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SAPIENZA UNIVERSITÀ DI ROMA

Jet production and suppression

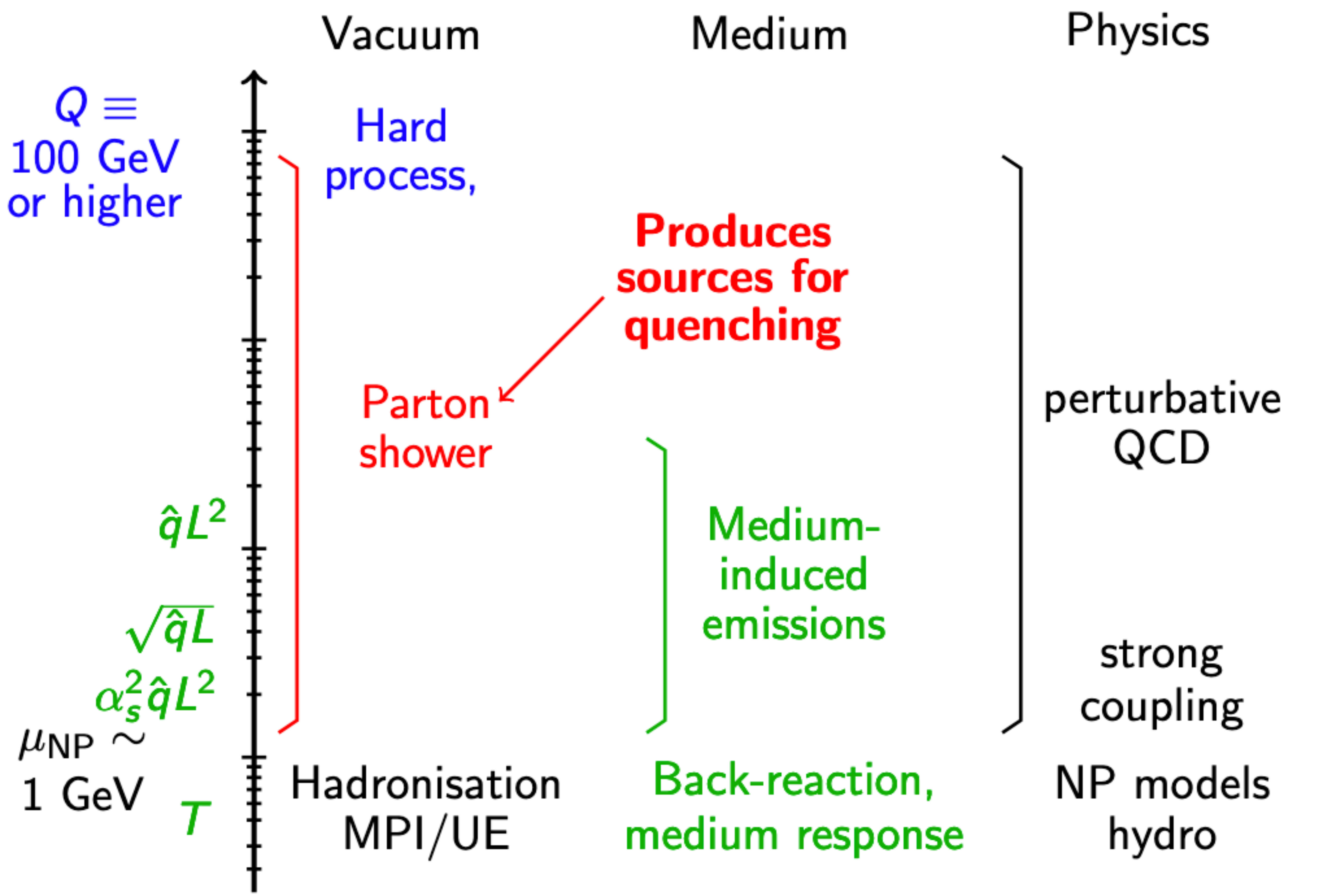
Leticia Cunqueiro

West side story 1961

Quark Matter 2022, Kraków, April 8th

Jets in heavy-ion collisions

Jets probe the medium at multiple scales

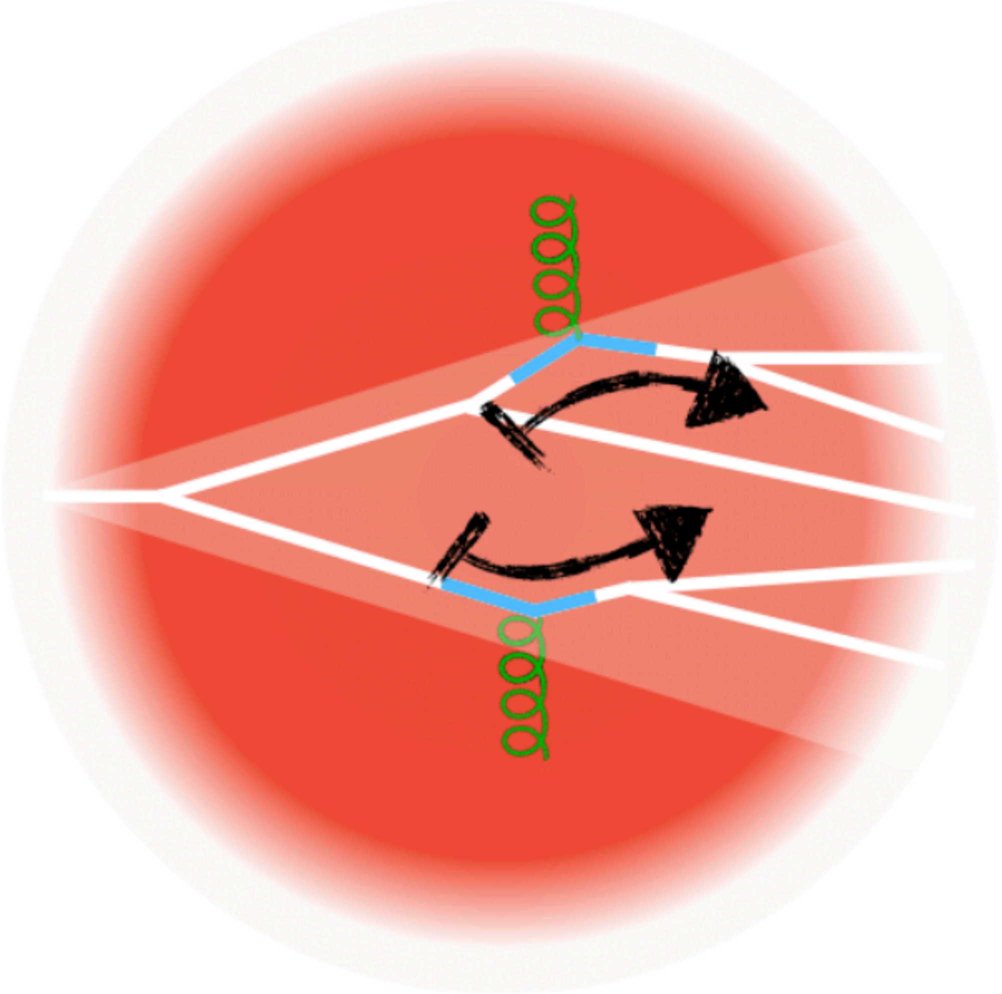


sketch from G.Soyez

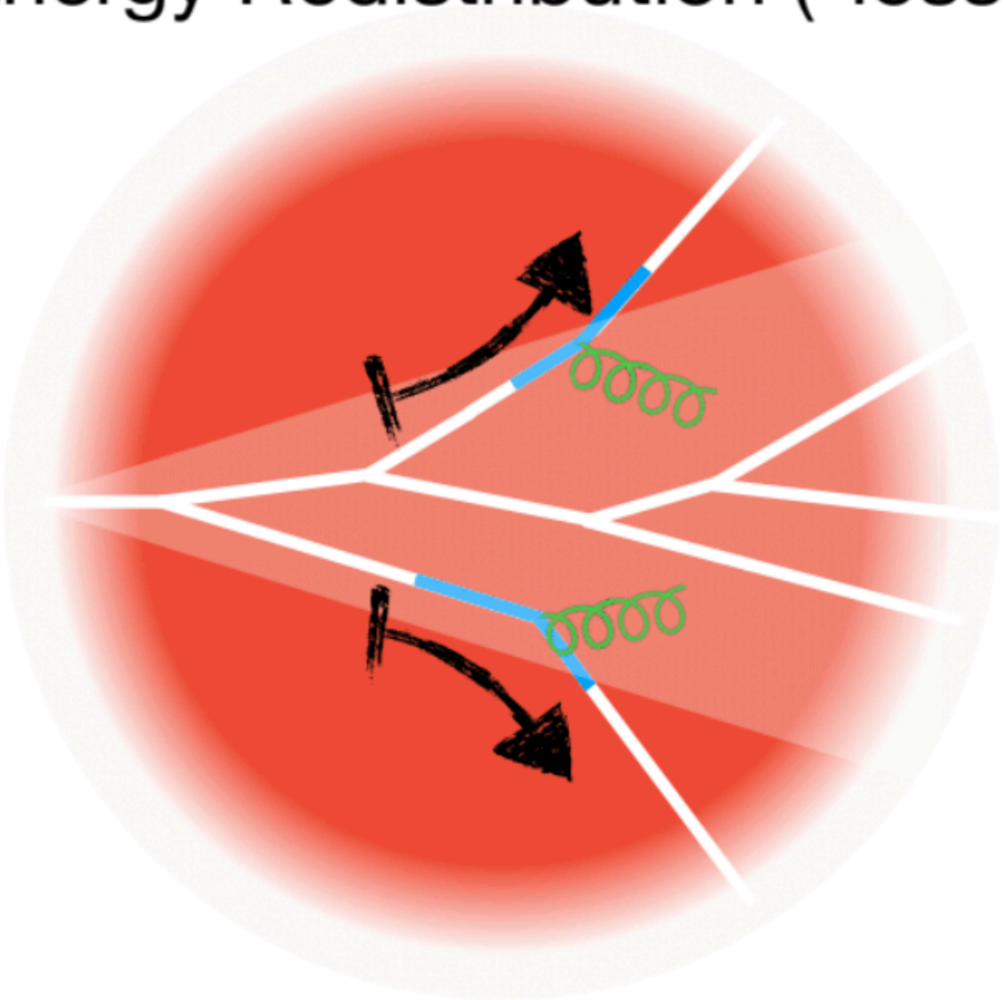
Different types of jet observables

We inspect modifications in the jet production and fragmentation pattern trying to isolate different physics mechanisms to validate theory ingredients and aproximations and ultimately characterize the QGP

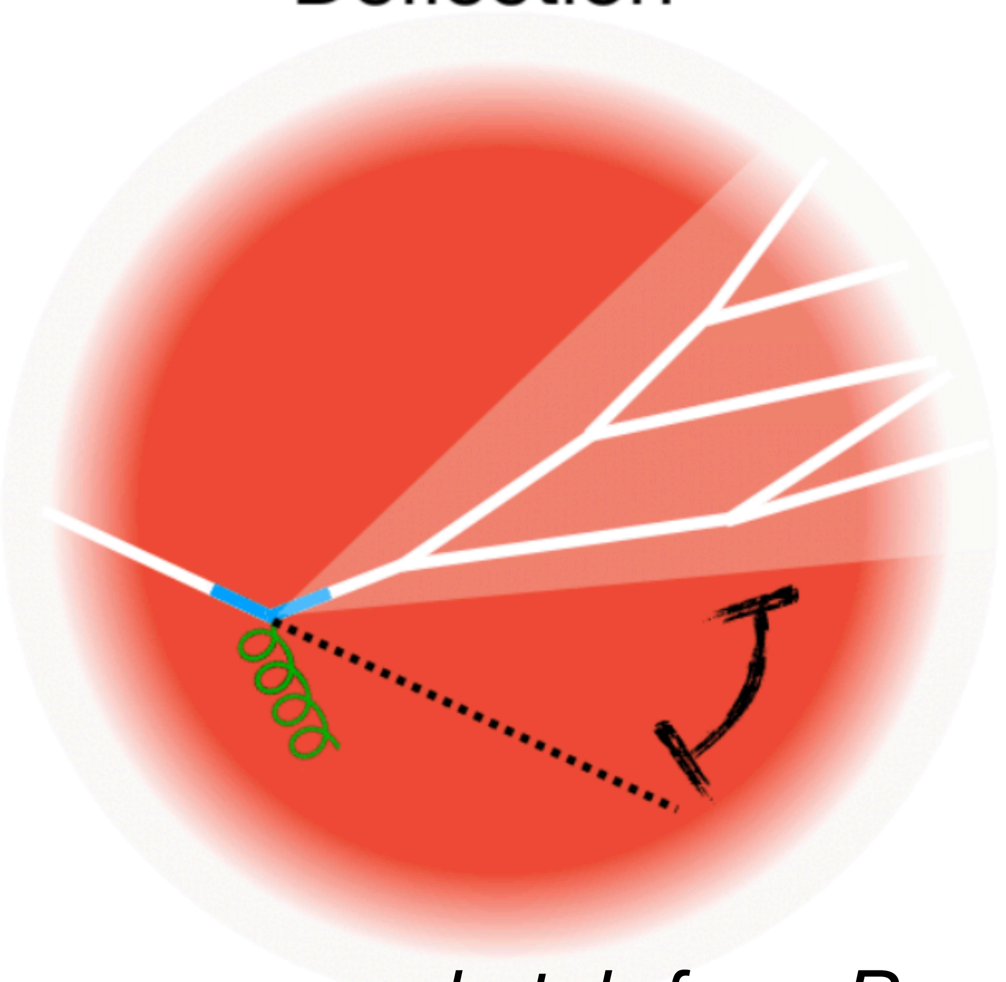
Substructure modification



Energy Redistribution ("loss")



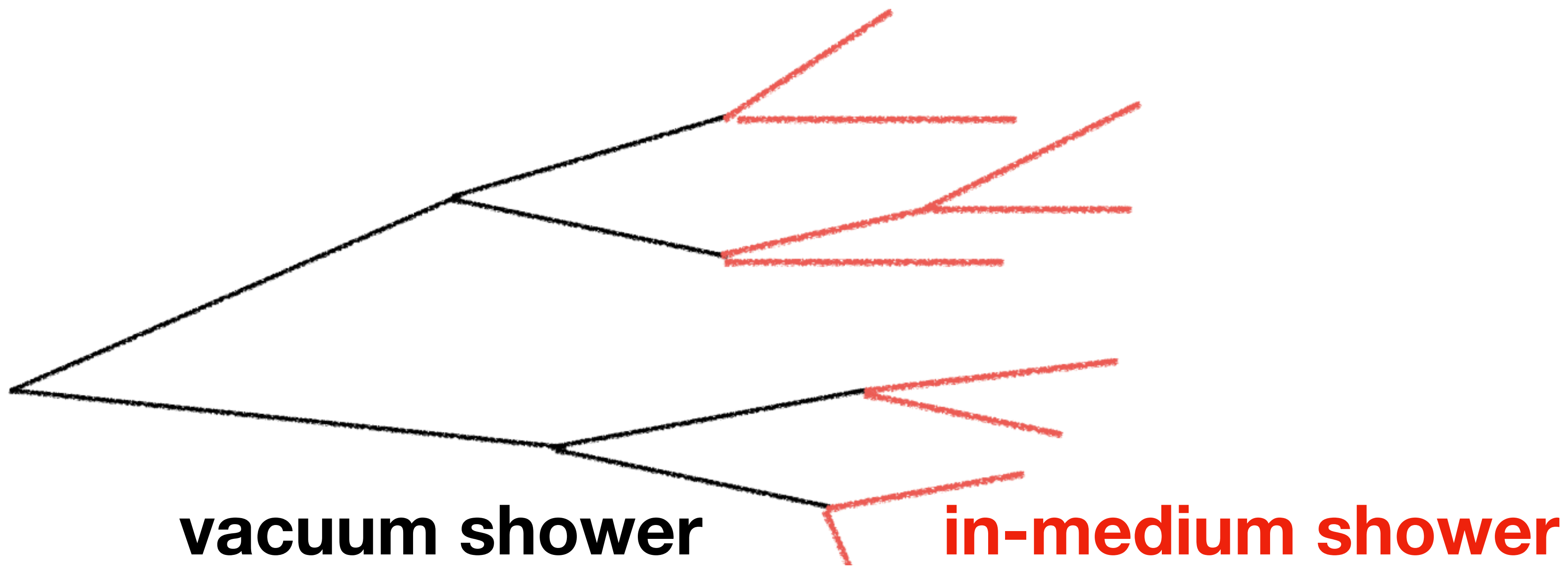
Deflection



sketch from Rey Cruz

Some of the questions we are trying to answer experimentally

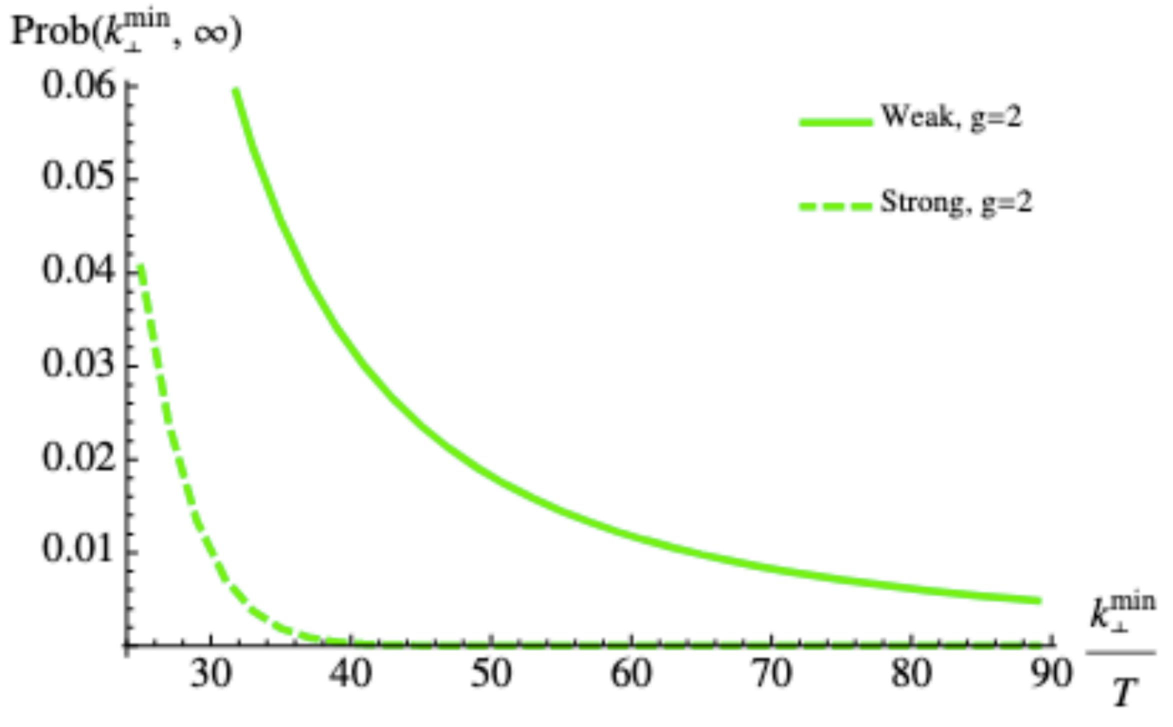
1. How does energy redistribution happen
   activity of the early vacuum shower and the number of resolved prongs set the degree of quenching



2. Role of color charge and mass
   color factors and mass effects lead to different parton showers in vacuum. Testing their impact in medium ongoing

3. Role of medium response
   lost energy reaches thermal scales and gets redistributed in the medium. Expected contribution at large angles. Model dependent.

4. Path length dependence
   different energy loss mechanisms predict different path-length dependence



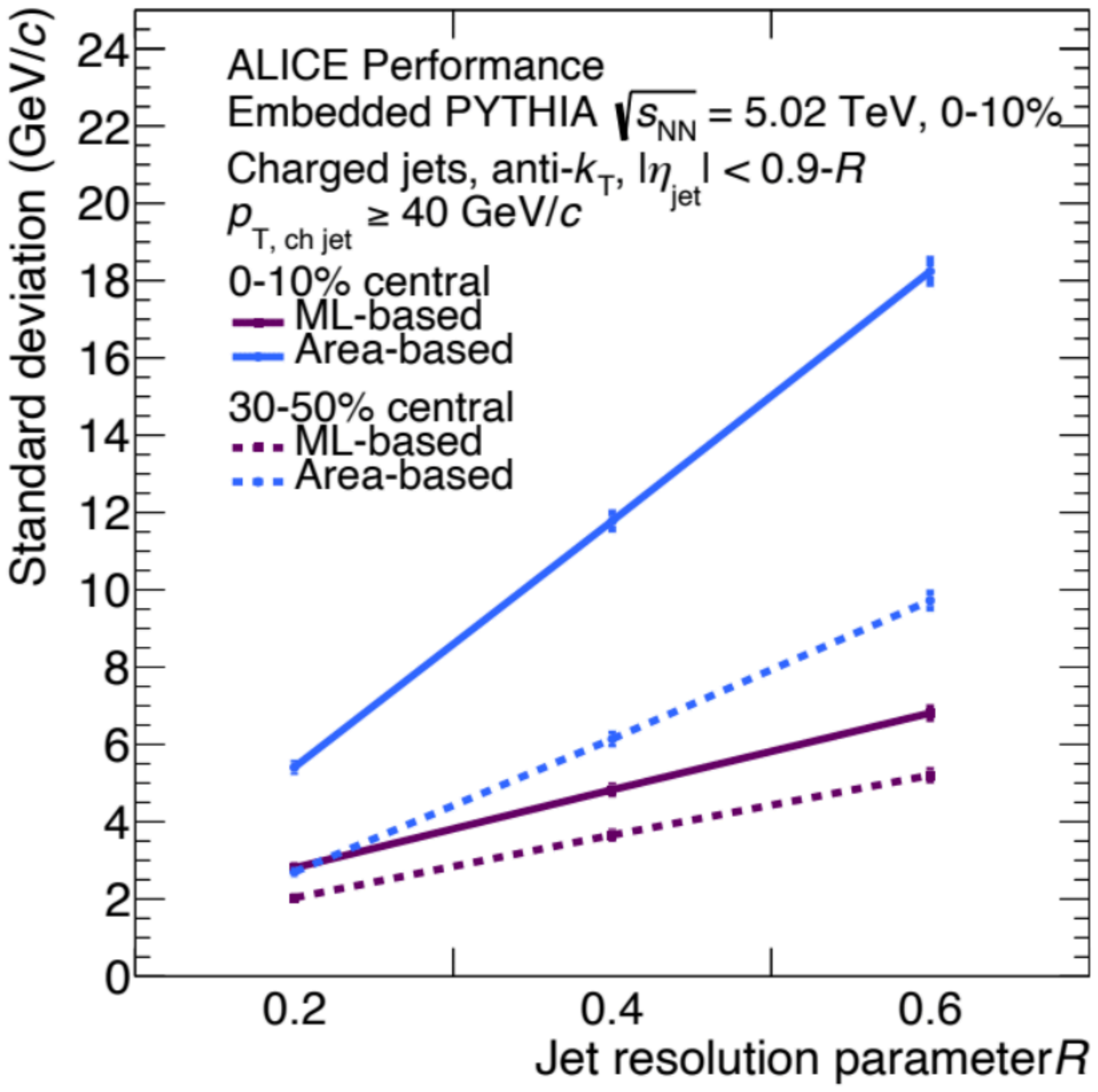
5. Can we probe the QGP at sufficiently short distances so that quasi-particles emerge?
   searches for large angle deflections/large k_T transfers

6. Critical medium size for jet quenching

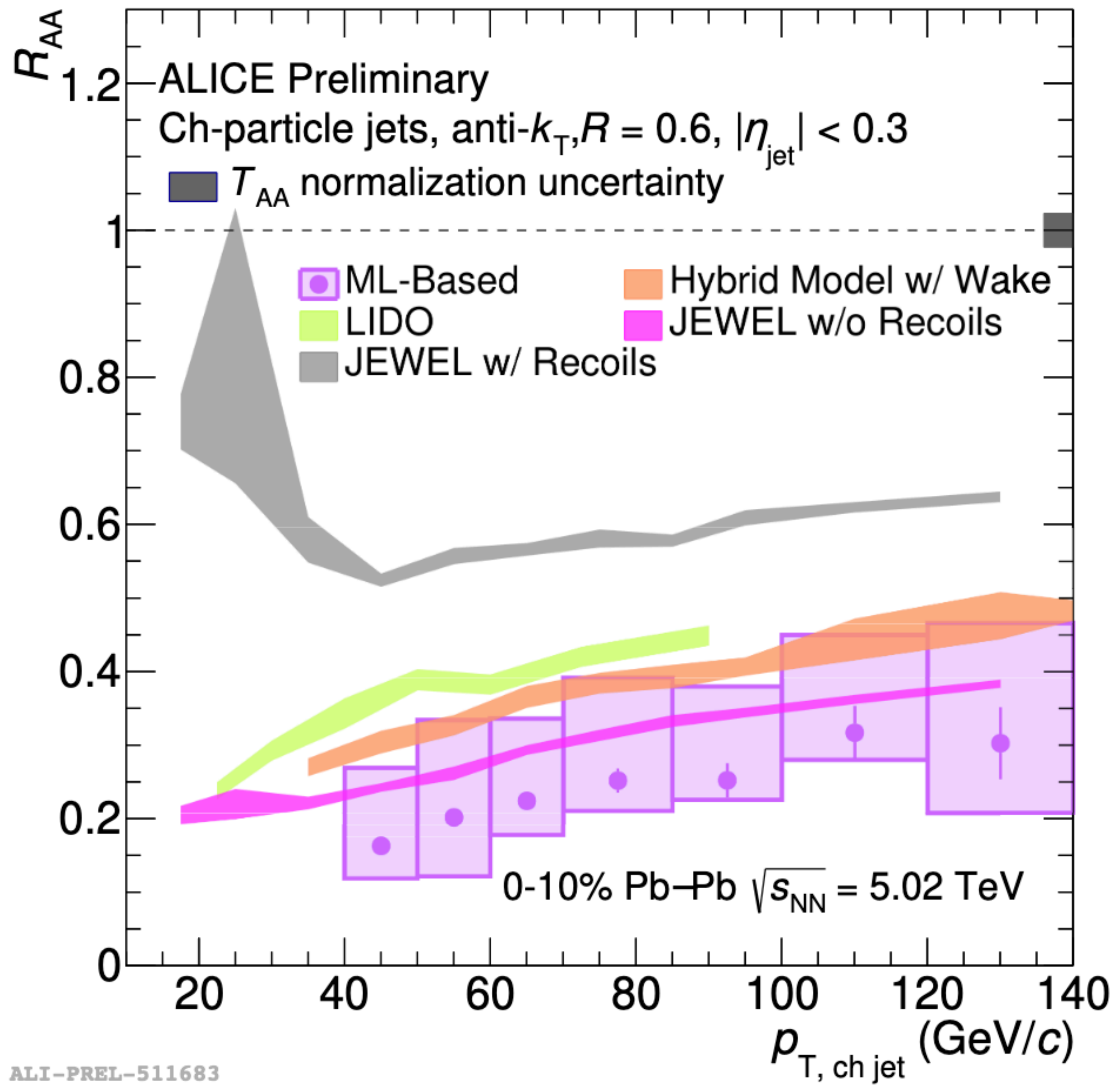
7. Is it possible to derive a space-time picture of jet quenching
   using splitting kinematics? profiting from the time delay of boosted particles?

Jet suppression and energy redistribution

Hannah Bossi's talk



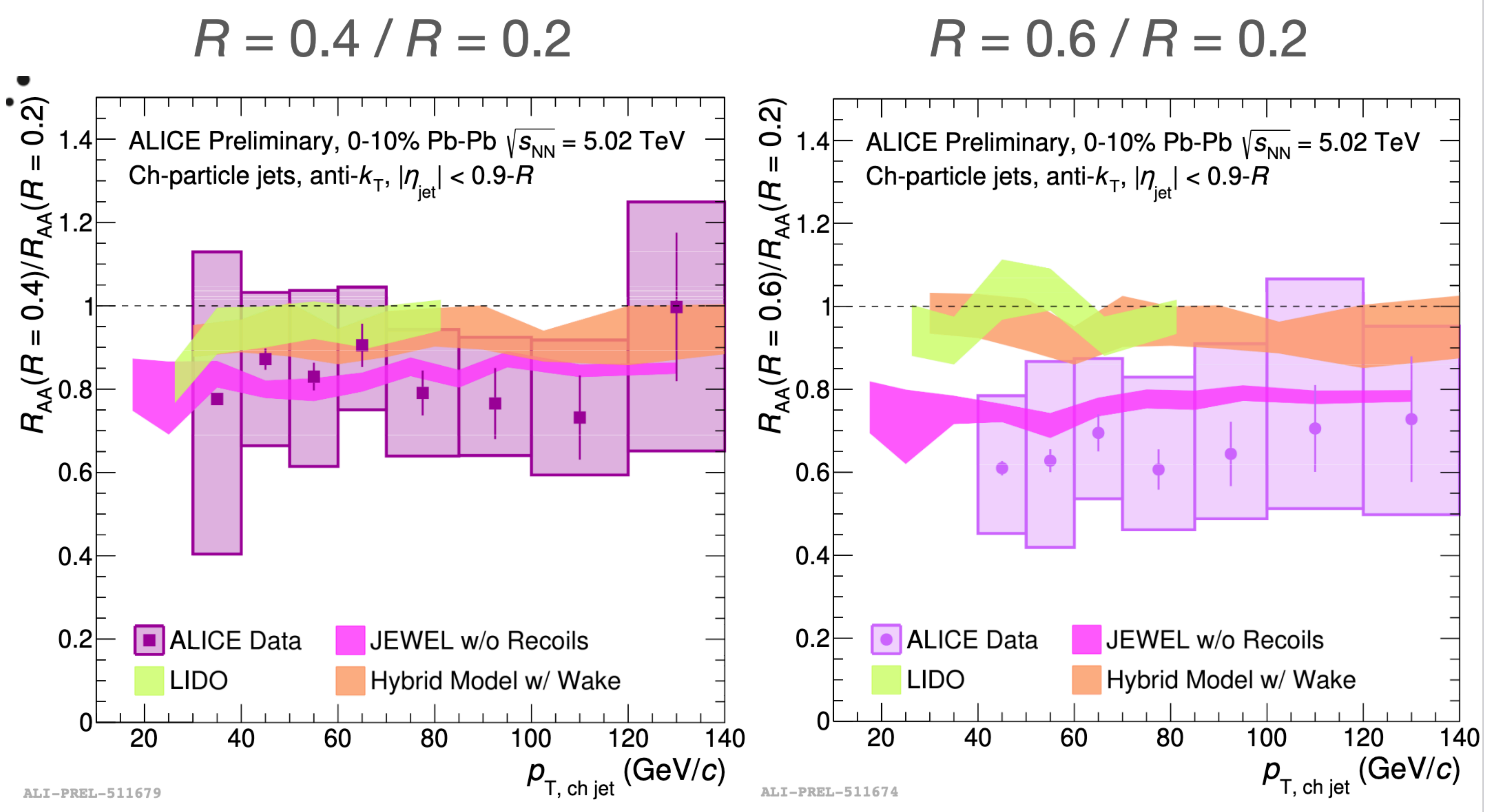
R=0.6



Learning on constituent information allows to reduce bkg fluctuations and to suppress combinatorial jets
Unique low p_T & large R reach at the LHC

Jet suppression and energy redistribution

Hannah Bossi's talk



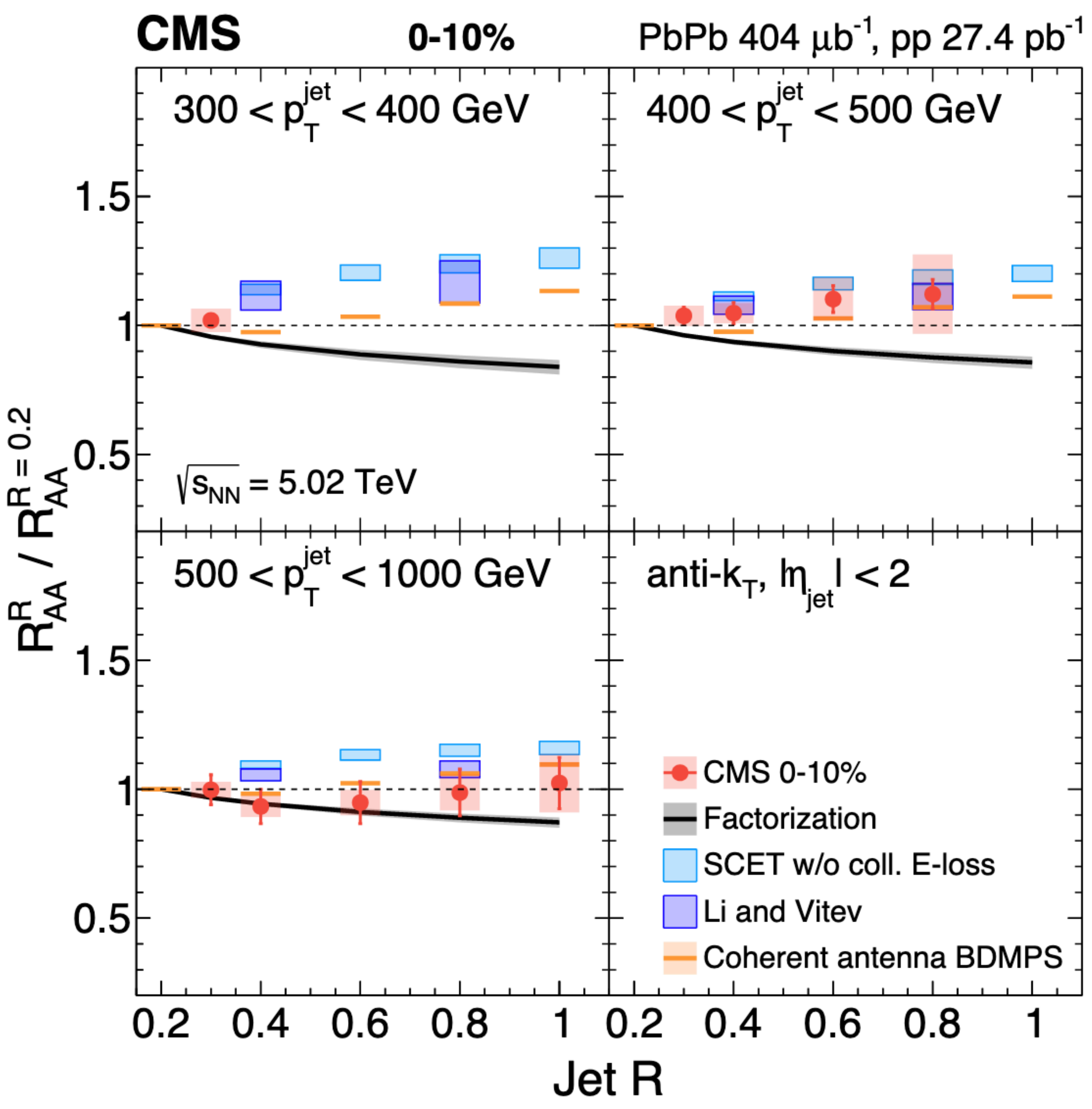
In general suppression is the result of **a)** amount/how energy is redistributed and **b)** ability to recover it

