Investigating the quark-gluon plasma with high-p_T probes (a selection of recent jet measurements)

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on behalf of the ALICE, ATLAS and CMS collaborations

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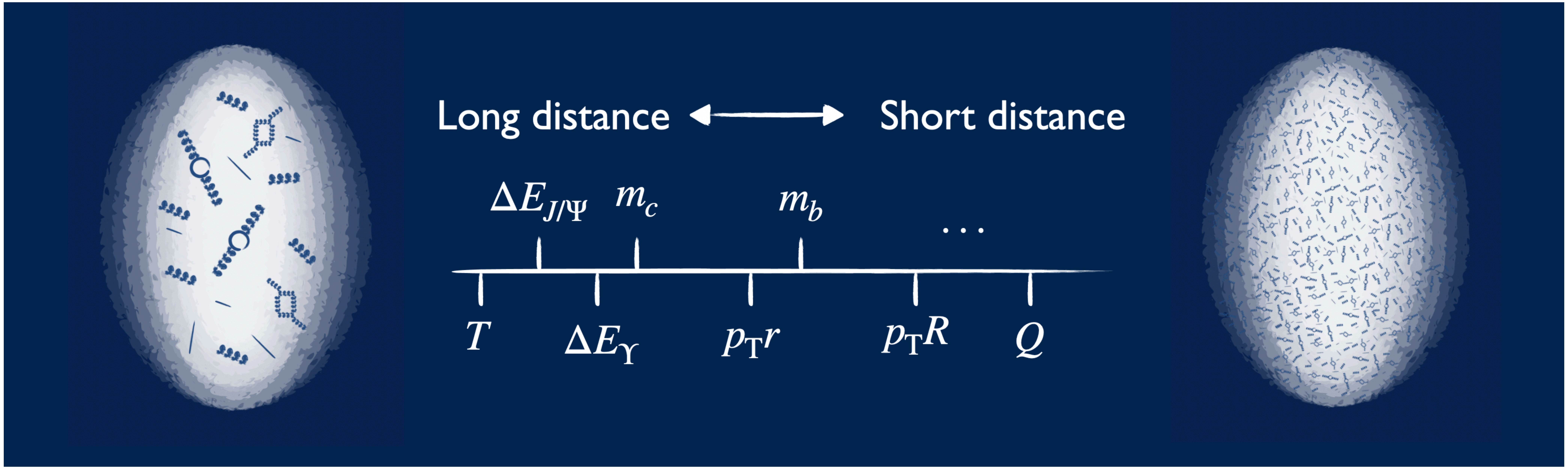
Jets are multiscale probes of the Quark Gluon Plasma

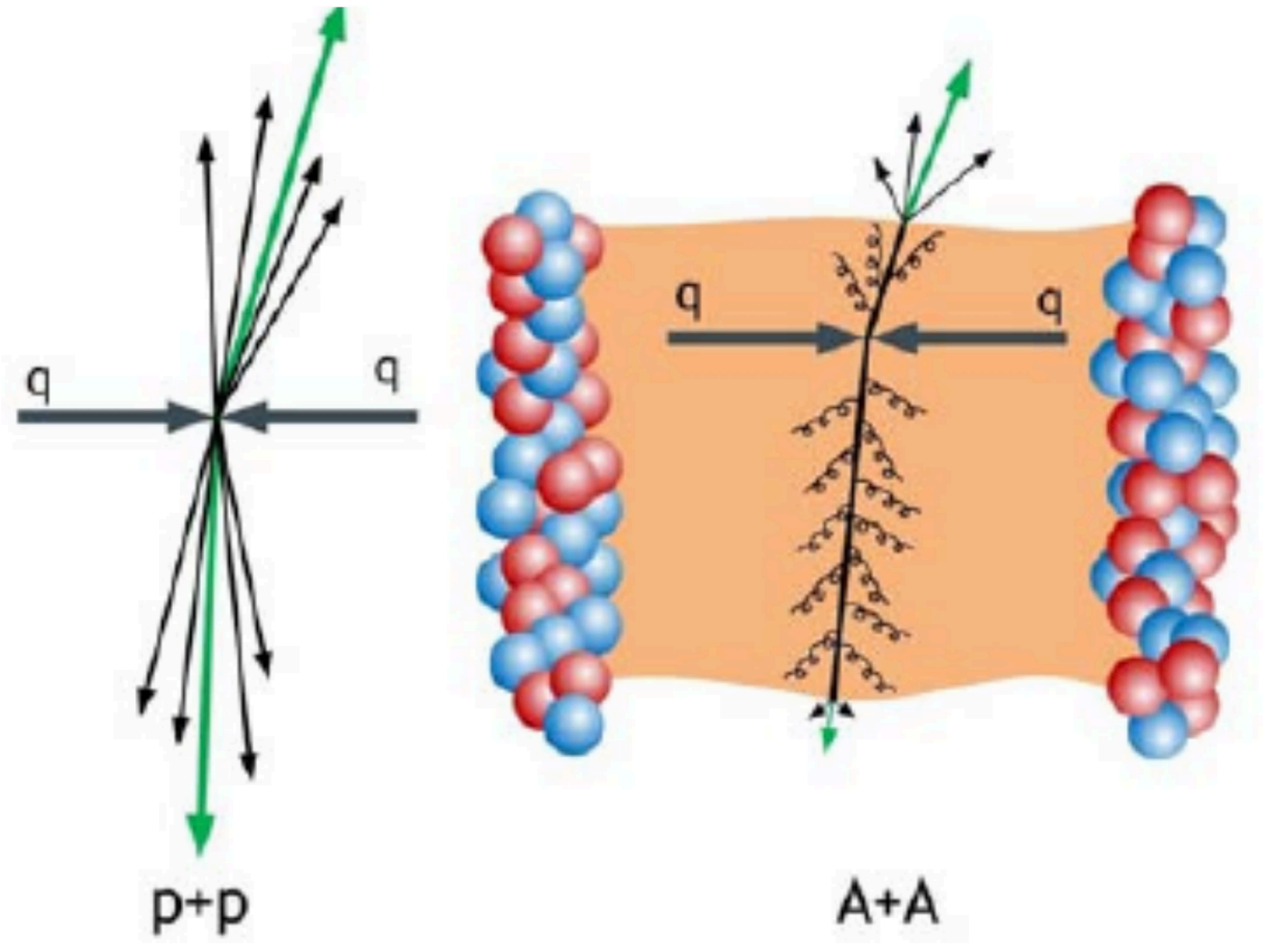


Sketch from J.Mulligan, HP2023

In PbPb collisions, the jet evolution is interwined with the evolution of the QGP.

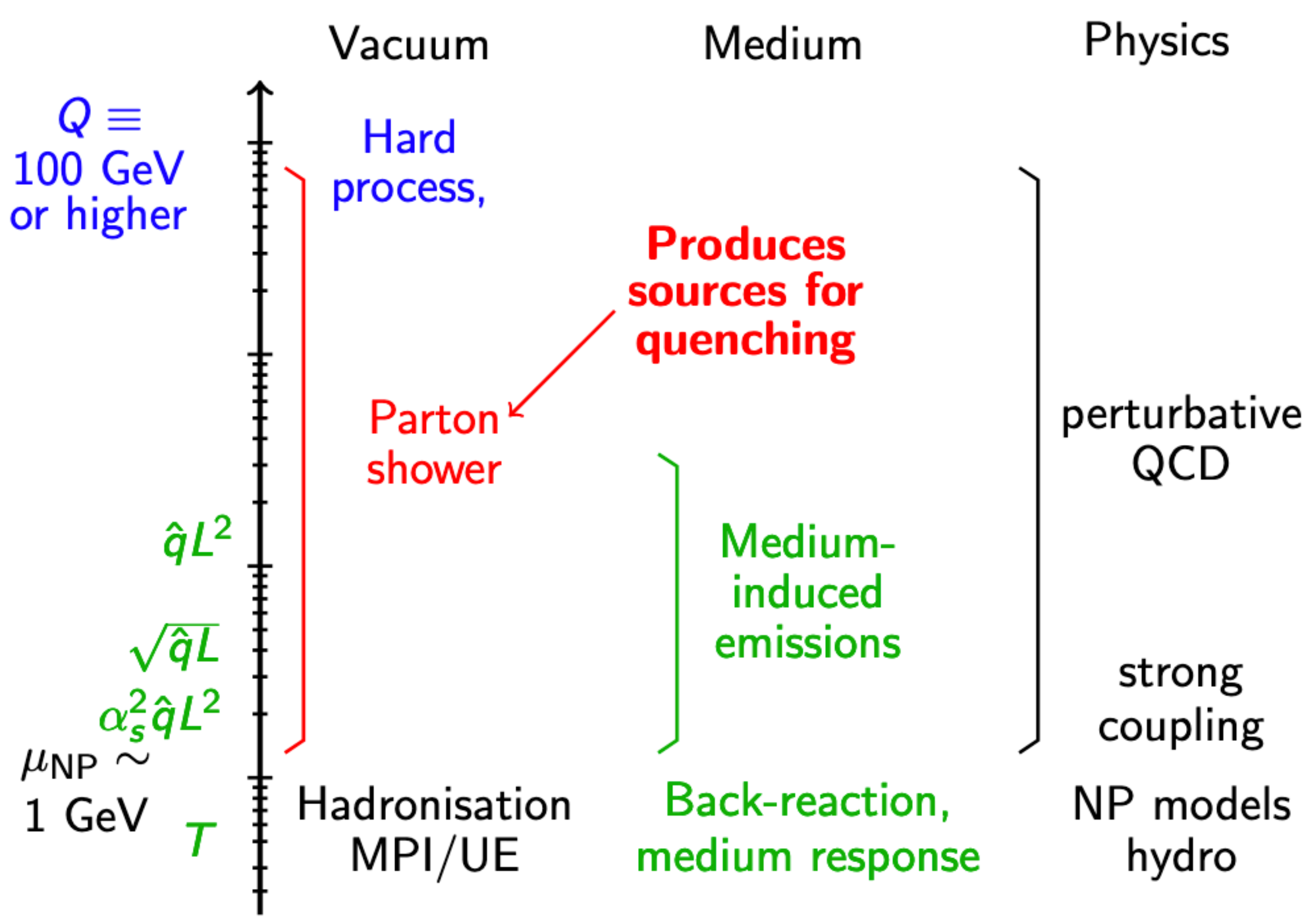
Interactions among the constituents of the jet shower and the medium happen at various scales and probe the QPG at different length scales

Jets are multiscale probes of the Quark Gluon Plasma



We inspect modifications in the jet production and fragmentation pattern in PbPb relative to pp to:

1. Isolate different physics mechanisms
2. Validate theory ingredients and aproximations
3. Ultimately characterize the microscopic properties of the QGP

