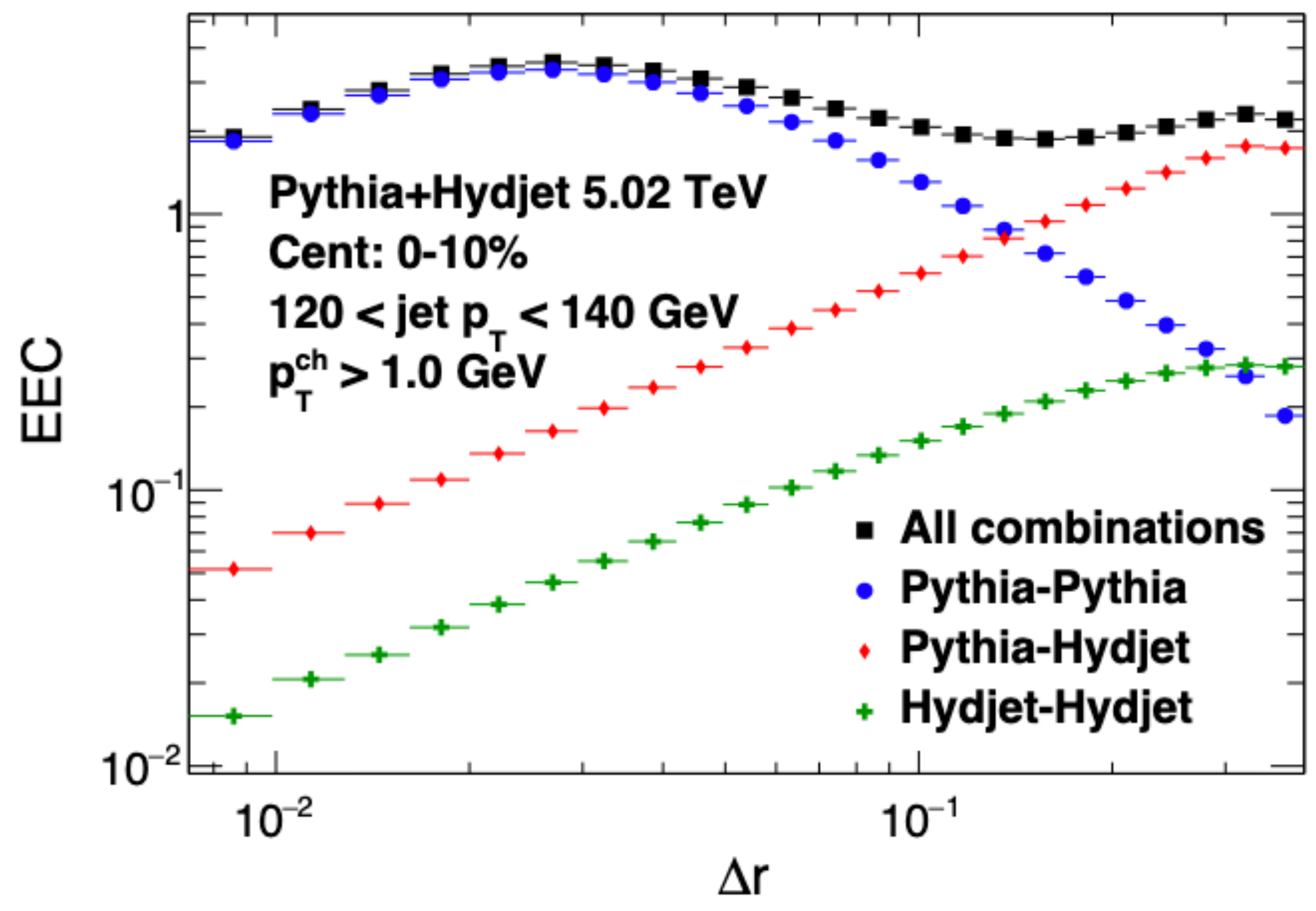
[CMS, 2402.13864 [hep-ex]](CMS, 2402.13864 [hep-ex])