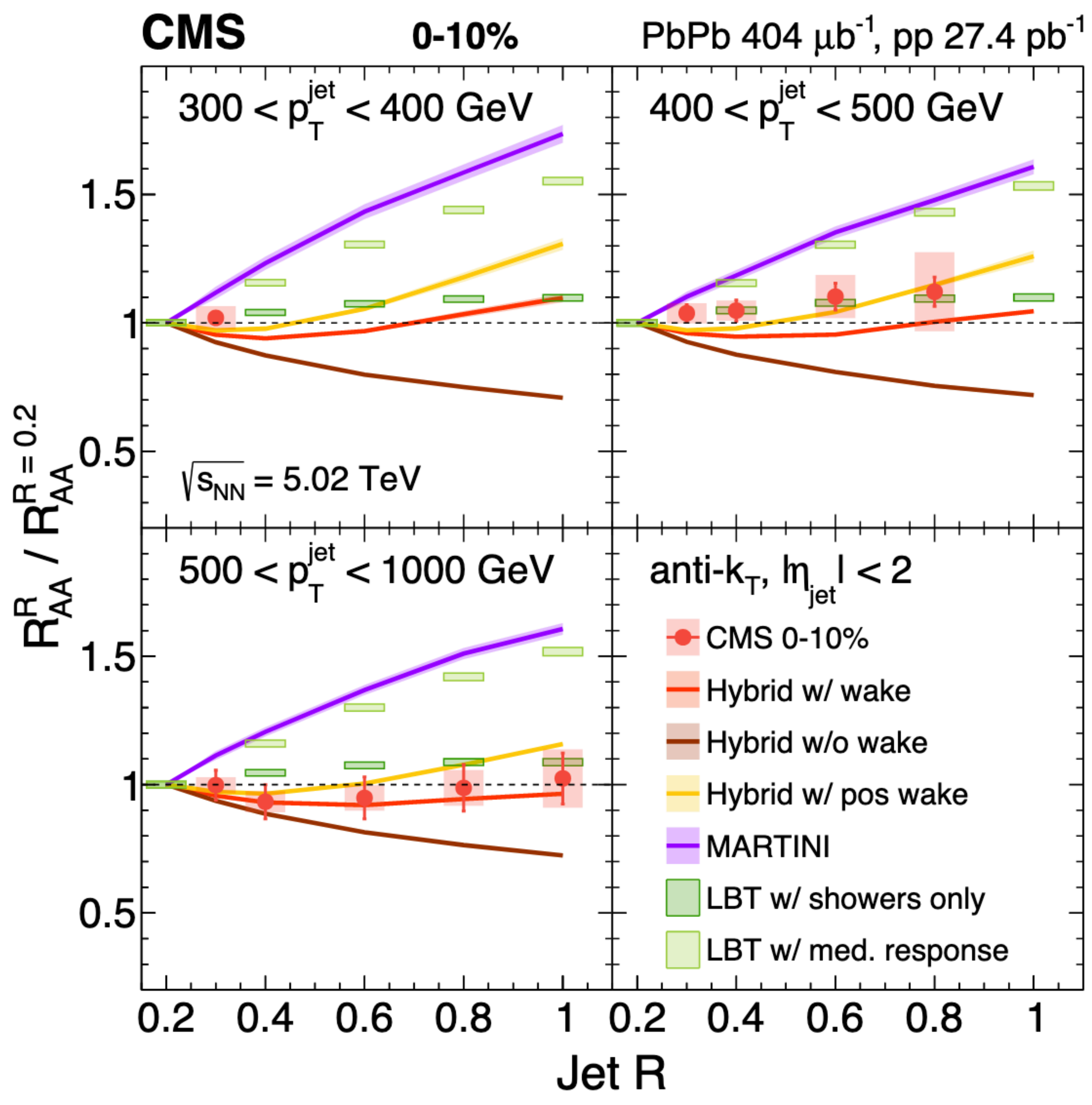
At fixed jet $p_{T,}$ large-R jets potentially select jets that were more “active” or that had more independent prongs interacting with the medium and that are thus more quenched

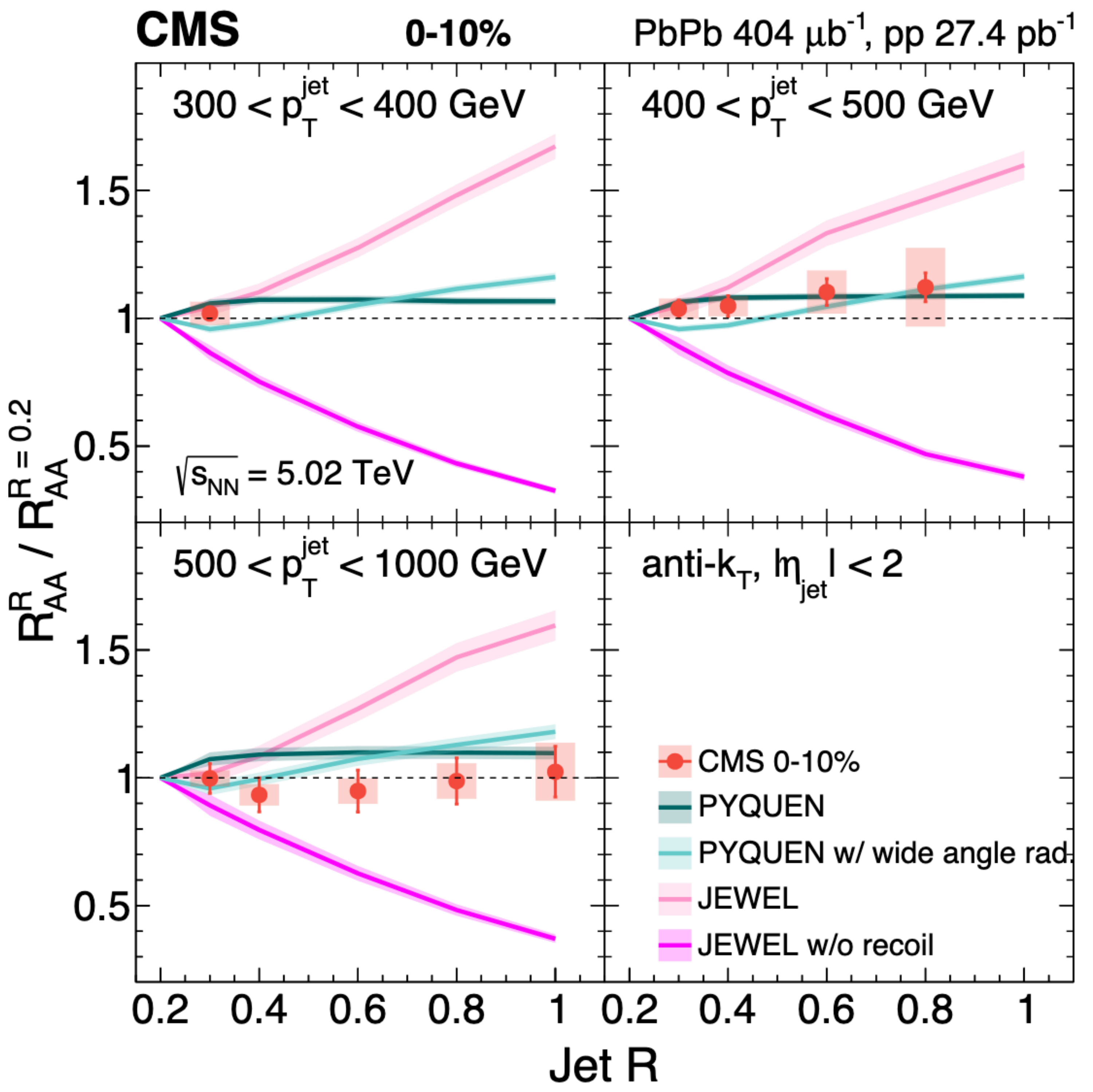
ALICE results seem to indicate an incomplete balance between a) and b) as opossed to CMS results at higher jet p_Ts and there is tension with ATLAS 2.76 TeV results (see Martins’ talk)

Jet suppression and energy redistribution

CMS JHEP 05 (2021) 284





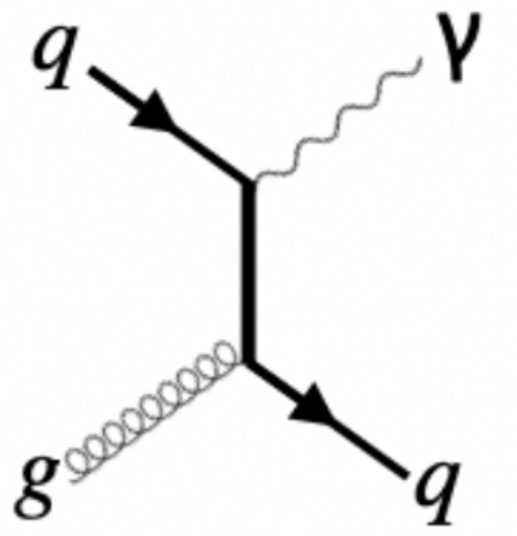


For instance, Hybrid model: larger-*R* jets bias towards jets with a **more active early vacuum shower** that are then more quenched (dark brown) but they can **recover better the medium response or wake**

Coherent antenna considers coherence effects and models recoils as low energy modes that are thermalized and smeared over a large angular region

But analytical calcualtions based on SCET describe the trends too without the need of the medium response!

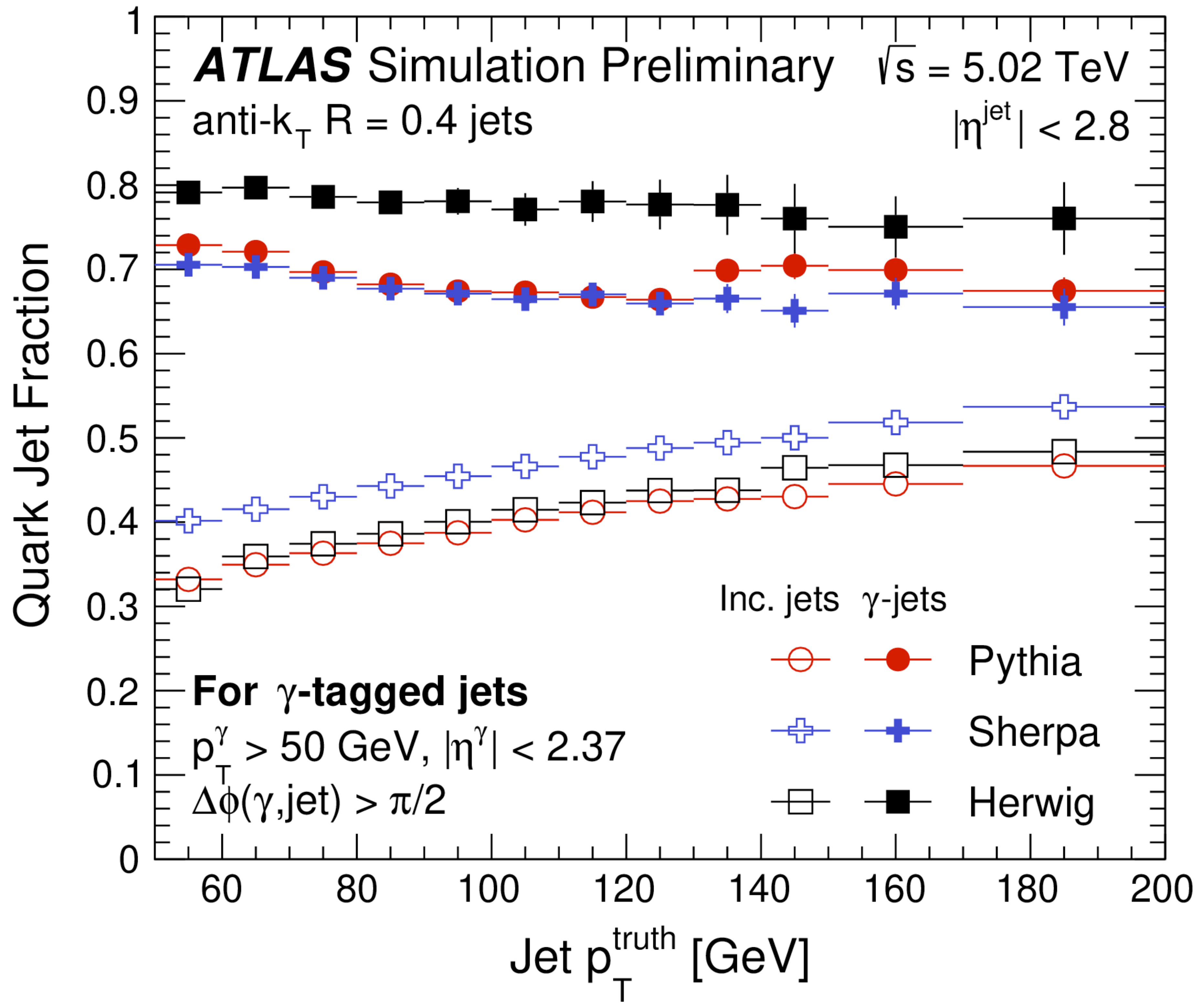
Jet suppression "fixing" the parton flavour

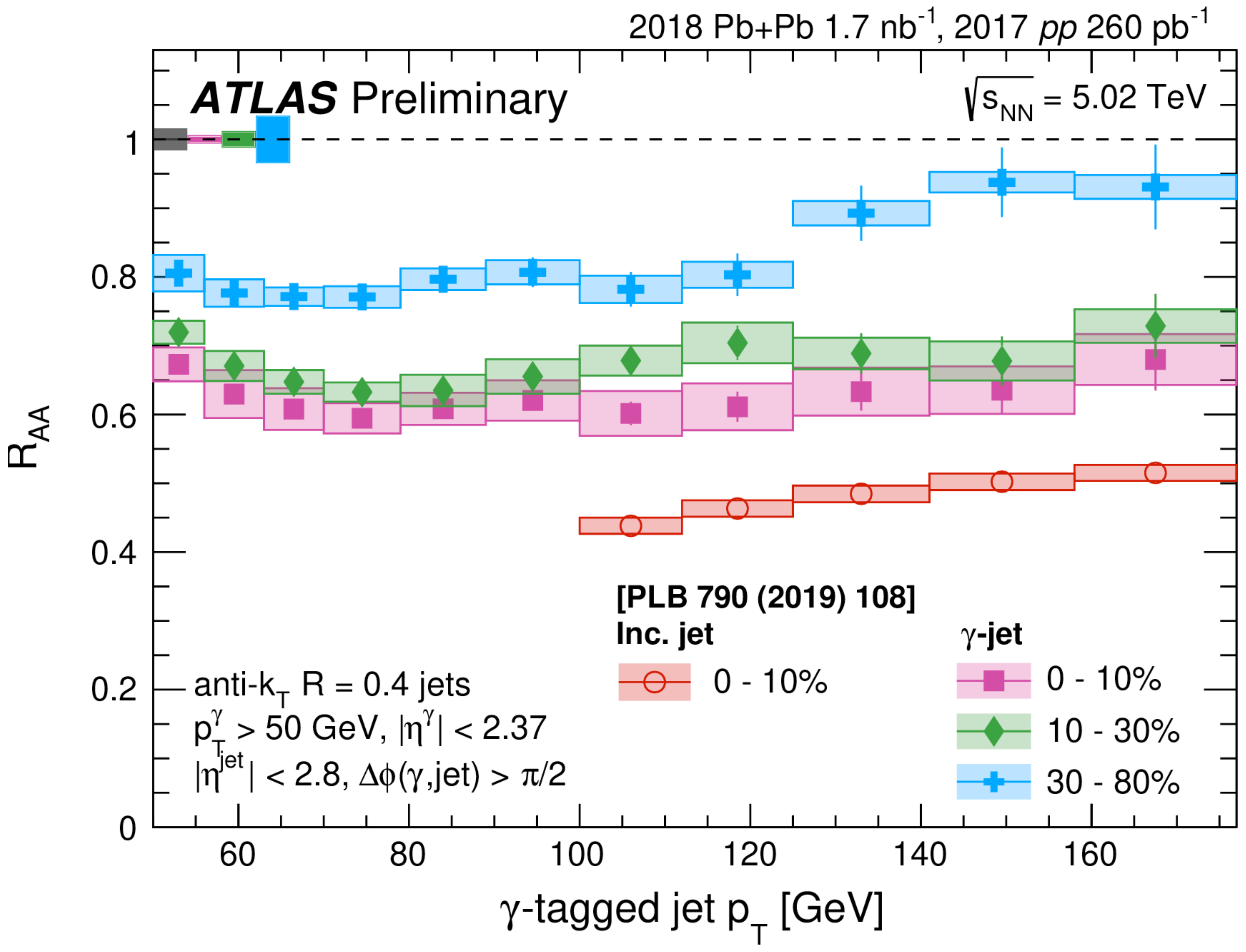


Sebatian Tapia's talk

Y.Go's poster

ATLAS-CONF-2022-019



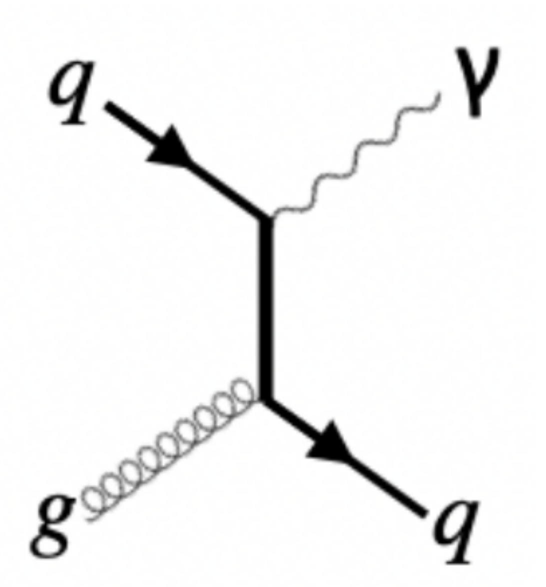


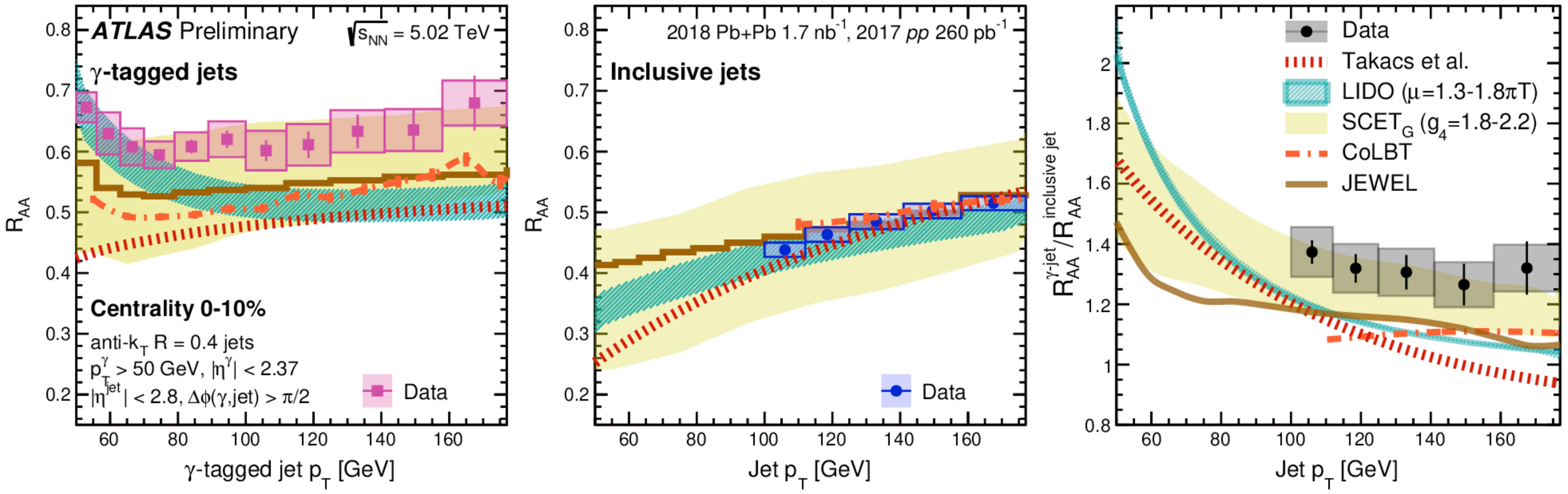
quark fraction can be enhanced up to 80% by selecting jets recoiling from a prompt photon
quark jets are less active in medium, fewer radiating prongs
Clear signature of recoil jets being significantly less suppressed than inclusive jets

[Sebatian Tapia's talk](#)

[Y.Go's poster](#)

Jet suppression "fixing" the parton flavour

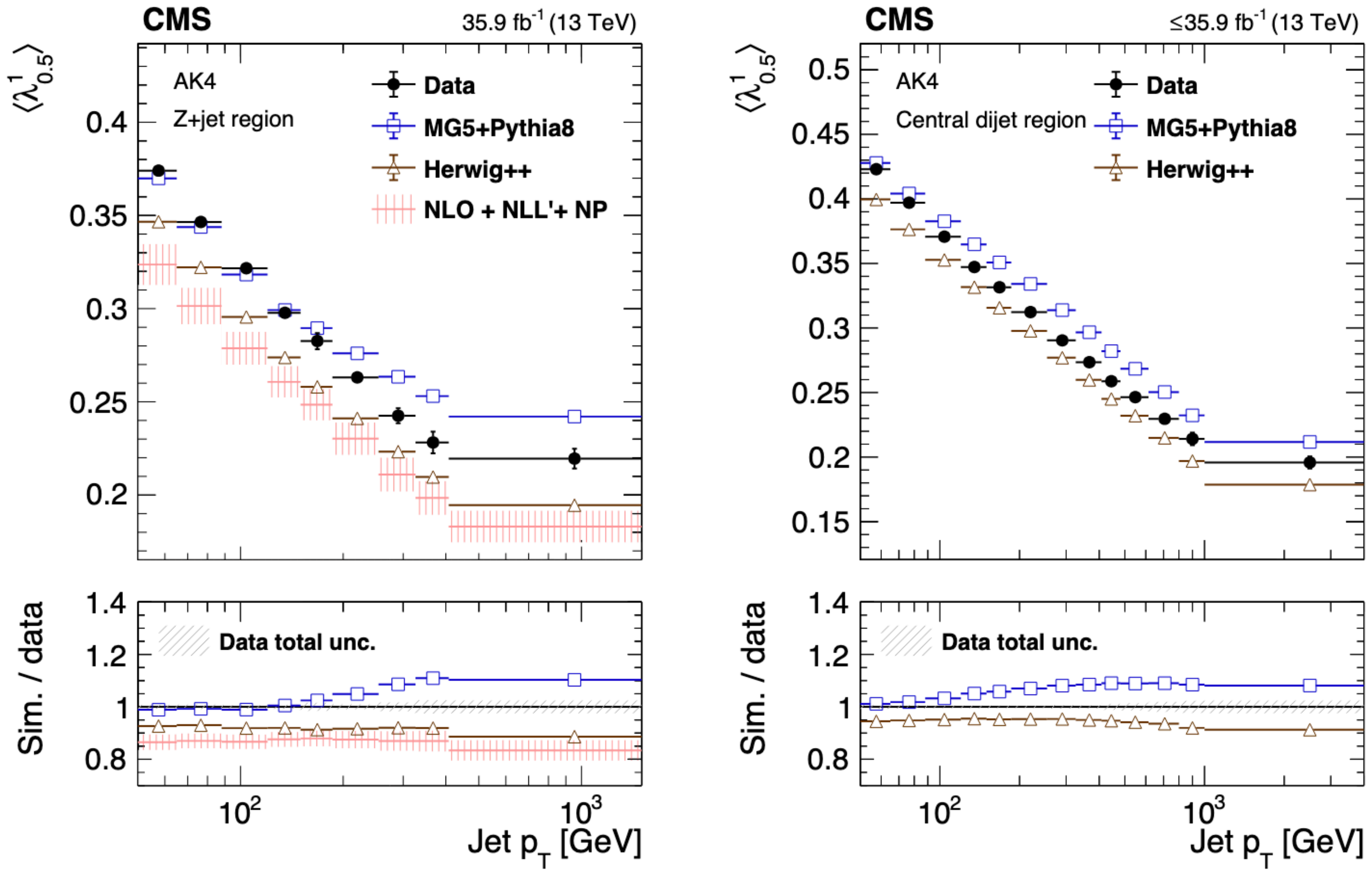




Calculations tend to understimate the γ-tagged jet R_{AA}

SCETg describes both

but note that MC calculations have a hard time describing observables in quark/gluon-enriched samples:



[CMS JHEP 01 (2022) 188](#)

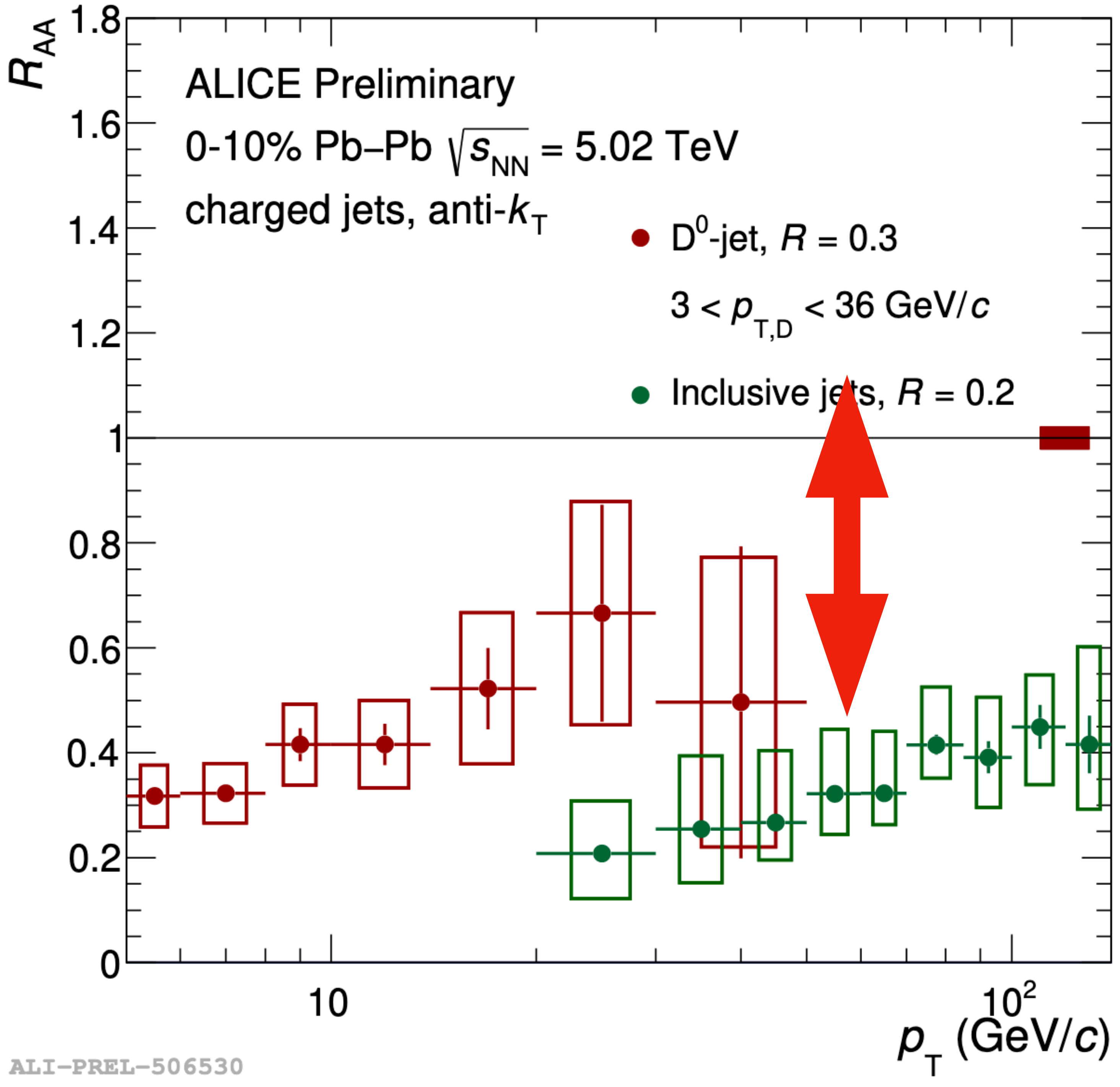
See other interesting talks on photon-tagged observables:

[Molly Taylor's talk](#)

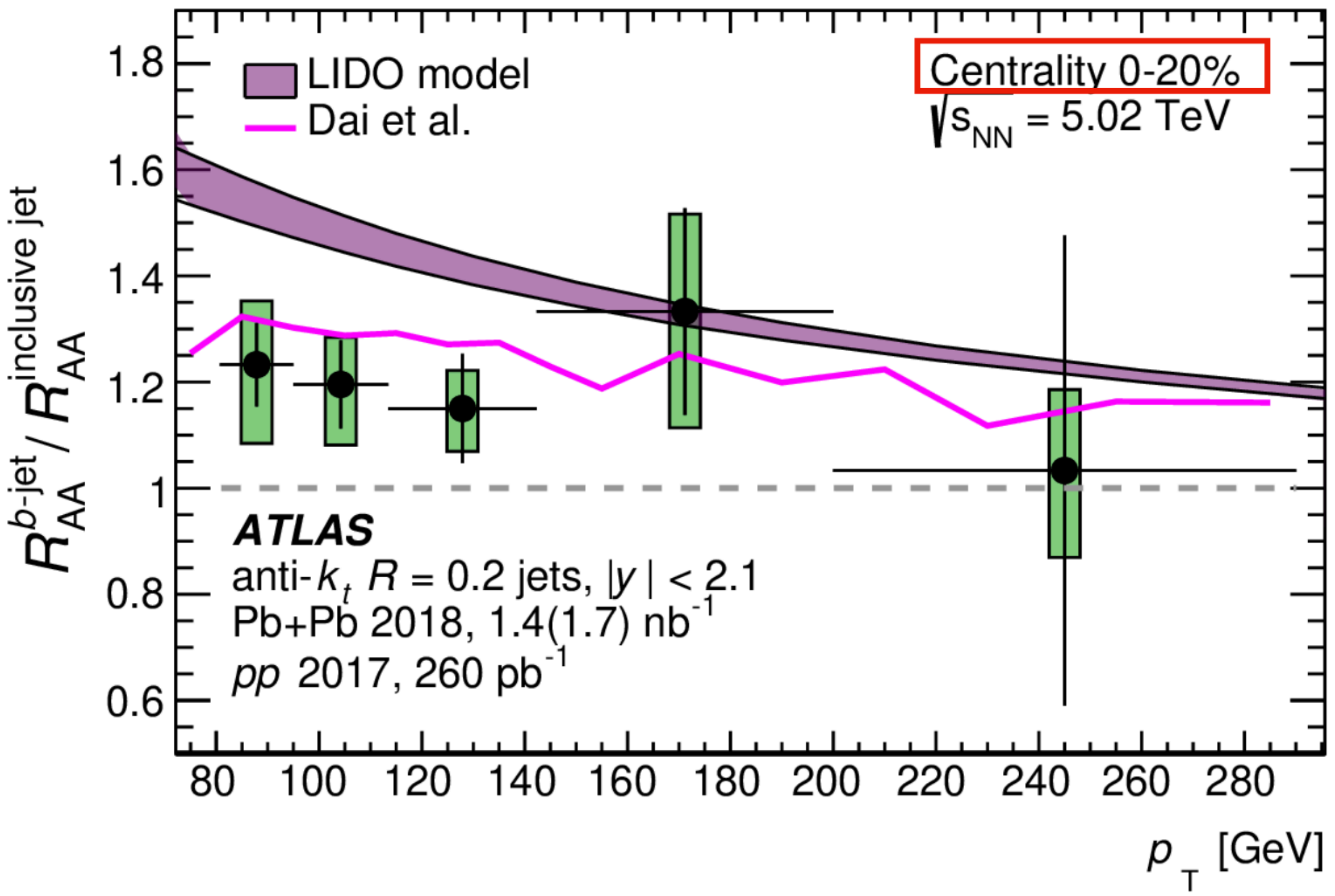
[Alwina Liu's talk](#)