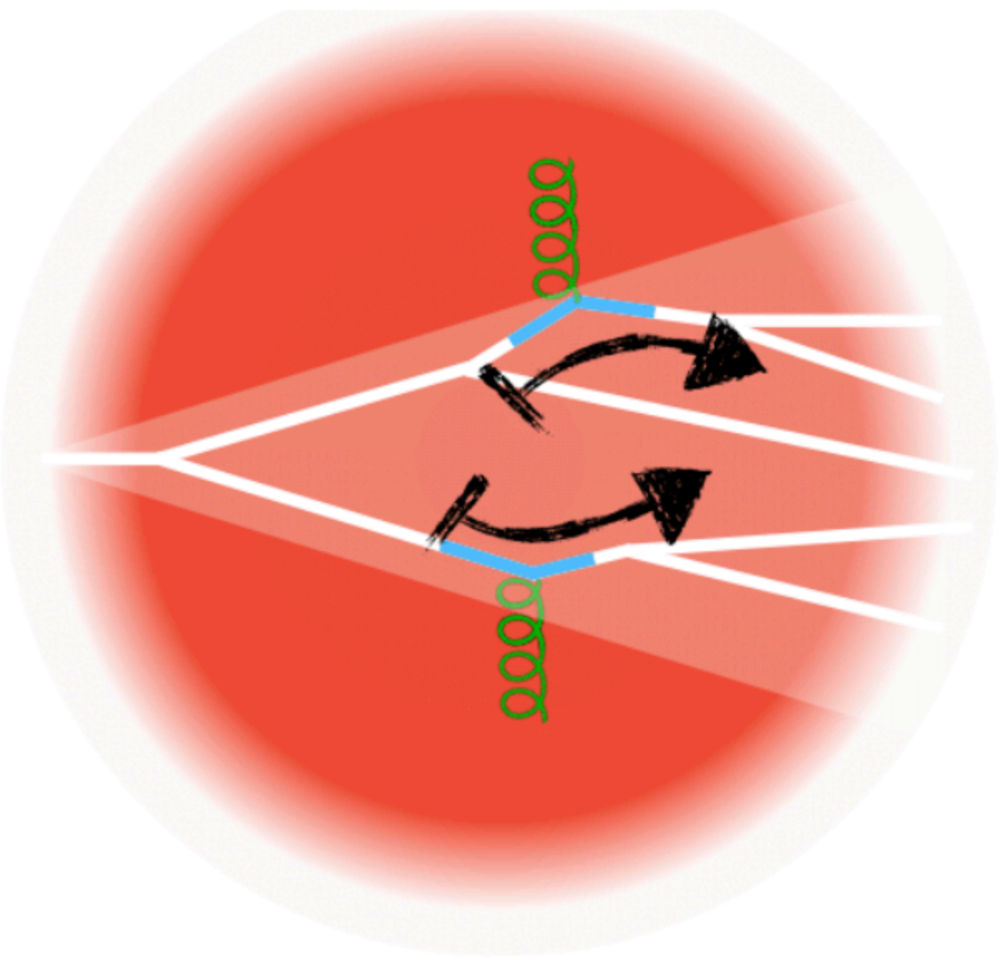


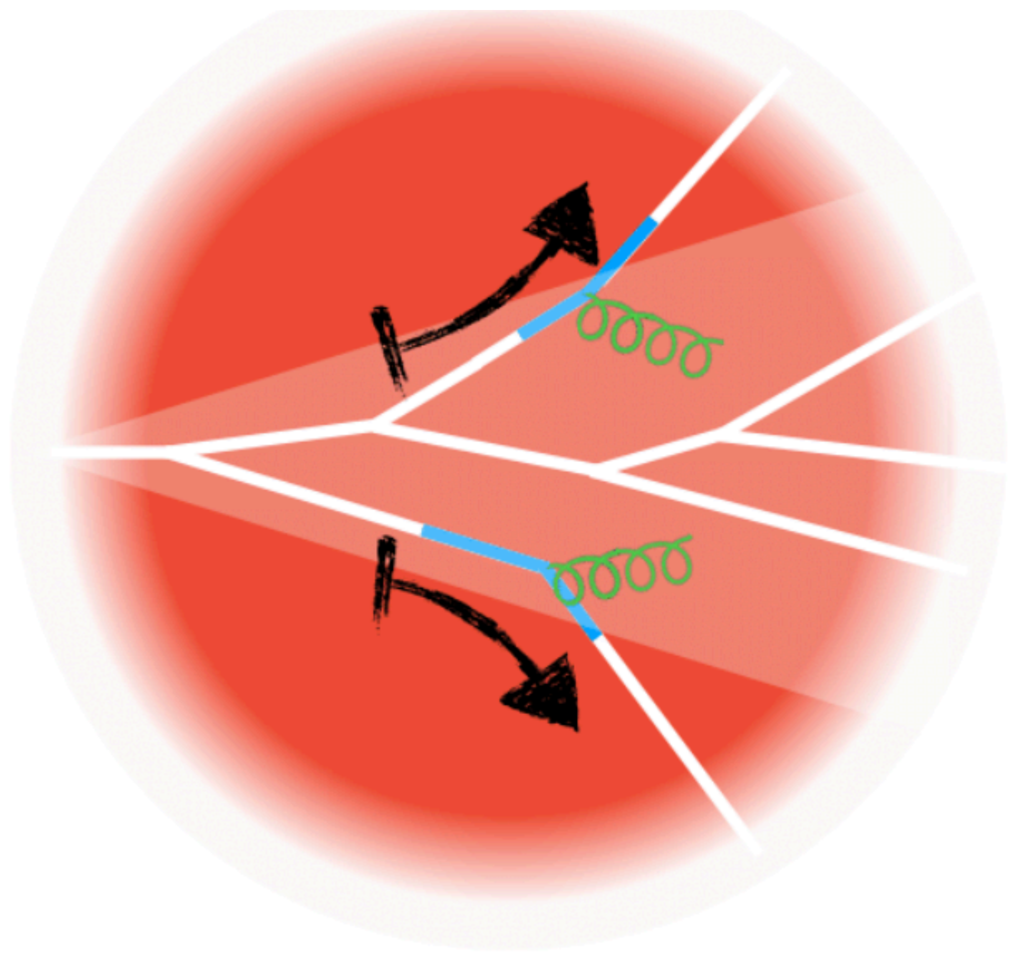
Sketch from G.Soyez

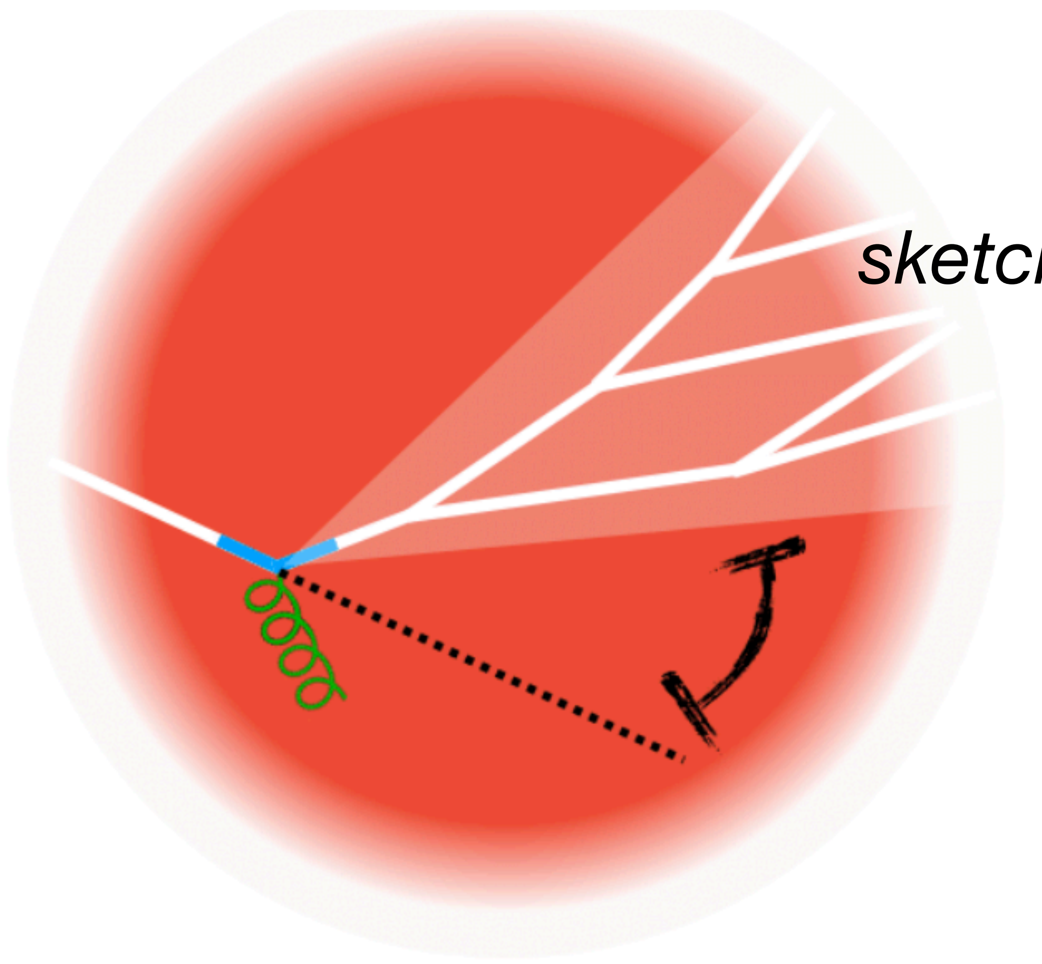
Many cofounding ingredients effecting the jet:

vacuum radiation
medium-induced gluon radiation
hard elastic scatterings in the medium
hadronization
the medium back-reaction

Different types of jet observables







sketch from Rey Cruz

To fully capture the dynamics of jet quenching we measure:

Jet suppression and its R and jet p_T dependence

Intra-jet distributions

jet shapes (using 4-momentum of the hadron constituents)
substructure (using the clustering history)

Inter-jet correlations

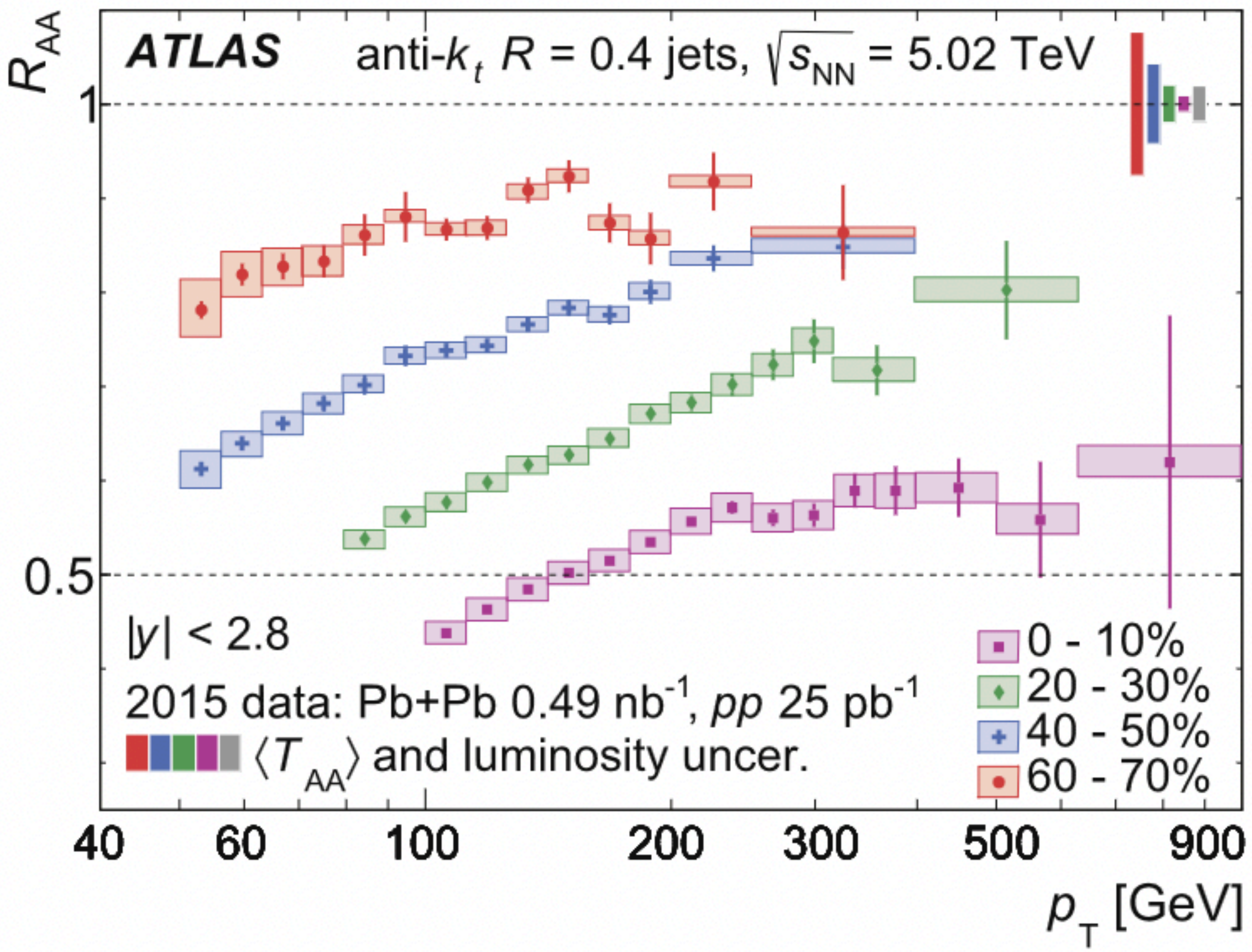
dijet acoplanarity, hadron/$\gamma/Z-$jet correlations…

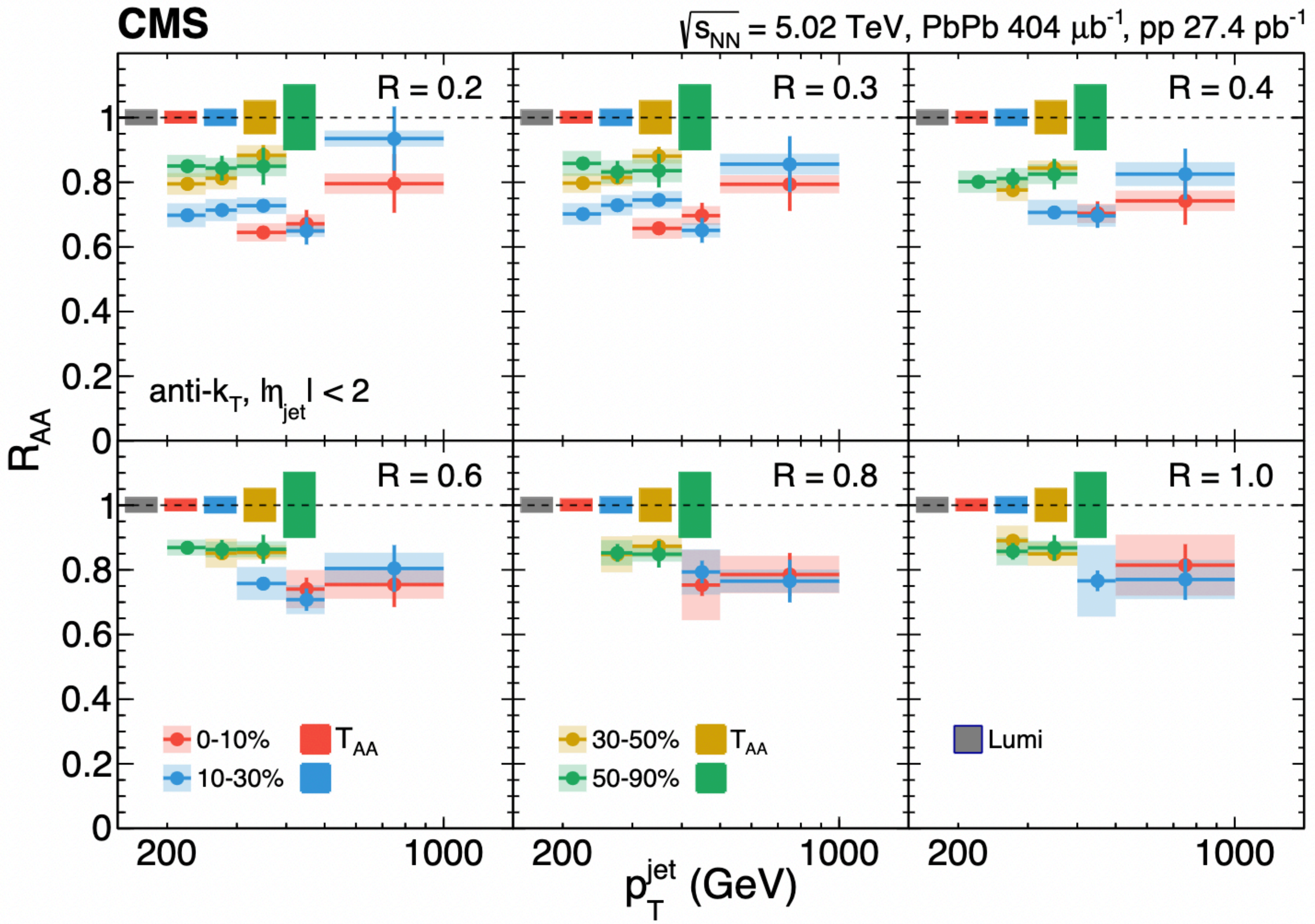
Different aspects, dynamically correlated

Jet suppression and R dependence

$$R_{AA} = \frac{d^2 N^{AA}_{jets} / dp_T\, d\eta}{\langle T_{AA} \rangle\, d^2 \sigma^{pp}_{jets} / dp_T\, d\eta}$$

ATLAS Phys.Lett.B 790 (2019) 108



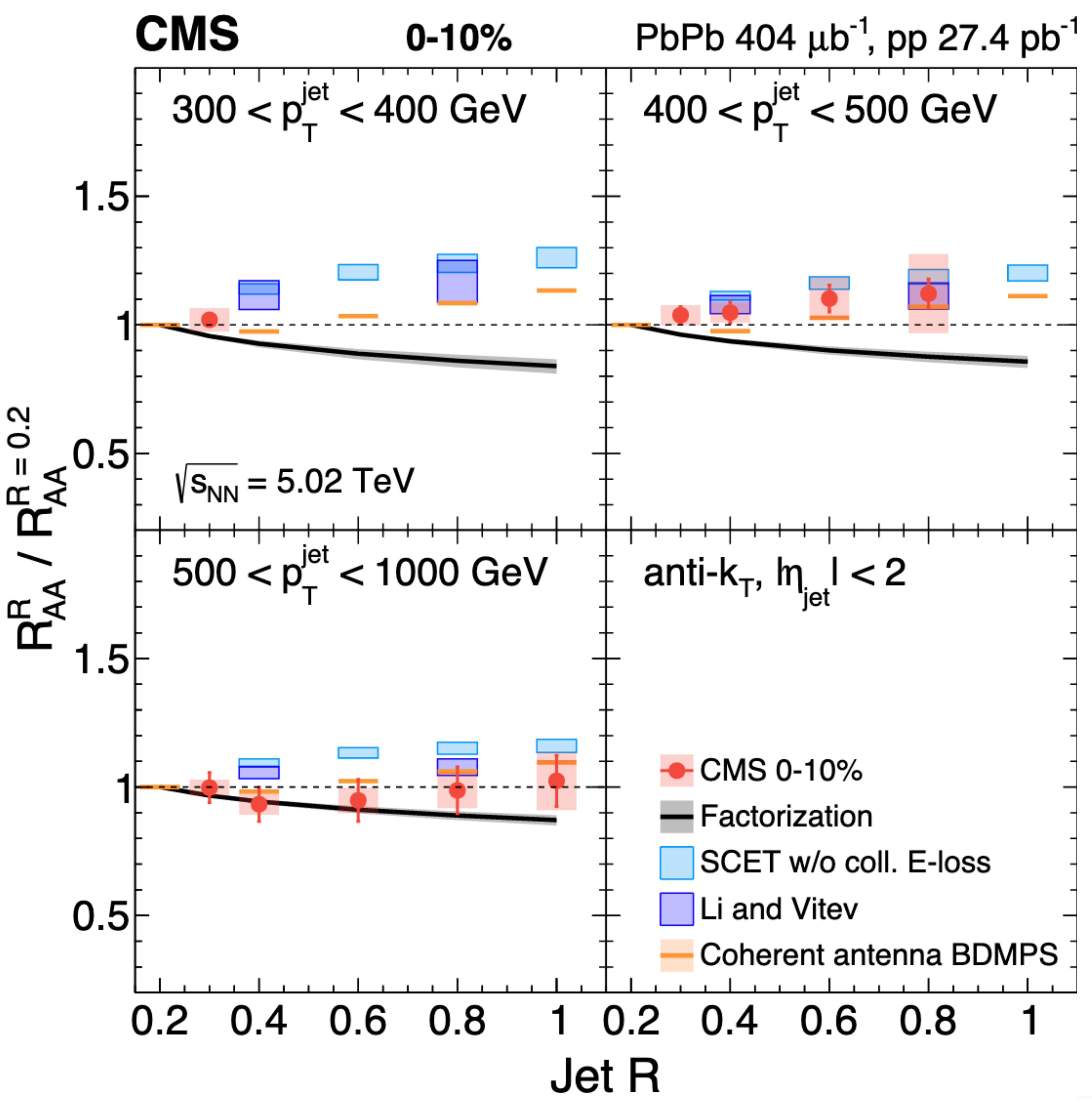


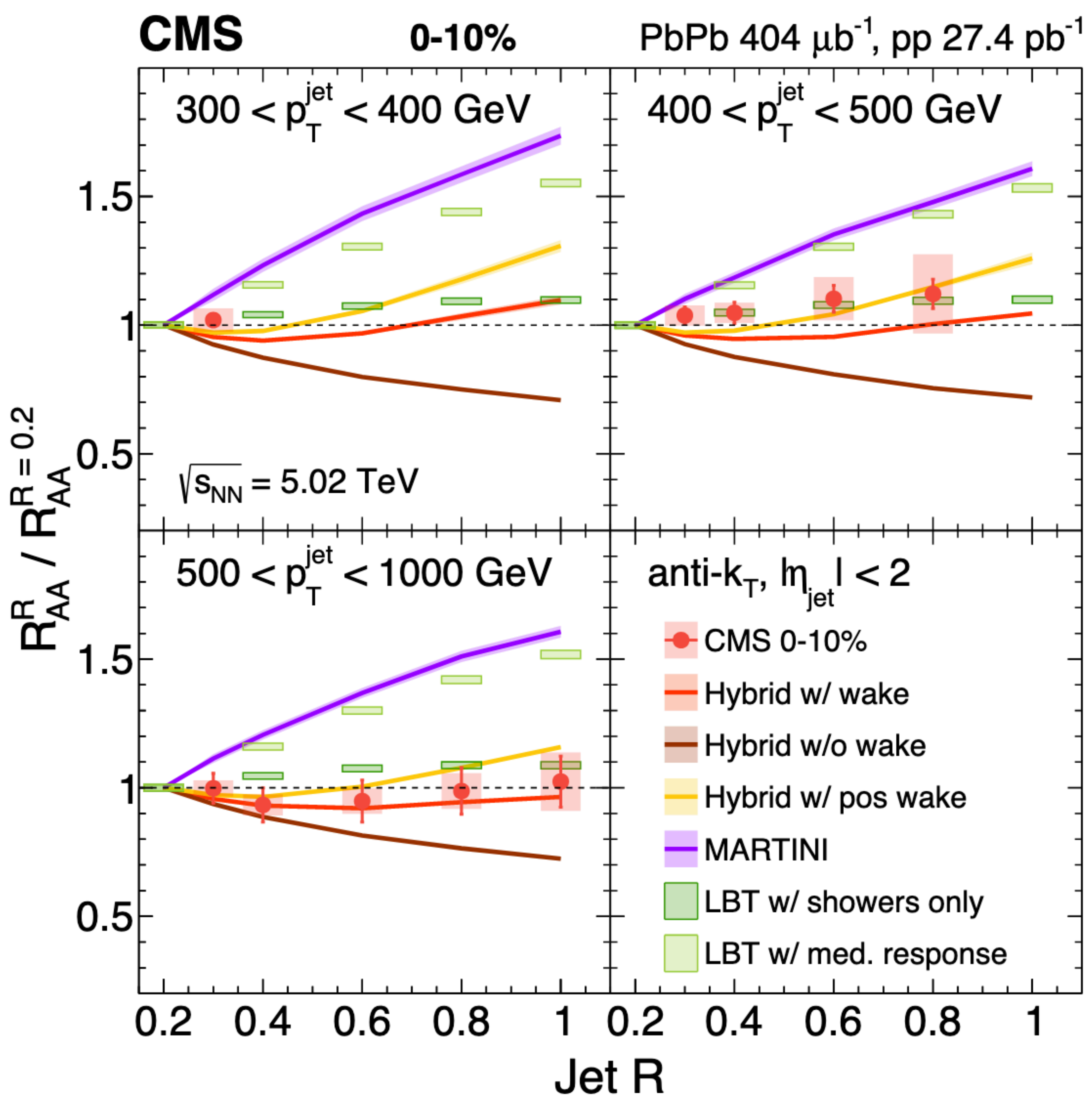
CMS JHEP 05 (2021) 284

Strong suppression of jet yields up to the TeV scale
Mild dependence of the suppression with the jet R
In general suppression is the result of **a)** amount/how energy is redistributed and **b)** ability to recover it