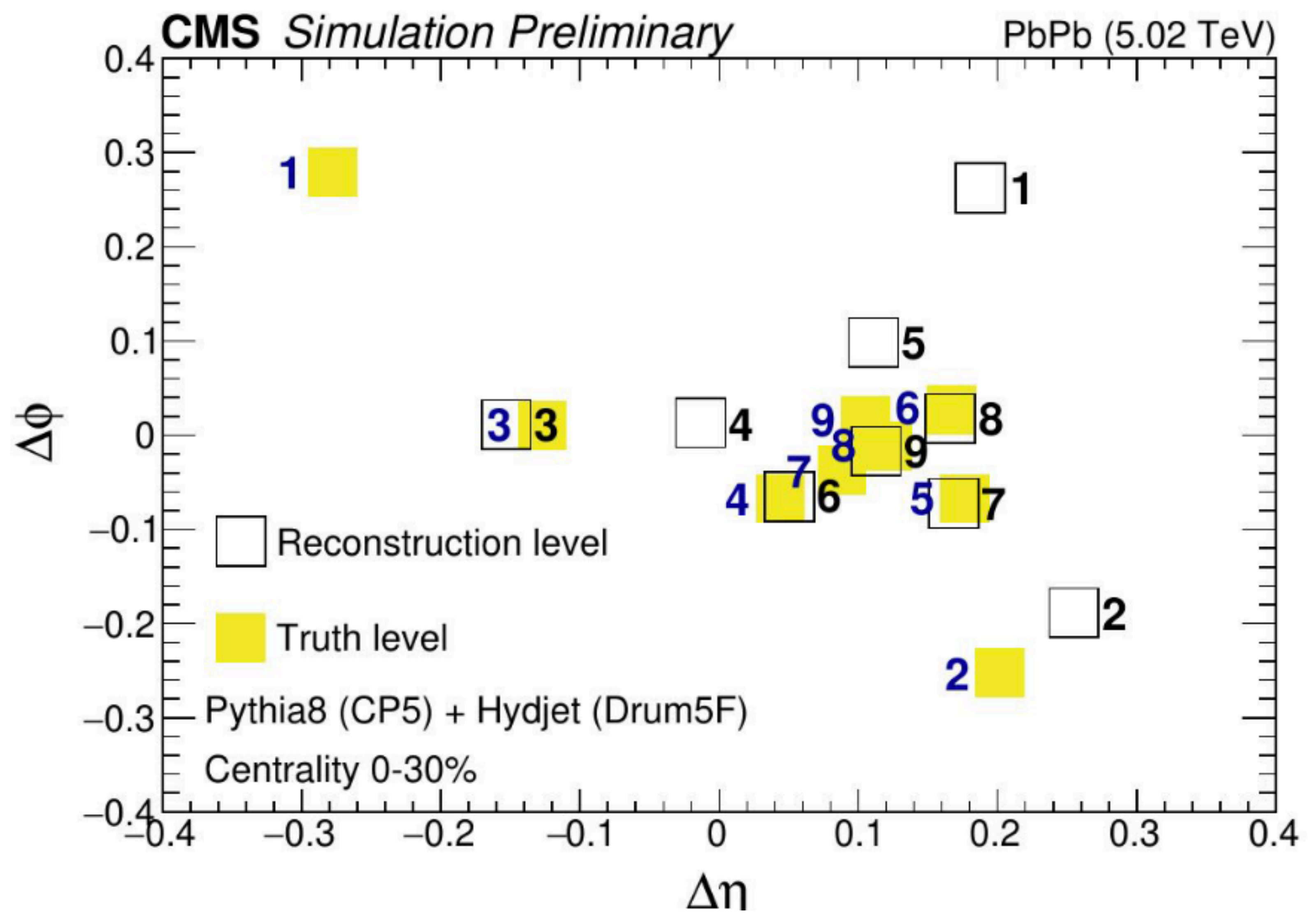
3-dimensional unfolding of jet p_T, x_L and weight (4400 bins)
Multi entry distribution for every jet, statistical correlations important