“Fixing” the color charge and potential sensitivity to quark mass

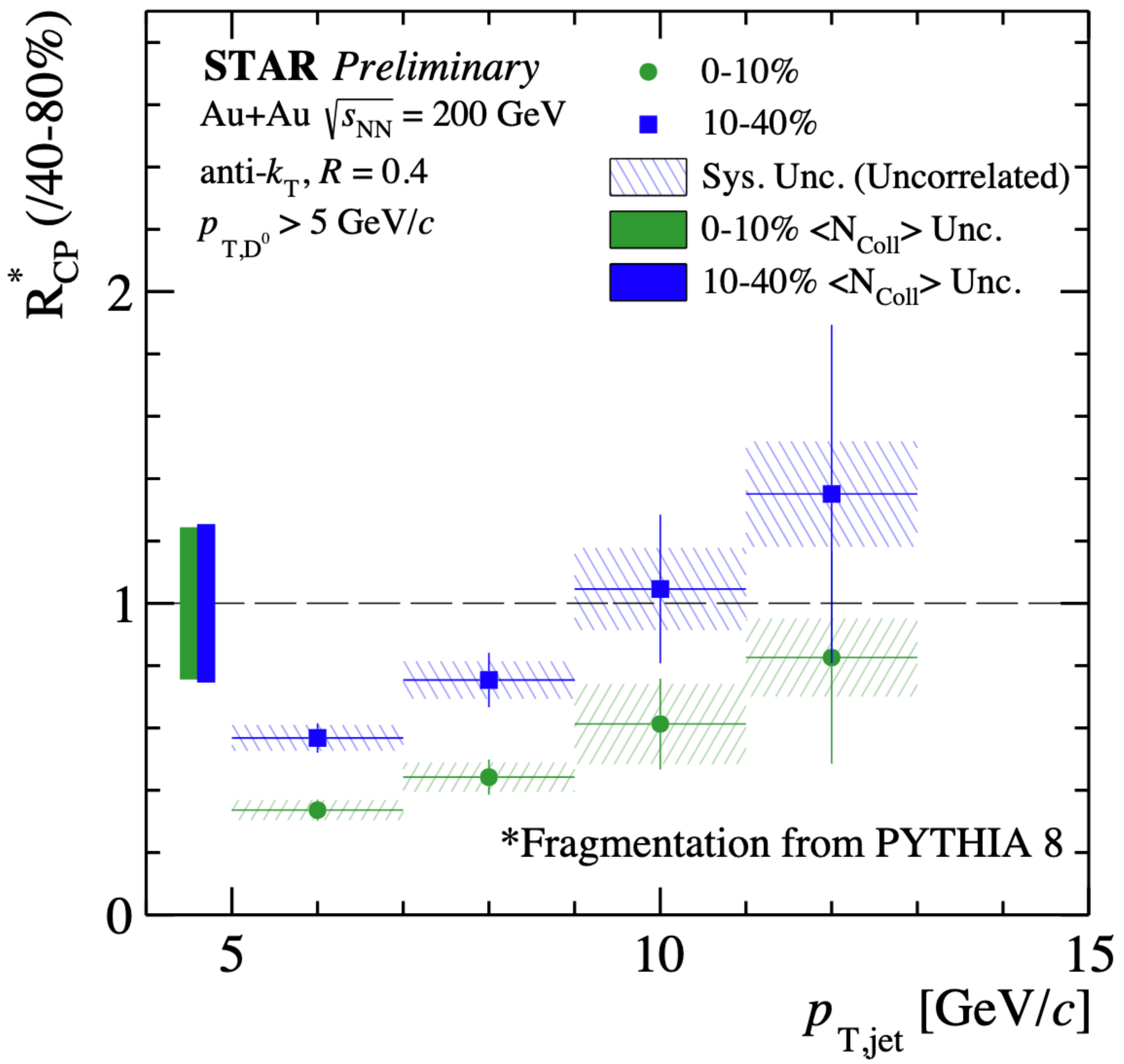
Marianna Mazzili’s talk



Sebatian Tapia’s talk



Dipantil Roy’s talk

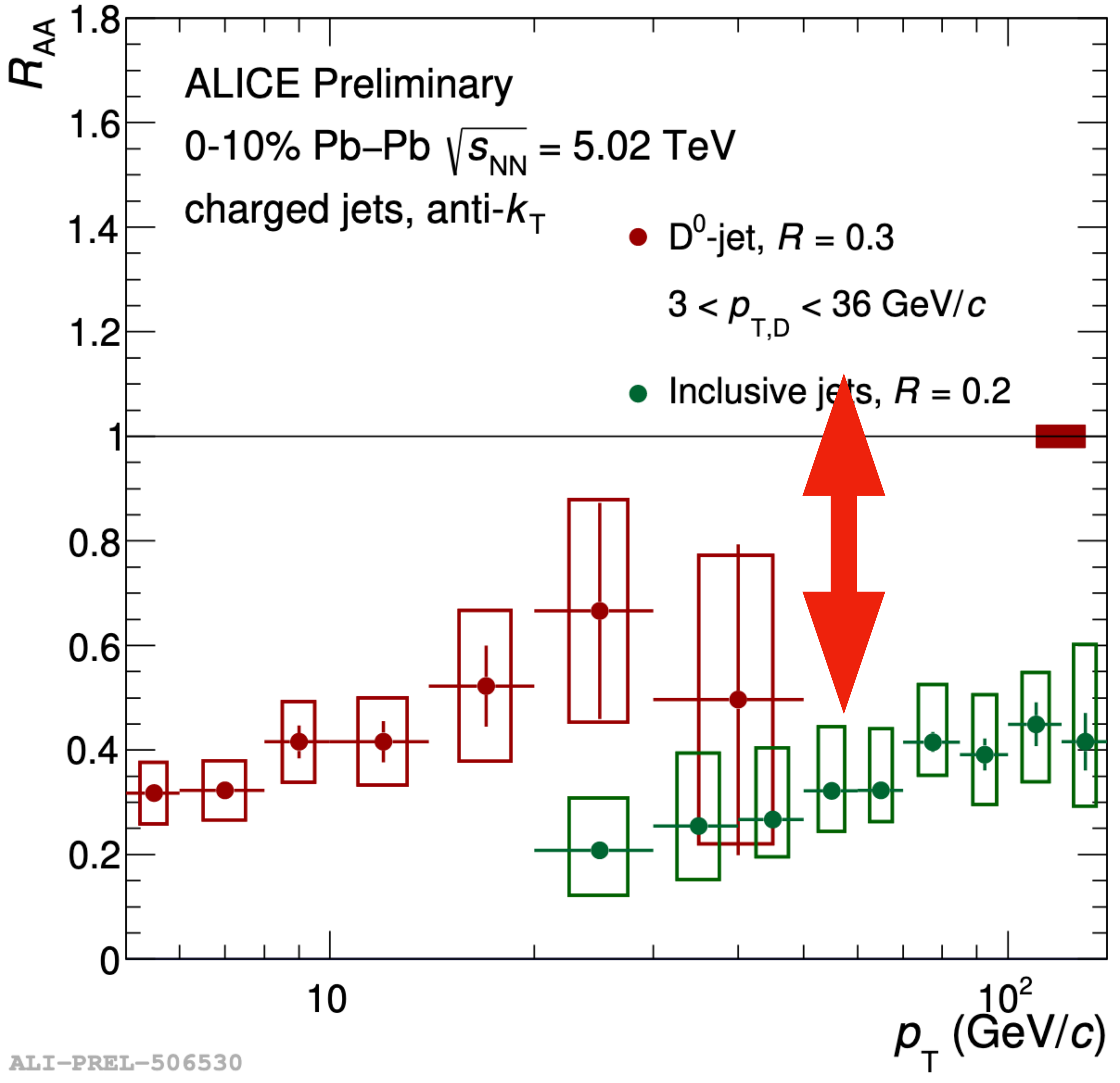


A way of fixing the parton flavour with high purity is to HF-tag at sufficiently high jet p_T

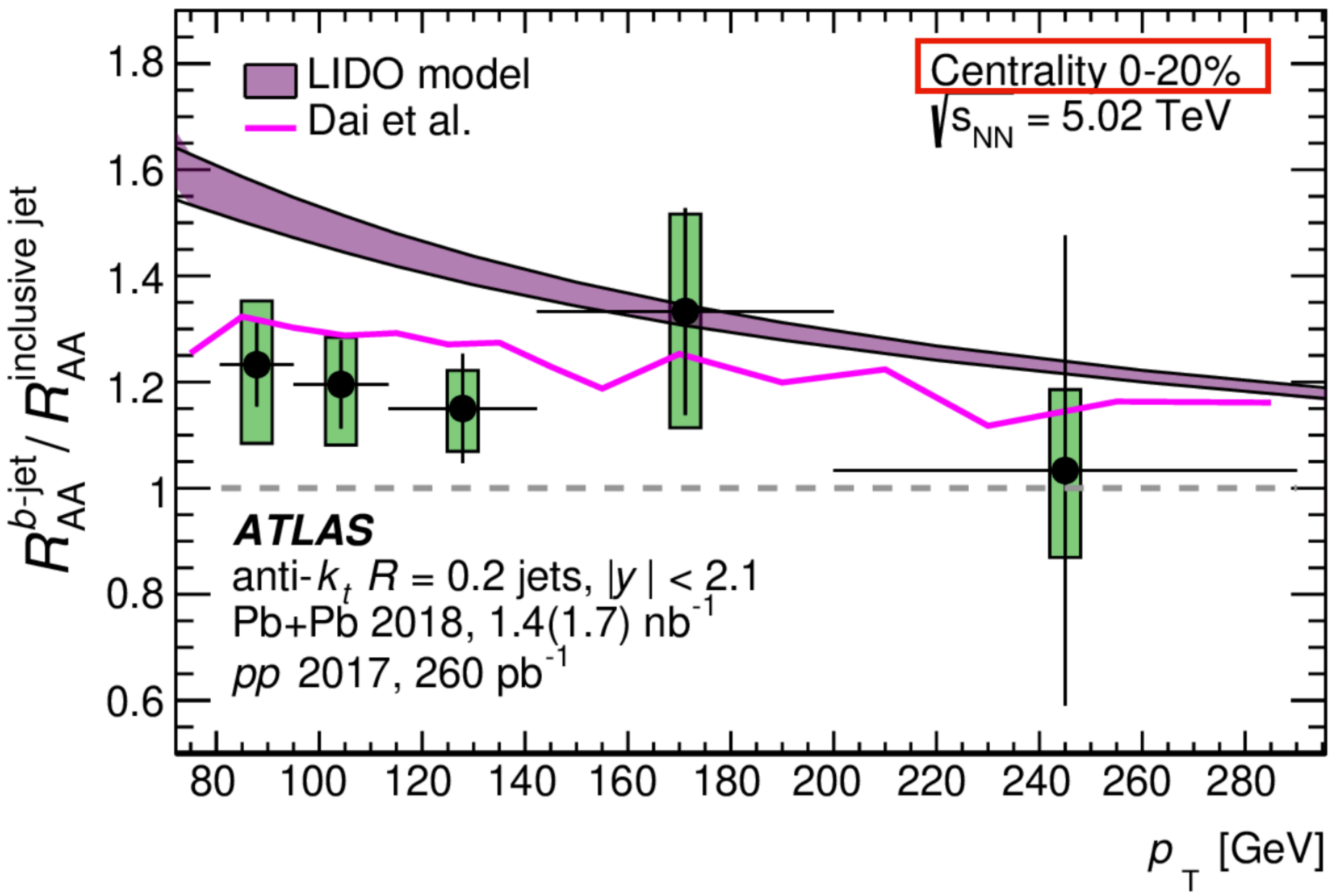
Differences between the D-jet and inclusive jets are due to **color factors** and potentially to the jet mass depending on the kinematic range and observable

“Fixing” the color charge and potential sensitivity to quark mass

Marianna Mazzili’s talk



Sebastian Tapia’s talk



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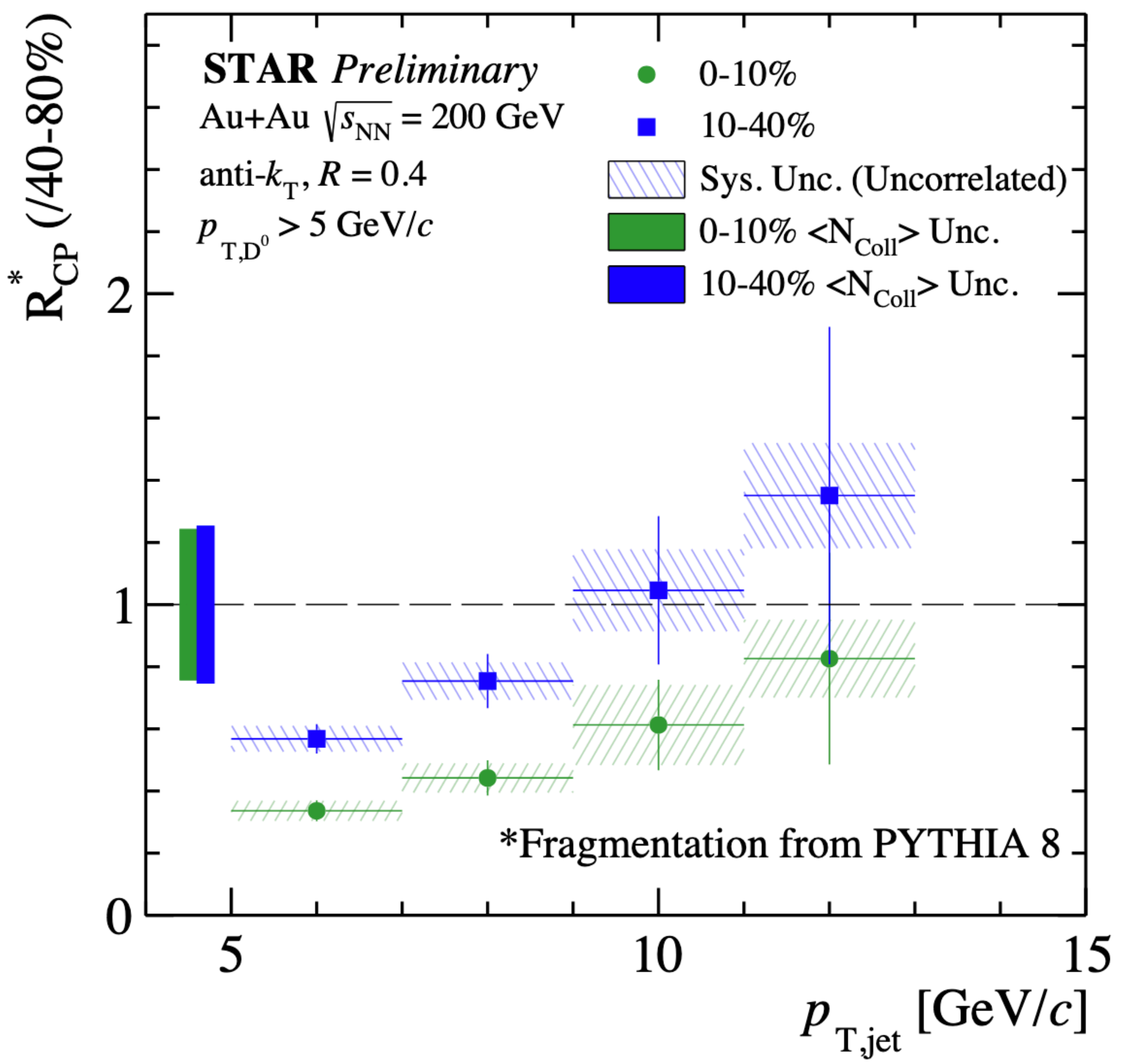
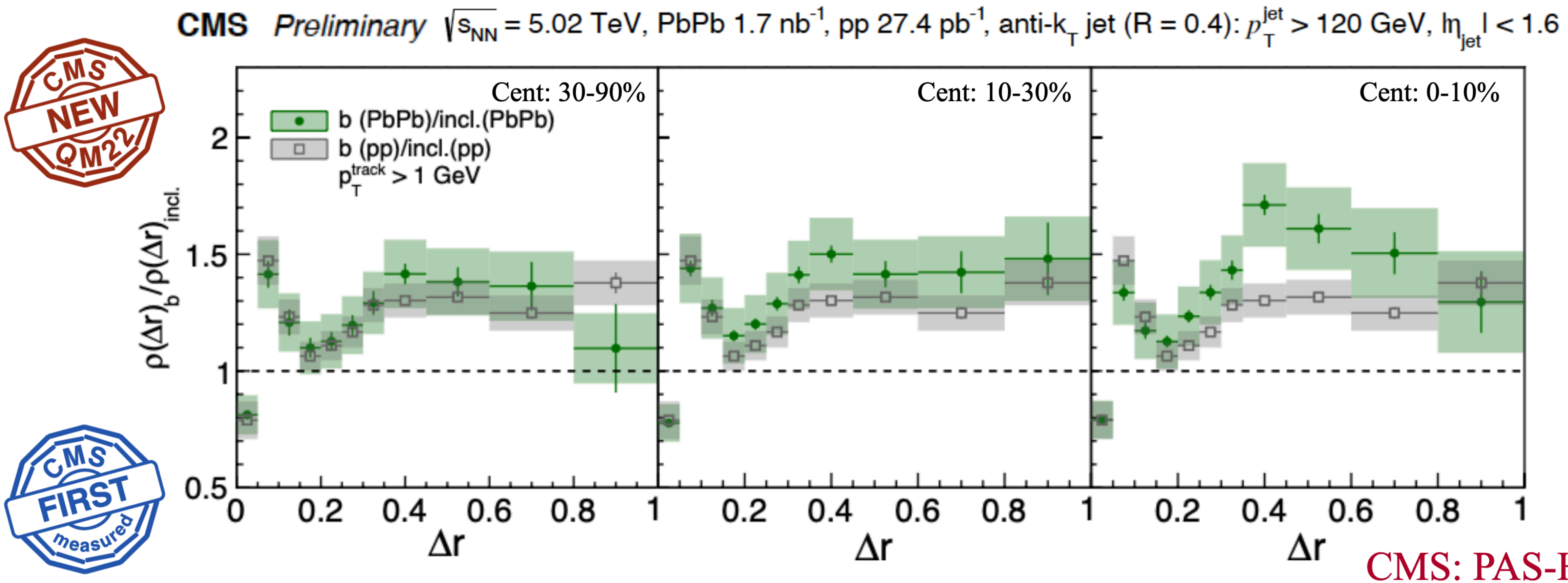


Would be interesting to study the ratio $R_{AA}^{b}/R_{AA}^{\gamma\text{-jet}}$ *to* disentangle mass from color effects, currently the two measurements are done with different *R* and different centrality

ALICE comparison between D-jets and inclusive jets potentially minimizes differences since small *R* can bias the inclusive sample towards quark jets

“Fixing” the color charge and potential sensitivity to quark mass

Xiao Wang’s talk



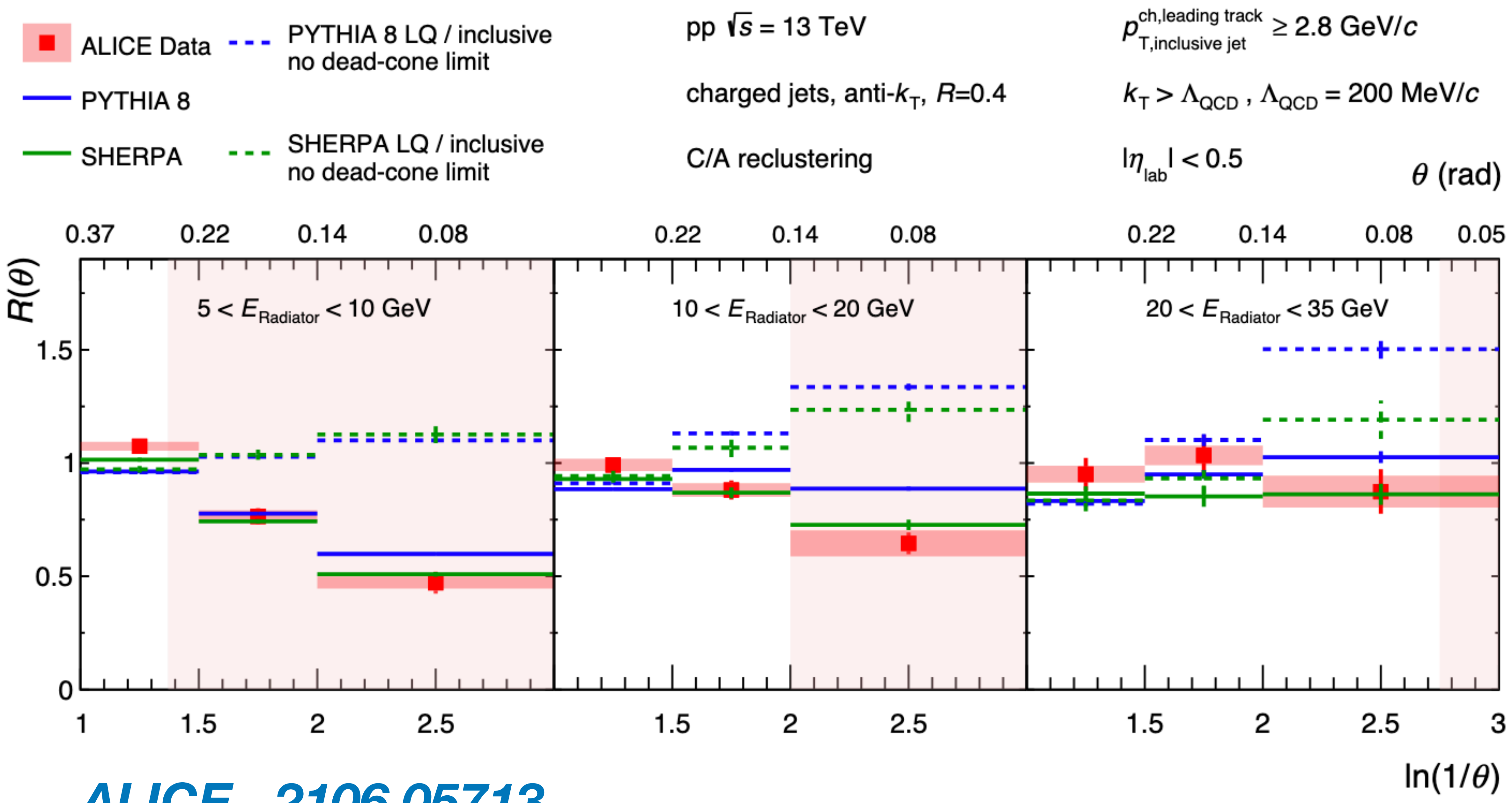
CMS: PAS-HIN-20-003

Relative differences between b-jets and inclusive jets in PbPb and pp collisions appear to be fairly consistent

Differences between the b-jet and inclusive jets are due to color factors and potentially to the jet mass

Single out mass effects and expose the dead cone

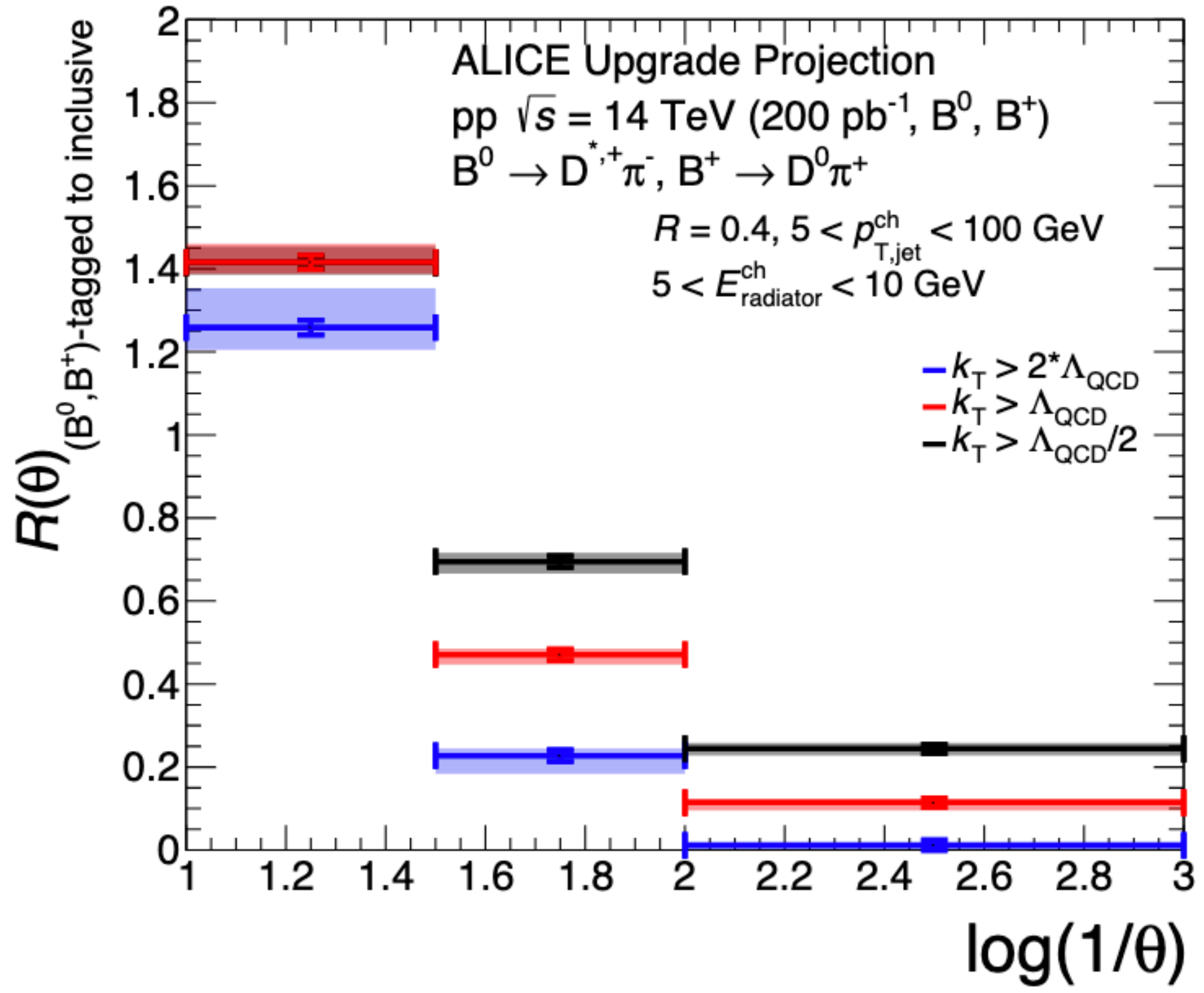
1.Reconstruct a proxy for the jet shower using declustering
Penetrate the jet tree down to the smallest splitting angles
Introduce k_T cuts to suppress hadronisation effects that obscure the dead cone



ALICE, [2106.05713]

$E_{radiator}$ is a proxy for the energy of the c quark at the given splitting
Pink areas define the expected vetoed region: m_c/E_c

B/D jet splitting angle

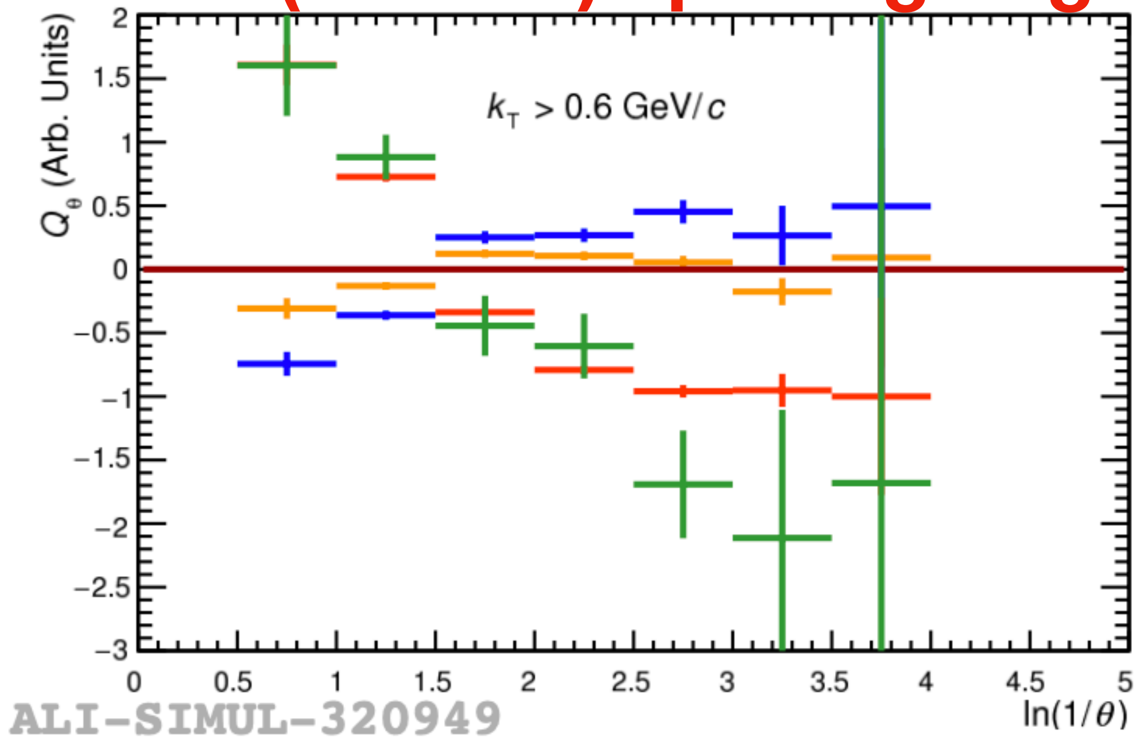


2. Ideally, full reconstruction of the heavy hadron

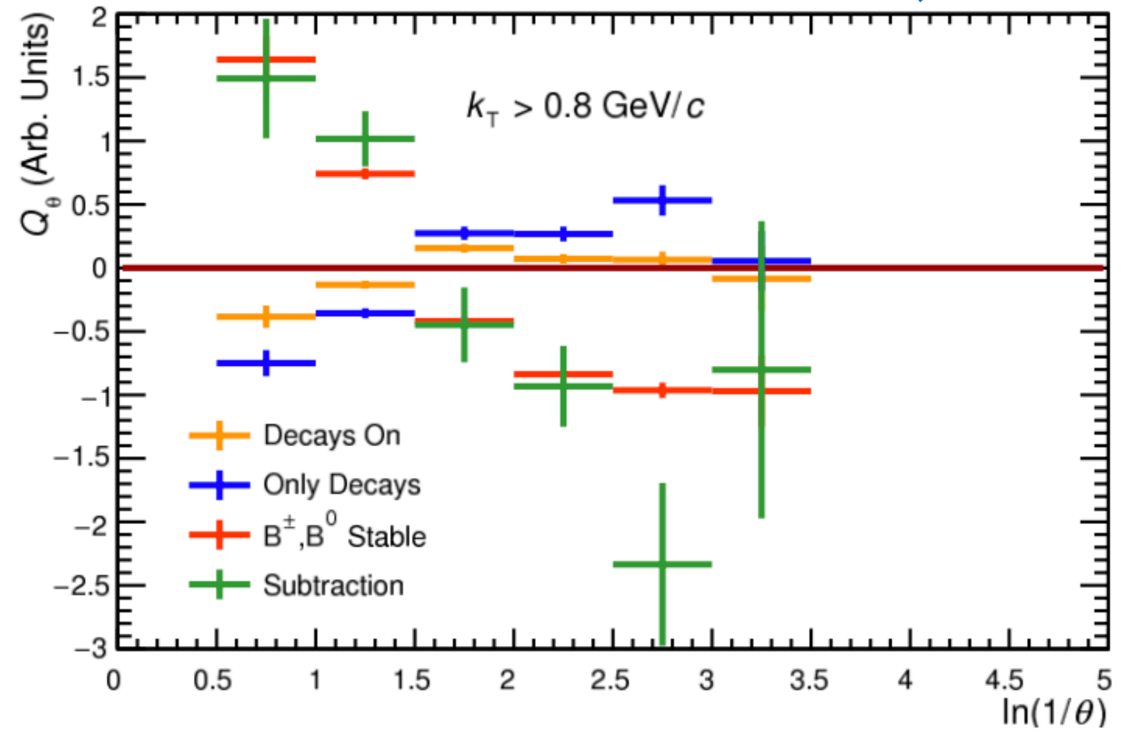
3. If b/c tagged, decays create extra splittings at small angles that fill the dead cone