Jet suppression and energy redistribution

[CMS JHEP 05 (2021) 284]

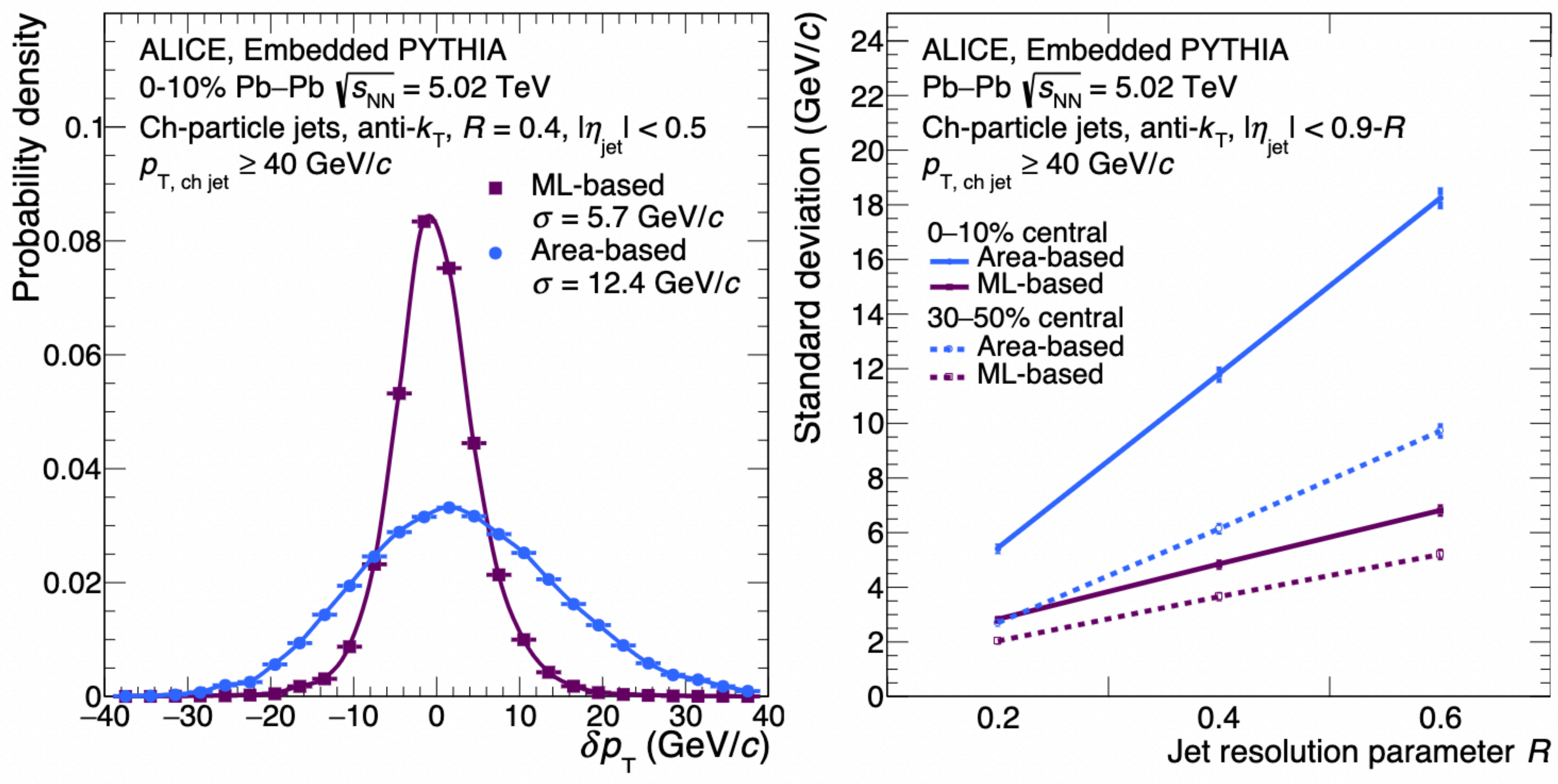




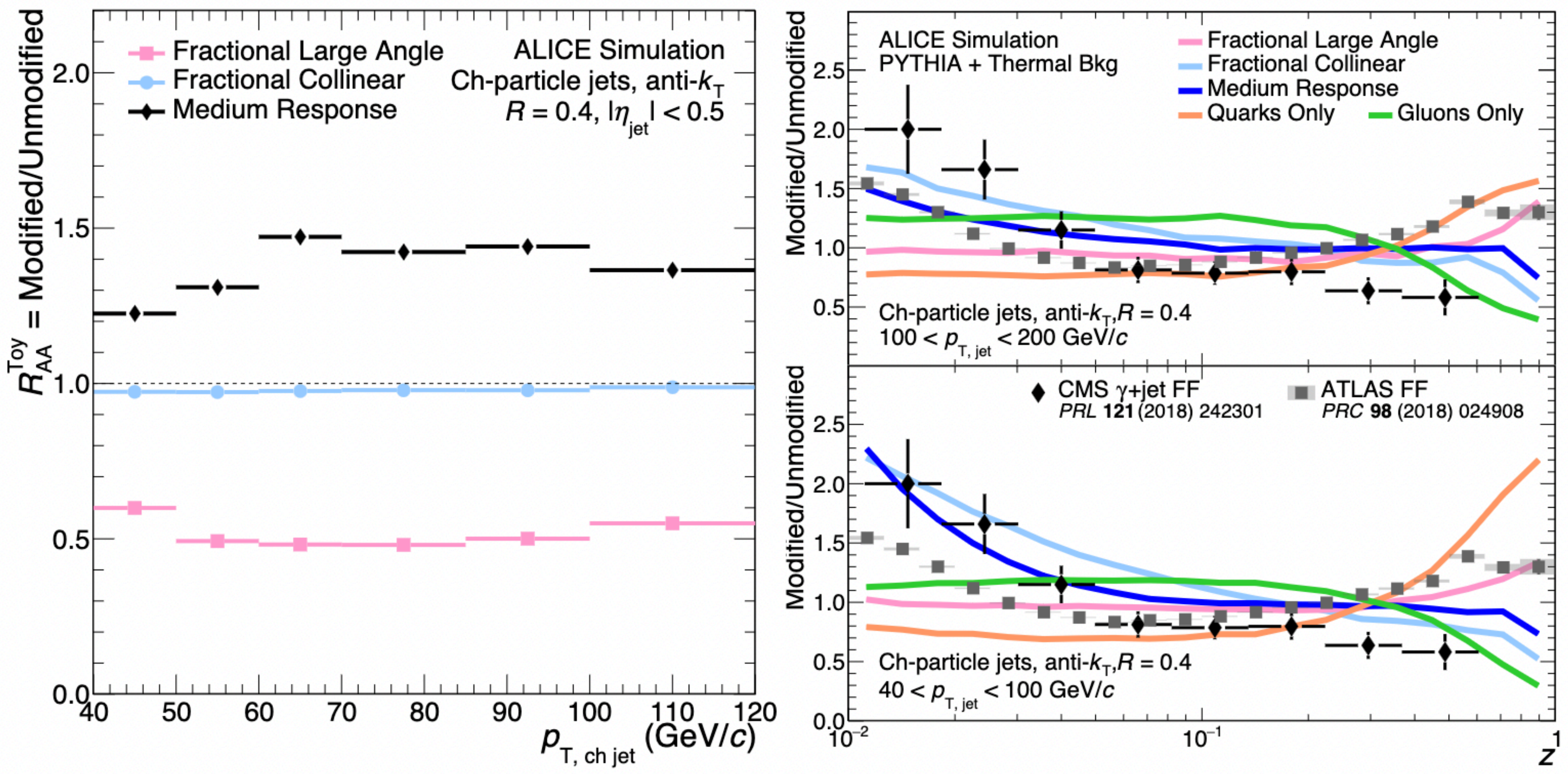
The balance of energy loss/recovery is illustrated by factorized models like the Hybrid model:
larger-*R* jets bias towards jets with a **more active early vacuum shower** that are then more quenched (dark brown) but that can **recover better the medium response or wake**

Jet suppression and R dependence: the challenge of low-p_T jets

[ALICE, arXiv: 2303.00592](#)



Parametric modification of the PYTHIA fragmentation



Standard area-based method *[1]* is unbiased but residual region-to-region background fluctuations are large
->strong contribution of combinatorial jets a low jet p_T, sets a limit on the lowest accessible jet p_T at given R

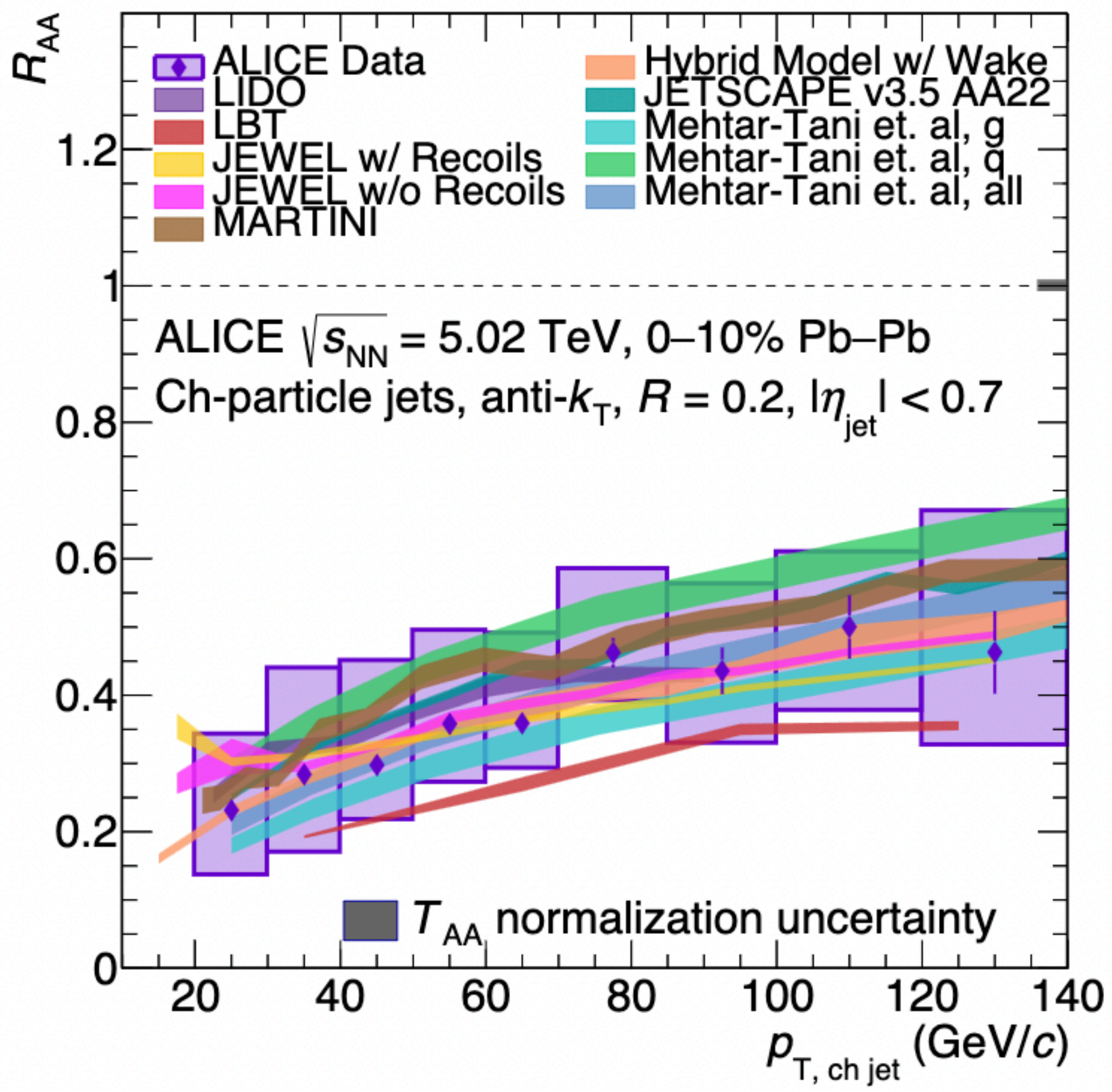
New ML techniques by ALICE mitigate background and allow to explore a unique regime of R and jet p_T after a careful assessment of the possible fragmentation bias

[1]Soyez et al, Phys.Rev.Lett.110 (2013) 16

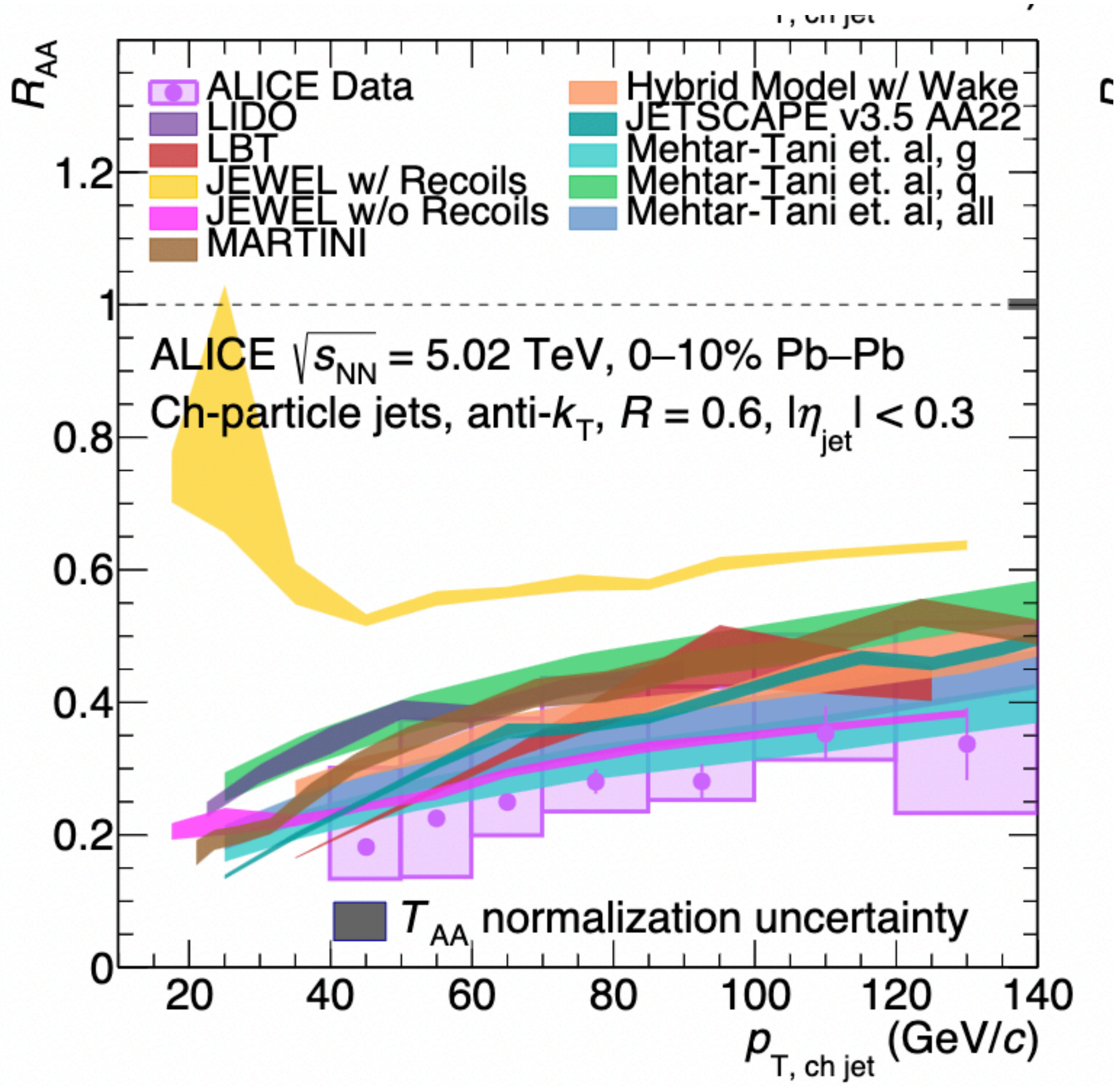
Jet suppression and R dependence: the challenge of low-p_T jets