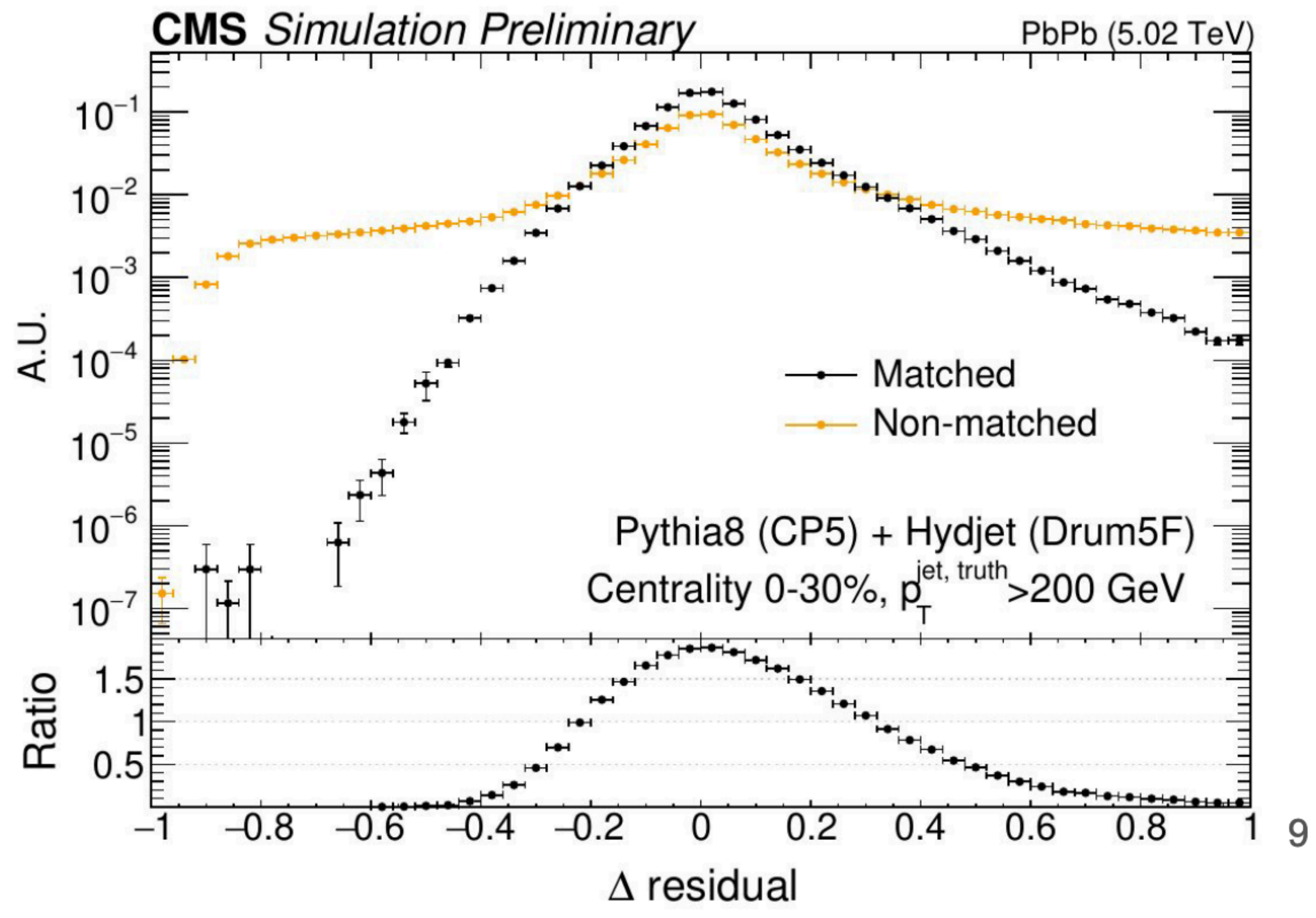
Subtraction of the different background components,
see *talks by Jussi Viinikainen and Andrew Tamis*