4. HI bkg will not be a big deal at very small angles

B/D (relative) splitting angle



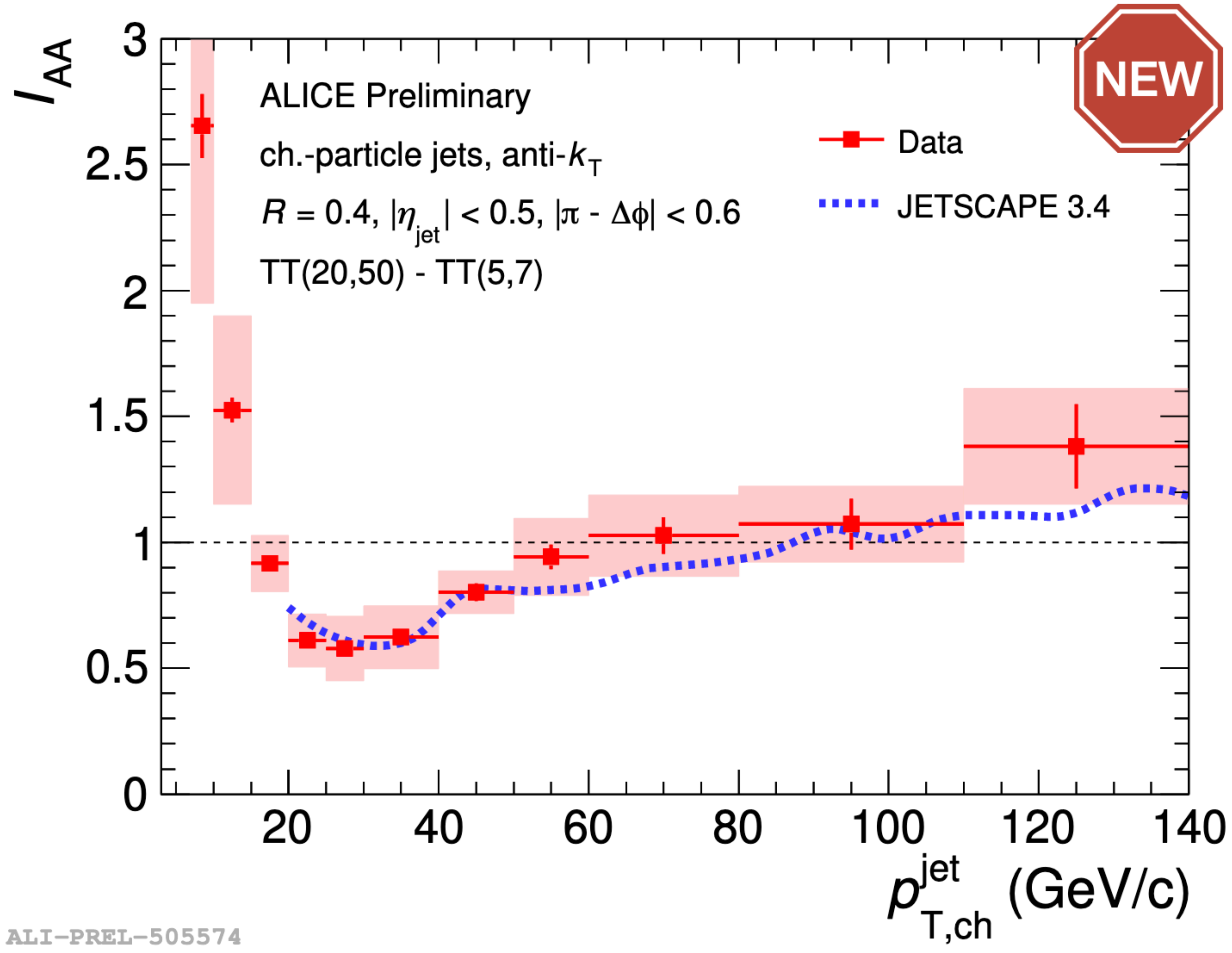
Katharina Garner sQM19



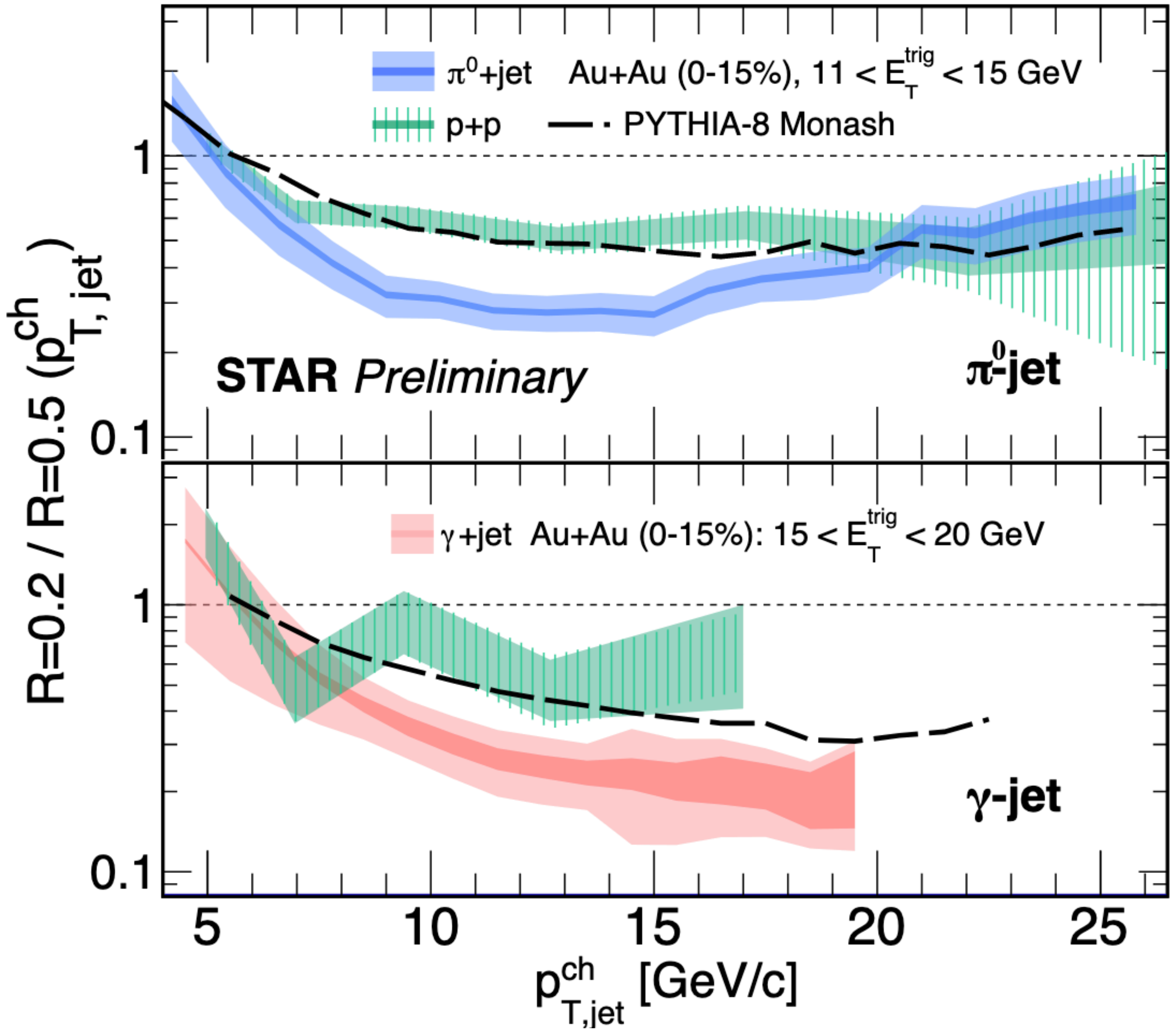
B stable, suppression
B decays, extra splittings at small angles

Coincidence measurements down to very low jet p_T

Rey Cruz-Torre's talk



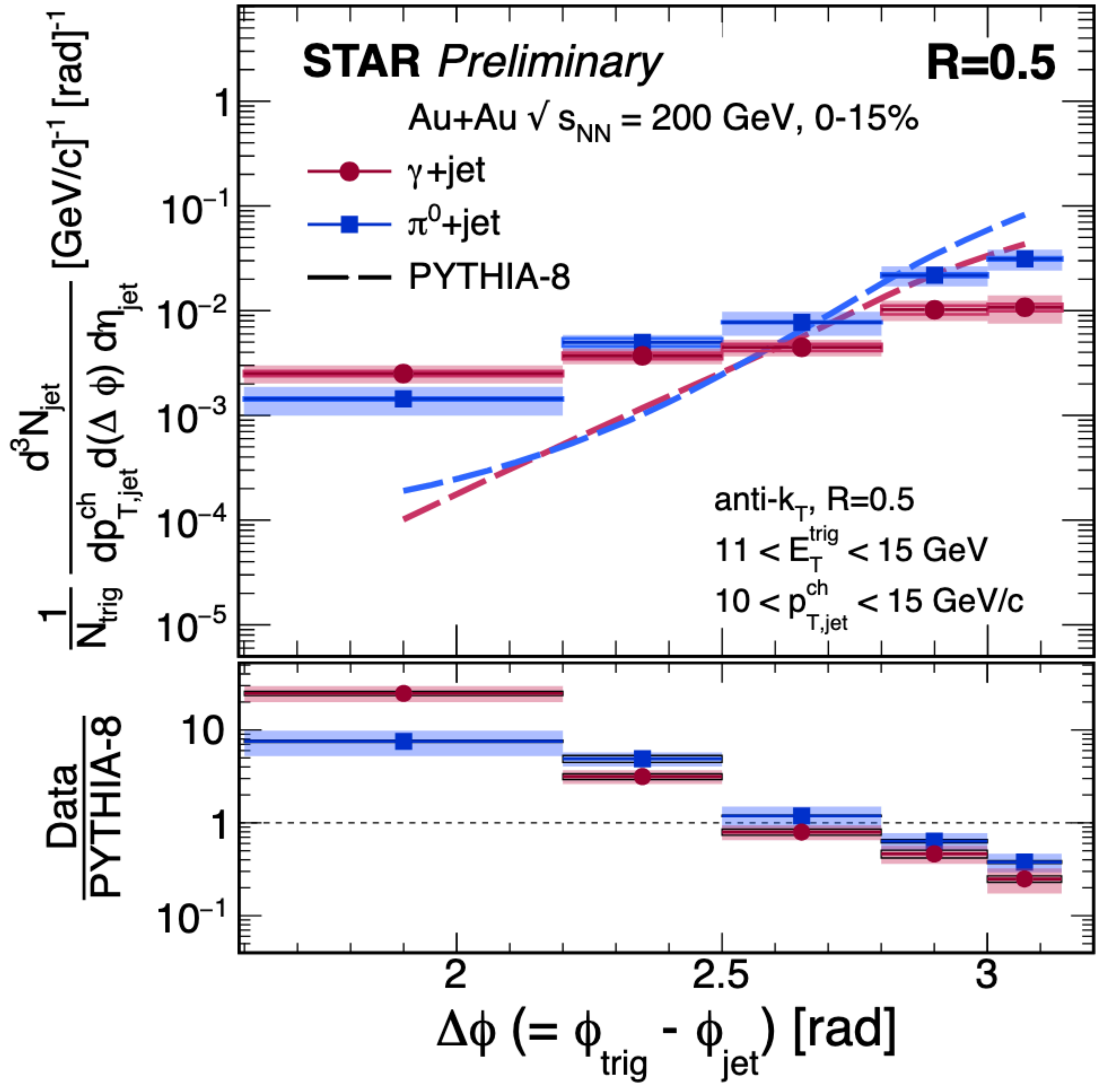
Derek Anderson's talk



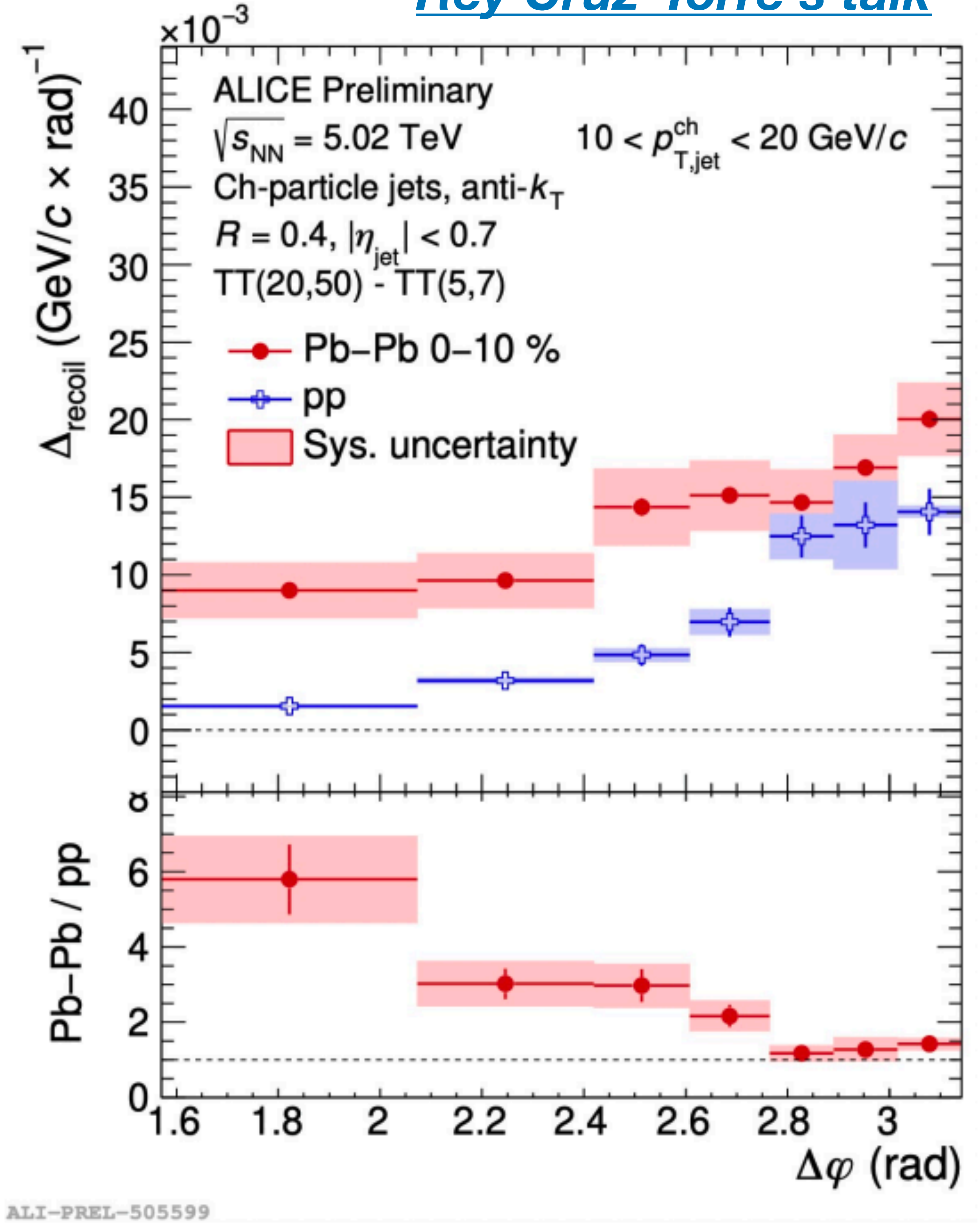
ALICE: Increase of correlated yield of very soft structures ($p_{T,jet}$<20 GeV, R=0.4)
STAR: clear signature of intrajet broadening for similarly soft structures

Coincidence measurements down to very low jet p_T

Derek Anderson's talk
Nihar Sahoo's poster



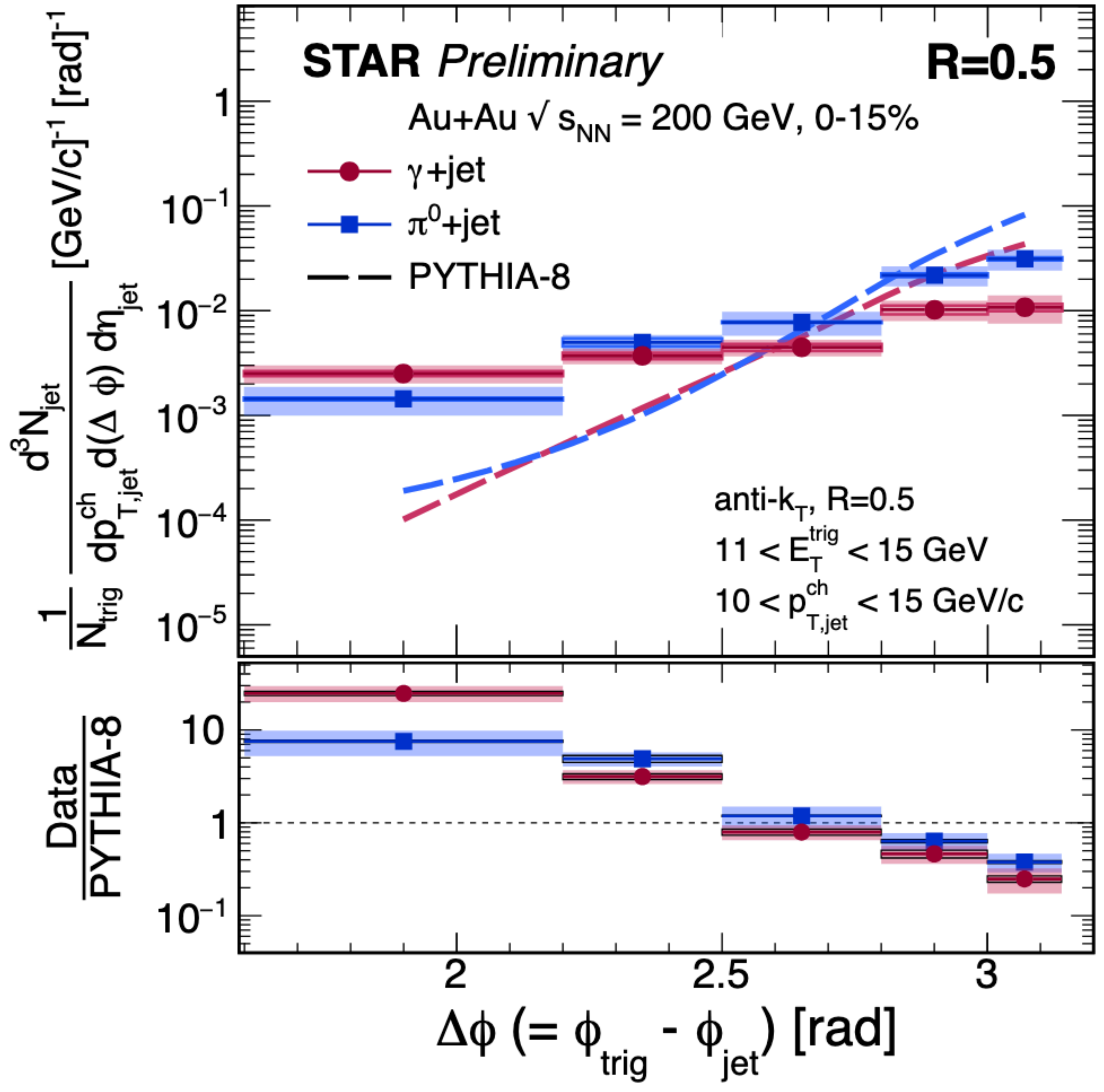
Rey Cruz-Torre's talk



Same statistical technique for uncorrelated jet bkg subtraction
First signature of azimuthal decorrelation of very soft jets!

Coincidence measurements down to very low jet p_T

[Derek Anderson's talk](#)
[Nihar Sahoo's](#)



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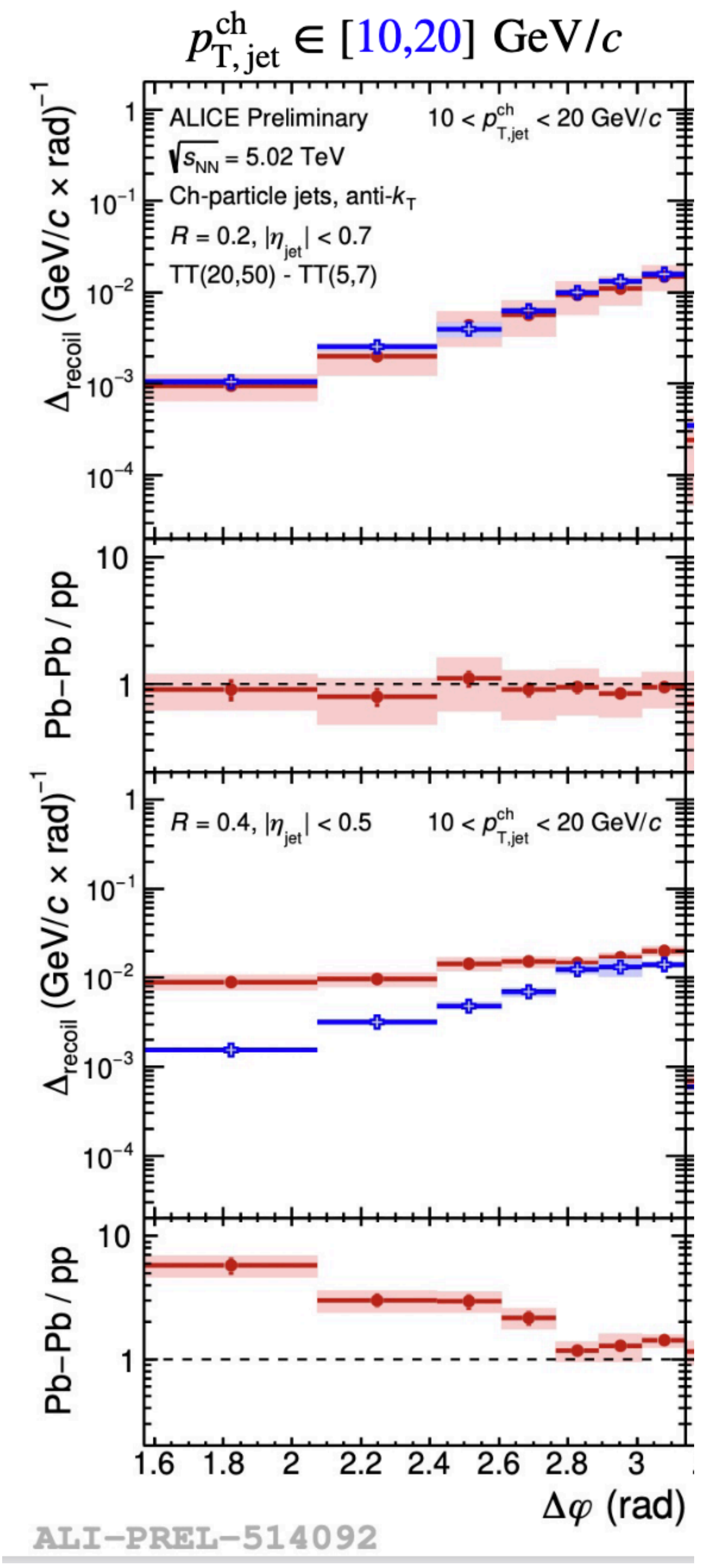
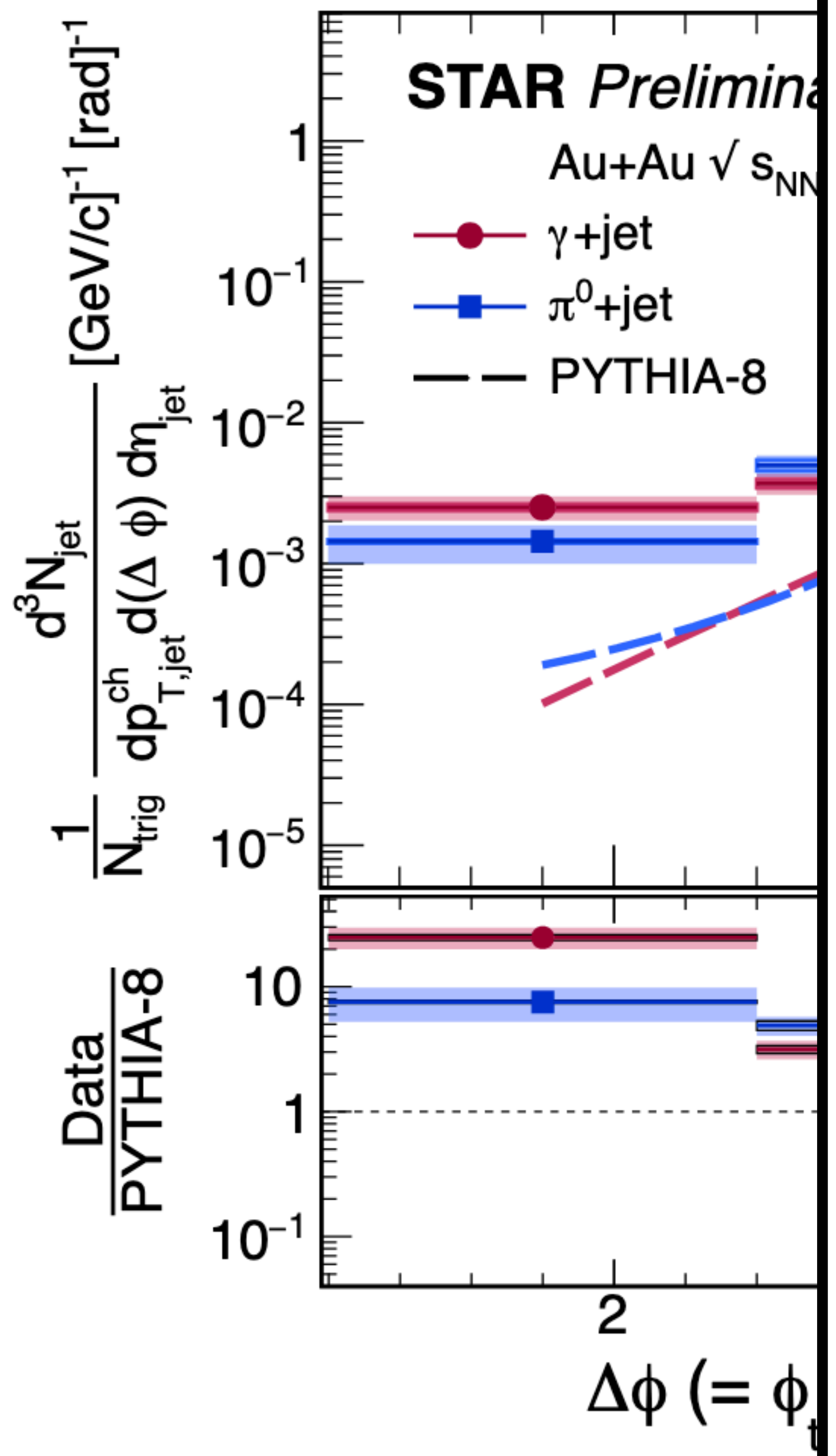
[Rey Cruz-Torre's talk](#)

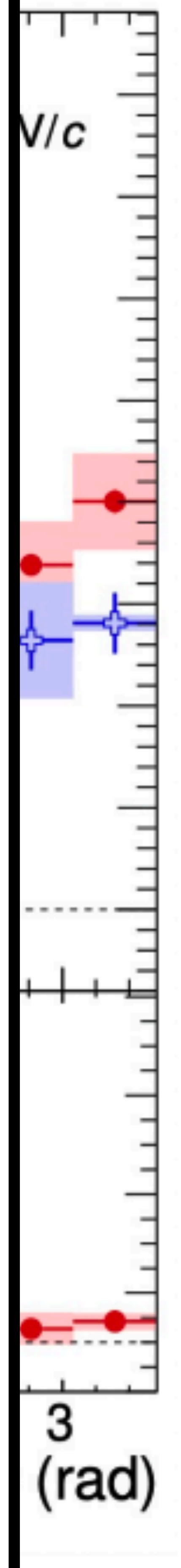


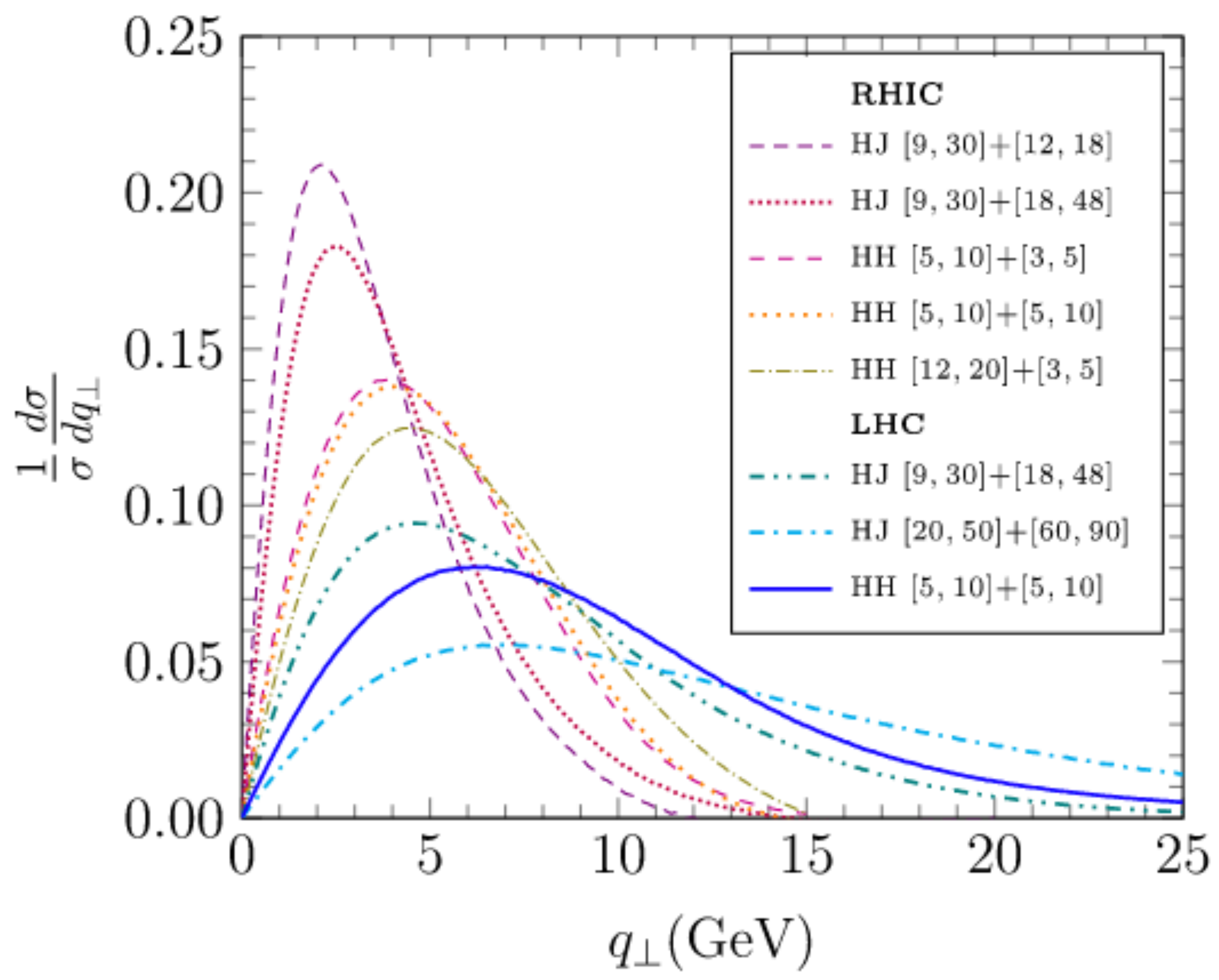
crucial to understand the R dependence

jet R

Inter jet correlations down to very low jet p_T







The broadening in high Q^2 processes is dominated by vacuum (Sudakov) radiation, so naturally low-Q^2 processes are better at exposing medium-induced broadening

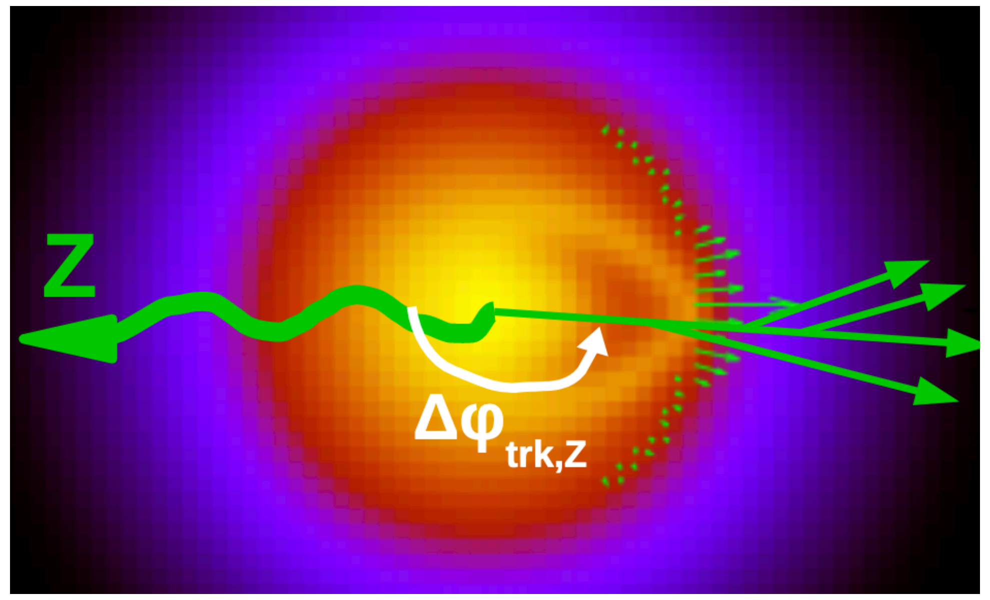
L.Chen et al, Phys.Lett.B 773 (2017)