ALICE, arXiv: 2303.00592

R=0.2



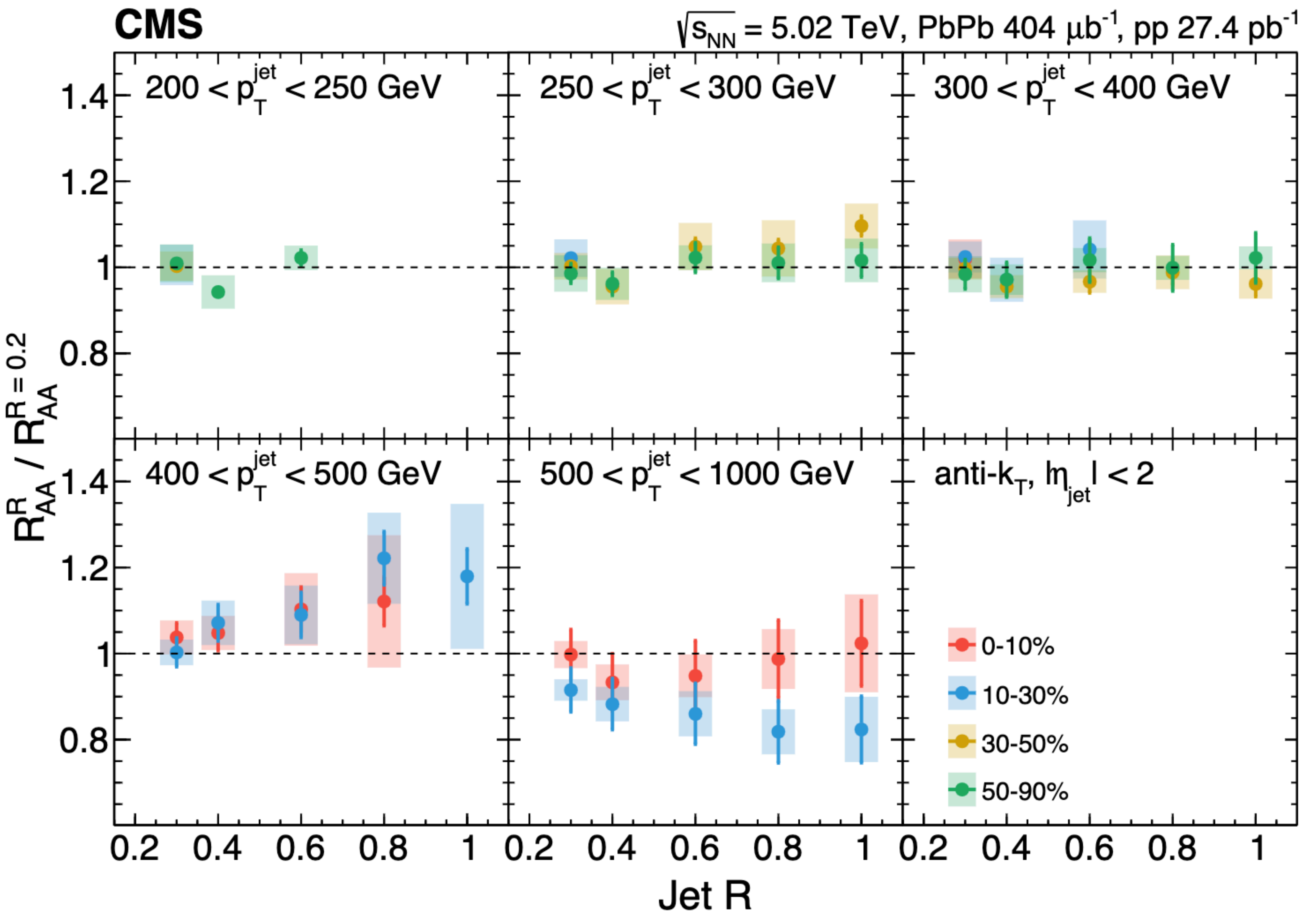
R=0.6



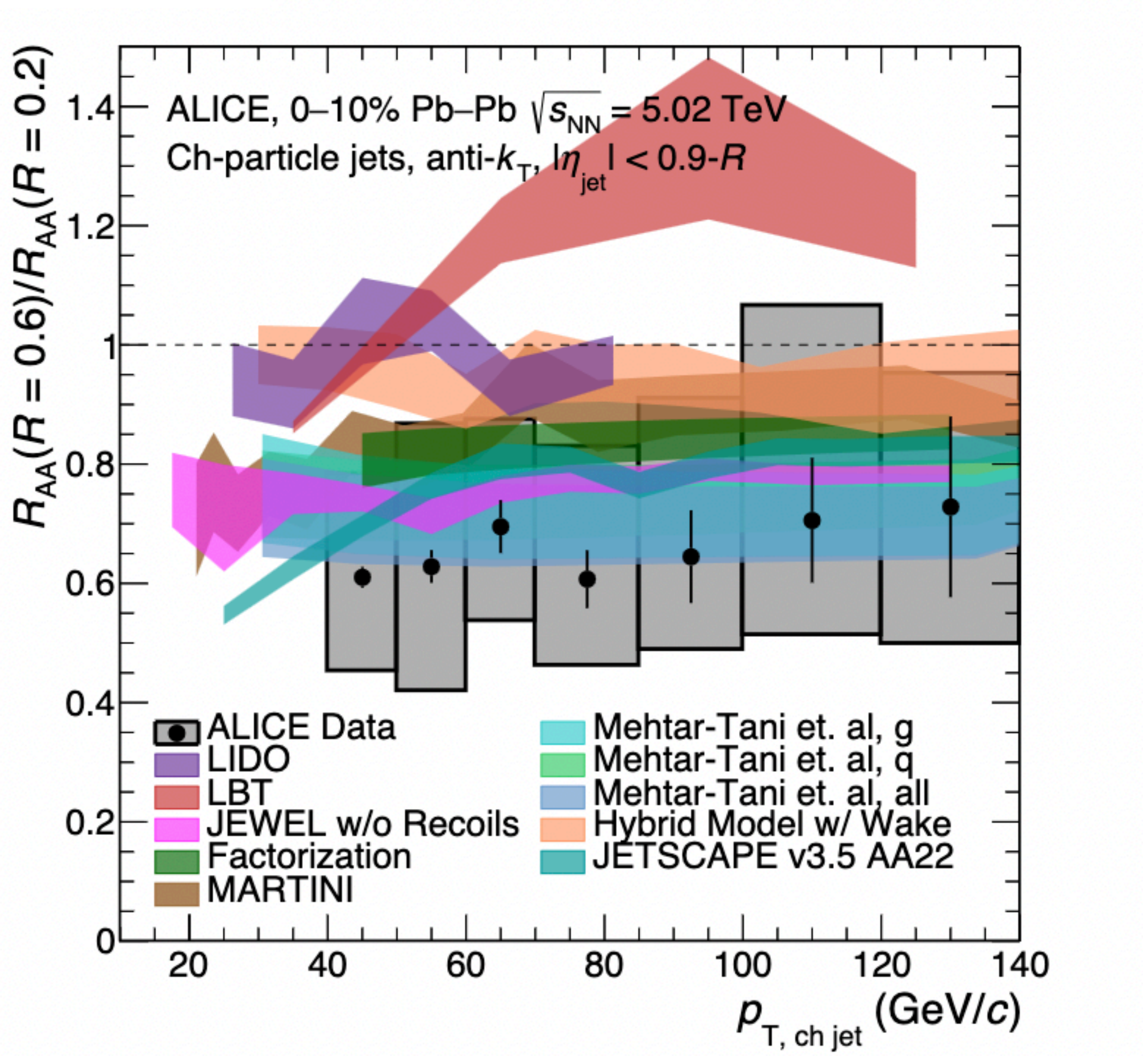
At low jet p_T large-R jets appear to be more suppressed than small-R jets, pattern reproduced by most models
A better experimental handle on jet fragmentation pattern will help reduce the uncertainties

Jet suppression and R dependence: the challenge of low-p_T jets

CMS JHEP 05 (2021) 284



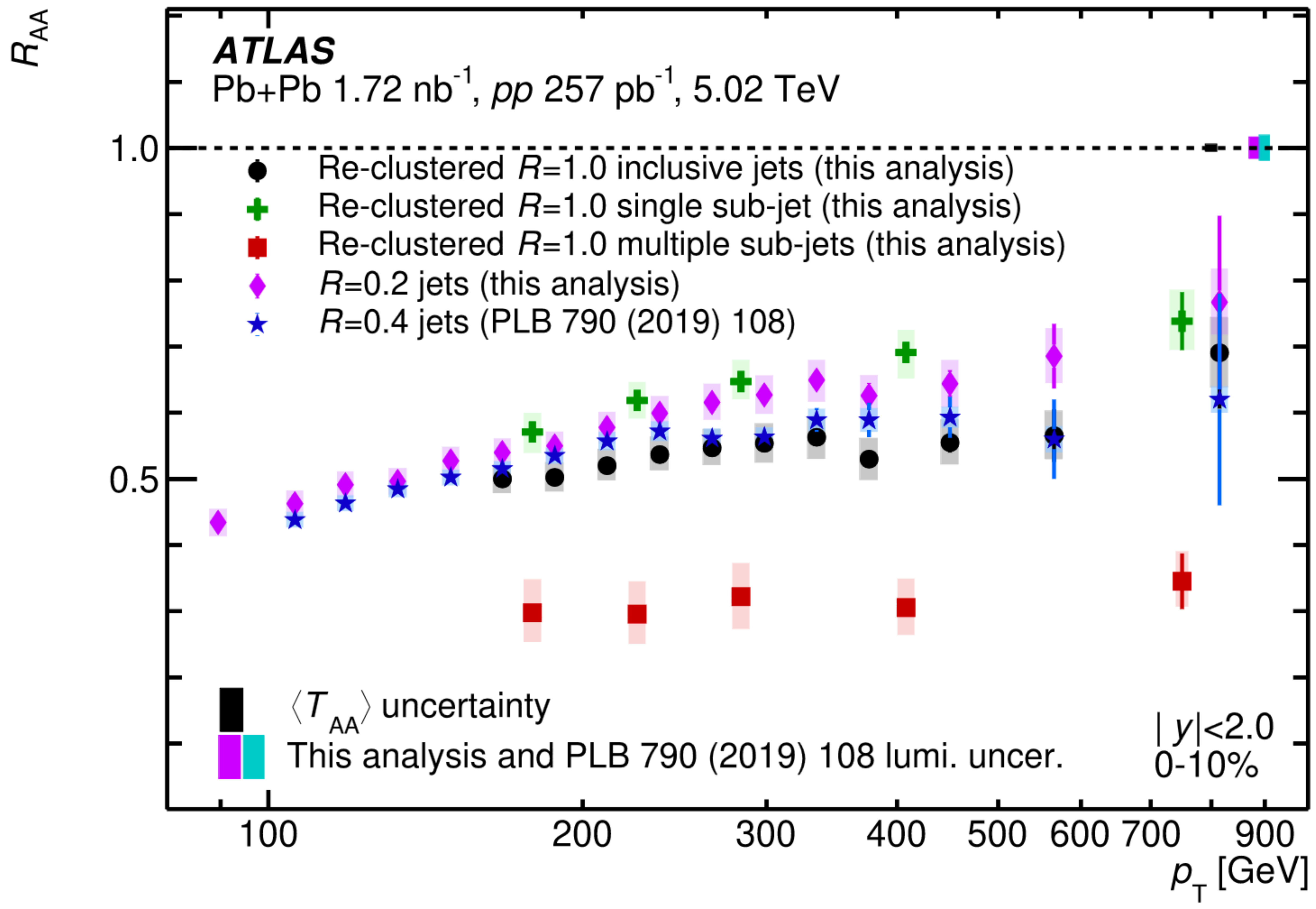
ALICE, arXiv:2303.00592



At low jet p_T large-R jets appear to be more suppressed than small-R jets, pattern reproduced by most models
Different trends at low and high jet p_T (but also different jet definitions, kinematic selections etc)

Jet suppression and subjet multiplicity

ATLAS, arXiv:2301.05606



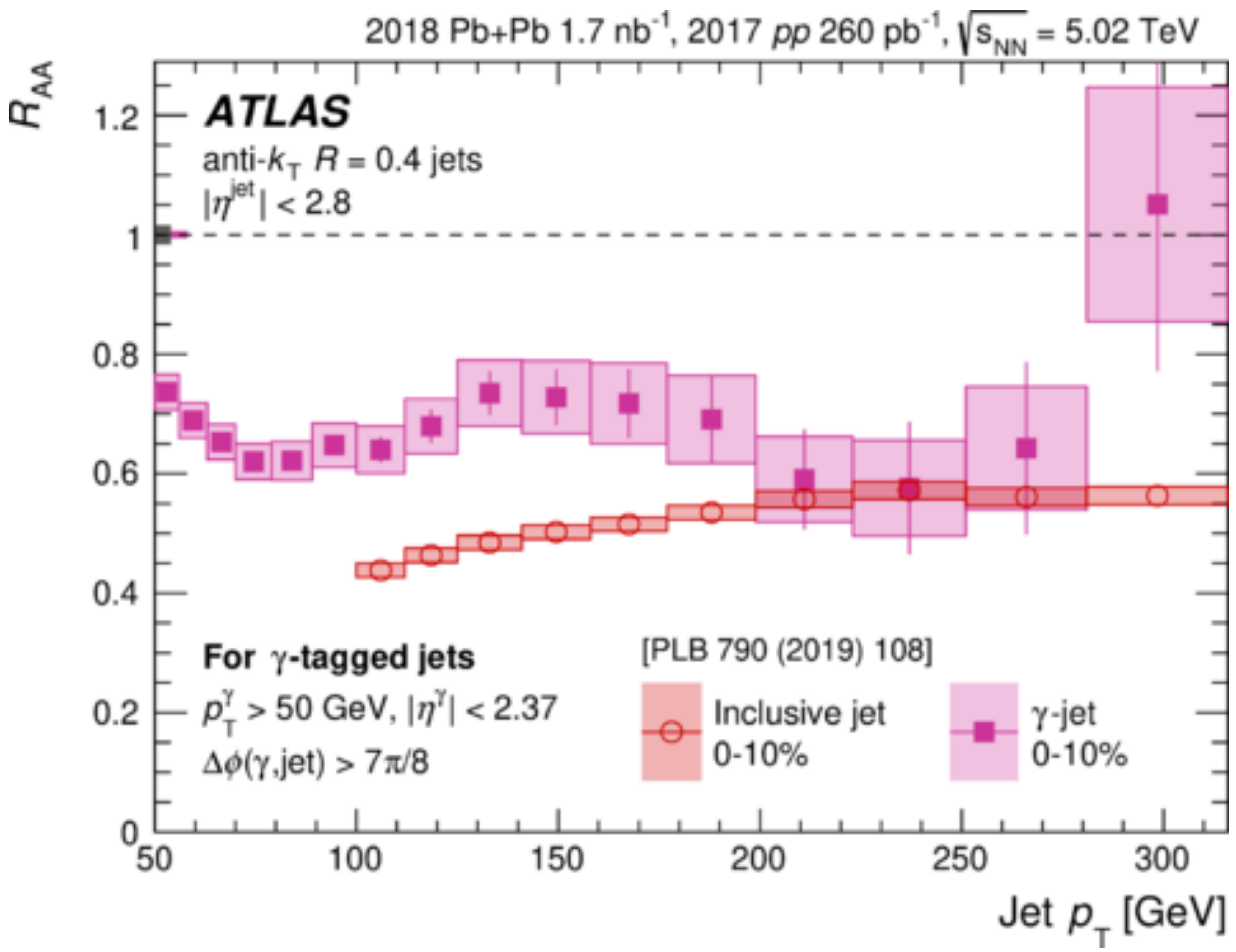
Single-prong jets are less quenched

Multiple-prong jets are strongly suppressed, more “active” jets in medium

R=1 jet constituents are R=0.2 jets
Single sub-jet dominate the inclusive sample and are significantly less suppressed than multiple sub-jet jets