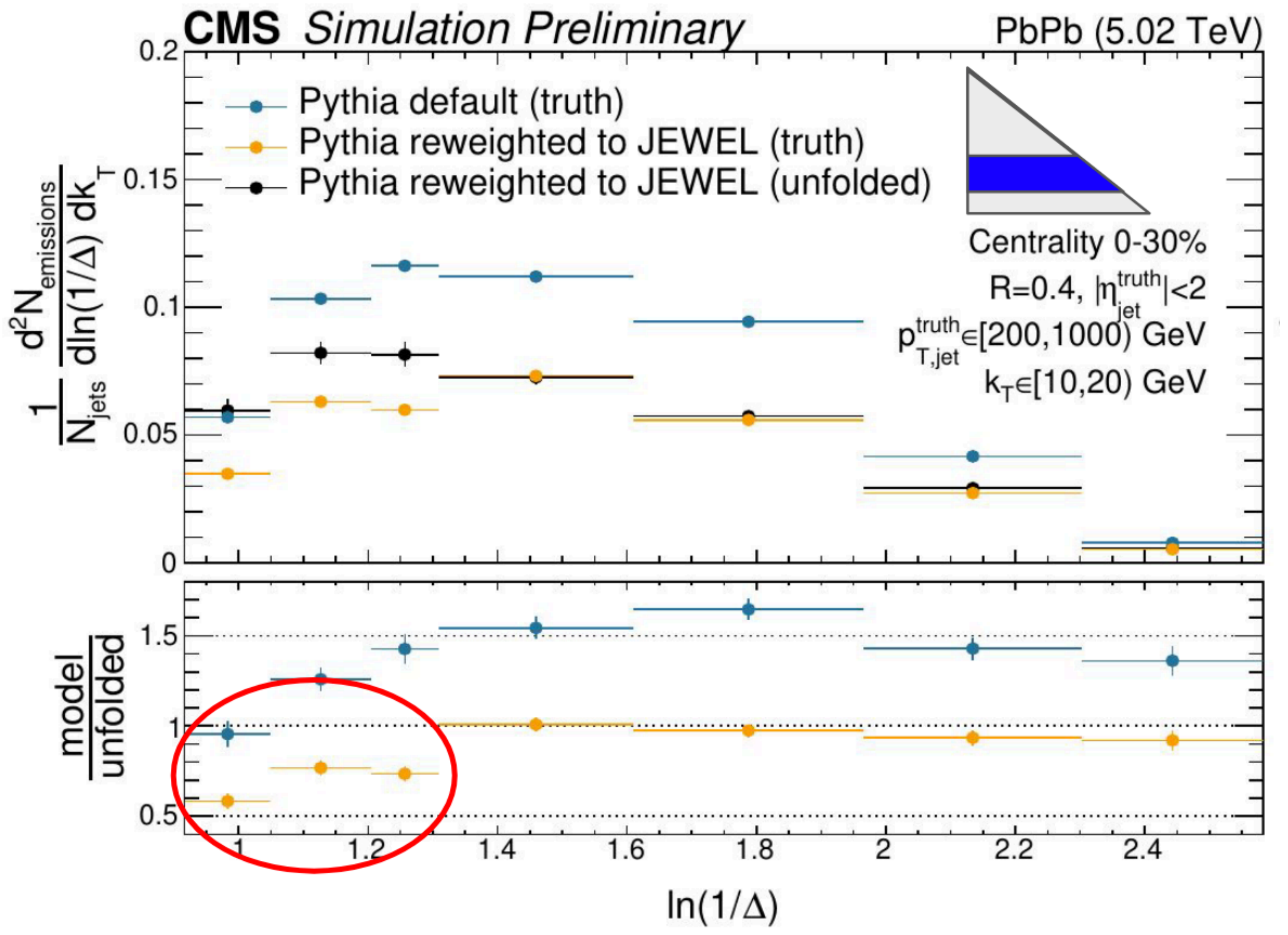


Technical challenges: The Lund Jet Plane in PbPb

Vangelis Vladimirov







The mapping between detector and true level emissions gets strongly distorted by detector and underlying event background effects

Splitting purity very low at low k_T and large angles

Strong prior dependence at low k_T and large angles