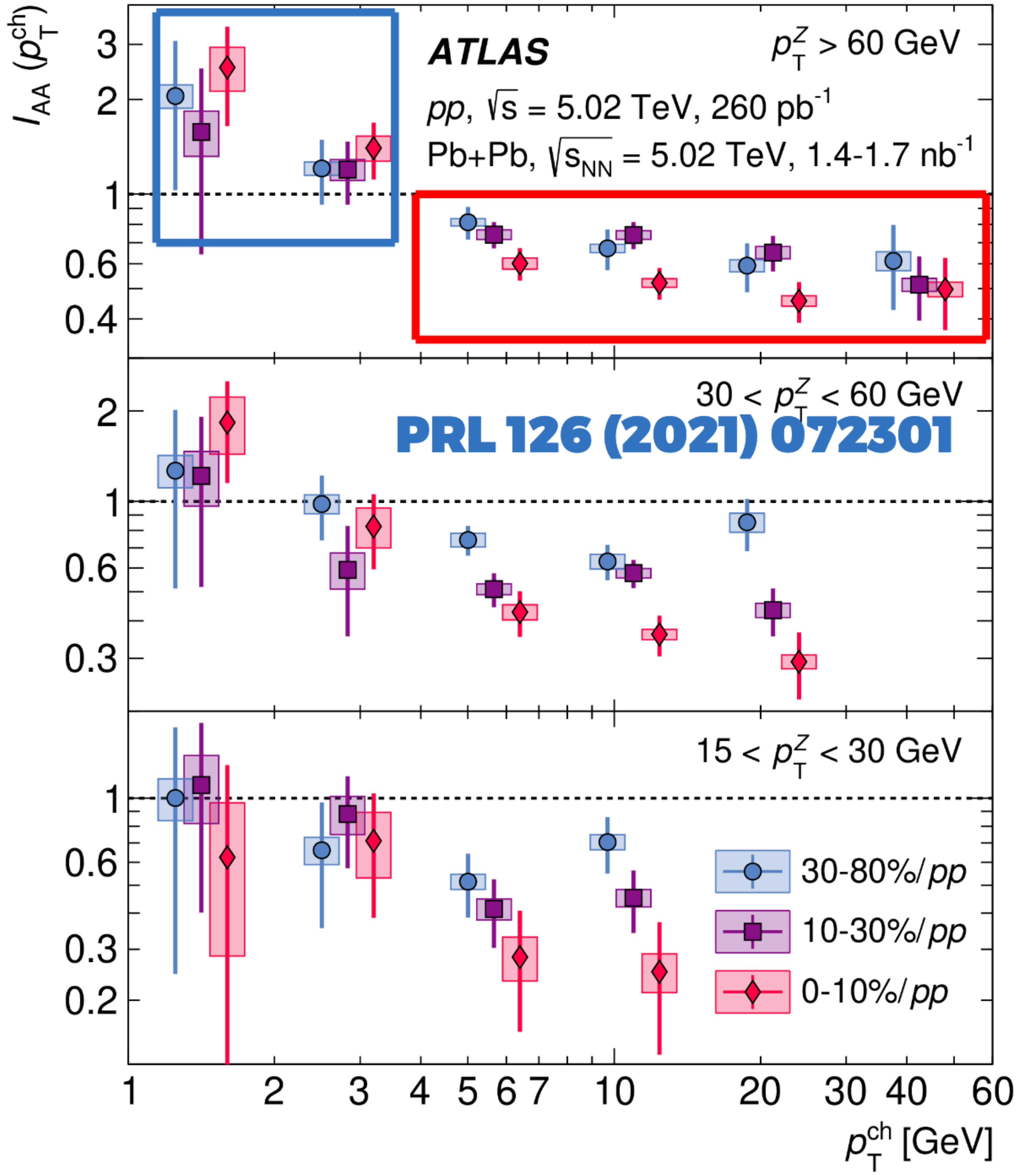
First signature of azimuthal decorrelation of very soft jets

Coincidence measurements without recoil jet

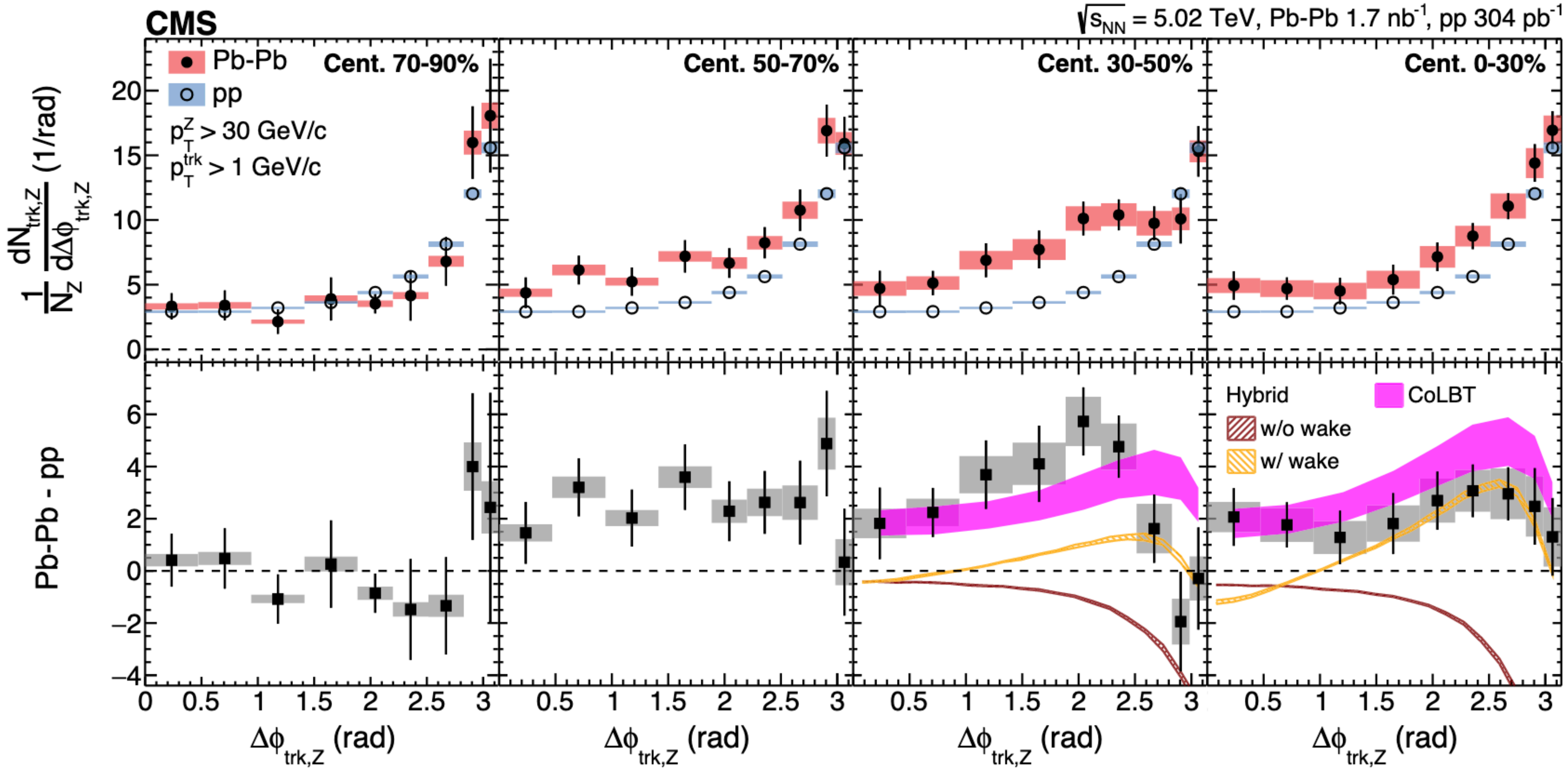
$$I_{AA} = \frac{\text{Particles per Z in Pb+Pb}}{\text{Particles per Z in p+p}}$$

Christopher McGin's talk





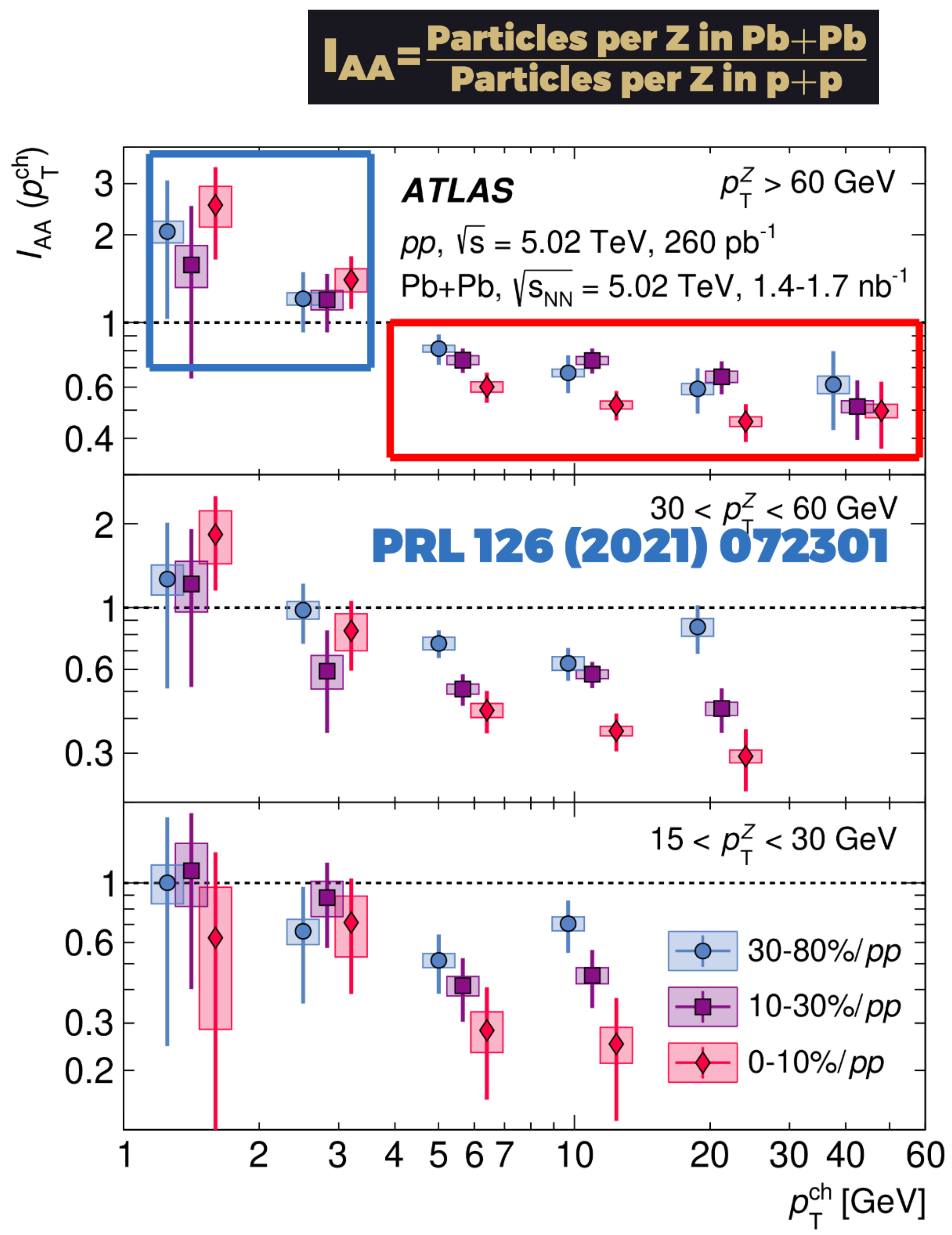
Kaya Tatar's talk



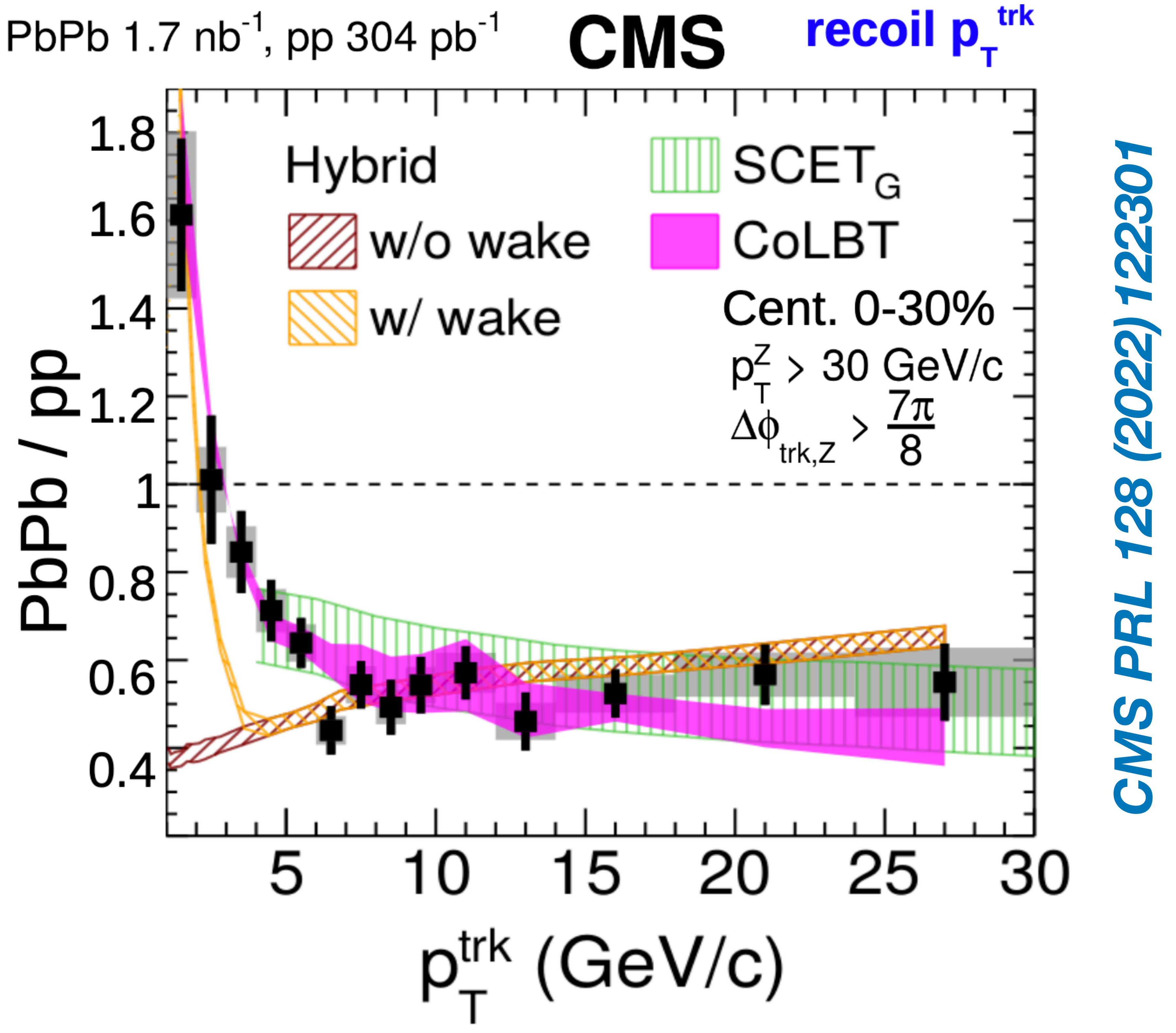
Modification of the particle spectra in the recoil region:

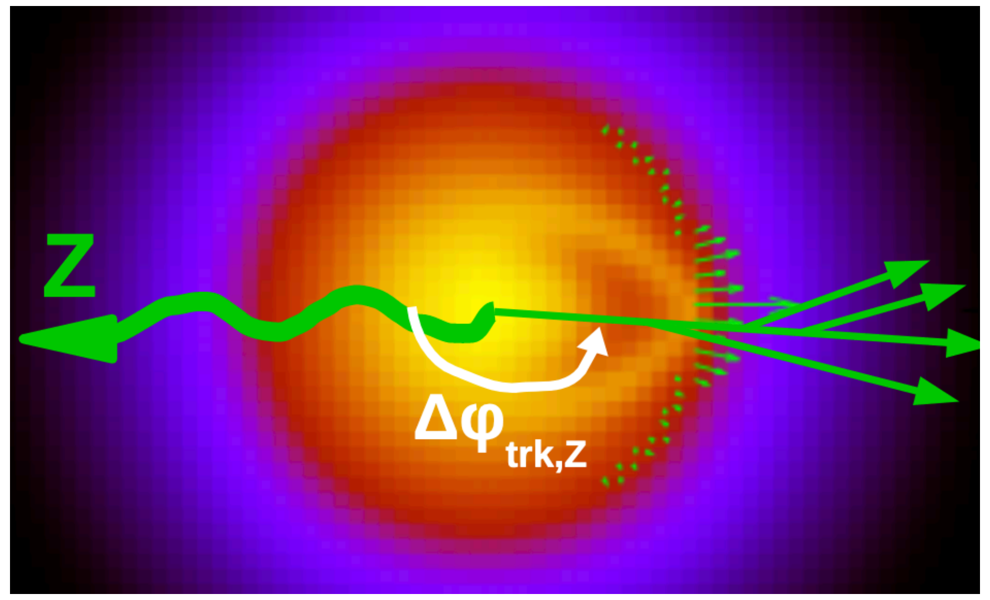
- excess of low-p_T particles
- suppression of high-p_T particles

Coincidence measurements without recoil jet



Kaya Tatar's talk



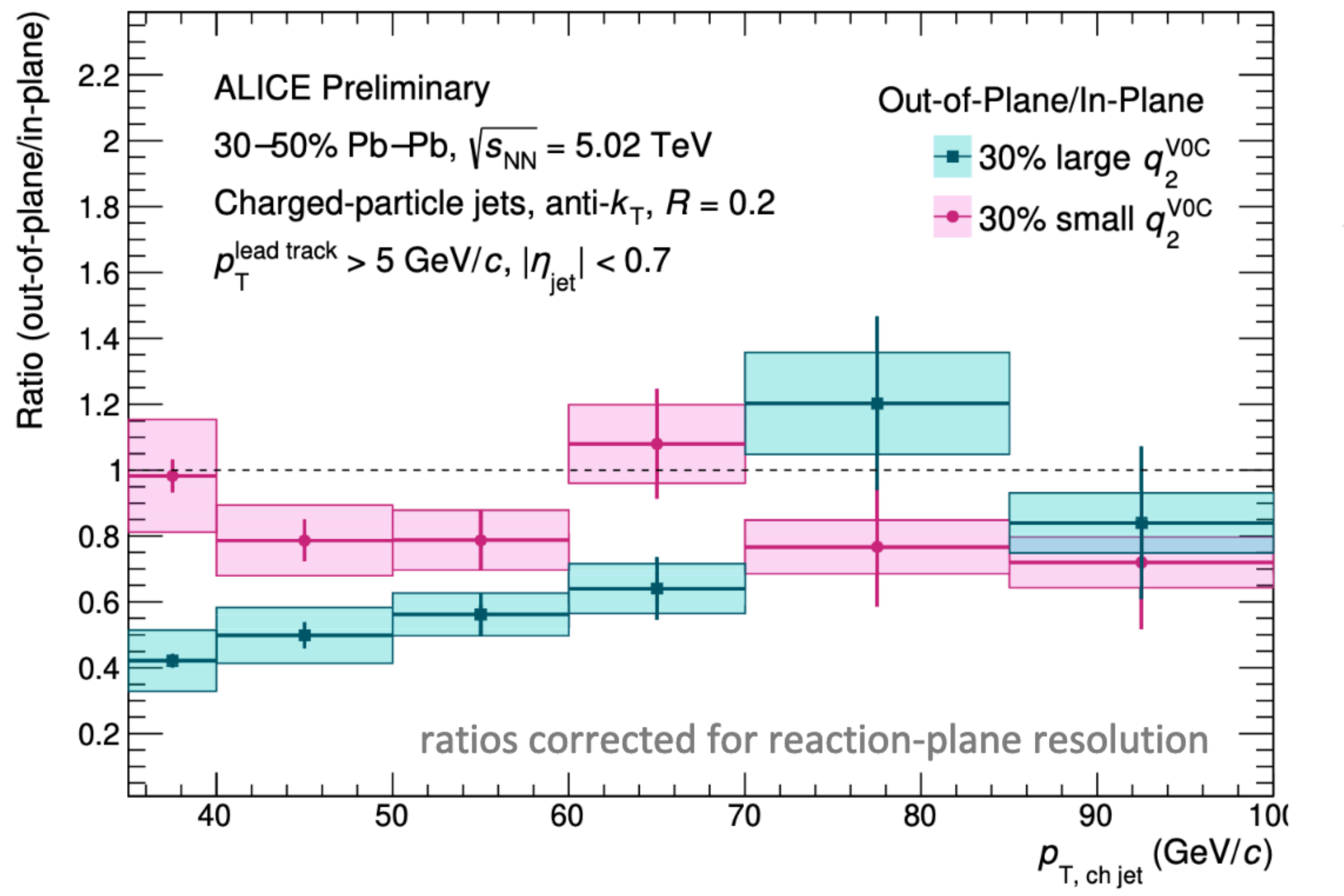


Modification of the particle spectra in the recoil region:
- excess of low-p_T particles
- suppression of high-p_T particles

Three different approaches:
- SCETG: no medium response
- CoLBT: quenched jet energy feeds into hydro evolution
- Hybrid: wake effect

The geometry: fixing the event shape

Caitlin Beattie's talk



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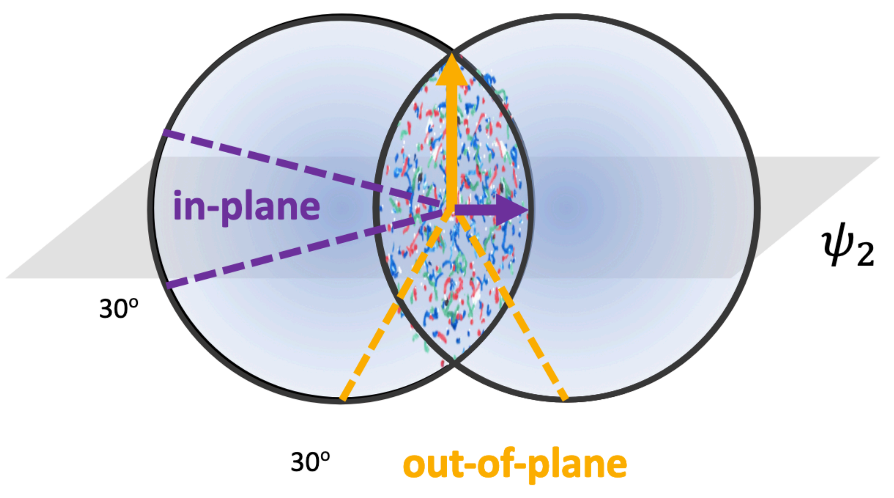
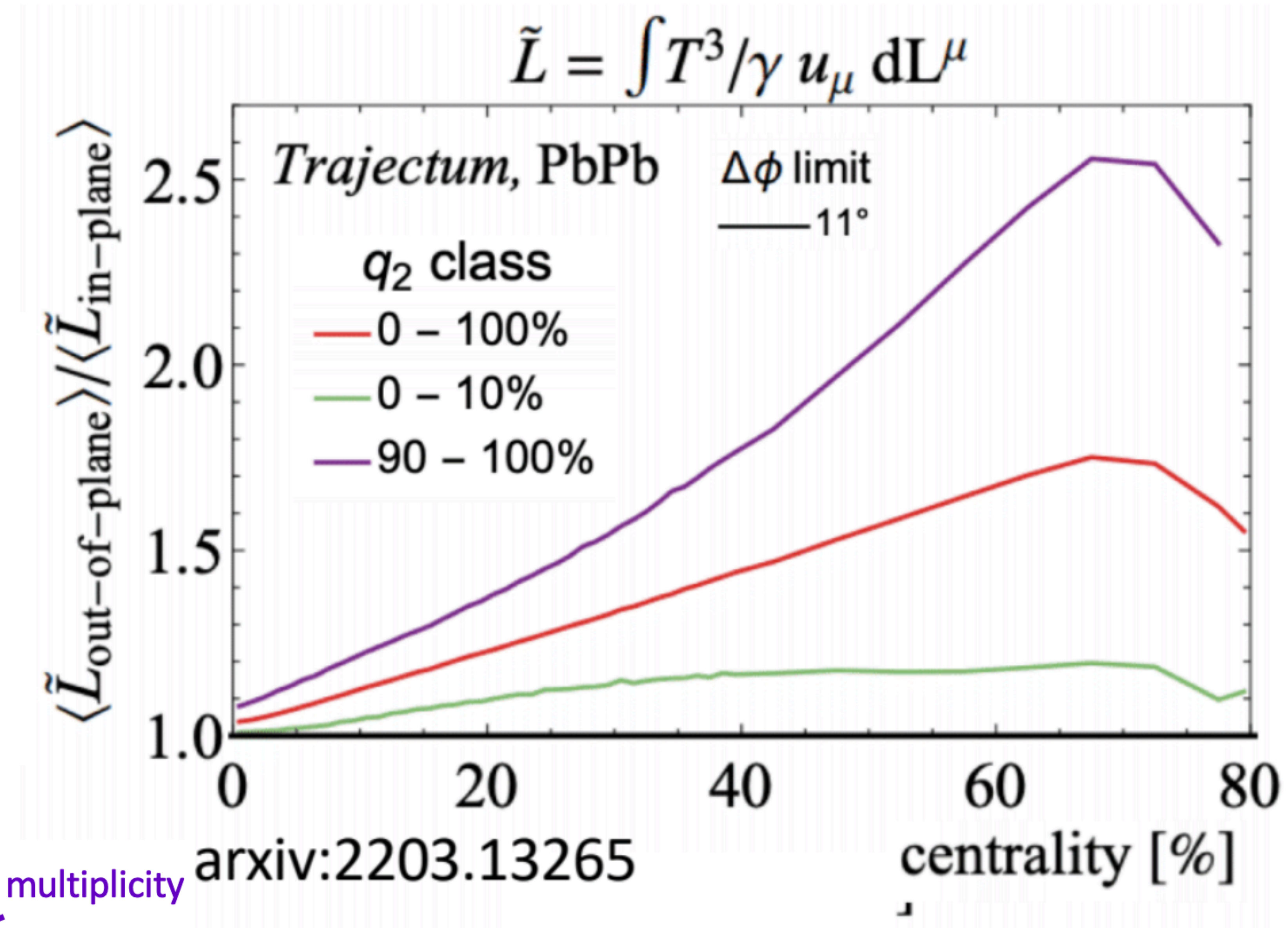


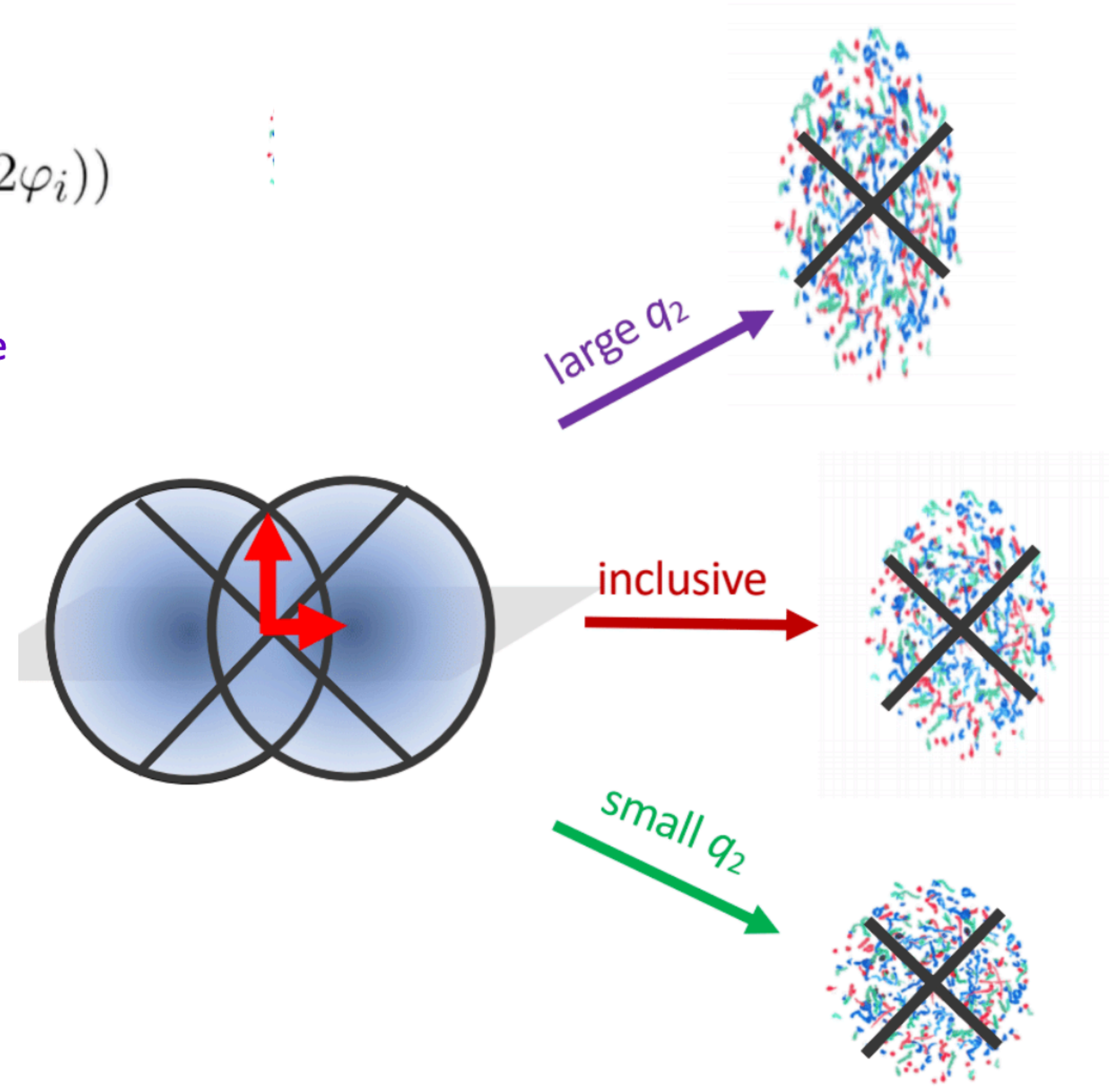


M = multiplicity

$$q_2 = |\mathbf{Q}_2|/\sqrt{M}$$

$$\mathbf{Q}_2 = \left(\sum_{i=1}^{M} \cos(2\varphi_i), \sum_{i=1}^{M} \sin(2\varphi_i)\right)$$

φ_i = azimuthal angle of i[th] particle

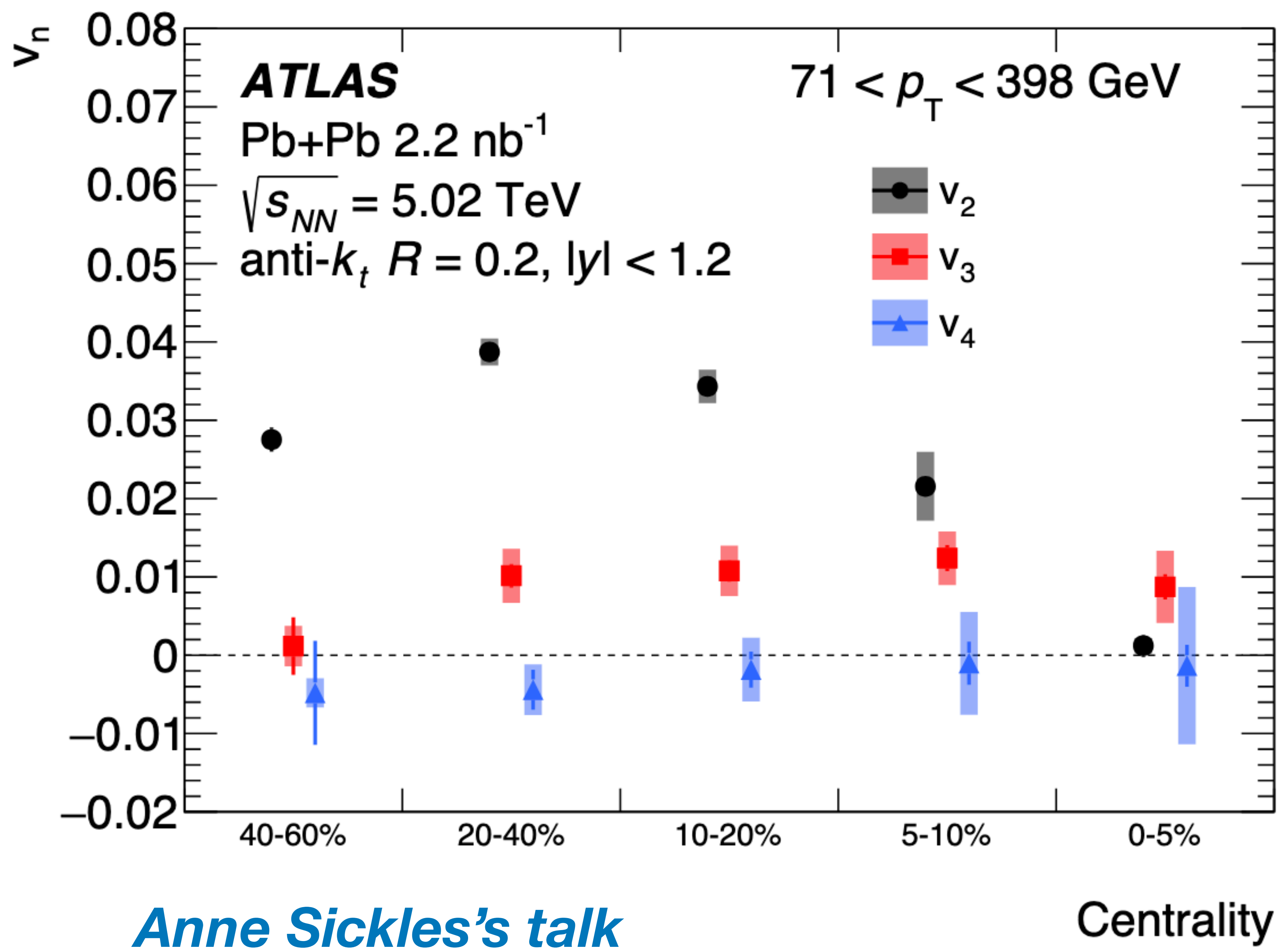


Selecting specific event shapes allows to maximize in plane and out of plane path length differences