Jet suppression and flavour: γ-tagged jets

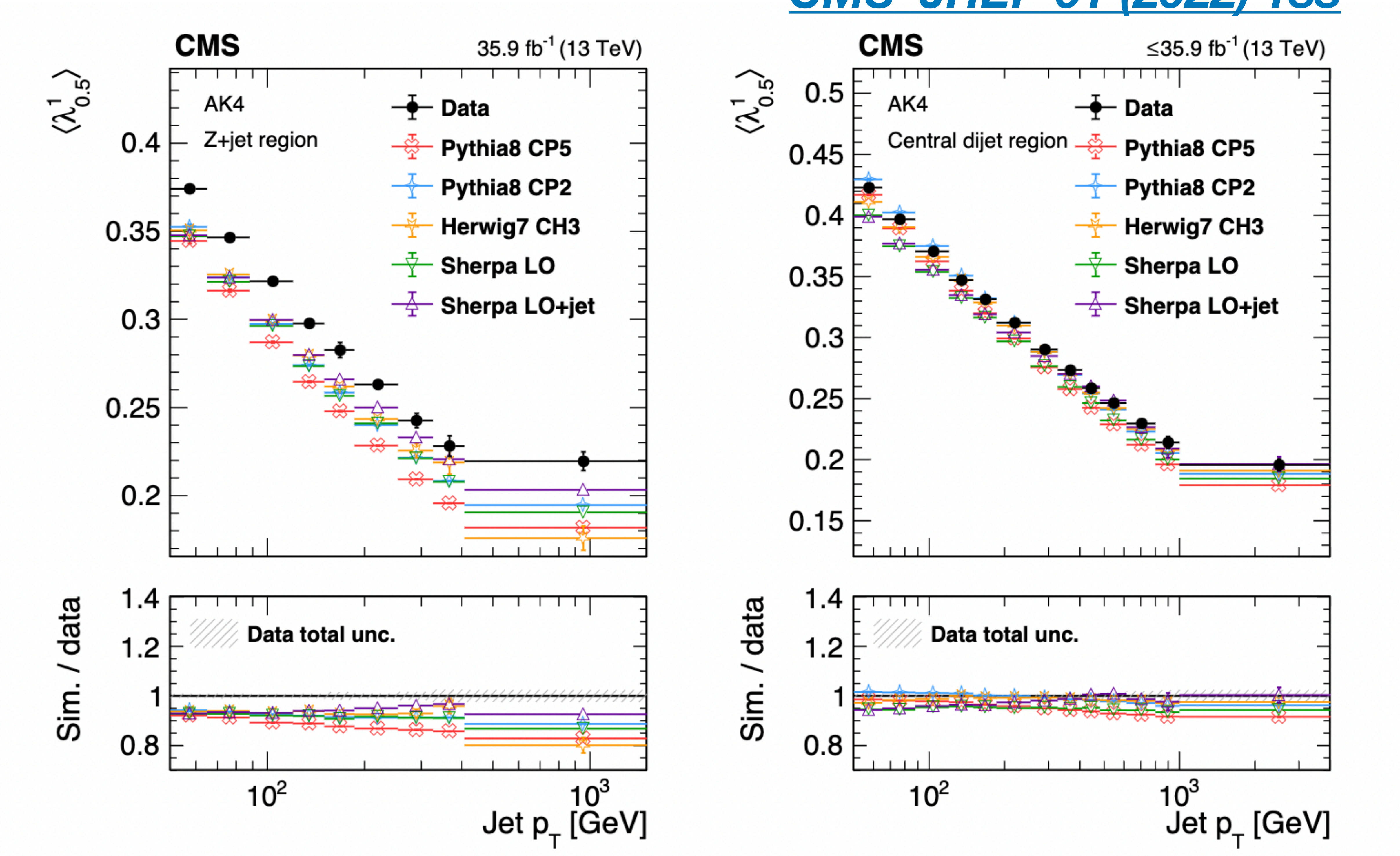
ATLAS, arXiv: 2303.10090



γ-tagged jets are less suppressed than inclusive jets
Enhanced quark fraction can play a role. Other effects on spectral shape are nPDFs, isospin.

Average Les Houches multiplicity as function of jet p_T in di-jets and Z-jets

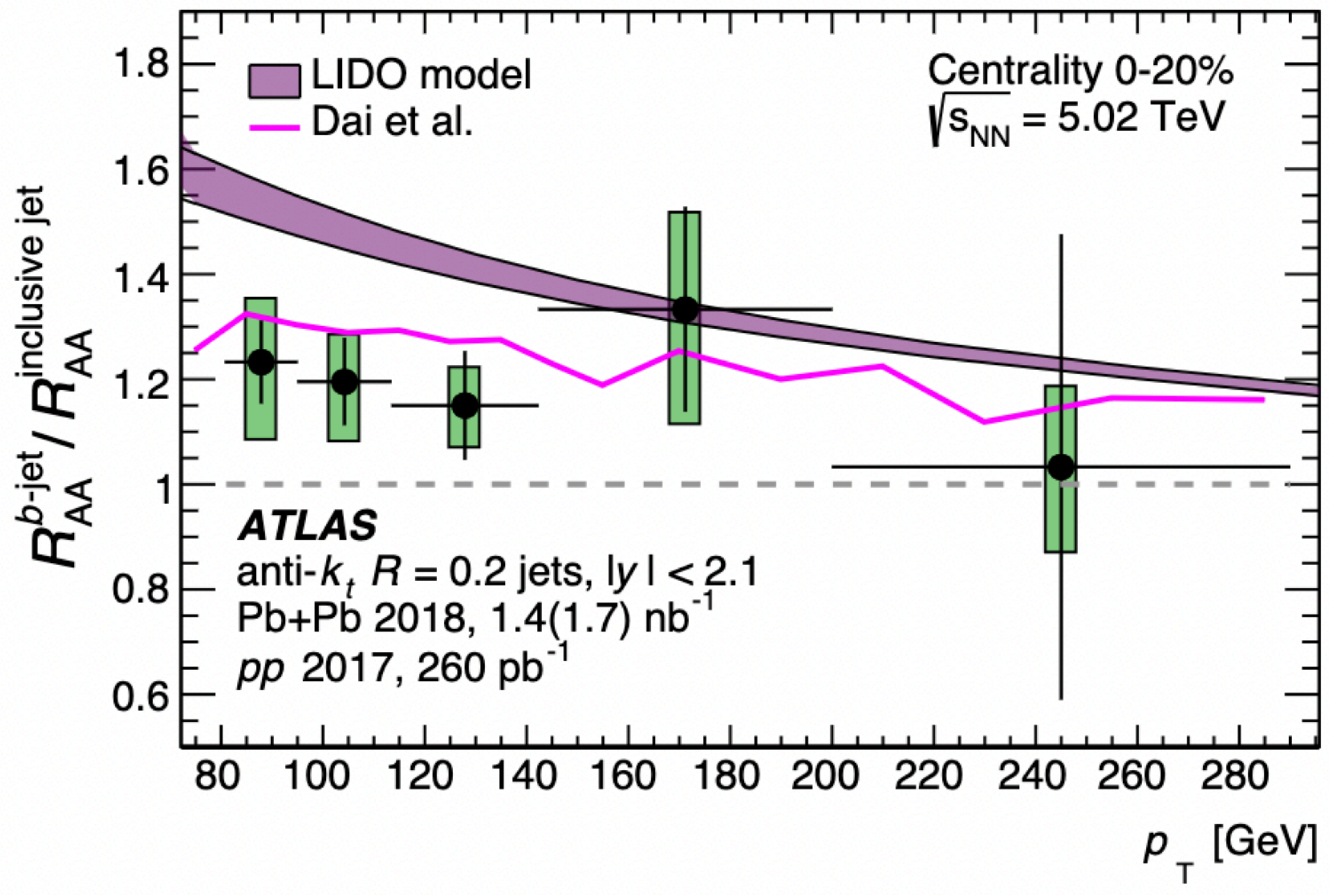
CMS JHEP 01 (2022) 188

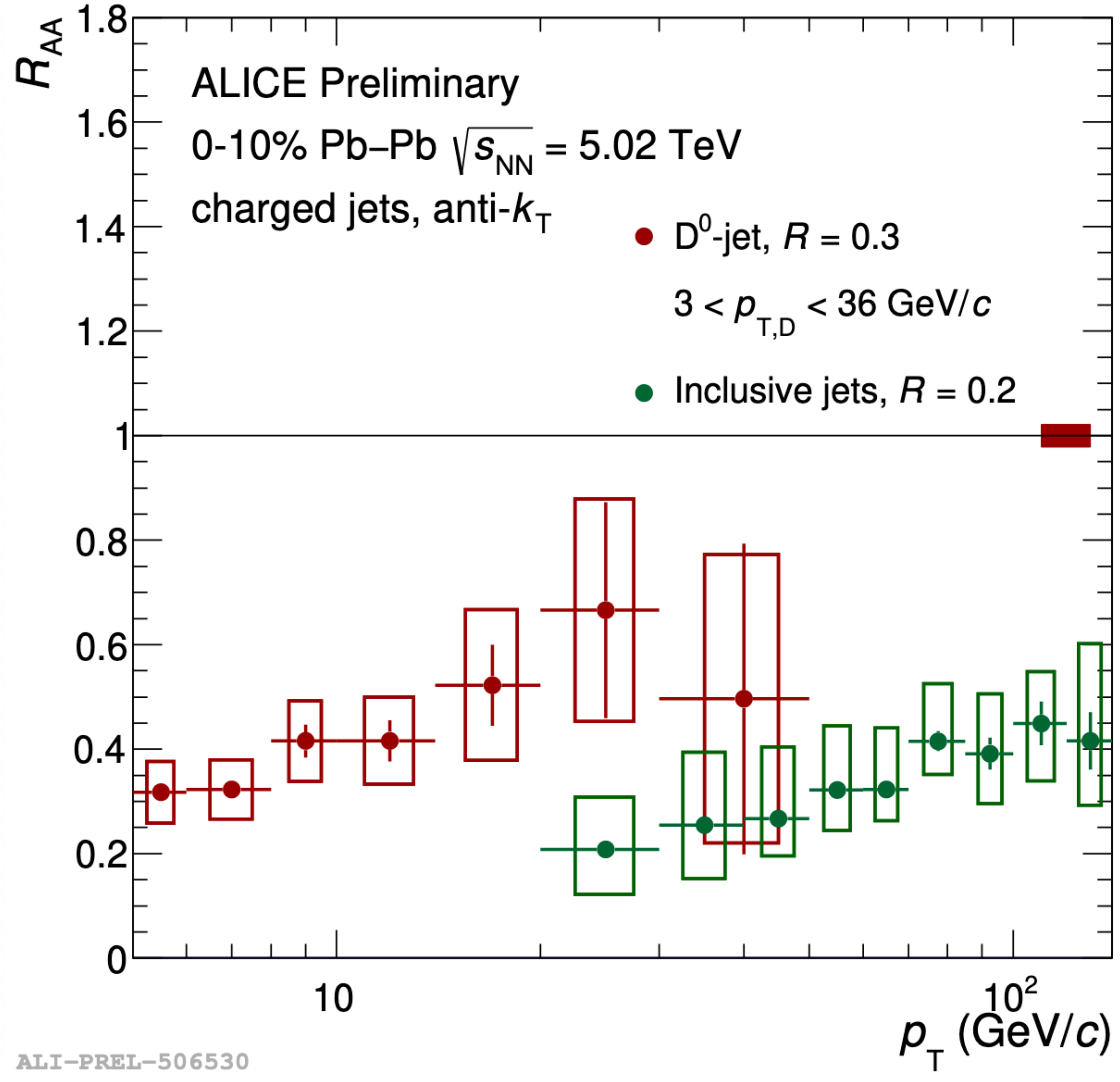


In pp, the quality of the modelling is found to depend on the flavour fractions.
Important for the vacuum baseline of jet quenching models

Jet suppression and flavour: b-tagged and D-tagged jets

[ATLAS, arXiv:2204.13530](#)

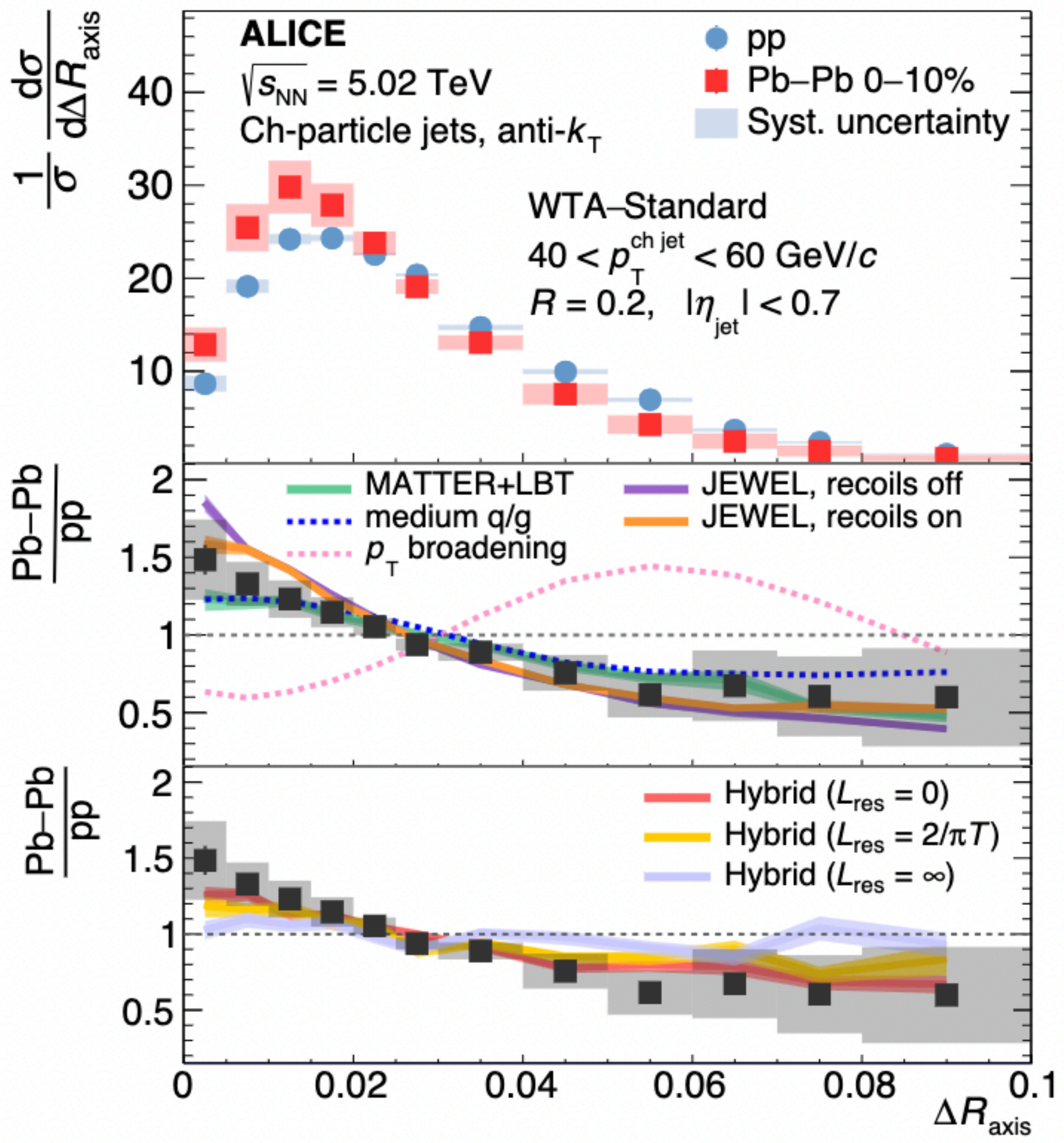


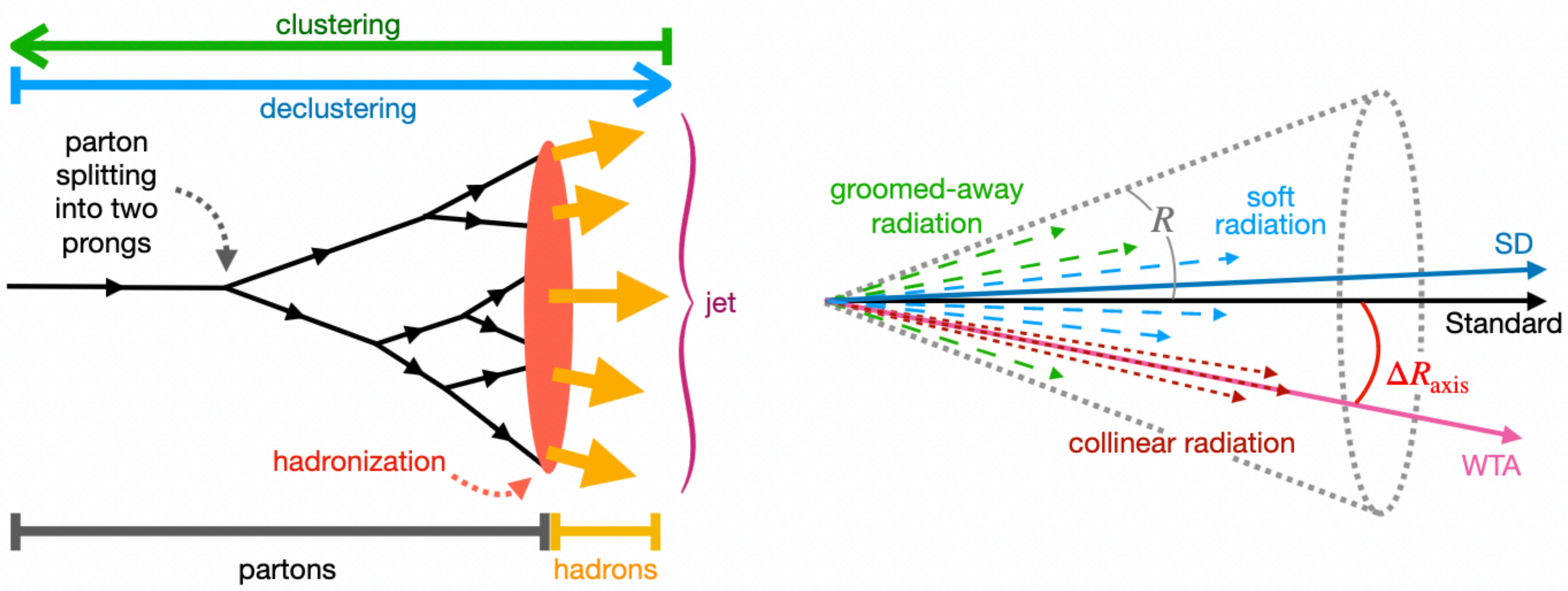


Differences between the b-jet/D-jet and inclusive jets are due to **color factor**s and <u>potentially</u> to the jet mass depending on the kinematic range and observable

