

Fundação  
para a Ciência  
e a Tecnologia

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# QGP tomography

Helena Santos

LIP, FCUL



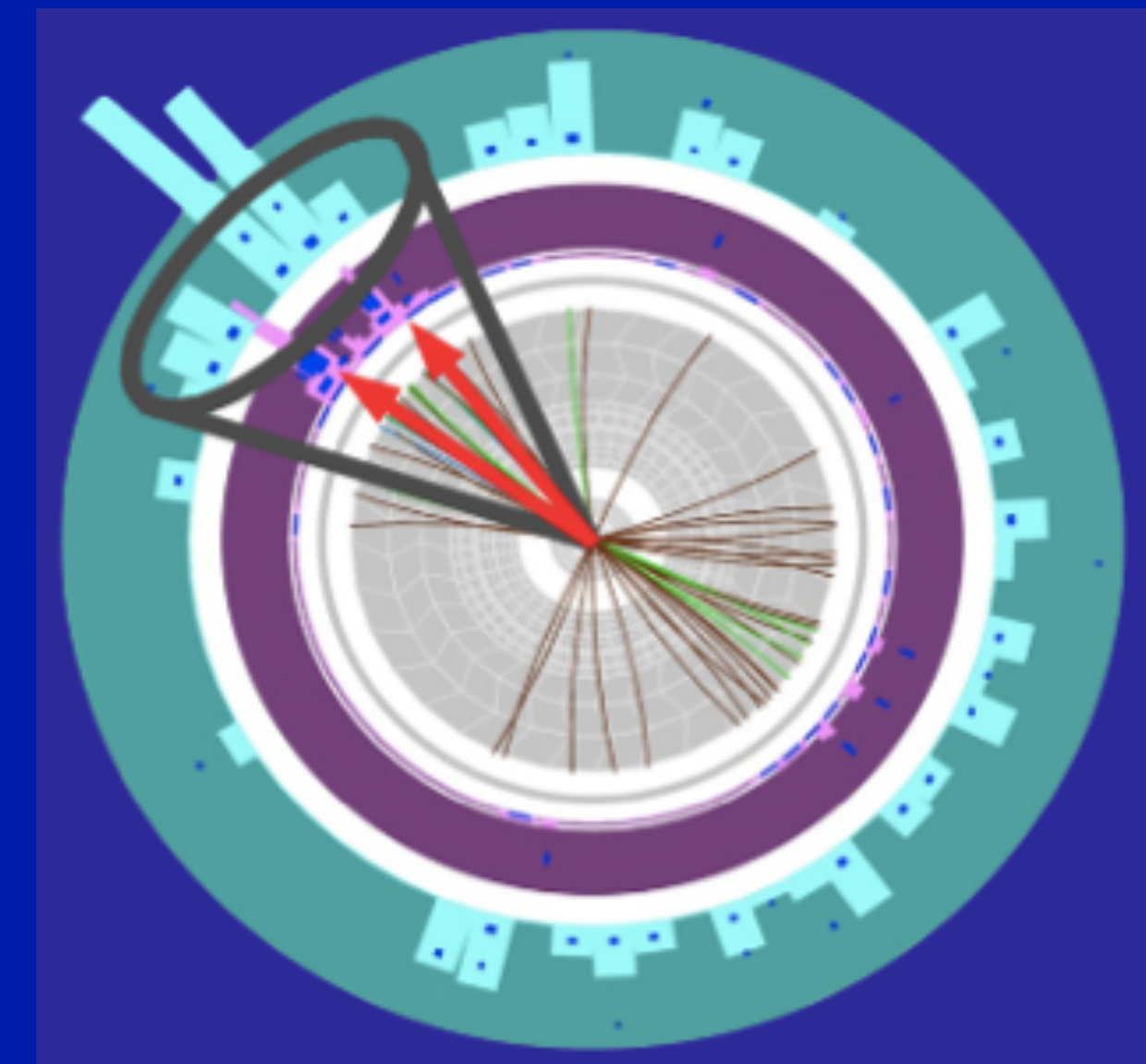
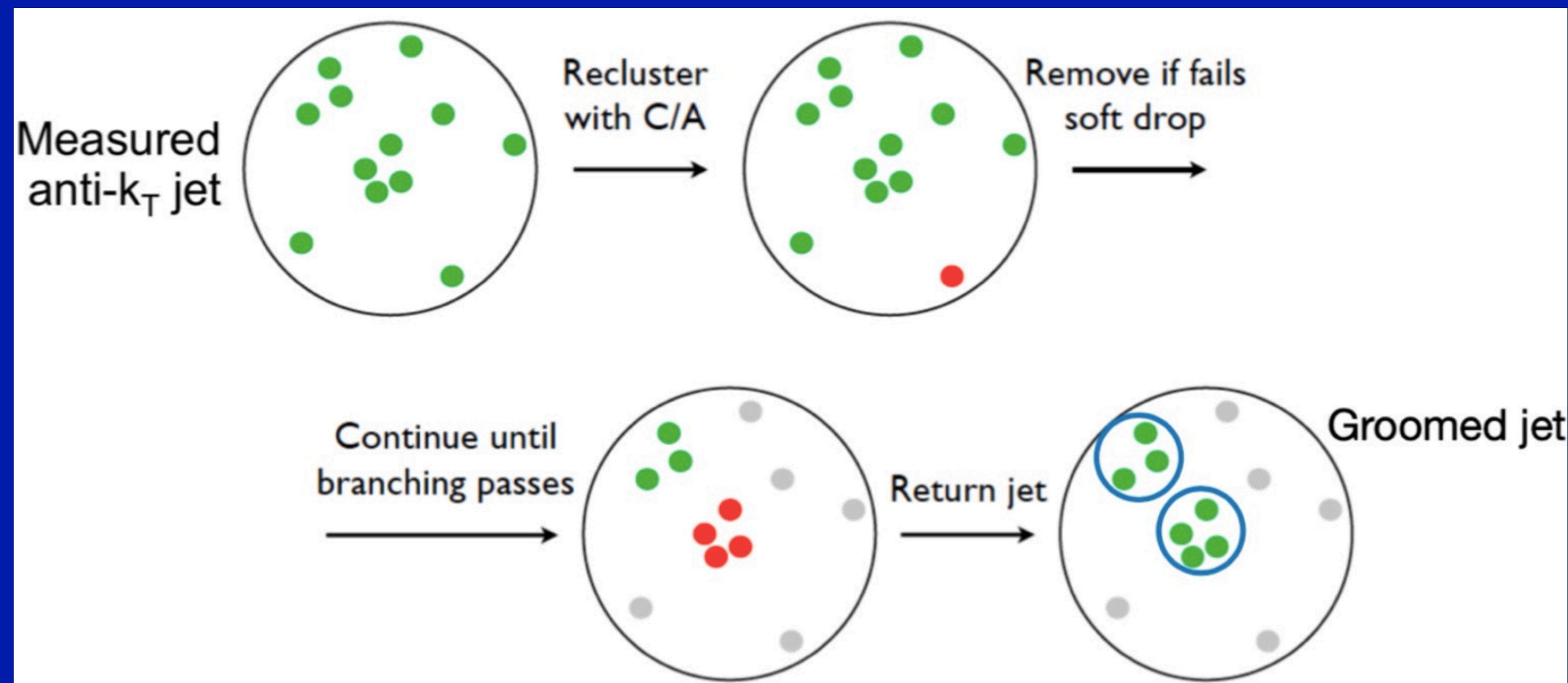
**CMS Heavy Ion Workshop 2023, 29-30 May, Trento**