Largest q_2 selects more suppressed ratio of jet yields, consistent with stronger suppression out-of-plane

The geometry: sensitivity to path length

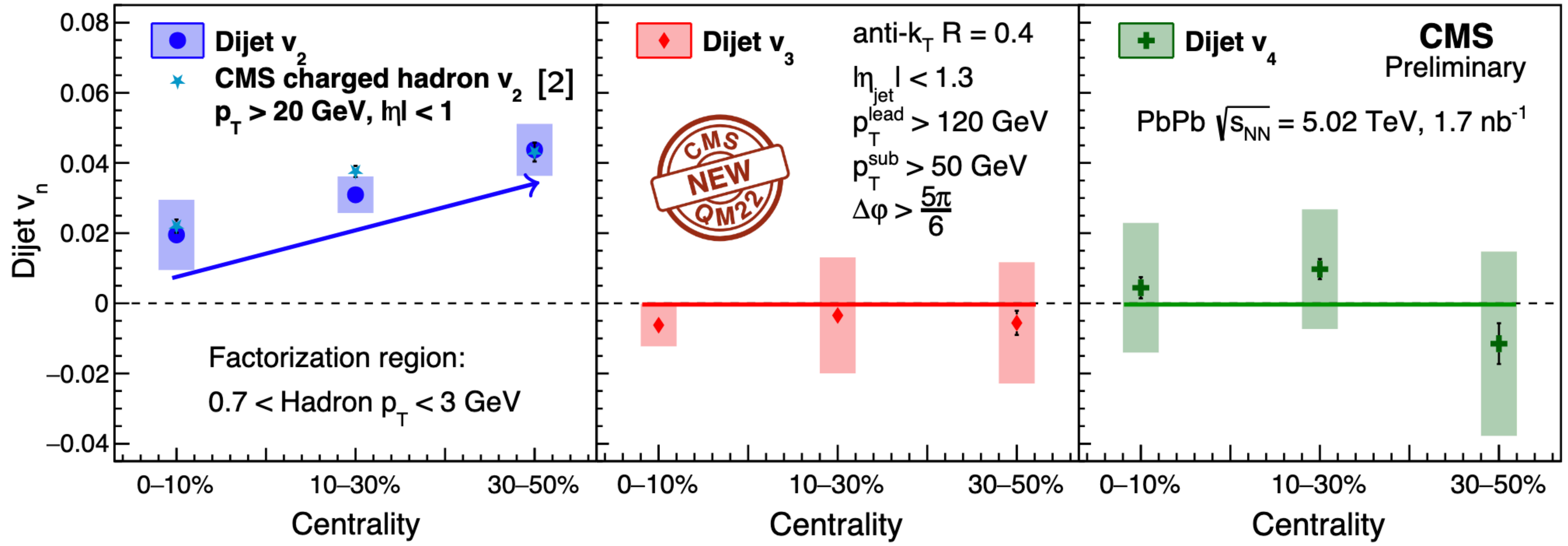
inclusive jets



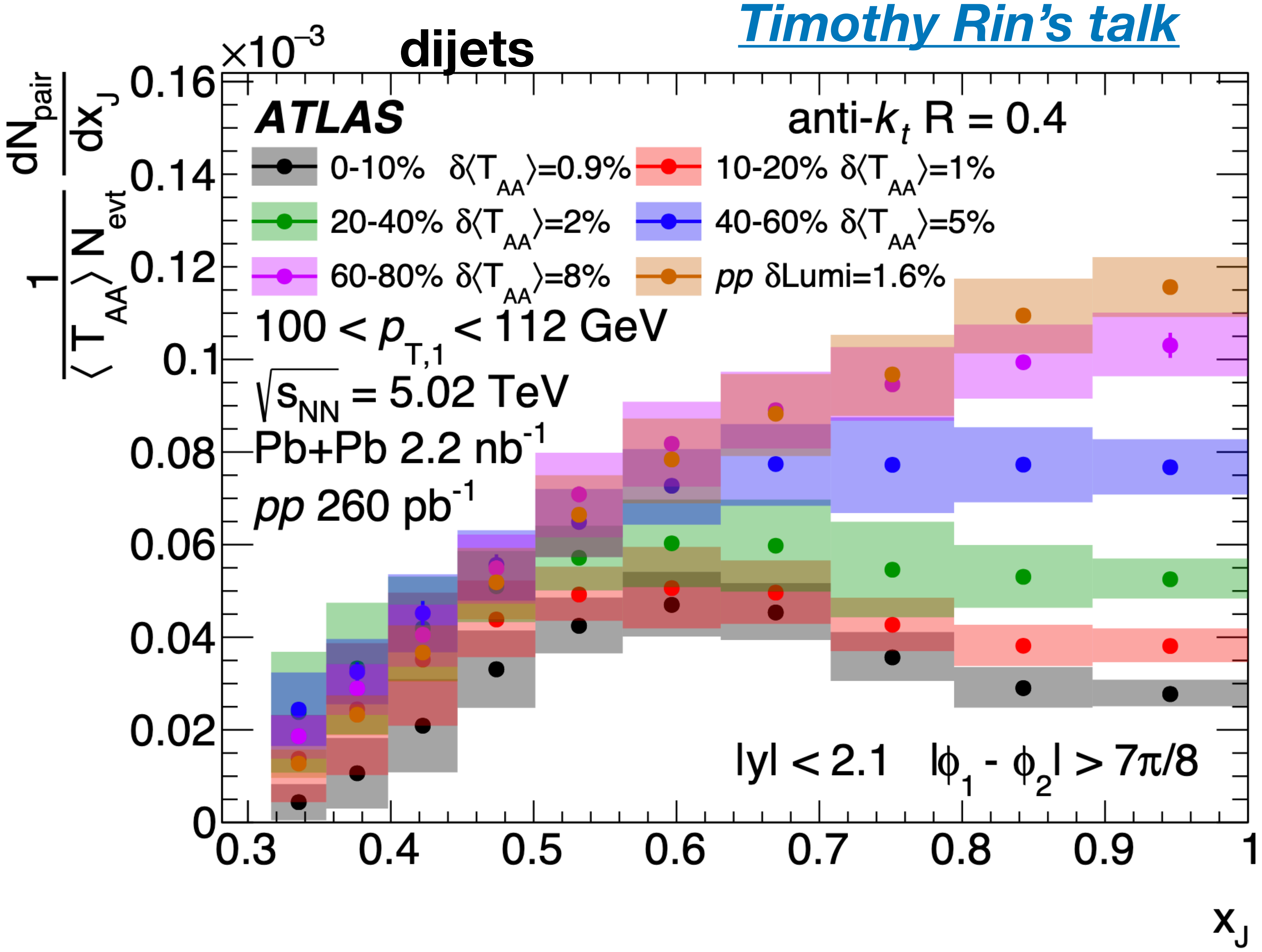
Anne Sickles's talk

dijets

Jussi Viinikainen's talk



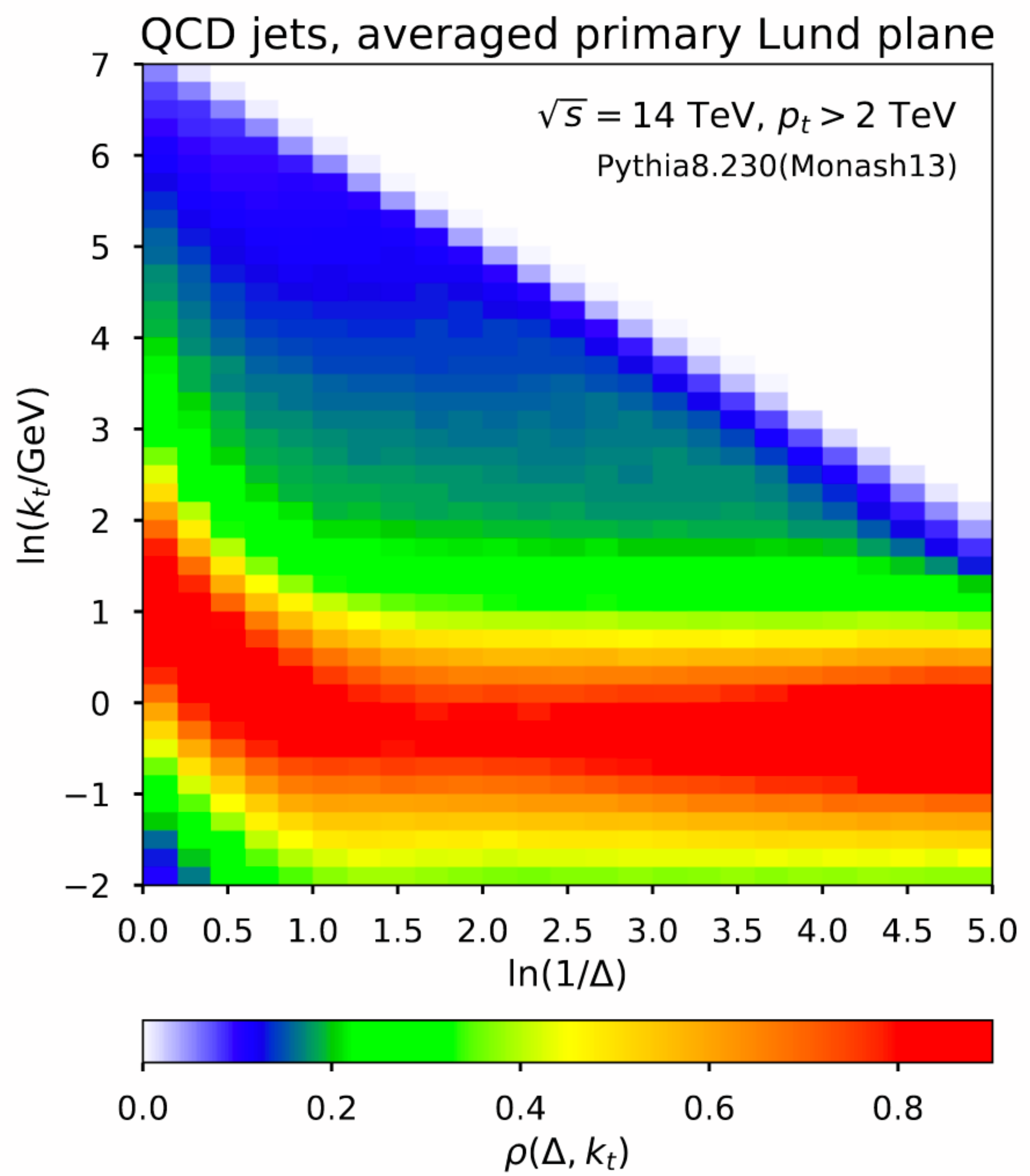
Timothy Rin's talk



Results consistent between dijet and inclusive vn except for v3, which is consistent with zero for dijets and positive for inclusive

ATLAS new absolute normalization: per event dijet xJ probability. Results show a systematic suppression of high-xJ pairs with centrality

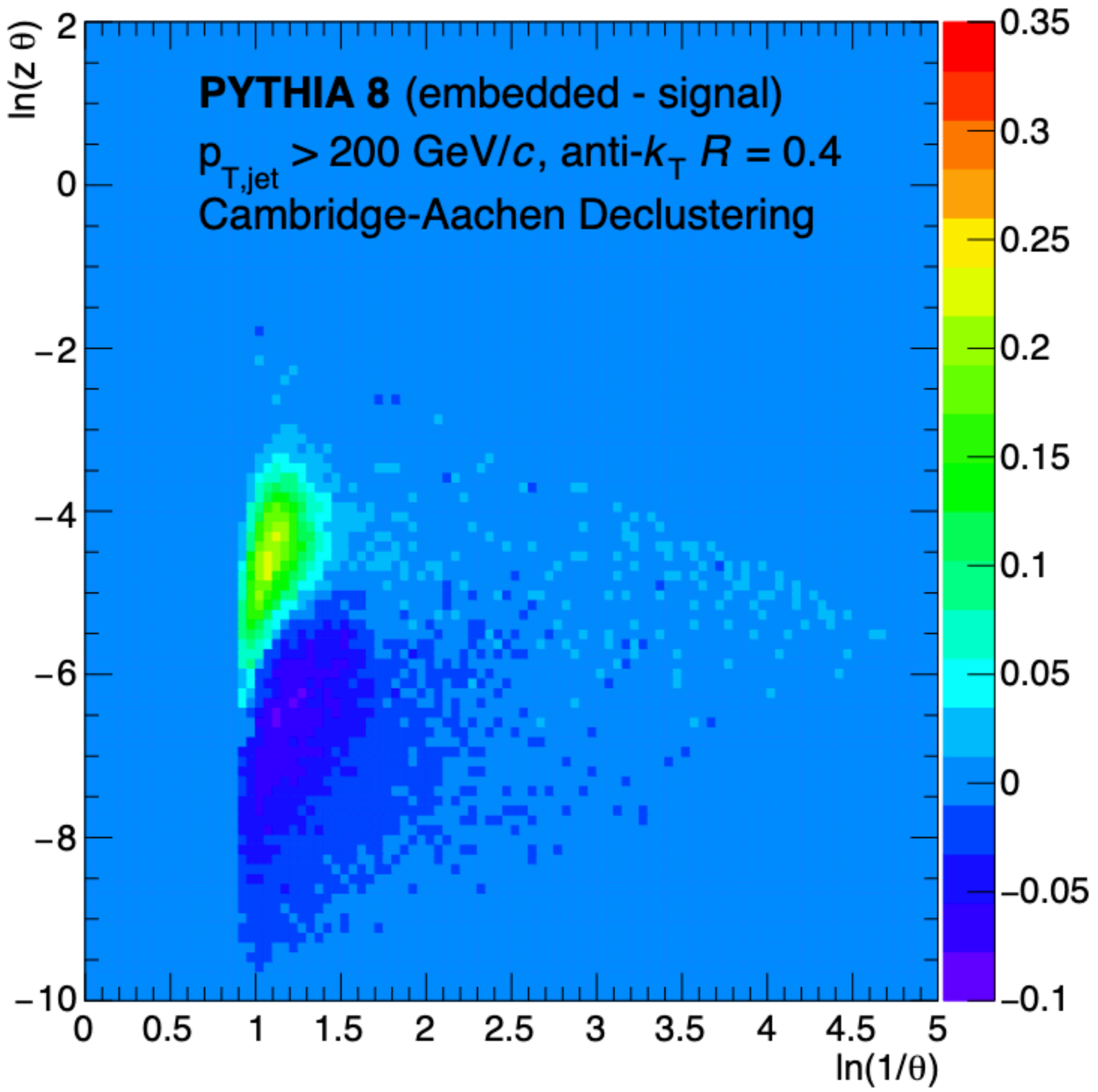
Substructure (just 2 comments, see Martin's talk next)



Dreyer et al JHEP12 (2018) 064

In vacuum, at LO, the Lund plane is filled homogeneously, the running of the coupling sculpts the plane

Substructure (just 2 comments, see Martin's talk next)



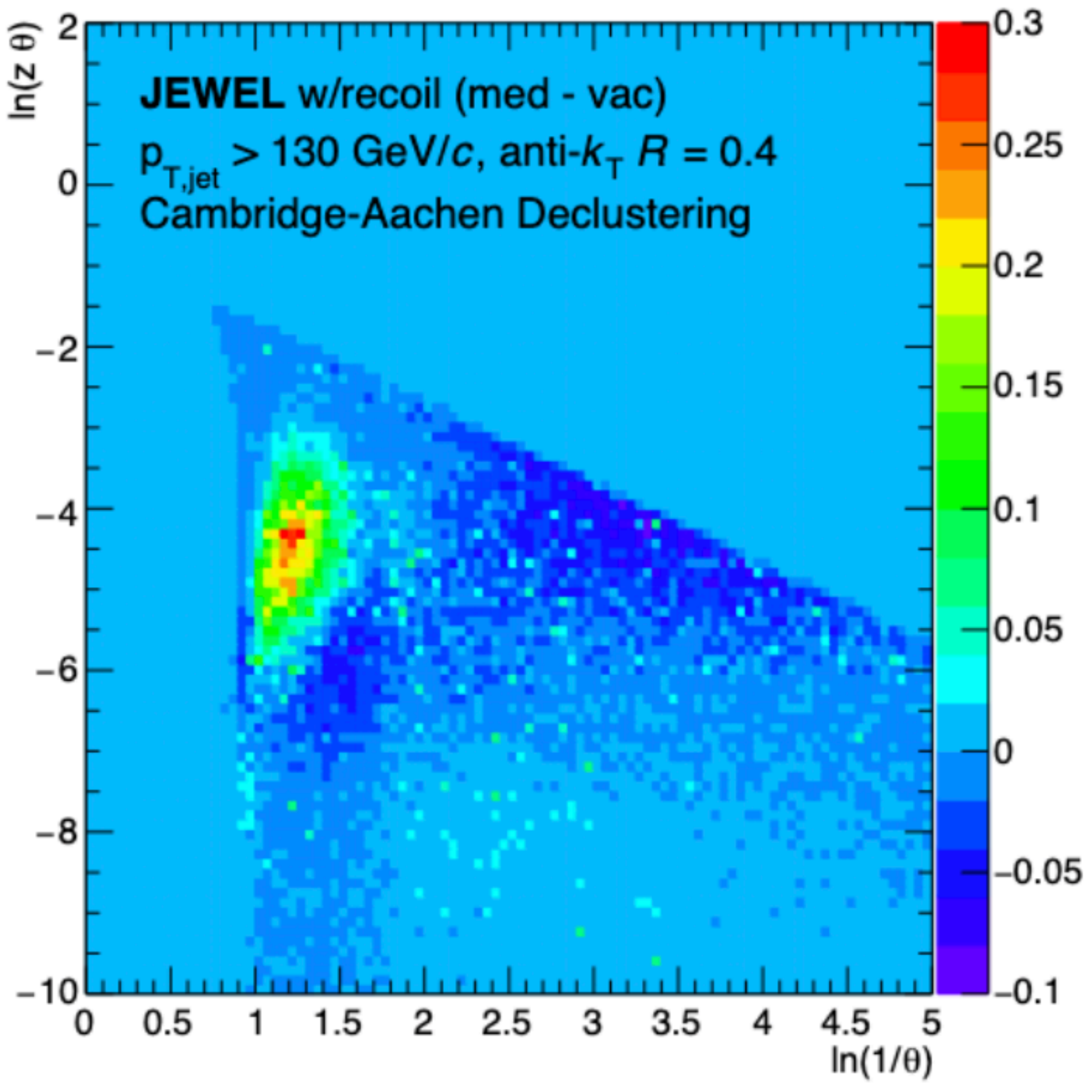
[Andrews et al, .Phys.G 47 (2020) 6]()

In vacuum, at LO, the Lund plane is filled homogeneously, the running of the coupling sculpts the plane

In medium, there are extra inhomogenities like the underlying event that populates the large-angle region of the plane with combinatorial prongs

A lot of work has been done in the last years to minimize the impact of combinatorial bkg to substructure and render the problem unfoldable

Substructure (just 2 comments, see Martin's talk next)



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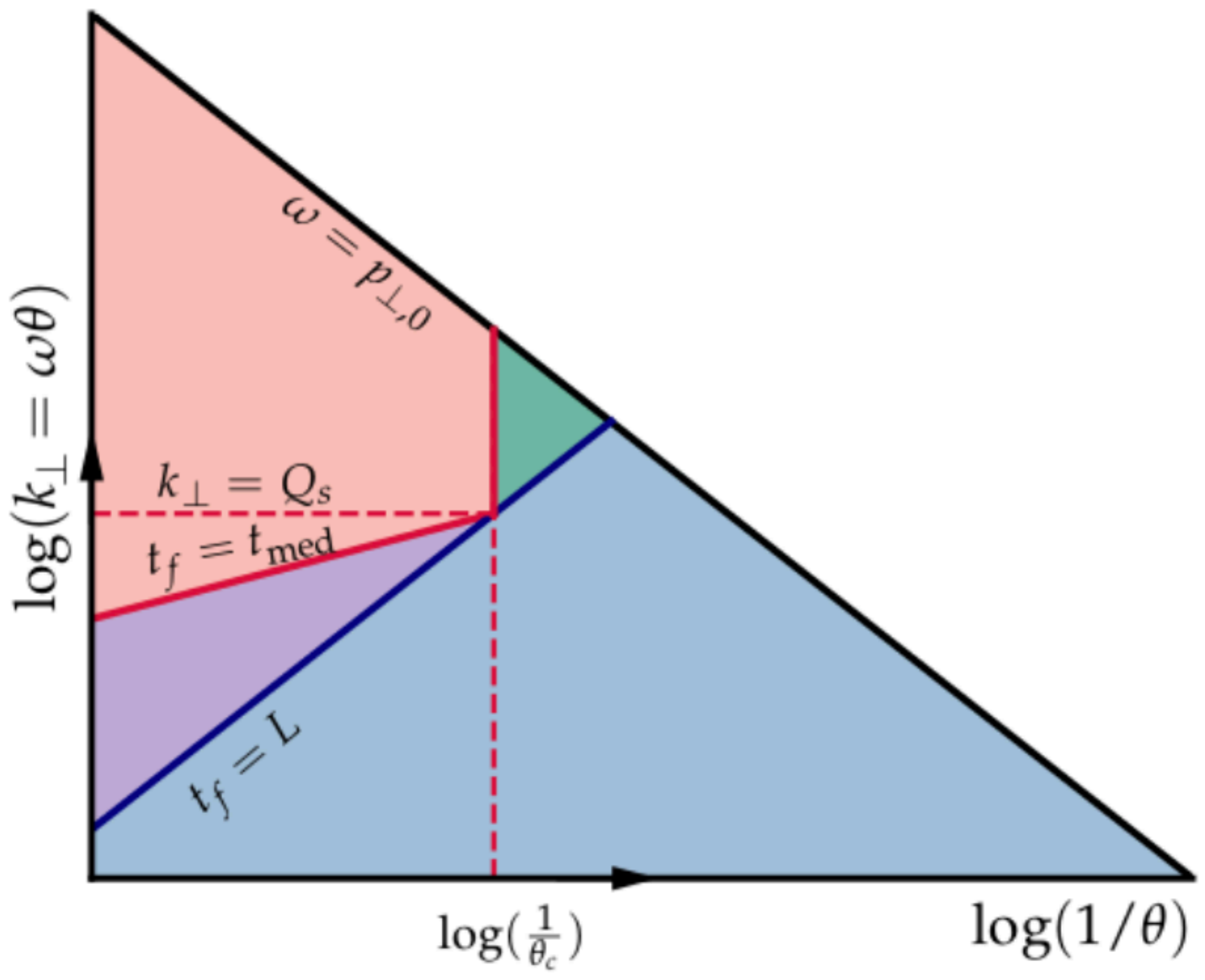
A lot of work has been done in the last years to minimize the impact of combinatorial bkg to substructure and render the problem unfoldable

The medium response might also contribute to substructure to the large-angle region

Substructure (just 2 comments, see Martin's talk next)



sketch from ***Paul Caucal's poster***

In vacuum, at LO, the Lund plane is filled homogeneously, the running of the coupling sculpts the plane

In medium, there are extra inhomogenities like the underlying event that populates the large-angle region of the plane with combinatorial prongs

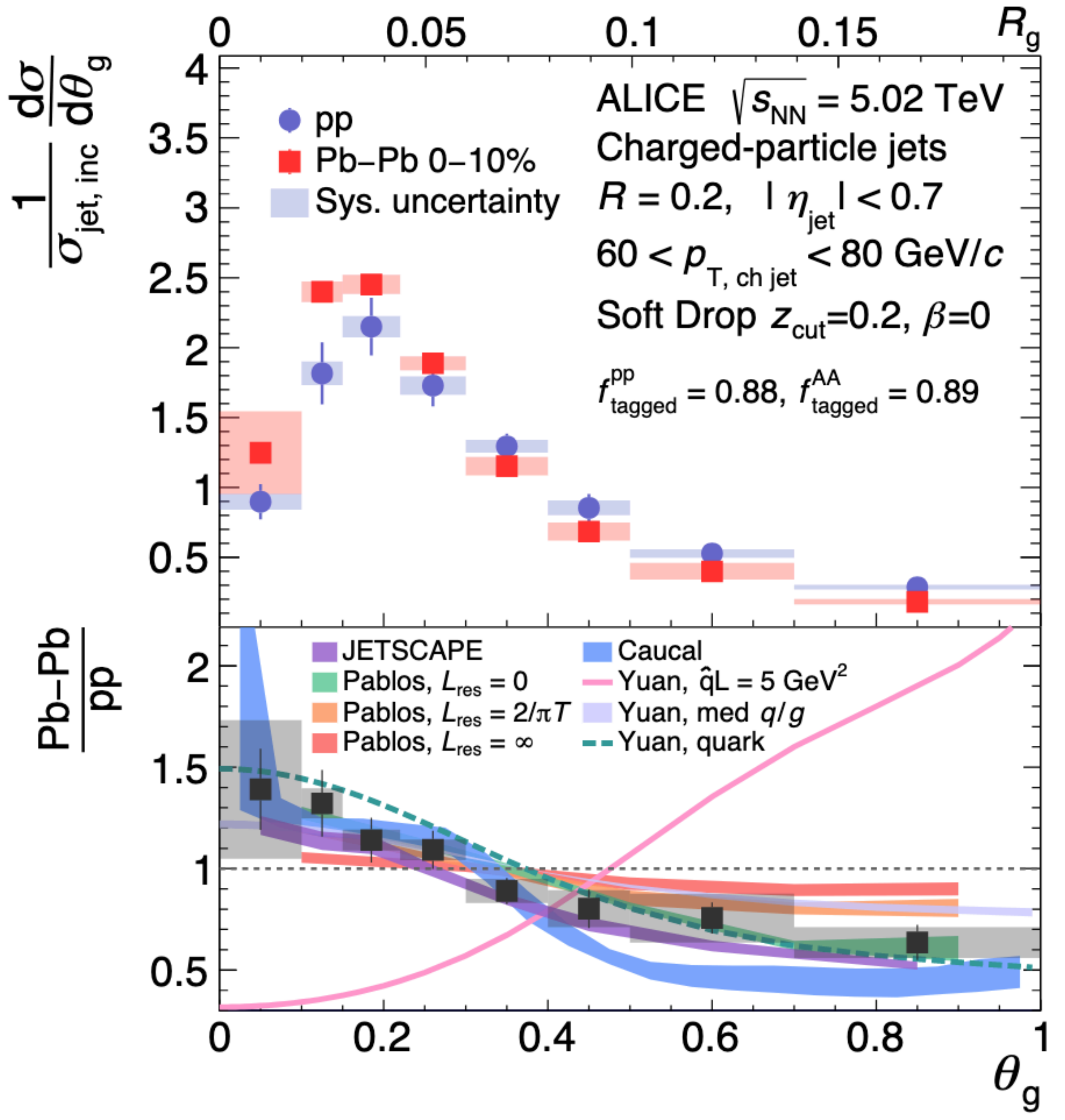
A lot of work has been done in the last years to minimize the impact of combinatorial bkg to substructure and render the problem unfoldable

The medium response might also contribute to substructure to the large-angle region

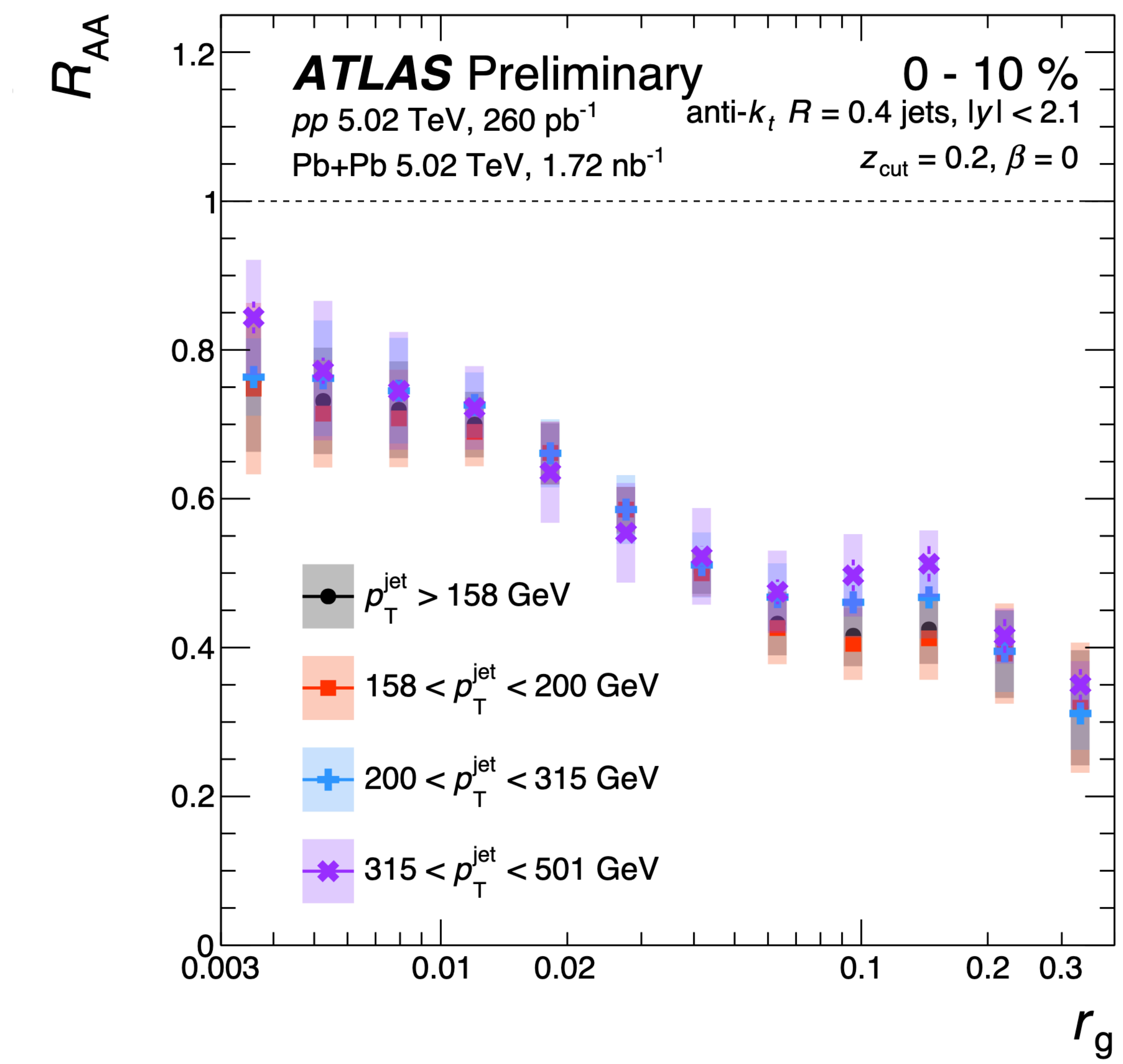
And on top of that there is medium-induced radiation that we try to characterize

Substructure (just 2 comments, see Martin's talk next)

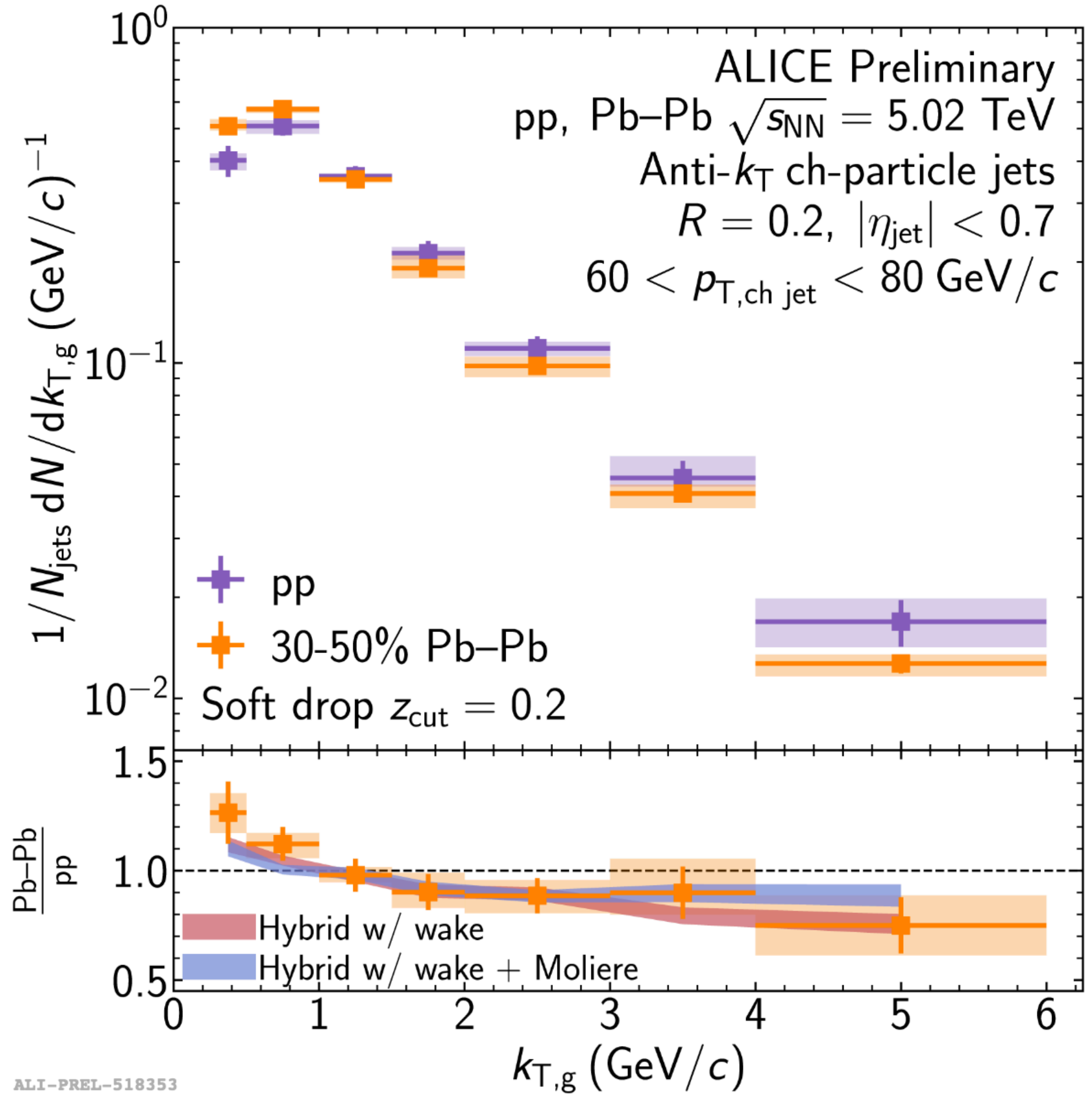
[*Hannah Bossi's talk*]