Jet shapes: jet axis distance

ALICE, arXiv:2303.00592



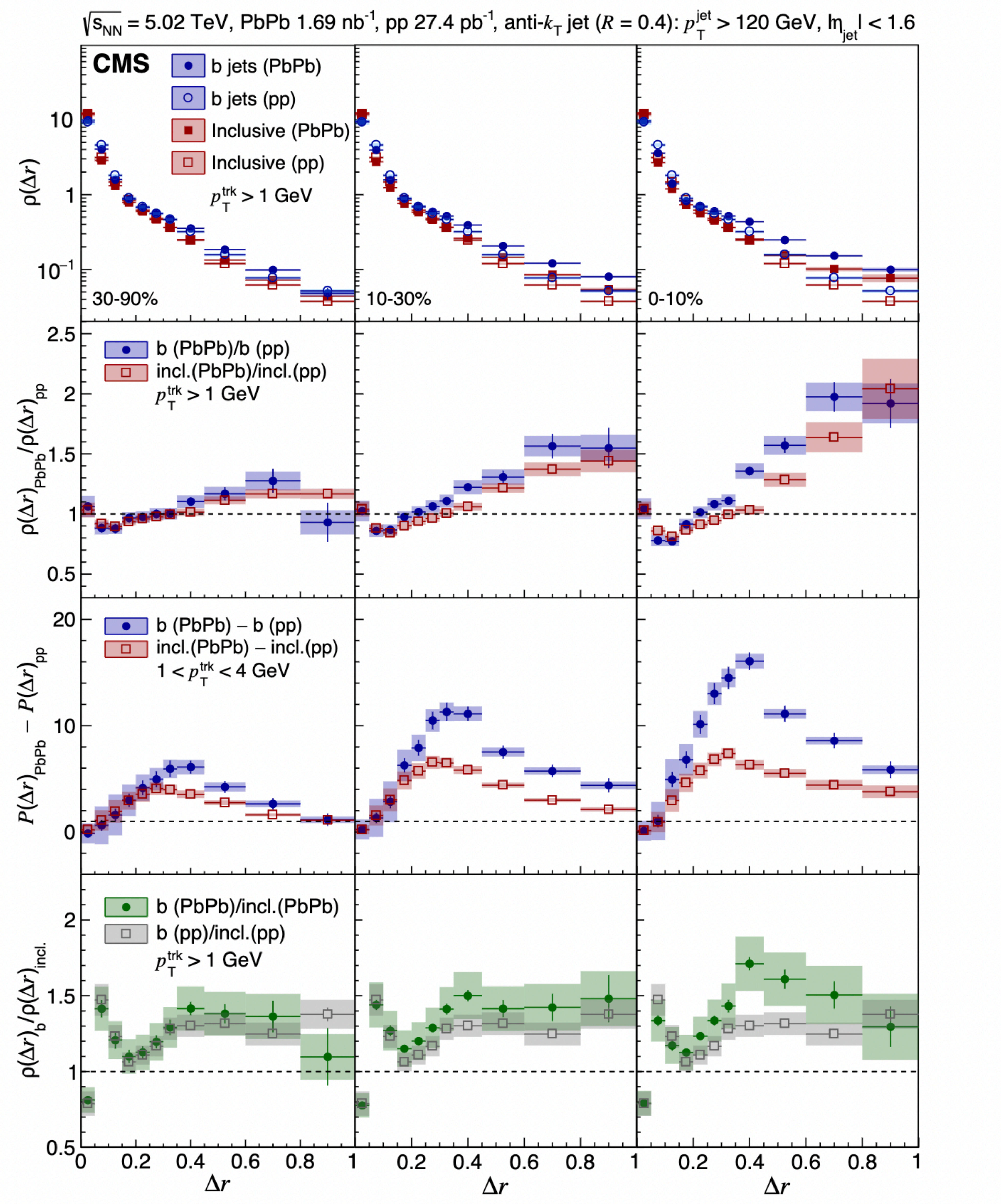


ΔR_{axis} measures the distance between standard E-scheme axis and WTA axis

Narrow fragmentation for which WTA and standard are similar, seem to be enhanced in PbPb

Similar narrowing pattern observed for angularities like the jet girth *ALICE, JHEP 10 (2018)139*

Jet shapes: transverse profiles of b-tagged jets



[CMS, arXiv:2210.08547v2](#)

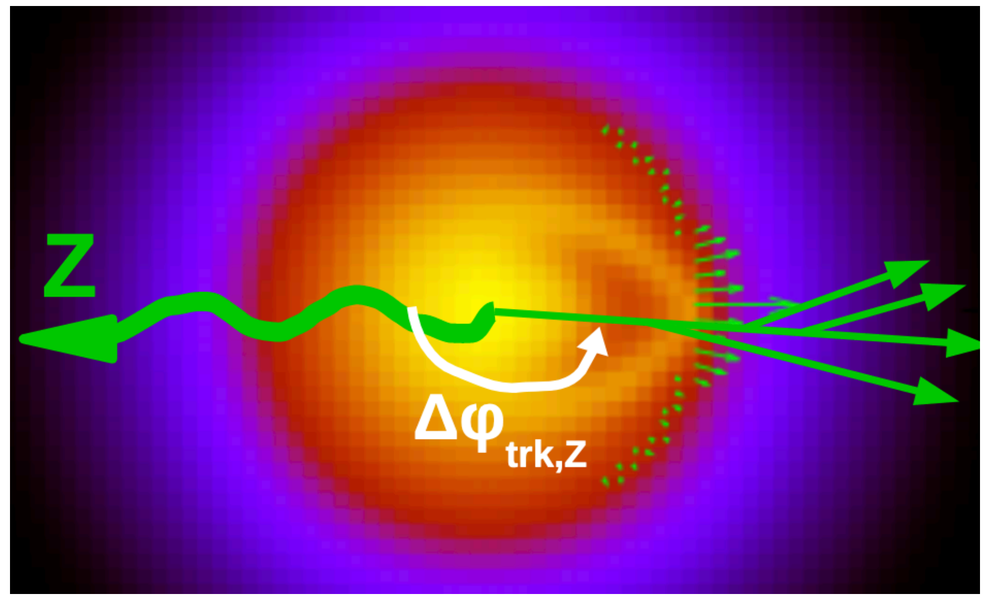
Depletion of transverse momenta at small radial distances from the jet axis, in both pp and PbPb profiles

The QGP modifies the energy flow around jets: depletion at small angles, enhancement at large angles. Stronger large-angle enhancement for b-jets.

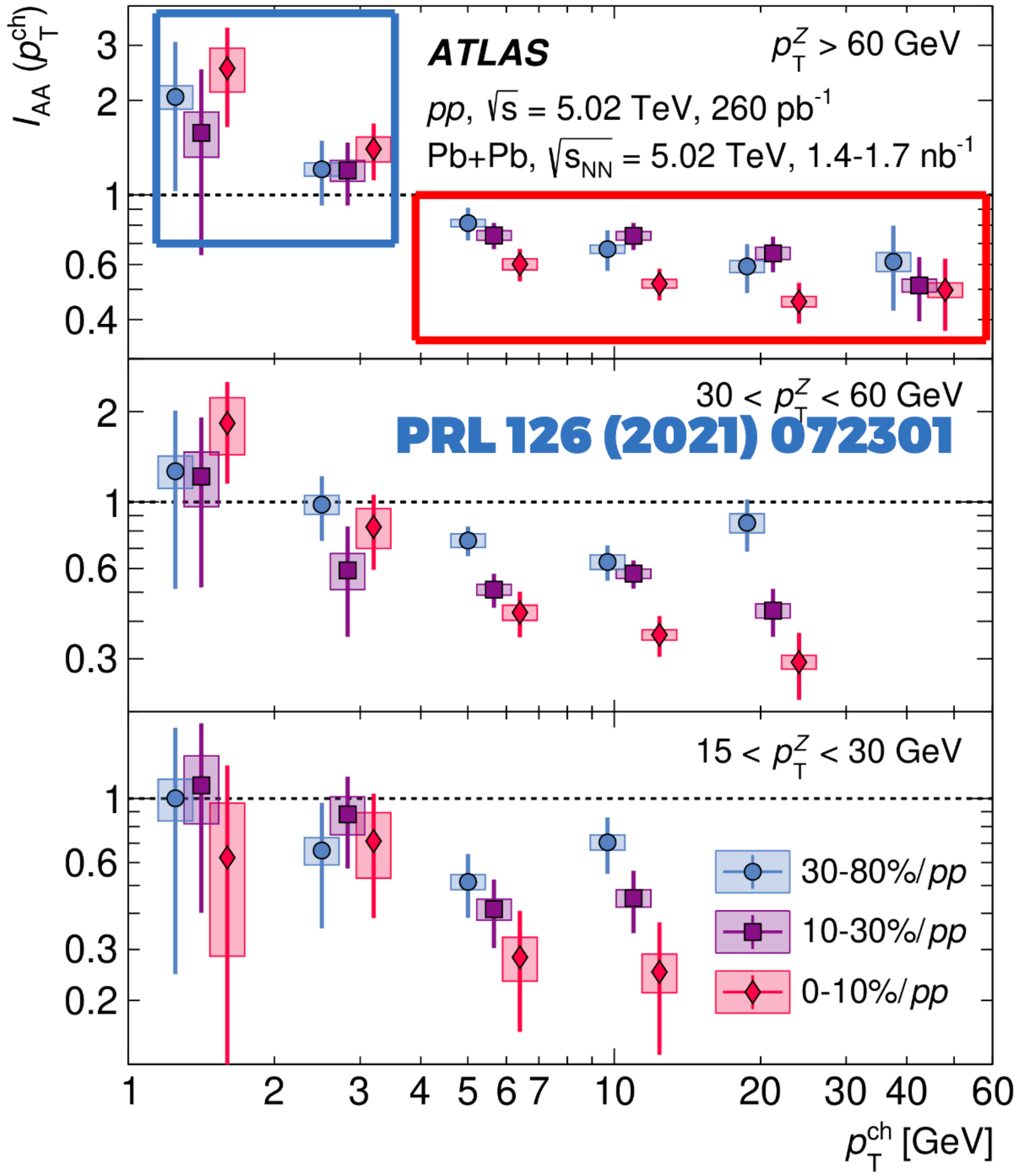
Both color factors and jet mass can impact the differences between b and inclusive jets

A quantitative link to mass effects requires the assessment of the impact of hadronisation and the B/D-hadron decays, see recent measurement of the dead cone in pp using substructure [ALICE, Nature 605,440 (2022)](#)

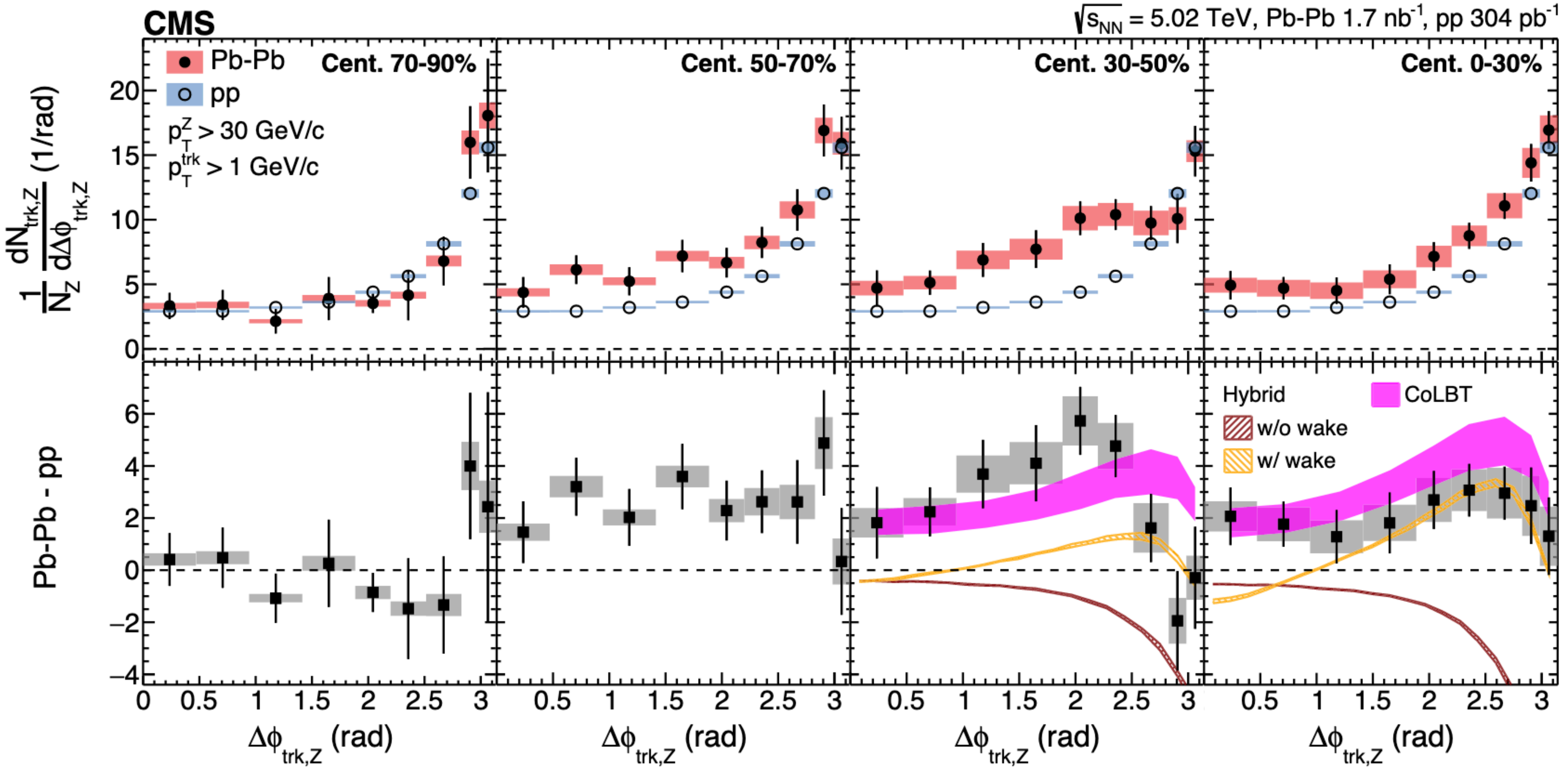
Coincidence measurements without recoil jet



$$I_{AA} = \frac{\text{Particles per Z in Pb+Pb}}{\text{Particles per Z in p+p}}$$