- How do jets allow us to see the QGP and vice-versa?
- Do jets disturb the QGP measurably?

## Explore:

- the jet substructure
- the path length dependence of quenching
- the recoil region

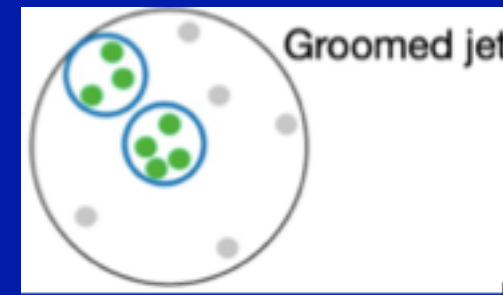
Substructure techniques like soft-drop or reclustering using subjects allow to experimentally access scales associated with individual branchings in the parton shower.





$$\frac{\min(p_T^{sj_1}, p_T^{sj_2})}{p_T^{sj_1} + p_T^{sj_2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$

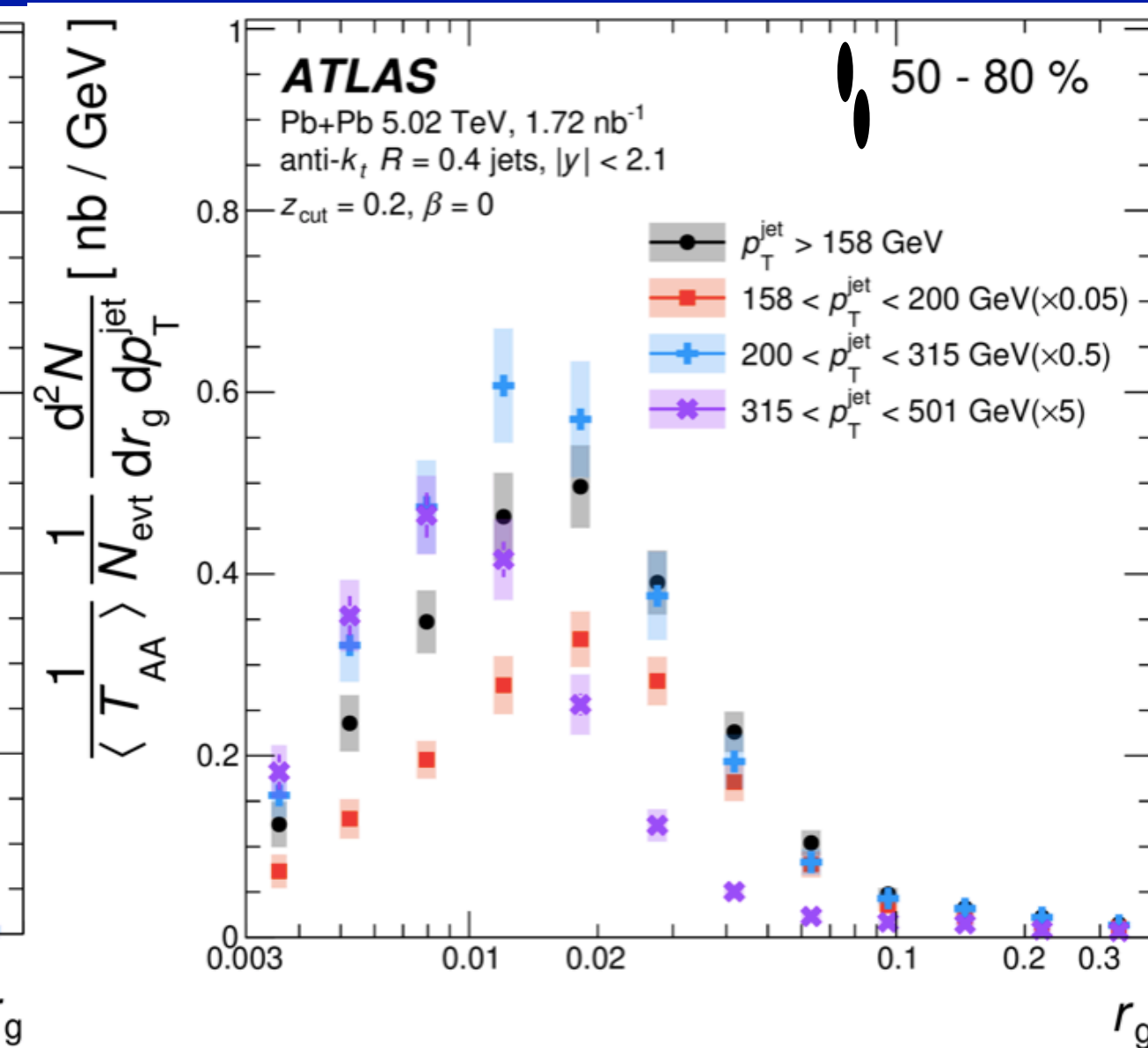
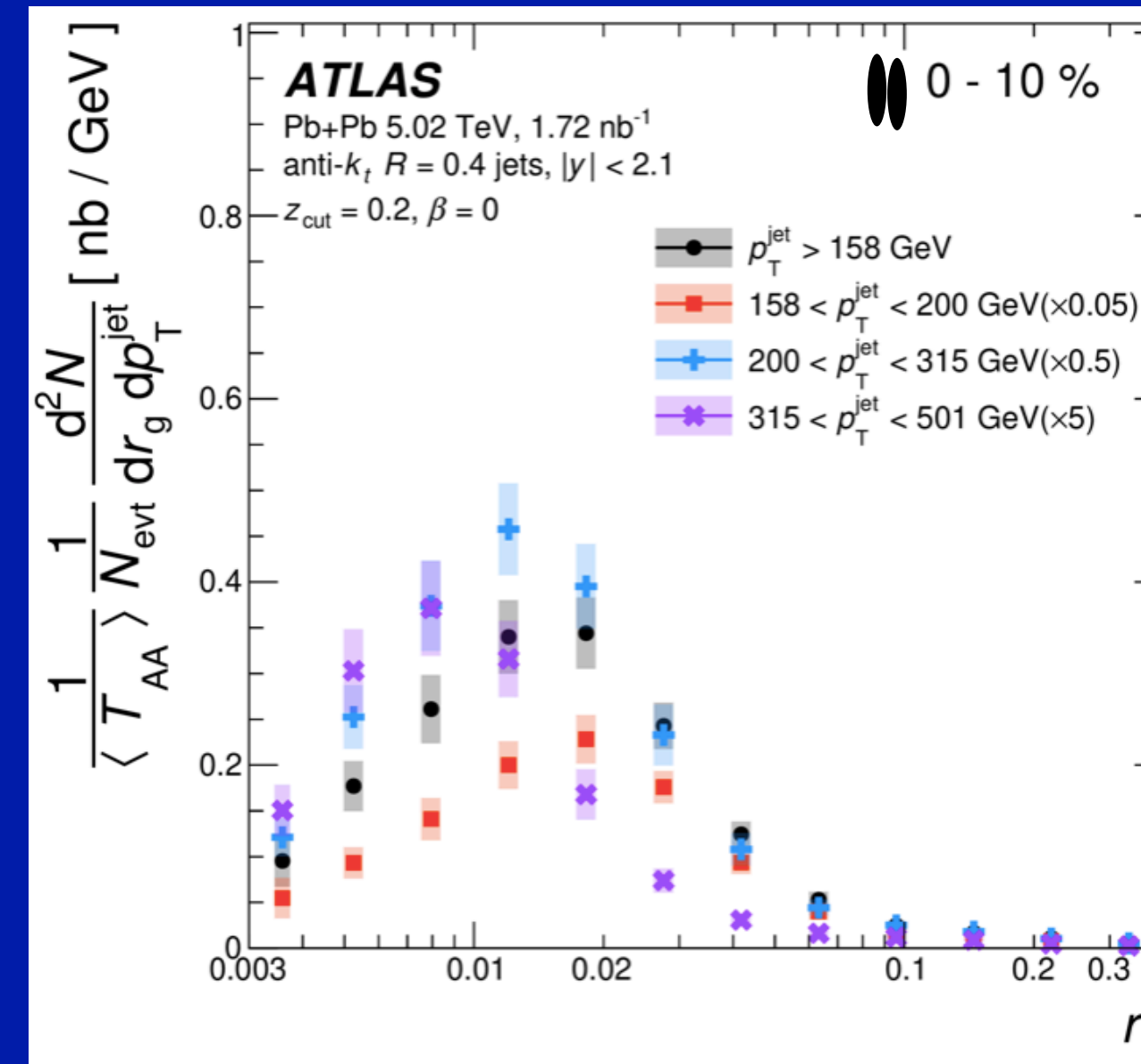
$$\Delta R_{12} = \sqrt{\Delta\eta_{12}^2 + \Delta\phi_{12}^2}$$