[*Anne Sickles's talk*]



[*Hannah Bossi's talk*]

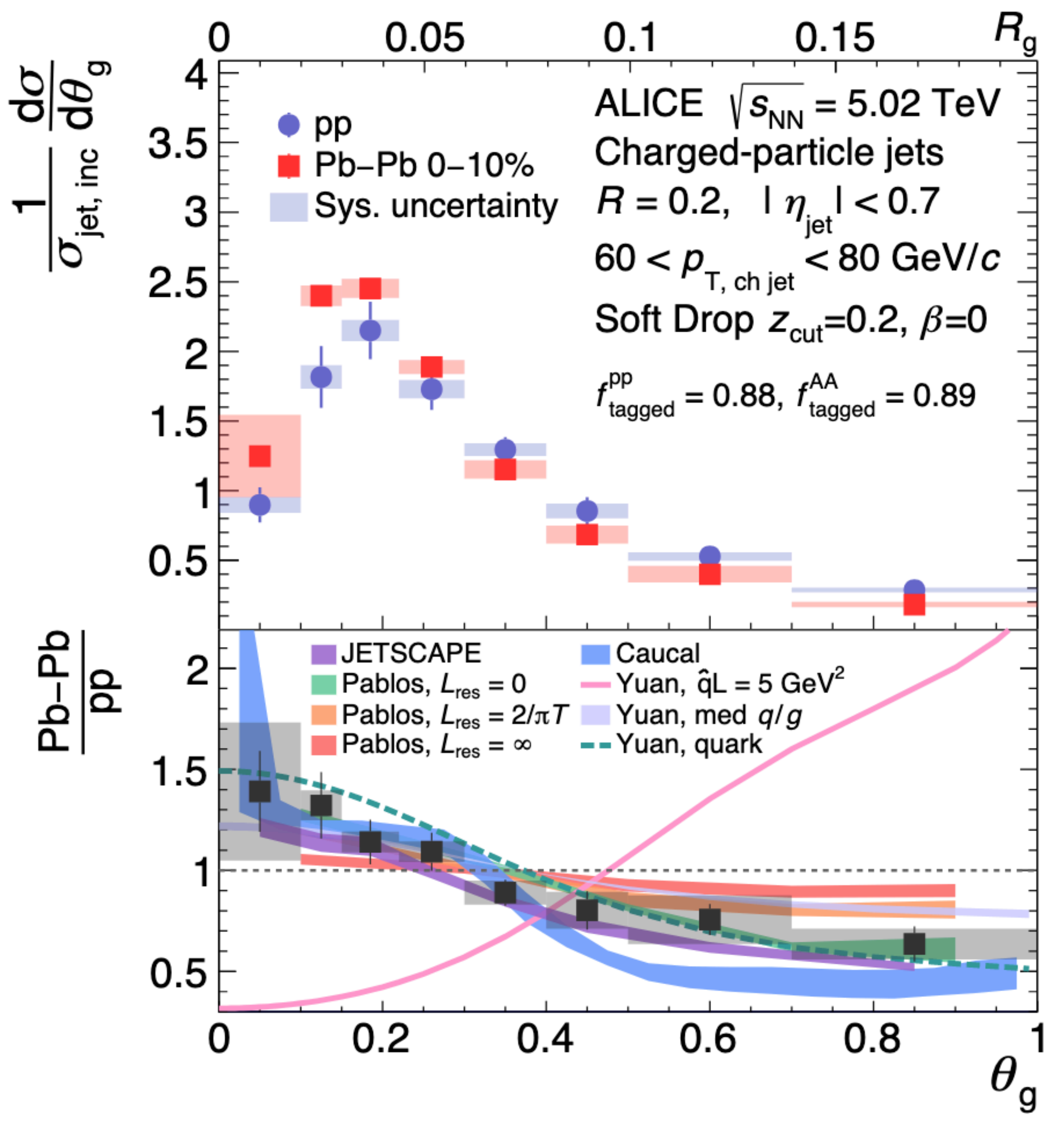


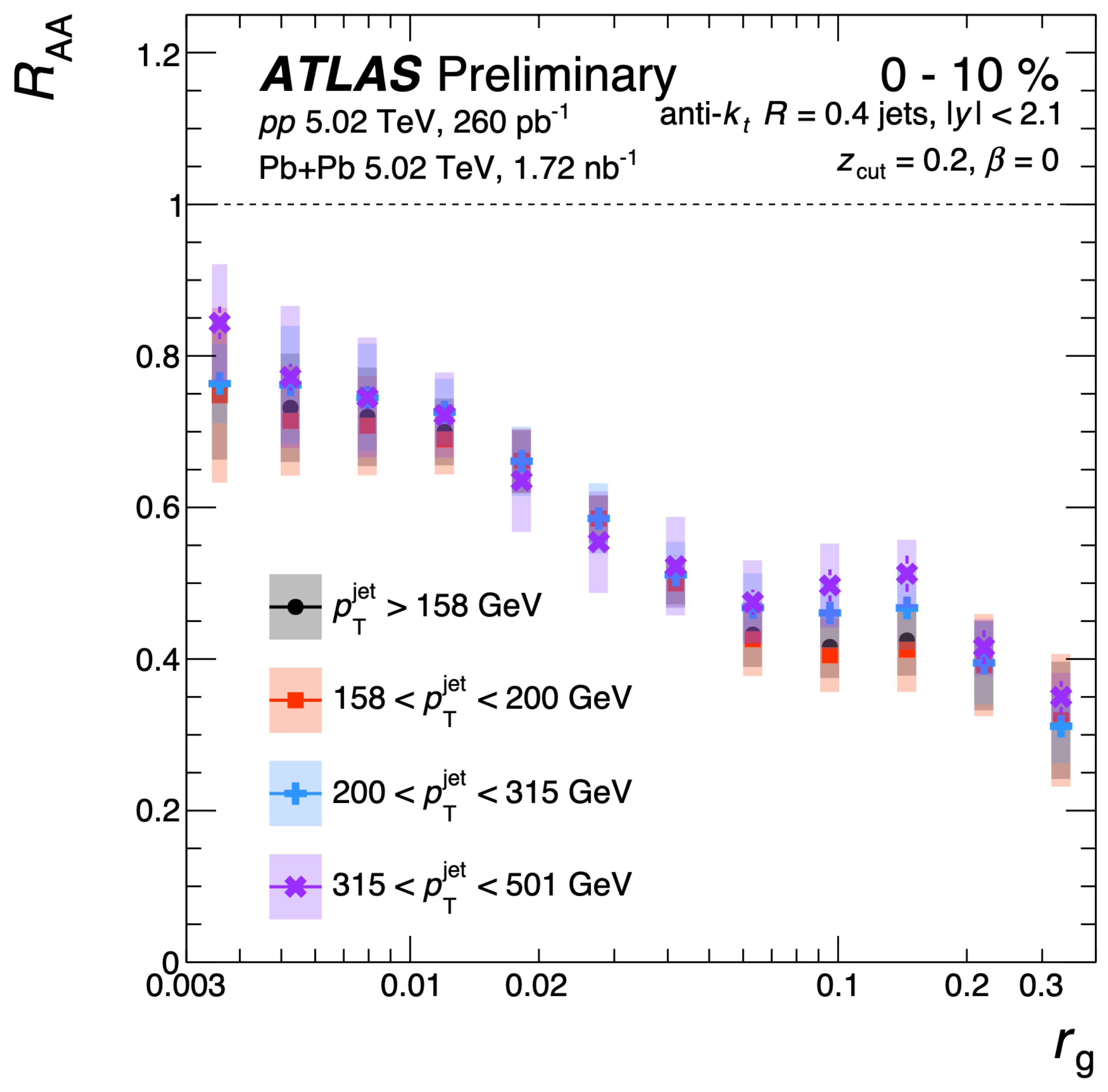
Is it early vacuum shower that dictates the trend in R_g? Large R_g selects active jets with multiple prongs that interact with the medium and are more quenched?

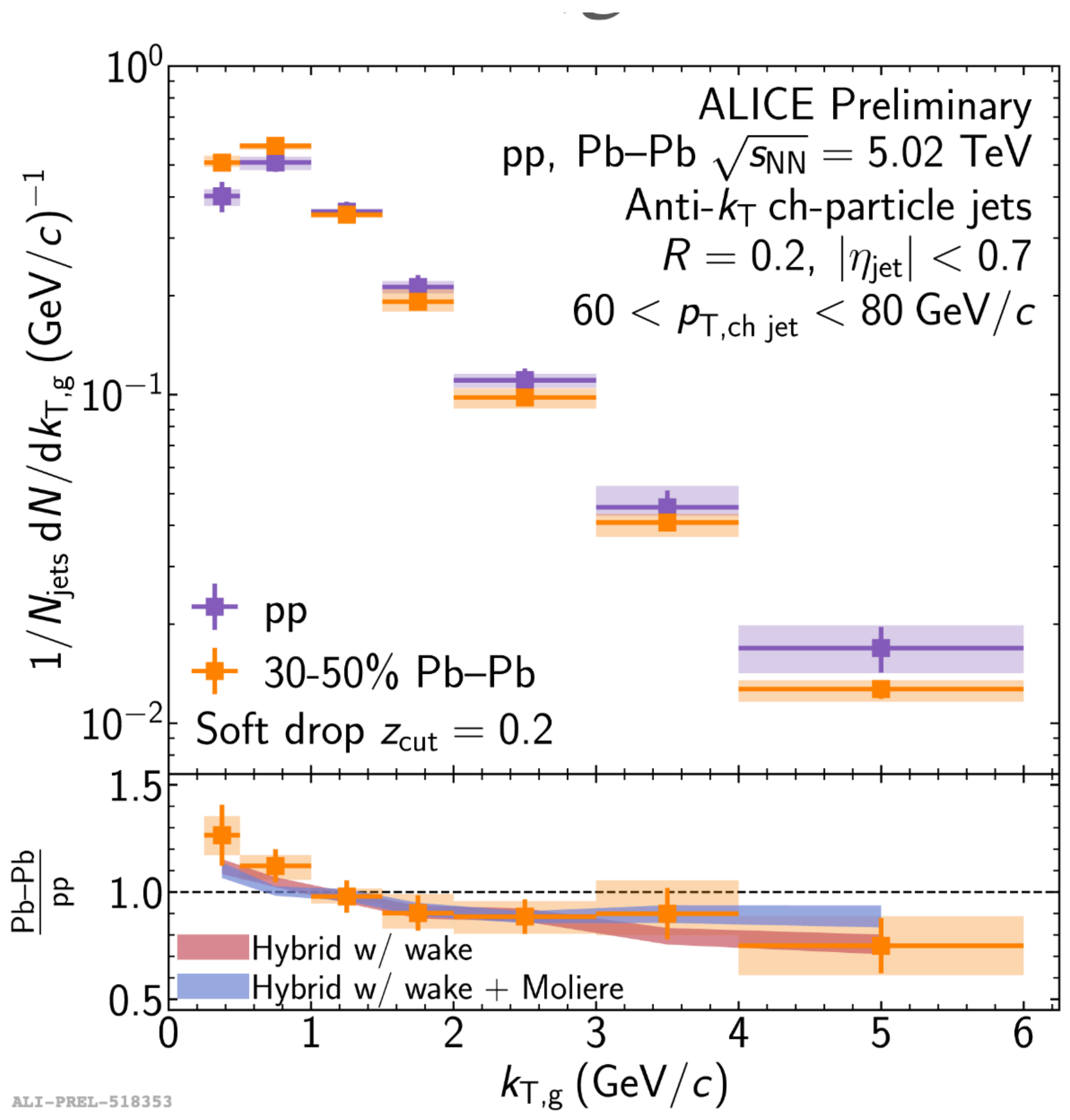
See studies showing that the broader strongly quenched jets migrate to lower jet p_T bins:
Du et al, 2106.11271, Brewer et al, 2009.03316. Substructure of jets recoiling from Z/γ is a promising step forward.

See the impact of coherence as implemented in the Hybrid model (oportunity to eventually constrain the medium color length) and note the impact of quark/gluon fractions in the extreme case of fully unresolved jets

Substructure (just 2 comments, see Martin's talk next)





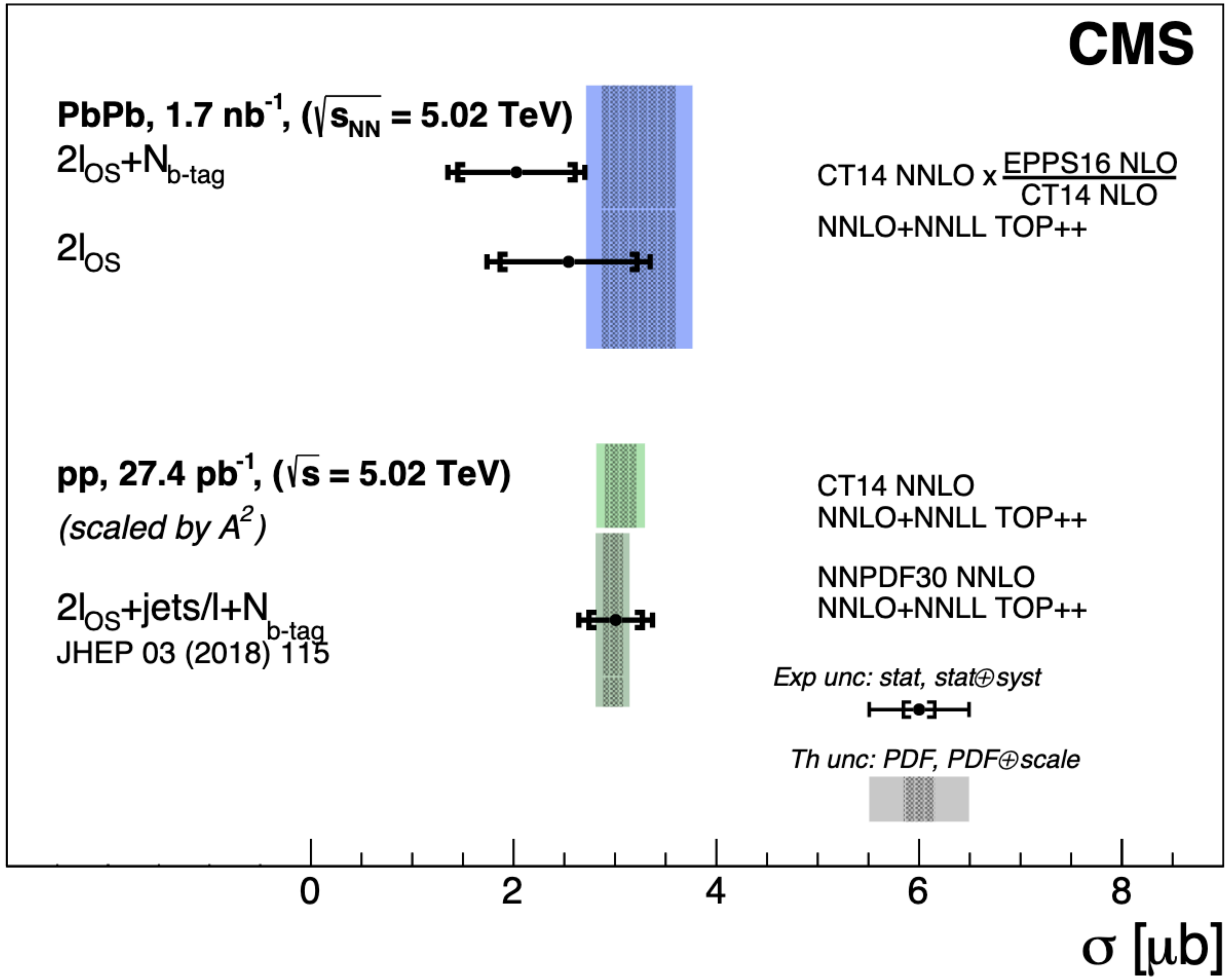


Note the enhancement in the groomed k_T due to the newly implemented Moliere scatterings
Current experimental uncertainties don't allow to discriminate between w and w/o Moliere
See ***Zach Hulcher's talk*** for the implementation of hard scatterings in the Hybrid model

See also analytical calculations in vacuum for dynamically groomed substructure in ***P.Caucal's poster***

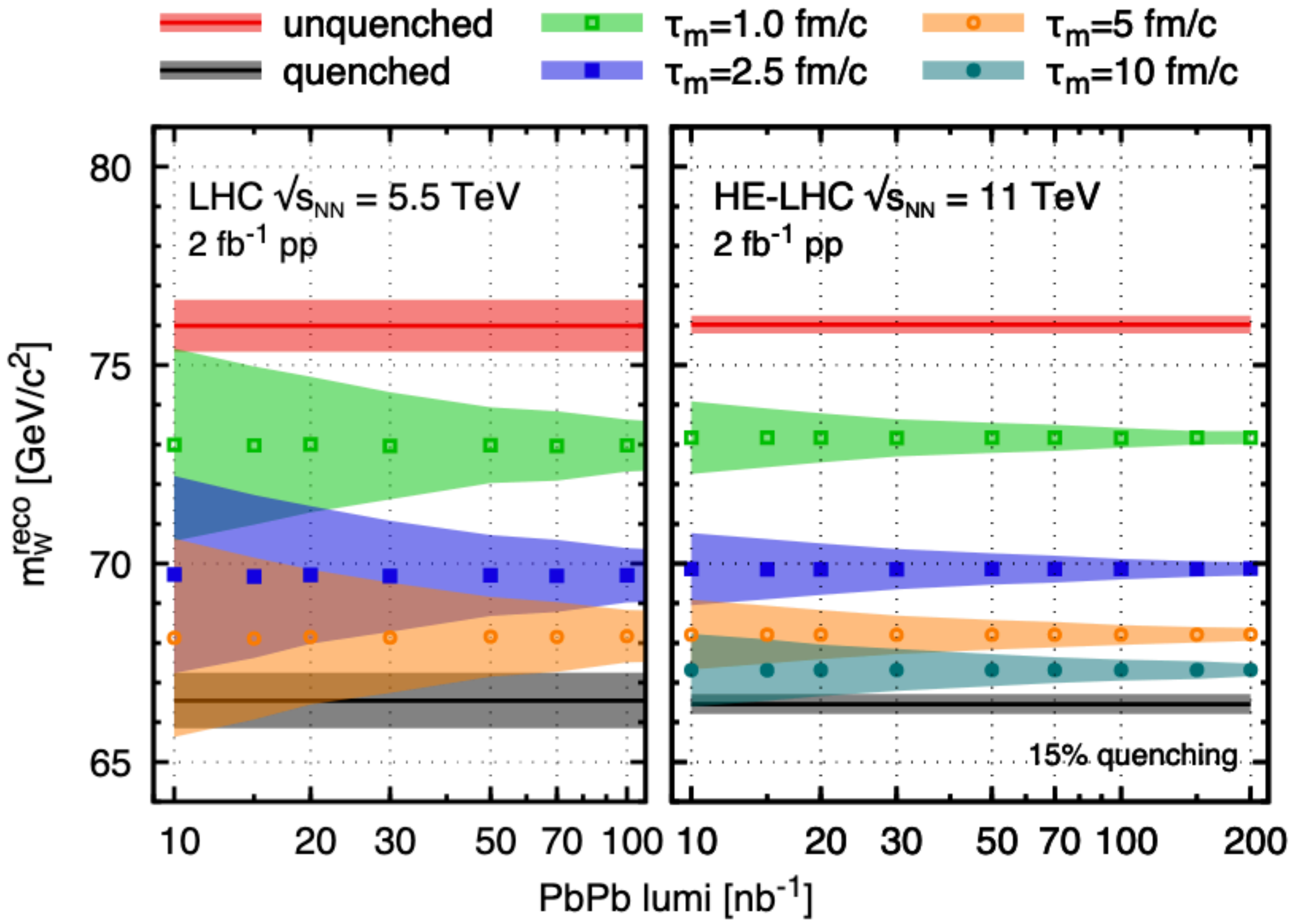
To finish: top quarks to build a time picture

Luis Alcerro's talk



First step is using the top quark as a QGP chronometer

Apolinario et al, Phys.Rev.Lett. 120 (2018) 23, 232301



quenching end-time that can be distinguished

A possible 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

-Some tensions in the R_{AA} vs R trends at the LHC at low jet p_T

-First evidence of the broadening of the γ-jet and h-jet azimuthal correlation for very soft jets

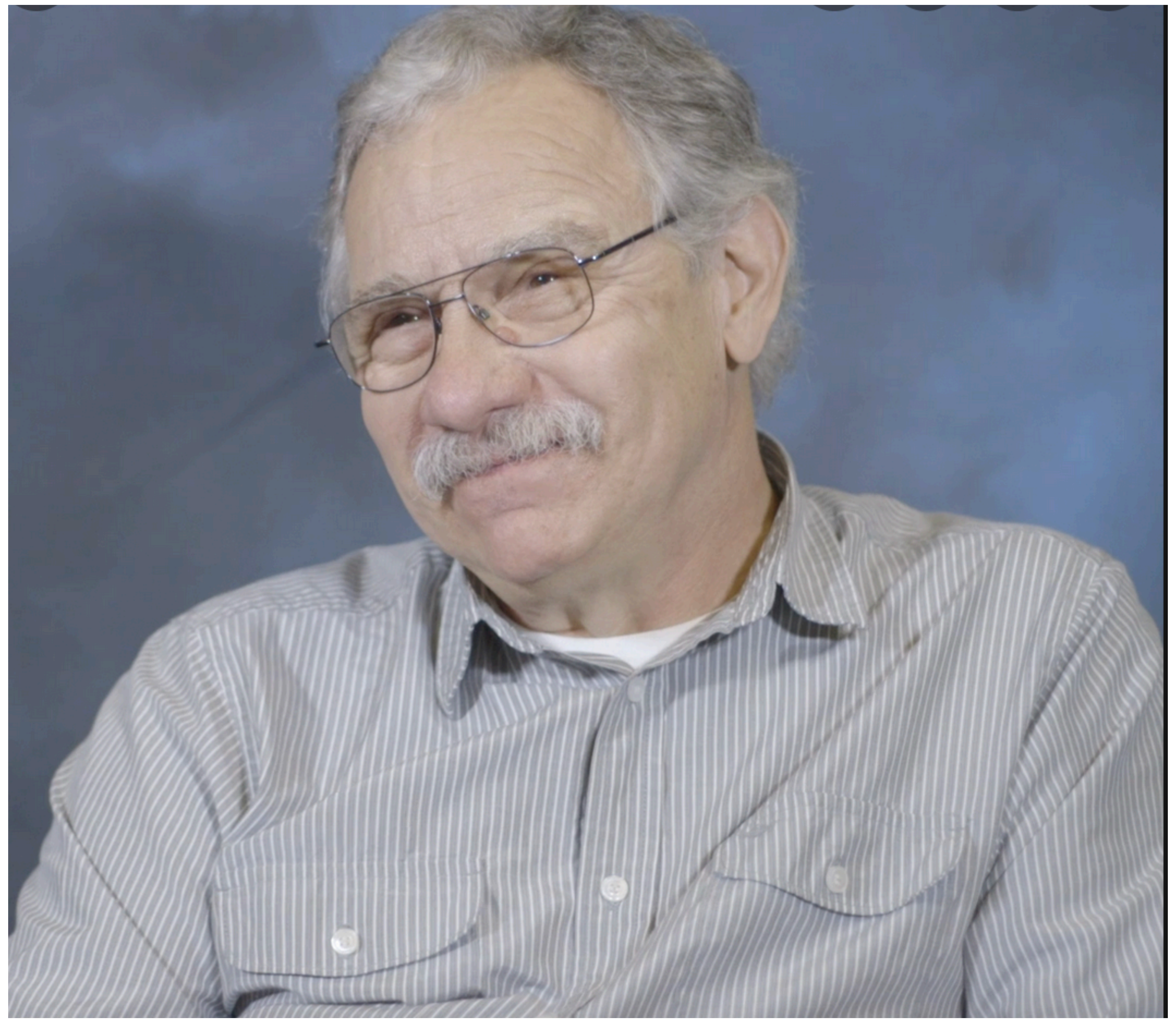
-Broader jets appear more suppressed (via angularities, jet axis difference, Rg, k_T^{dist} with different degrees of signal strength)
Probing fundamental properties of the medium like color correlation length or probing the point-like scatterers in the medium are within reach

-Interesting prospects for Z/γ-jet and heavy flavour jet substructure

-Searches for jet quenching signal in small systems (not covered here)

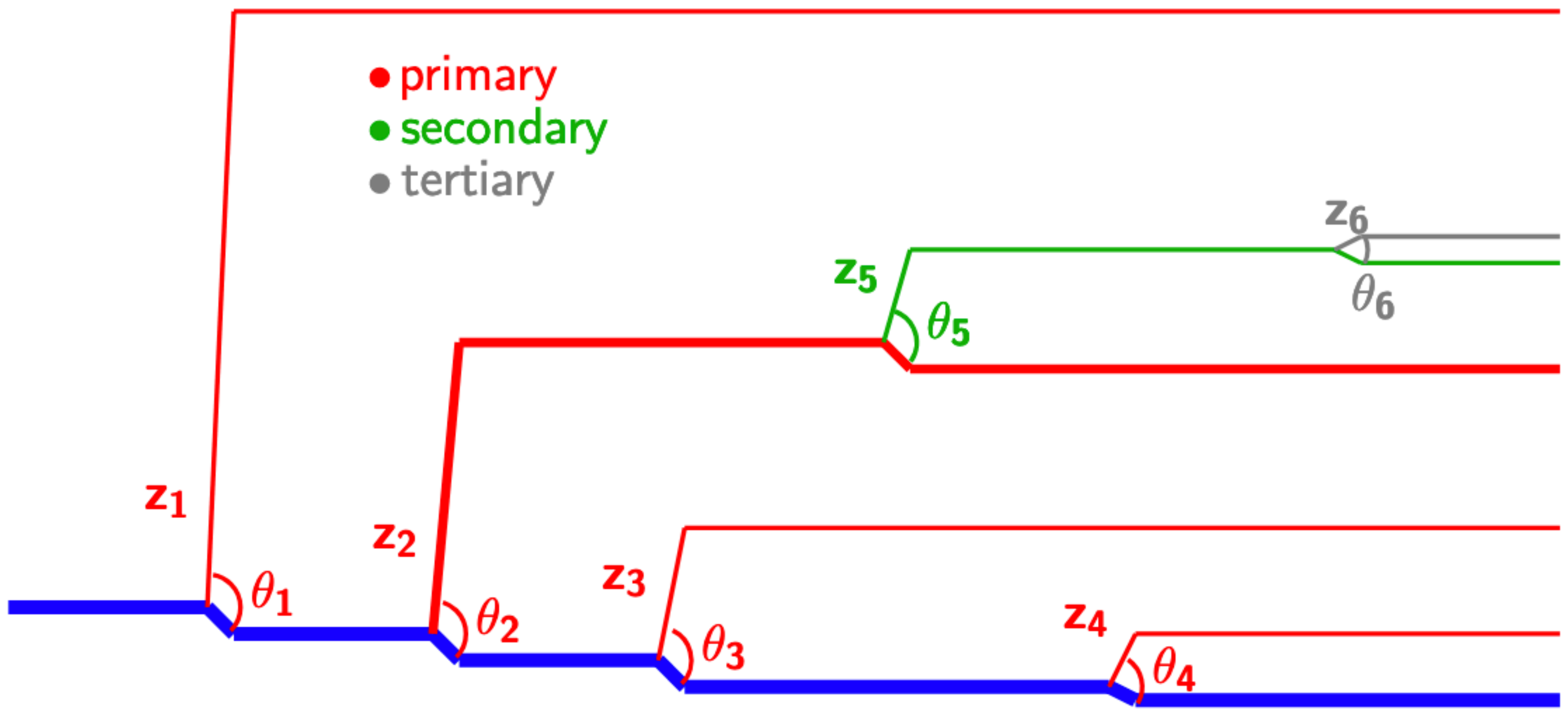
-Plenty of encouraging new theoretical developments discussed in talks and posters

In memory of Tom Cormier, team leader ORNL



thanks to friends and collaborators for input: *Laura Havener, Peter Jacobs, Matt Nguyen, Konrad Tywoniuk, Nima Zardoshti, Marta Verweij and many more*

Jet substructure using the clustering history



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)

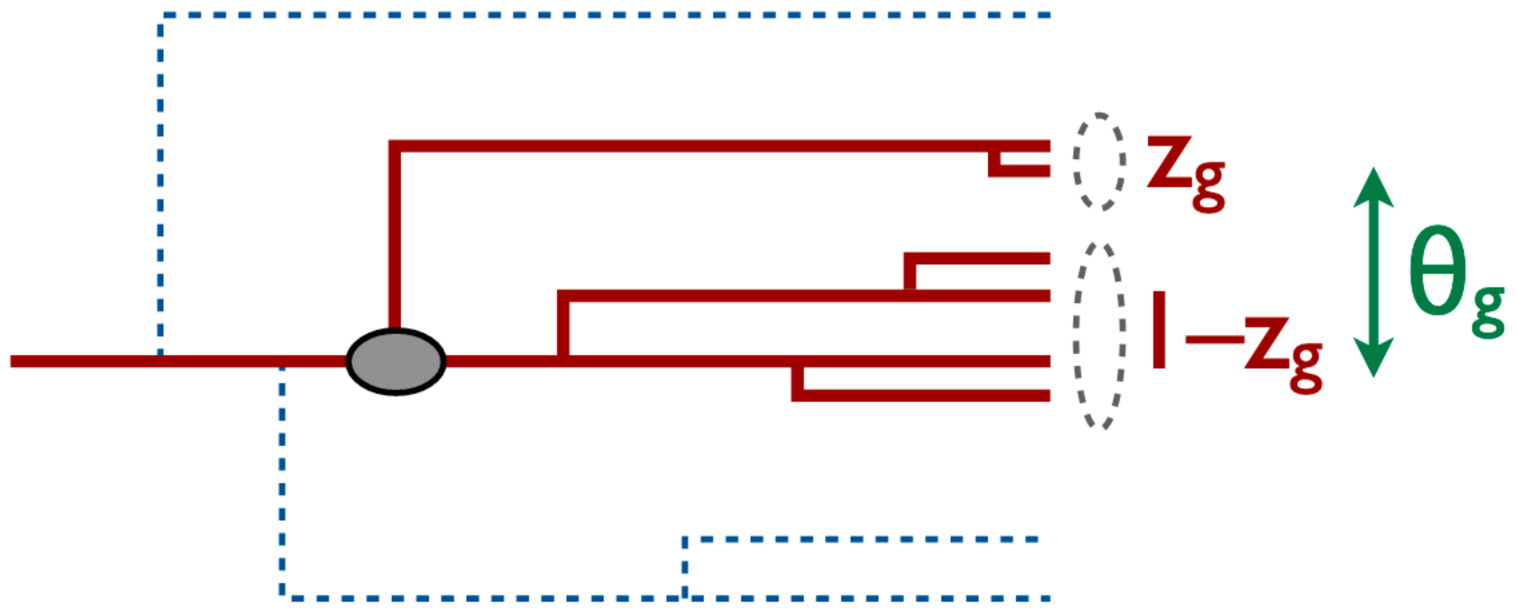
Grooming

Groom away branches in order to **access hard parts of the jet that are under better theoretical control**

- **mMDT/SofDrop grooming**

Remove branches of an angular-ordered clustering tree until you find a splitting that satisfies:

$$z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



Larkoski et al, JHEP 05 (2014) 146
(Recursive SD) Dreyer et al, JHEP 06 (2018) 093
Butterworth et al,Phys.Rev.Lett. 100 (2008) 242001