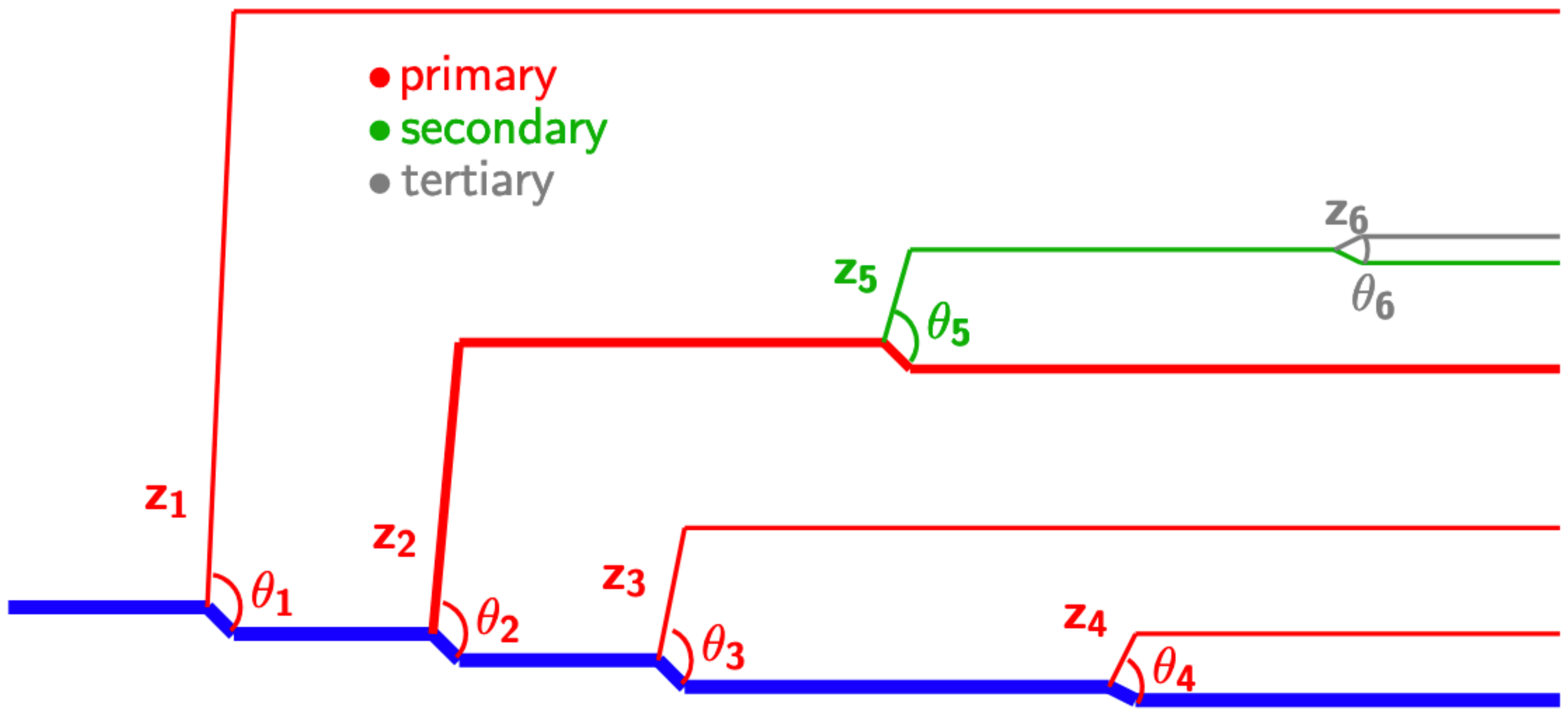


CMS, Phys.Rev.Lett.128 (2022)



Modification of the particle spectra in the recoil region: excess of low-p_T particles, suppression of high-p_T particles
Low-p_T particle excess potentially from medium back-reaction

Jet substructure using the clustering history



Another sketch from G.Soyez

The Cambridge/Aachen algorithm sequentially combines the closest pairs

The clustering history can be undone iteratively, following always the hardest branch

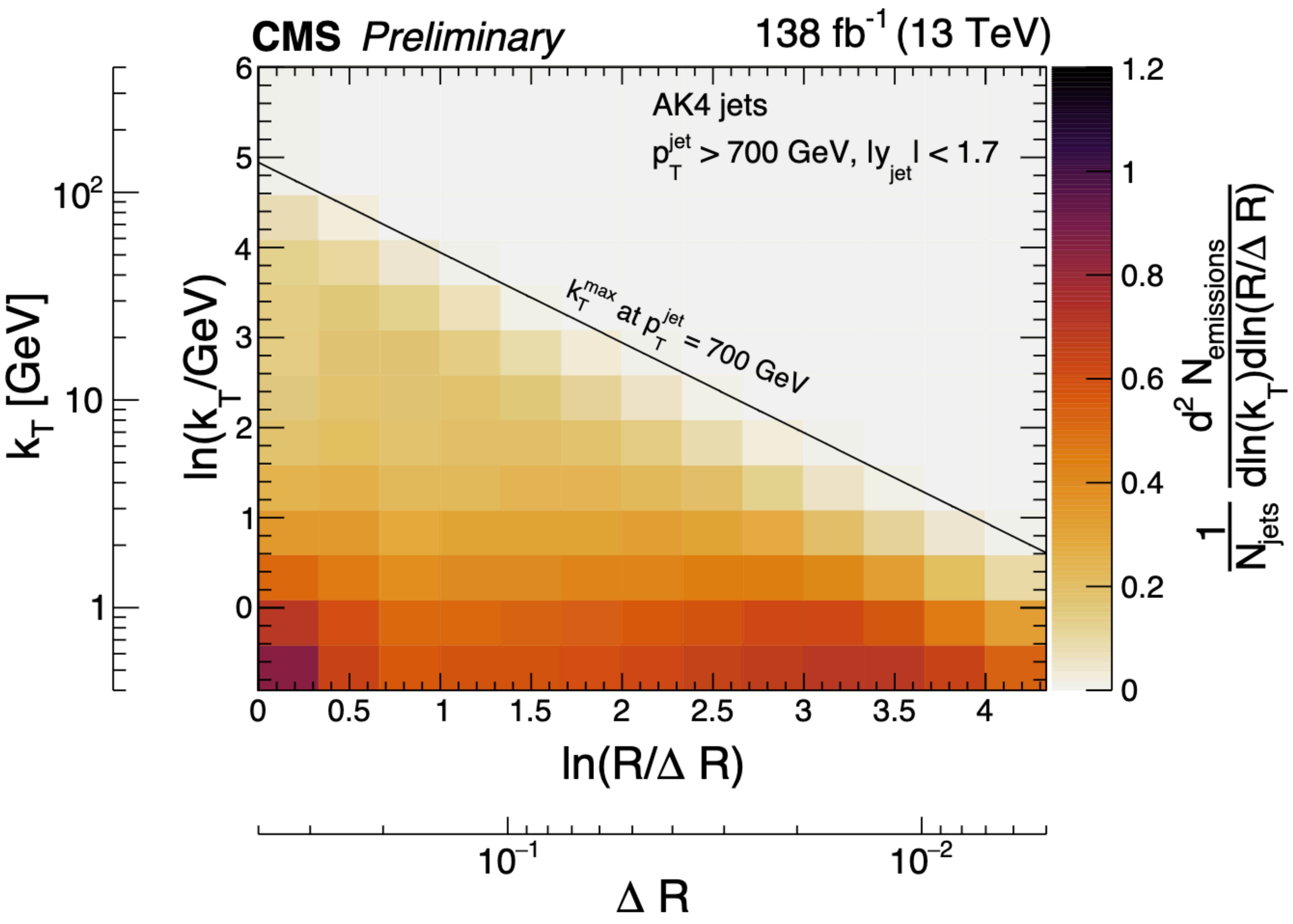
At each step, two subjet prongs are obtained, j1 and j2 , with $p_{T,1} > p_{T.2}$

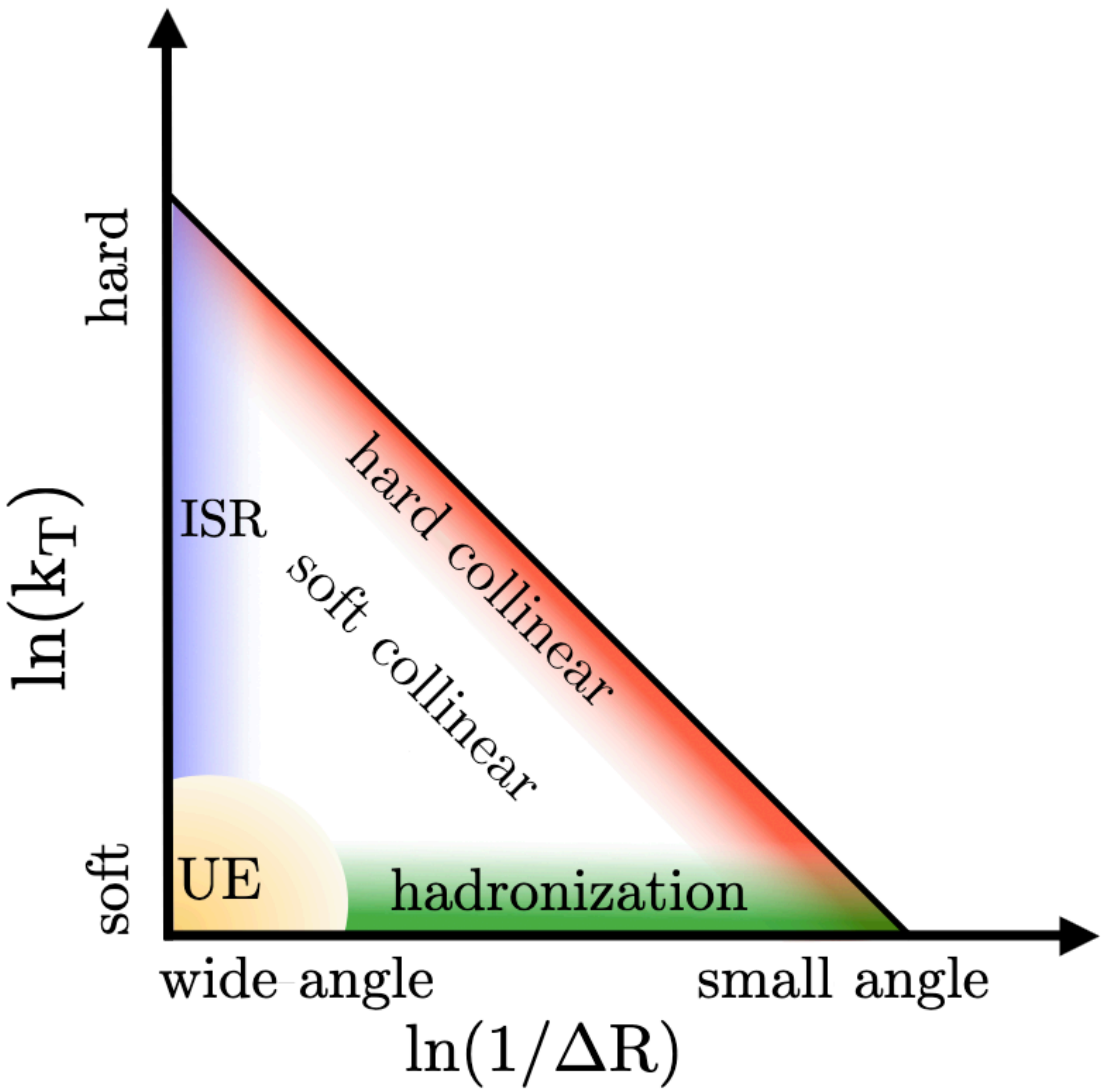
where θ is the angle between the prongs,
$k_T = \theta p_{T,2}$
and $z = p_{T,2}/(p_{T,1} + p_{T,2})$

The iterative declustering proceeds until substructure is found (grooming)
or the jet can be fully declustered to study the kinematics of all the emissions (Lund jet plane)

The primary Lund plane density in pp collisions

[CMS-PAS-SMP-22-007]





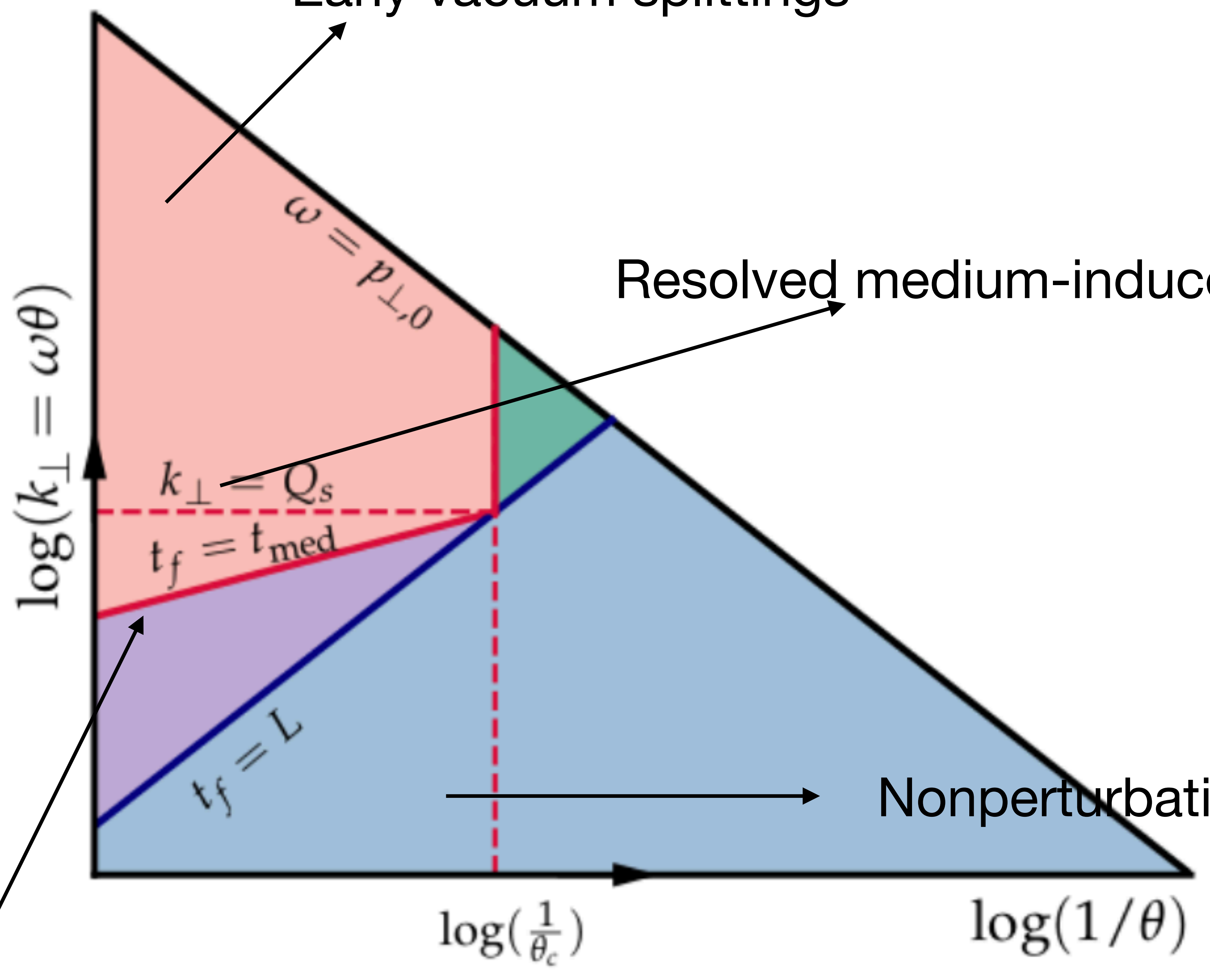
New possibility to access the building blocks of the parton shower, in pp and PbPb collisions