- New: Dynamical Grooming

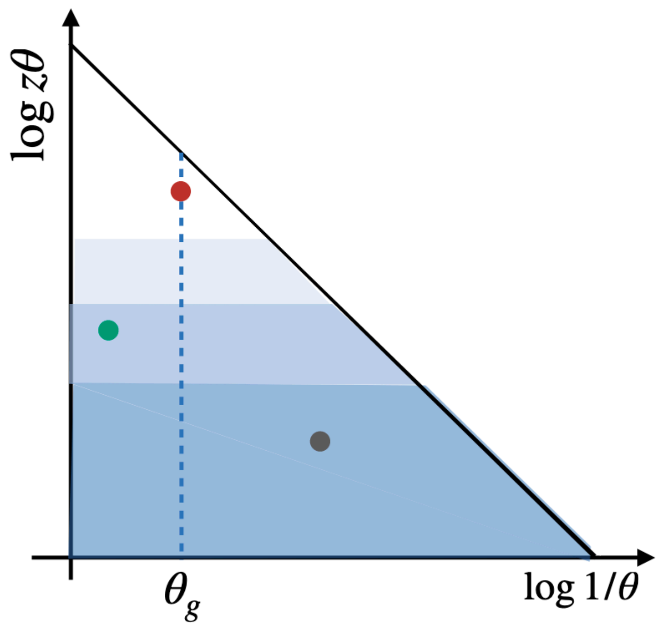
1. Select the hardest branch in the C/A sequence
2. Drop all branches at larger angles

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$

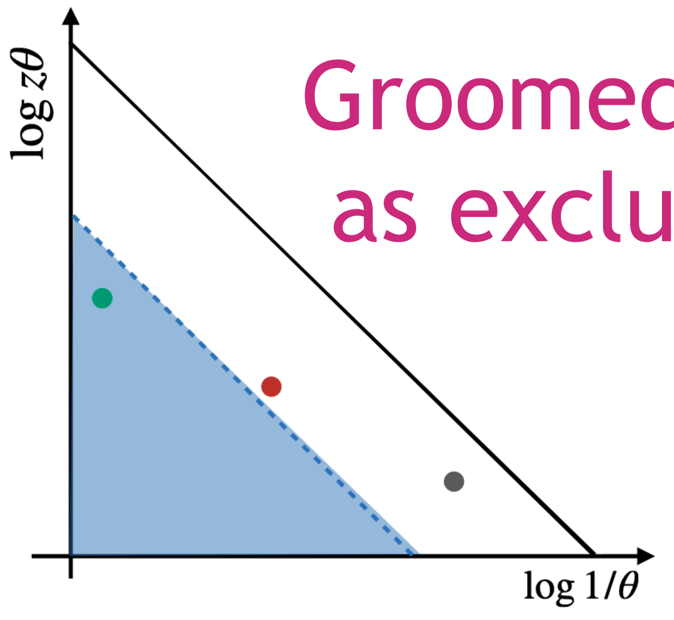
More aggressive grooming with decreasing parameter a

Mehtar-Tani et al, Phys.Rev.D 101 (2020) 3, 034004

DyG:

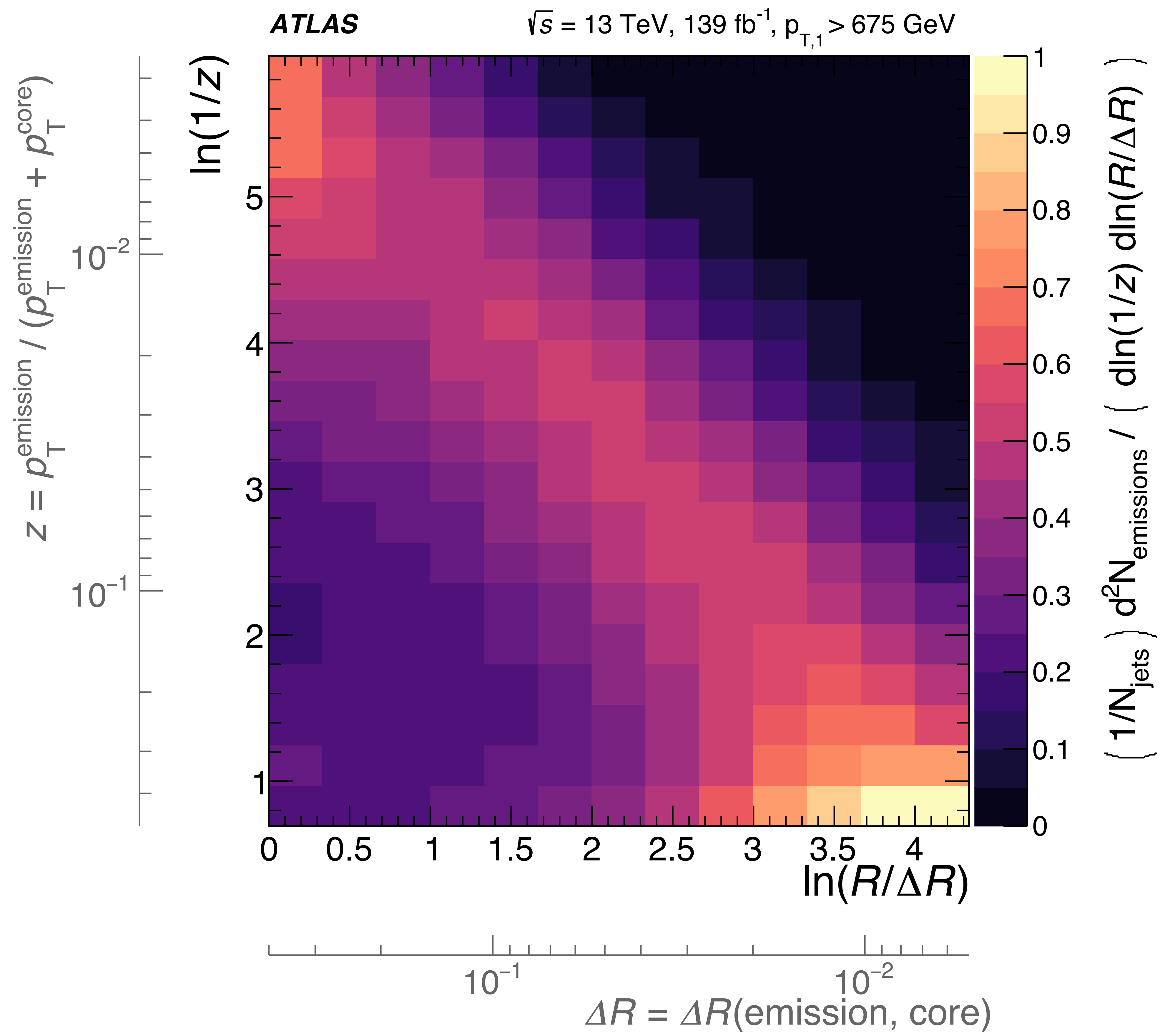


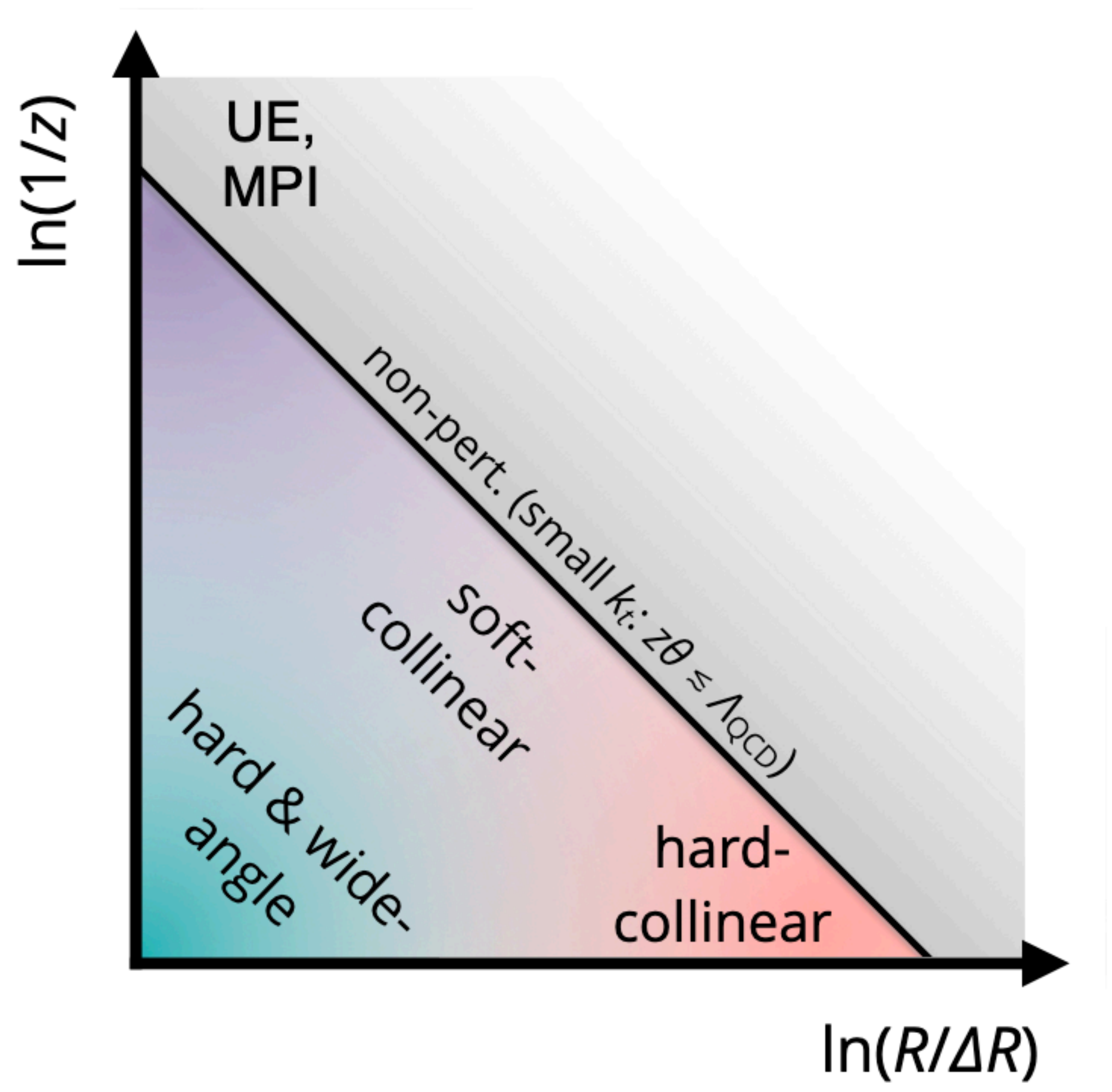
SD:



Groomed-away areas can we drawn as exclusion regions in the Lund Jet Plane

Declustering in pp gives access to salient features of the parton shower I

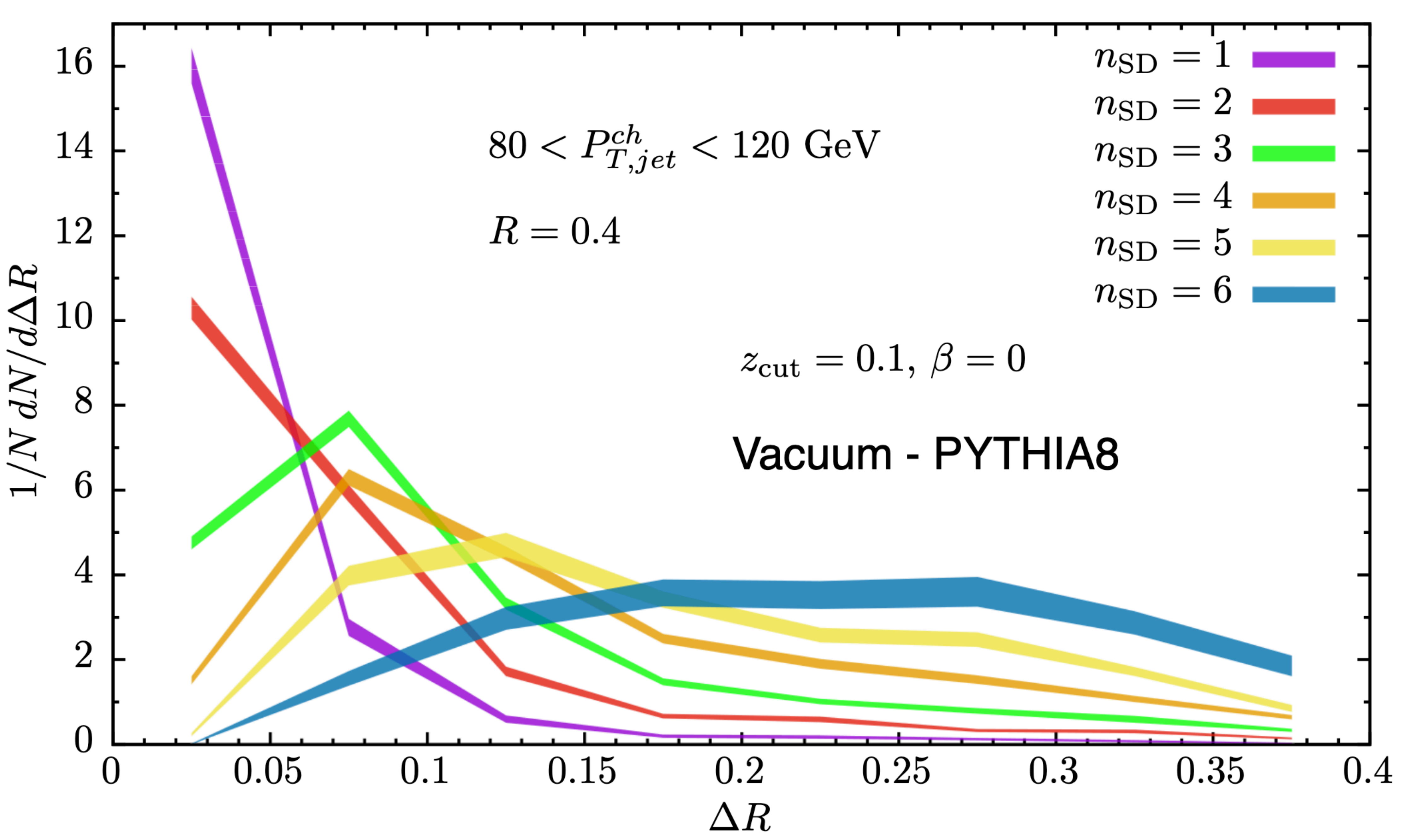


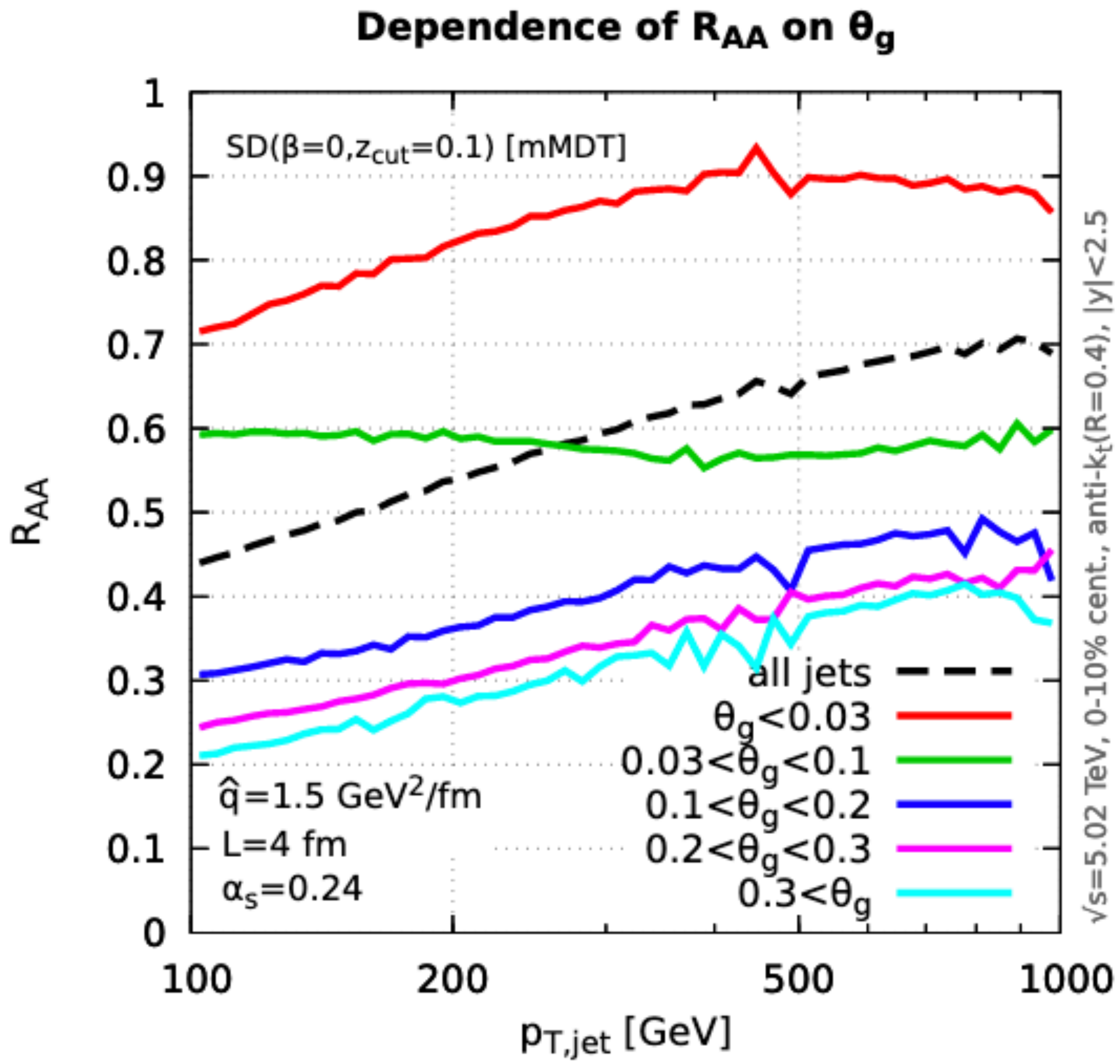


- Multiple physics effects contribute beyond the LO uniformly-filled plane
- However the measurement captures salient features of the q/g parton shower: the running of the coupling sculpts the plane

ATLAS, Phys.Rev.Lett. 124 (2020) 22, 222002

Early vacuum structure dominance





Jets with larger R_g are more active and thus more quenched if resolved

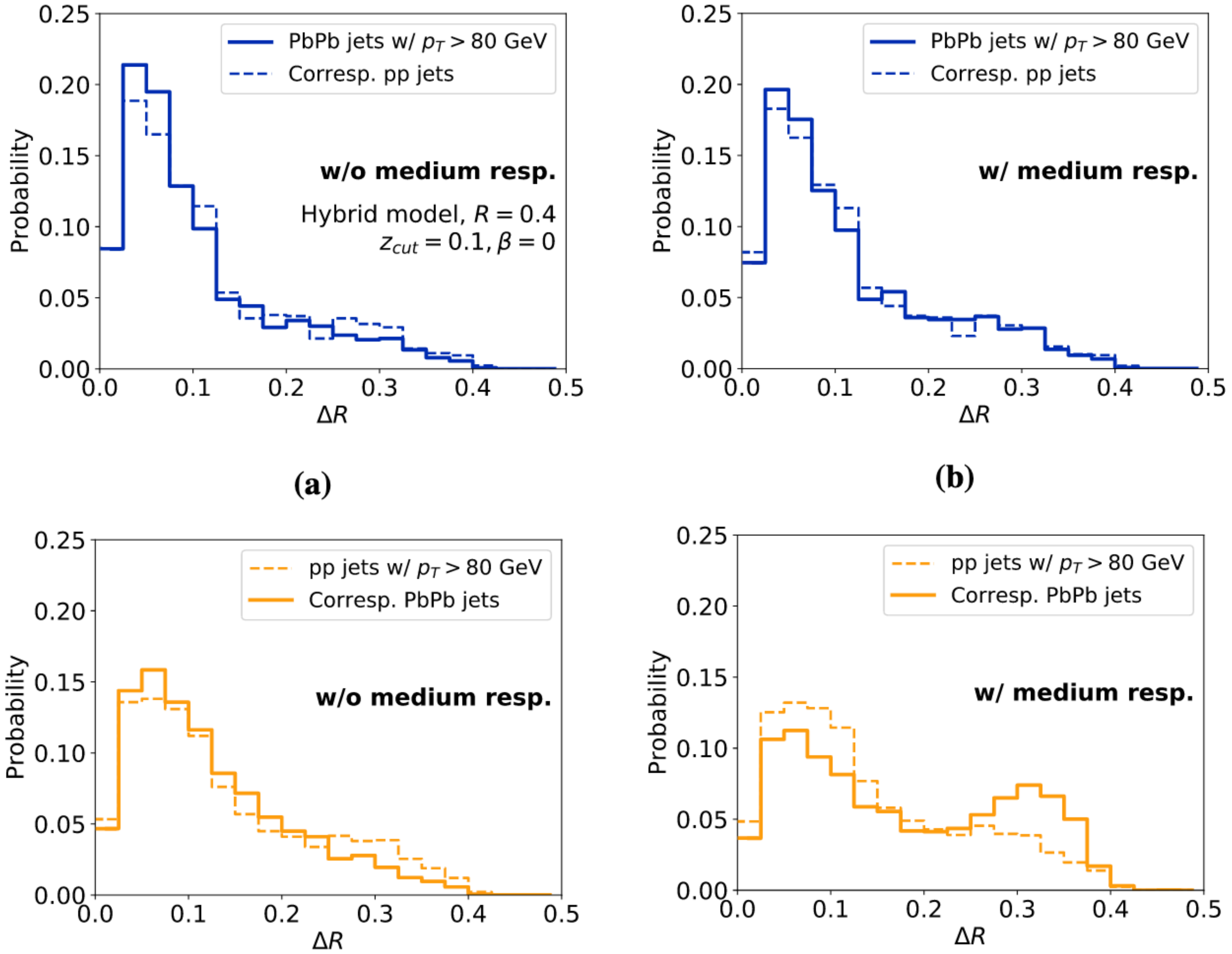
Casalderrey et al, JHEP'20

Large-R_g jets are those with more phase space for VLE and are thus more quenched

Caucal et al, JHEP 10 (2019) 273

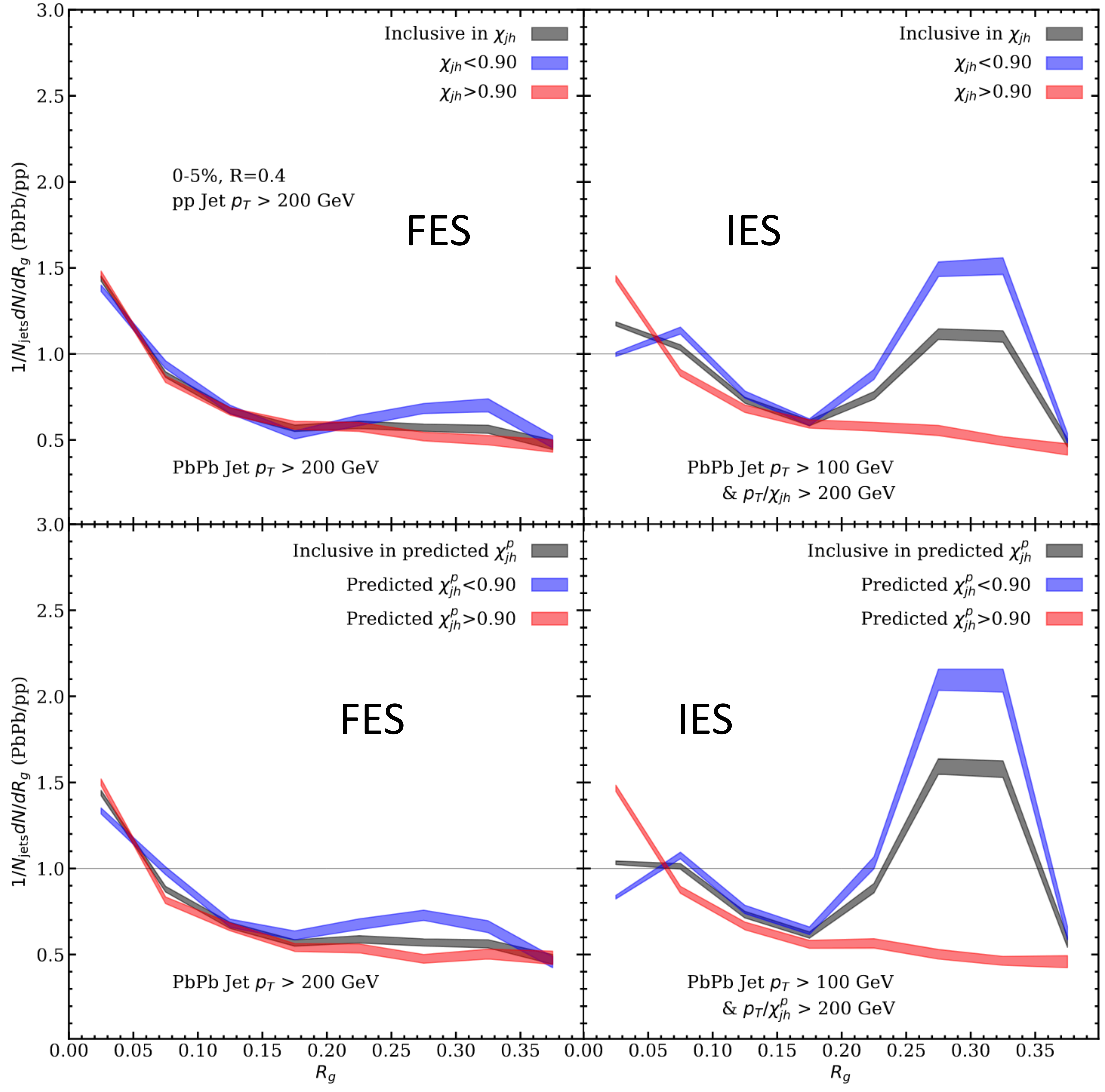
A selection bias possibly playing a key role

Brewer et al, 2009.03316



- When binning on the reconstructed jet momentum, jet sample dominated by weakly quenched jets. Strongly quenched jets, which are broader, migrate to lower jet p_T bins
- When binning on true jet energy, broader & more quenched jets are included in the p_T bin and the effects of the medium response are visible

A selection bias possibly playing a key role



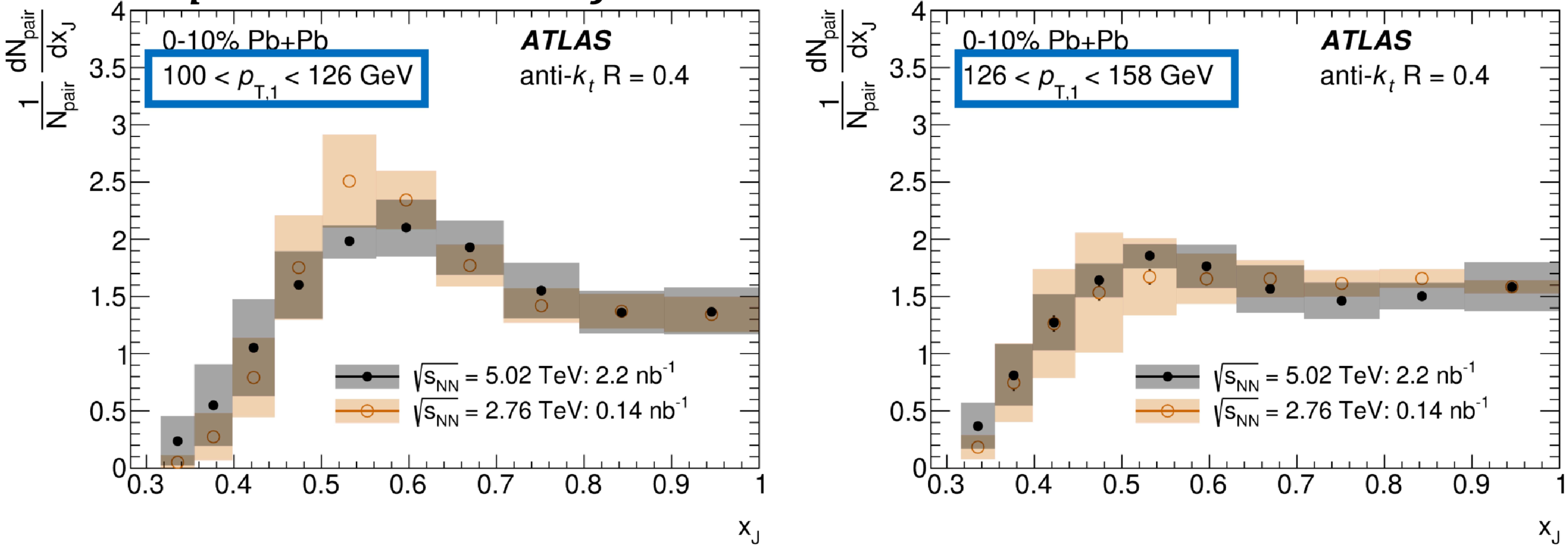
Du et al, 2106.11271

Unquenched class: $\chi > 0.9$

Quenched class: $\chi < 0.9$

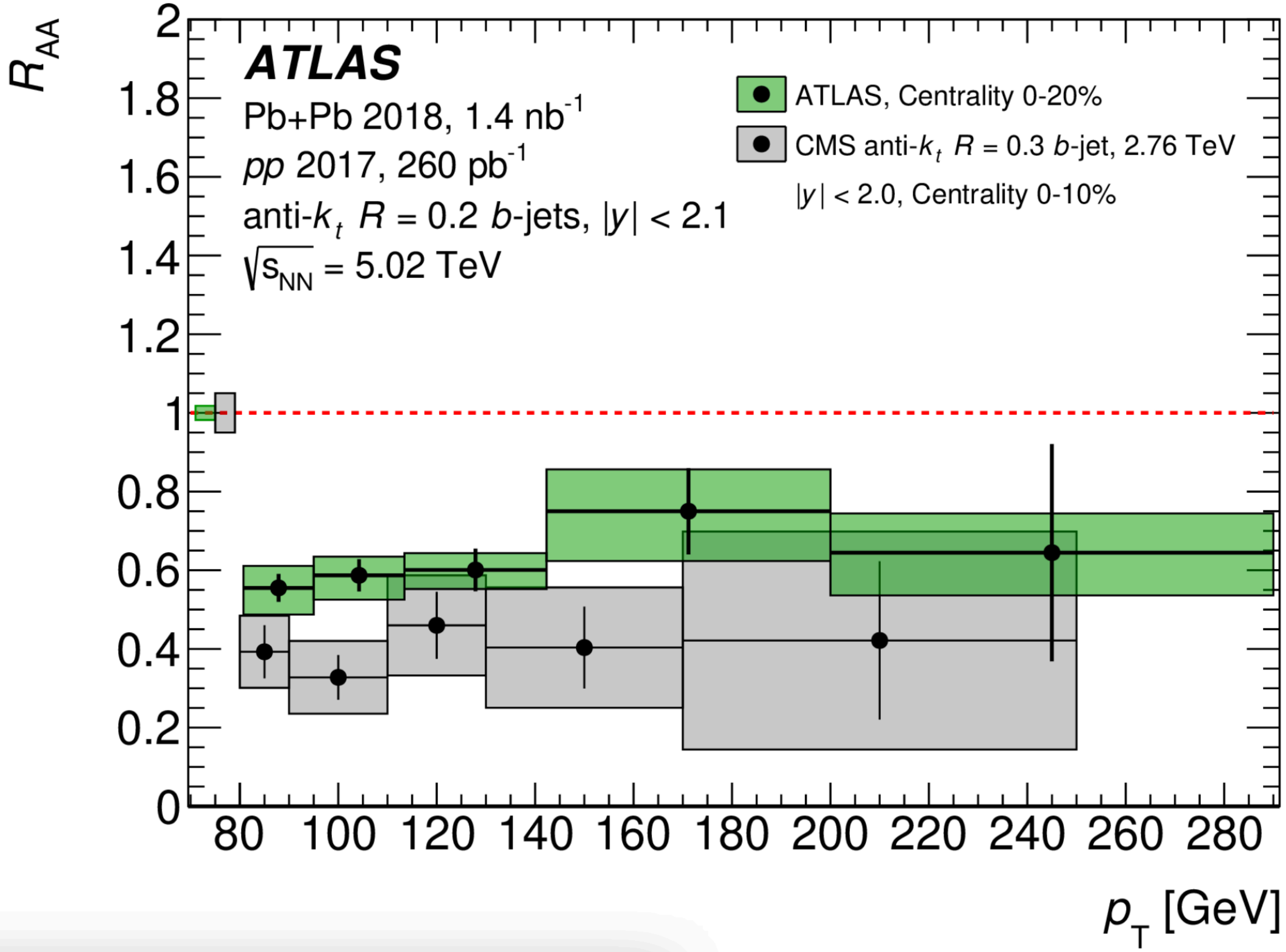
Similar conclusion when accessing the true jet energy via ML

$1/N_{pair} \; dN_{pair}/dx_J$ distributions



Data consistent with previous results measured in $\sqrt{s_{NN}} = 2.76$ TeV collisions

- Peak observed at intermediate x_J at low $p_{T,1}$ in central events, although milder



ATLAS
Pb+Pb 2018, 1.4 nb-1
pp 2017, 260 pb-1
anti-kt R = 0.2 b-jets, |y| < 2.1
√sNN = 5.02 TeV
ATLAS, Centrality 0-20%
CMS anti-kt R = 0.3 b-jet, 2.76 TeV
|y| < 2.0, Centrality 0-10%
RAA
pT [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
80
100
120
140
160
180
200
220
240
260
280