The Lund plane in PbPb collisions

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

Early vacuum splittings

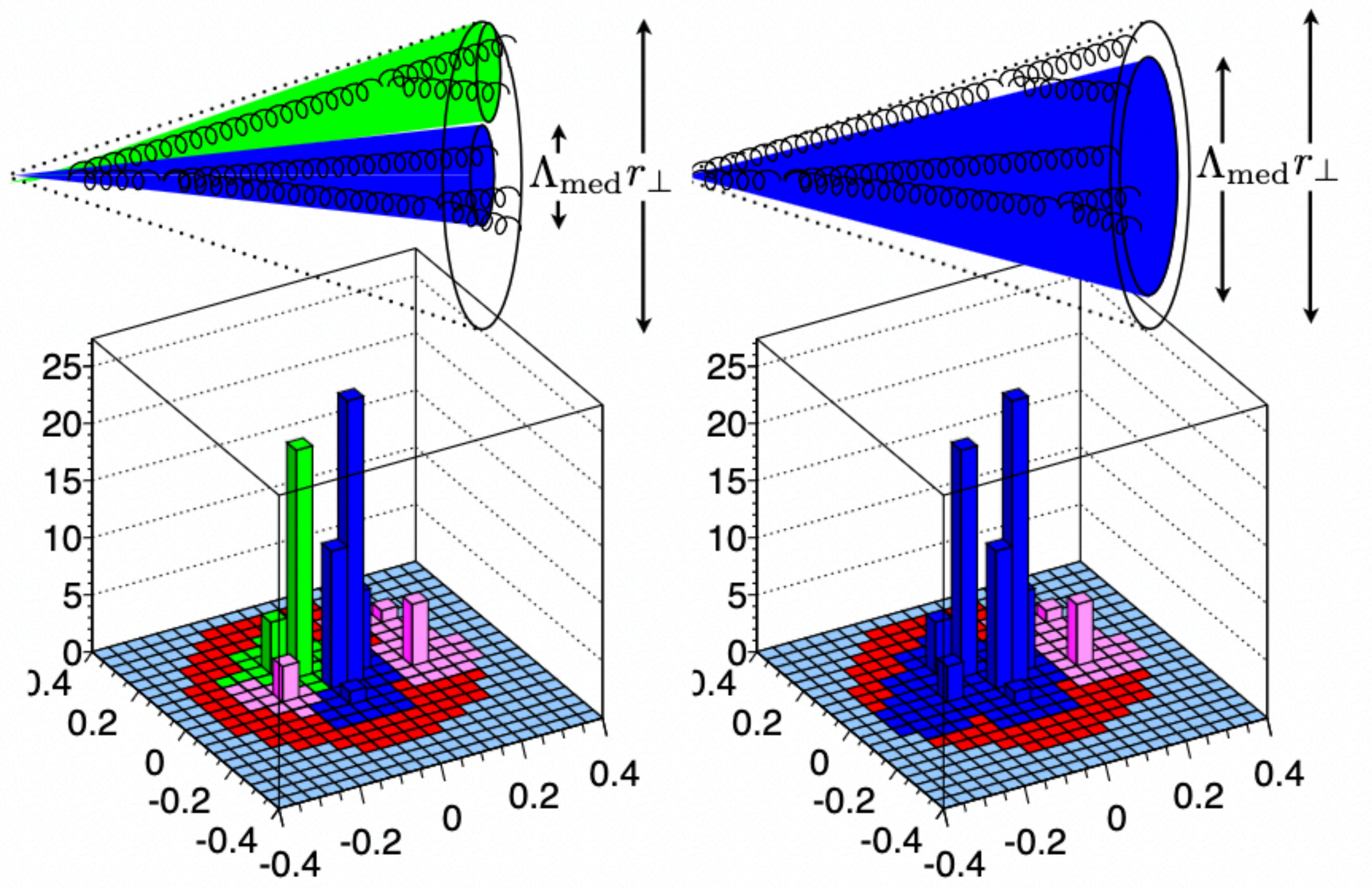
Resolved medium-induced emissions



Nonperturbative effects

Large-angle, soft emissions,
Strong fake contribution

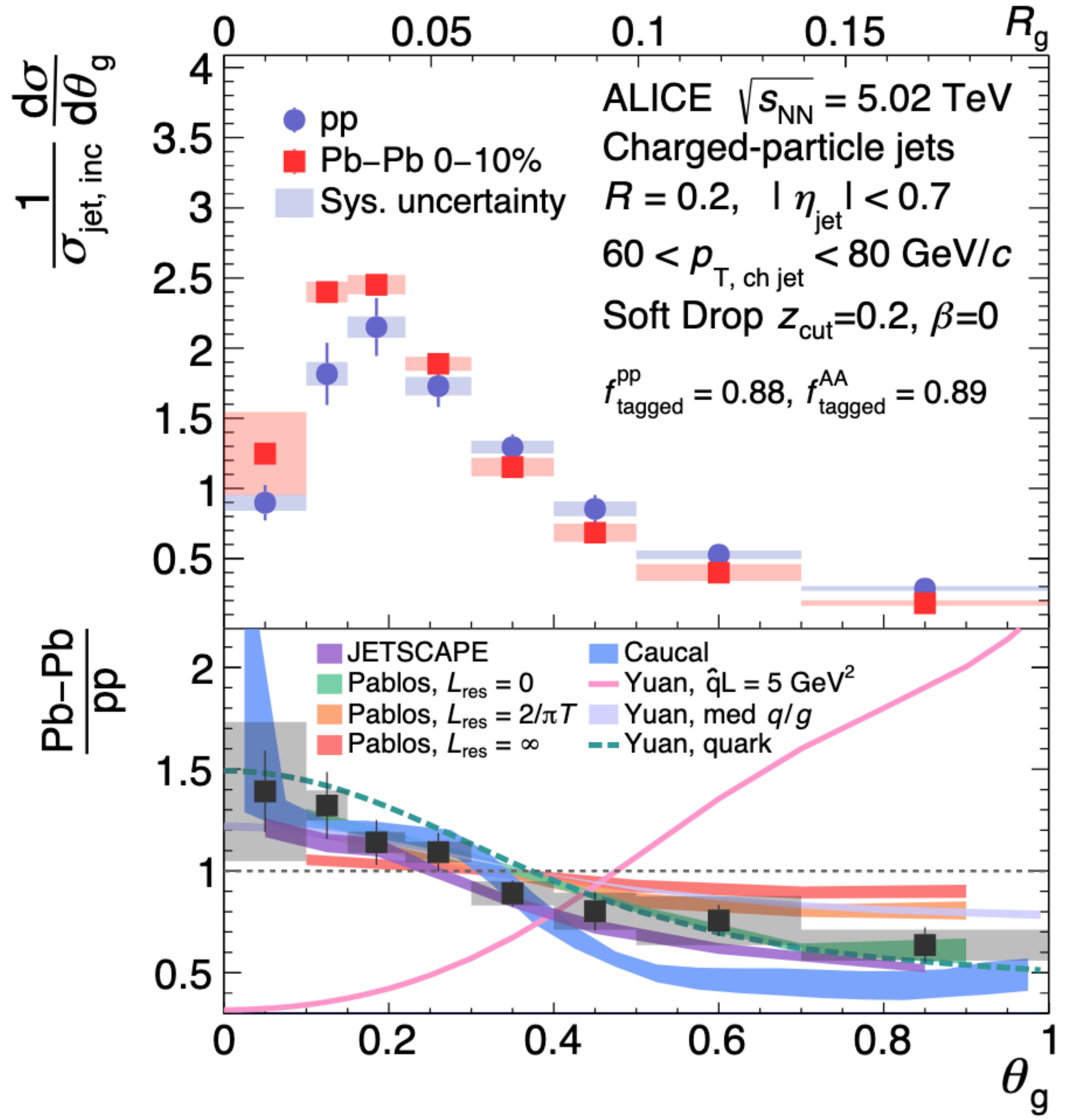
[Casalderrey et al, Phys.Lett.B725 (2013)](#)



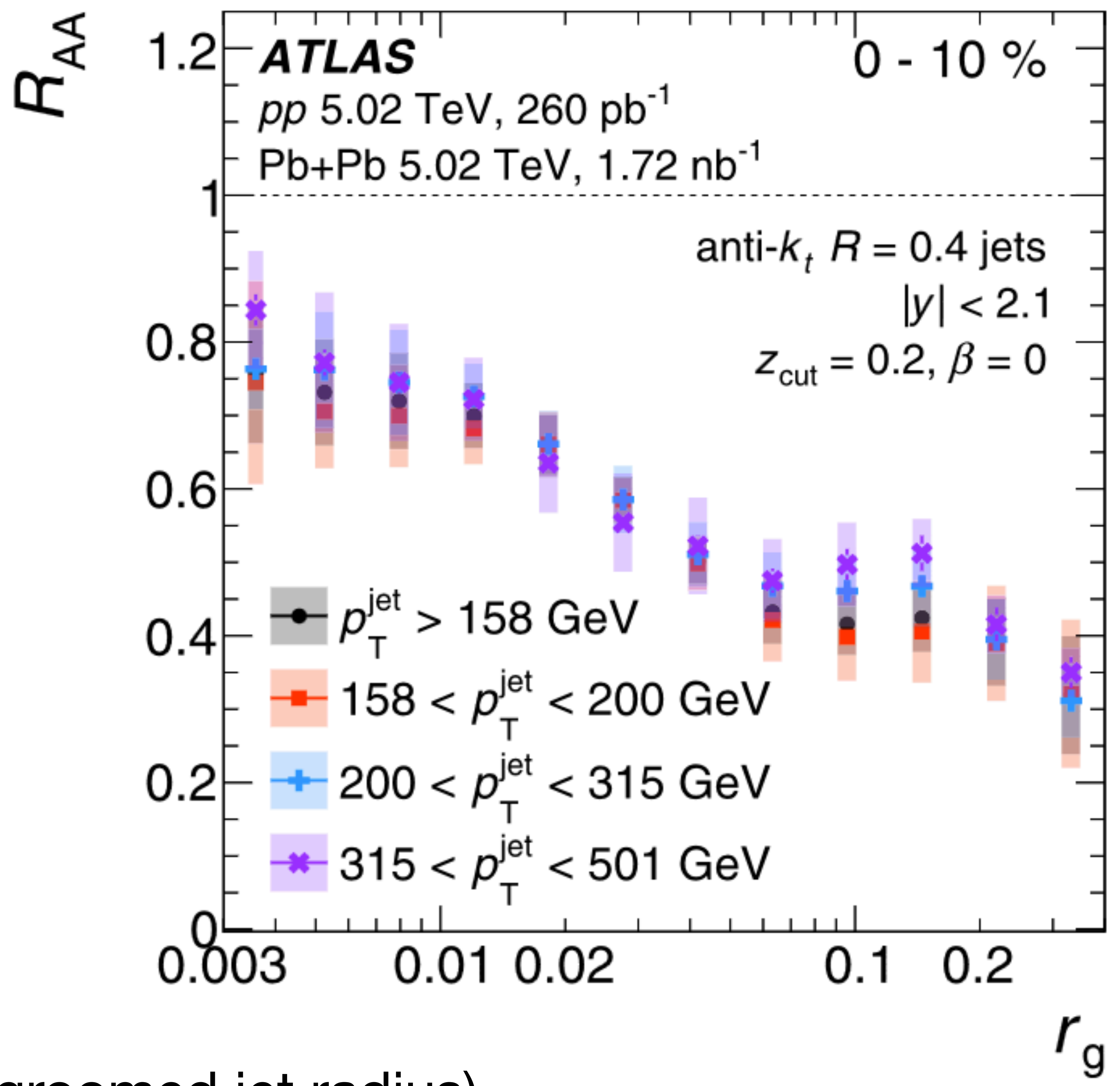
New scales in medium: emissions with $\theta < \theta_C$ are not resolved by the medium

Scanning the Lund plane in PbPb: the groomed jet radius

ALICE,Phys.Rev.Lett.128(2022)



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

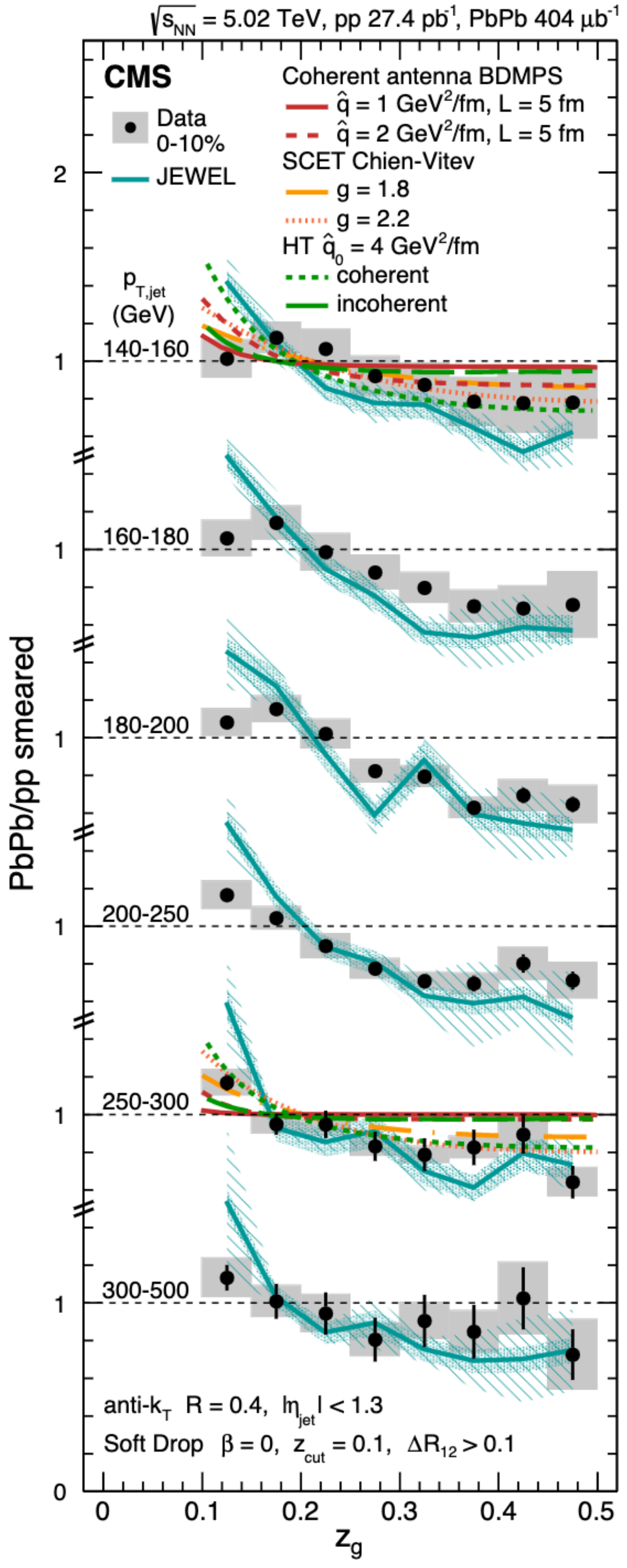


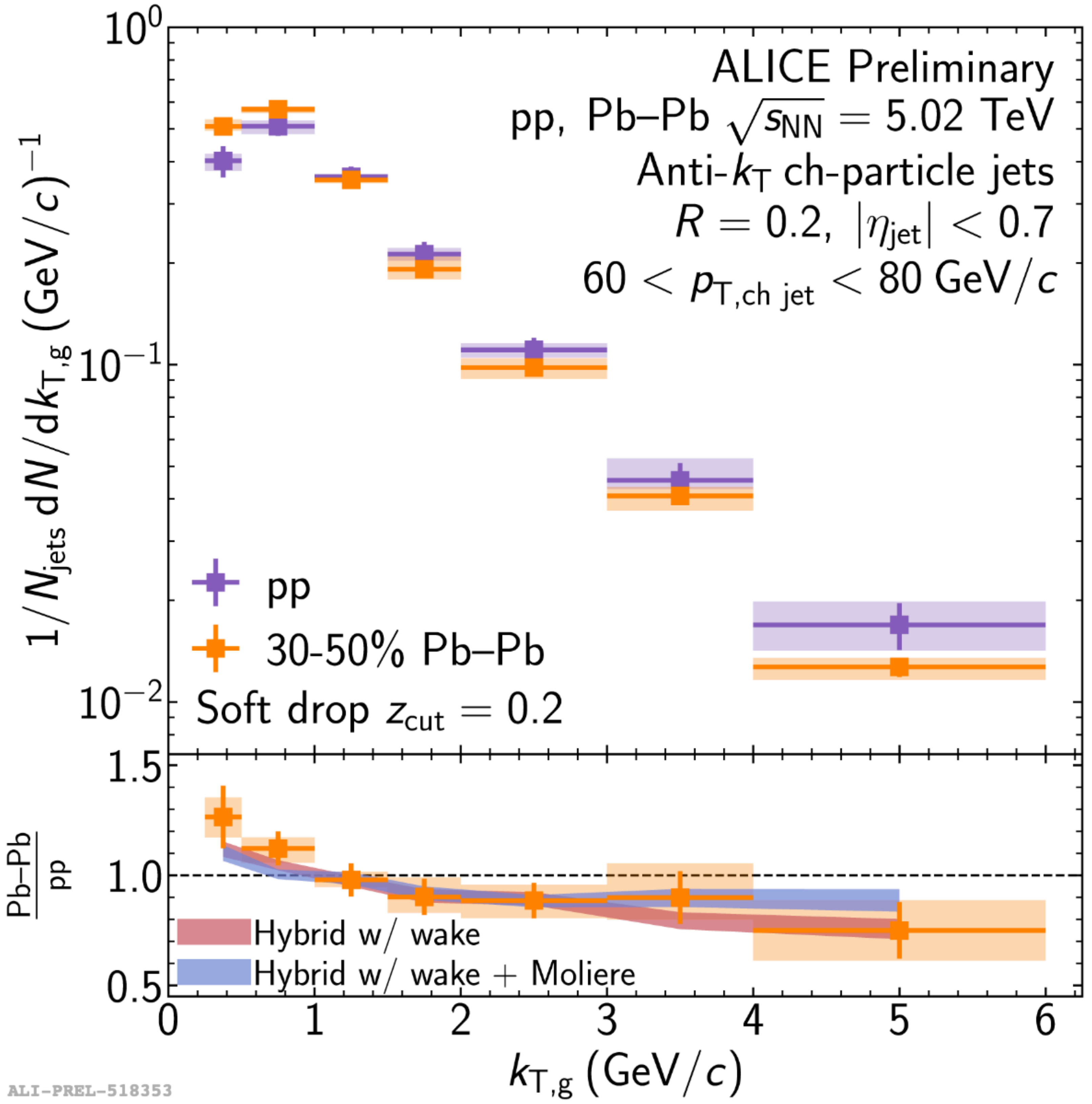
Data indicates a suppression of broad splittings (large groomed jet radius)

Is this linked to the color coherence scale or is this the result of a selection bias by which at given jet p_T we select narrower, less quenched jets while broader, more quenched jets migrate to lower p_Ts?

Scanning the Lund plane in PbPb: the groomed jet k_T and z_g

CMS, Phys.Rev.Lett. 120 (2018)





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Summary

-New and more precise information on color and mass dependence of energy loss

-New kinematic regimes explored (low p_T/ large R) in order to fully capture the dynamics of jet quenching
->interesting complementarity with RHIC program

-Broader jets appear more suppressed (via angularities, jet axis difference, Rg, k_T^{dist} with different degrees of signal strength)
Probing fundamental properties of the medium like color correlation length or probing the point-like scatterers in the medium are within reach

-Interesting prospects for Z/γ-jet substructure, to mitigate the potential selection bias by controlling the degree of quenching of the jets via $x_J = p_{T,jet}/p_{T,Z/\gamma}$

-New substructure techniques bring new possibilities to heavy flavour jets which are flourishing now in pp and can be extended to PbPb

-Plenty of encouraging new theoretical developments