$z_{\text{cut}}=0.2, \quad \beta=0$

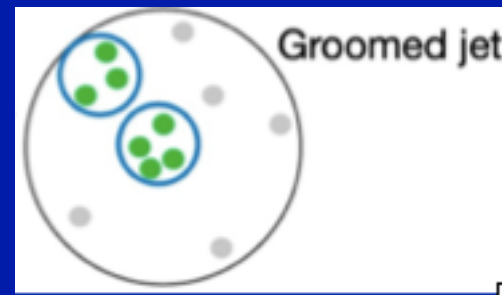
$r_g = \Delta R_{12}$  between the subjets from the first splitting satisfying the soft drop condition

- Jets are narrower with increasing  $p_T$ , independently on centrality



$$\frac{\min(p_T^{sj1}, p_T^{sj2})}{p_T^{sj1} + p_T^{sj2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta$$

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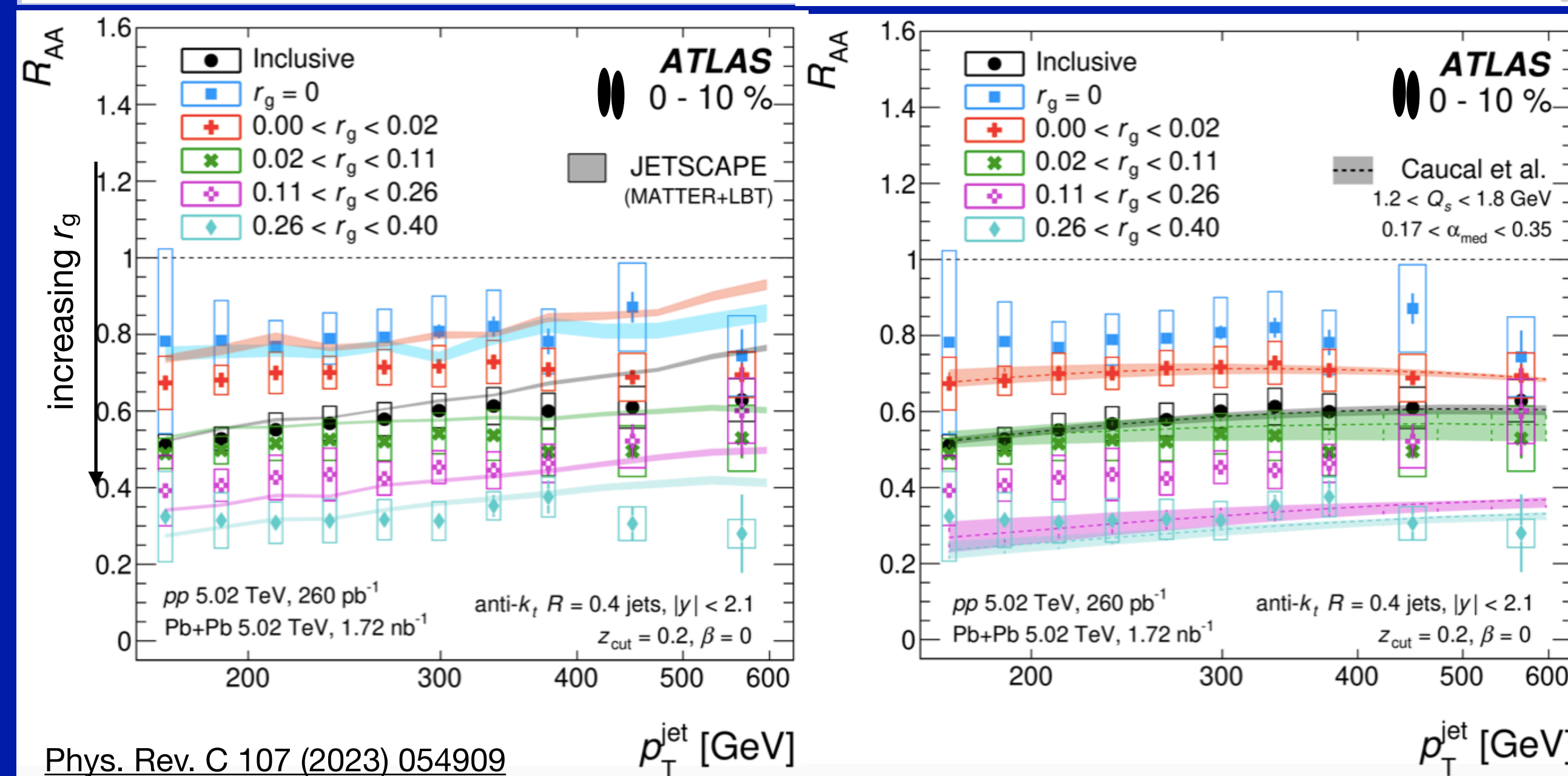
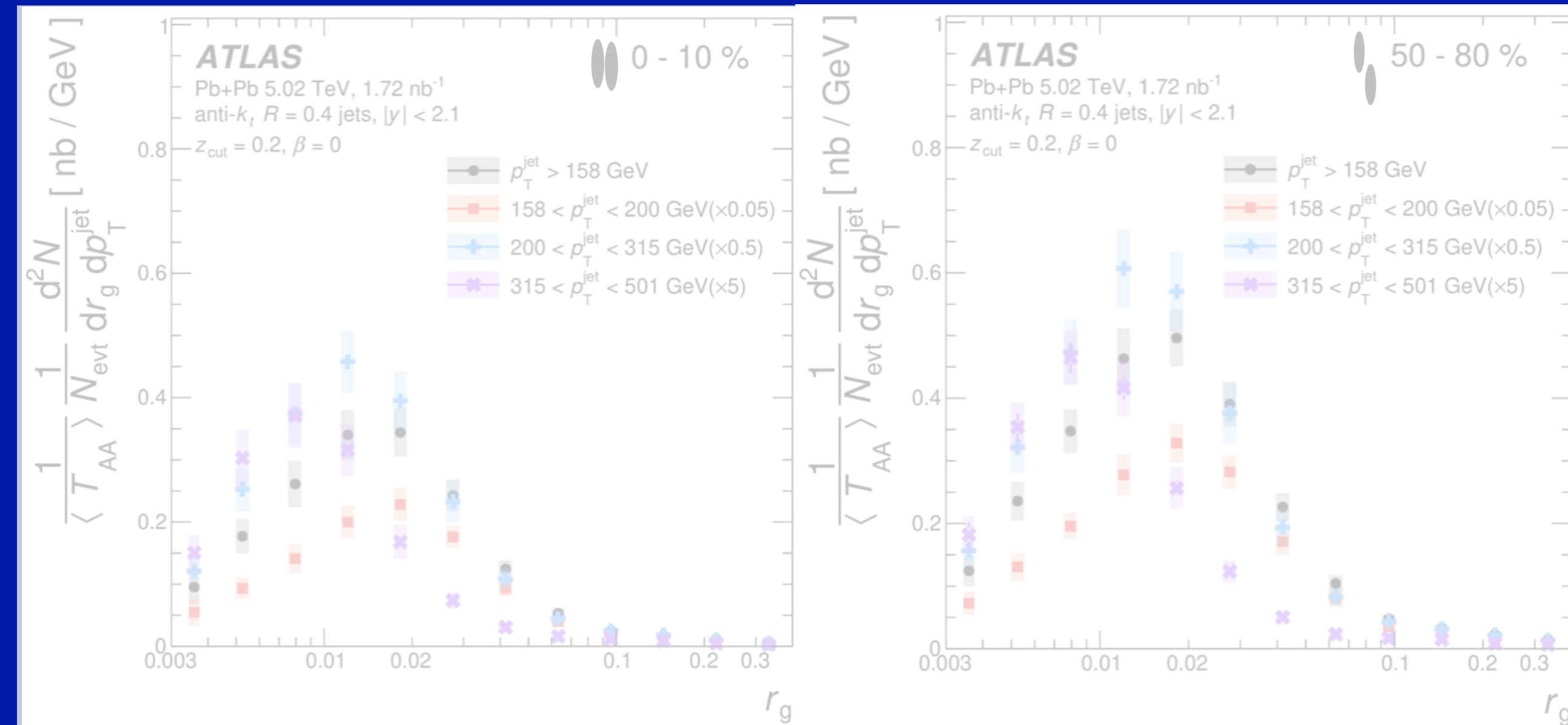
- Jets are narrower with increasing  $p_T$ , independently on centrality

- Jets with wider hard splittings are significantly more suppressed in central collisions

Result points to decoherent energy loss

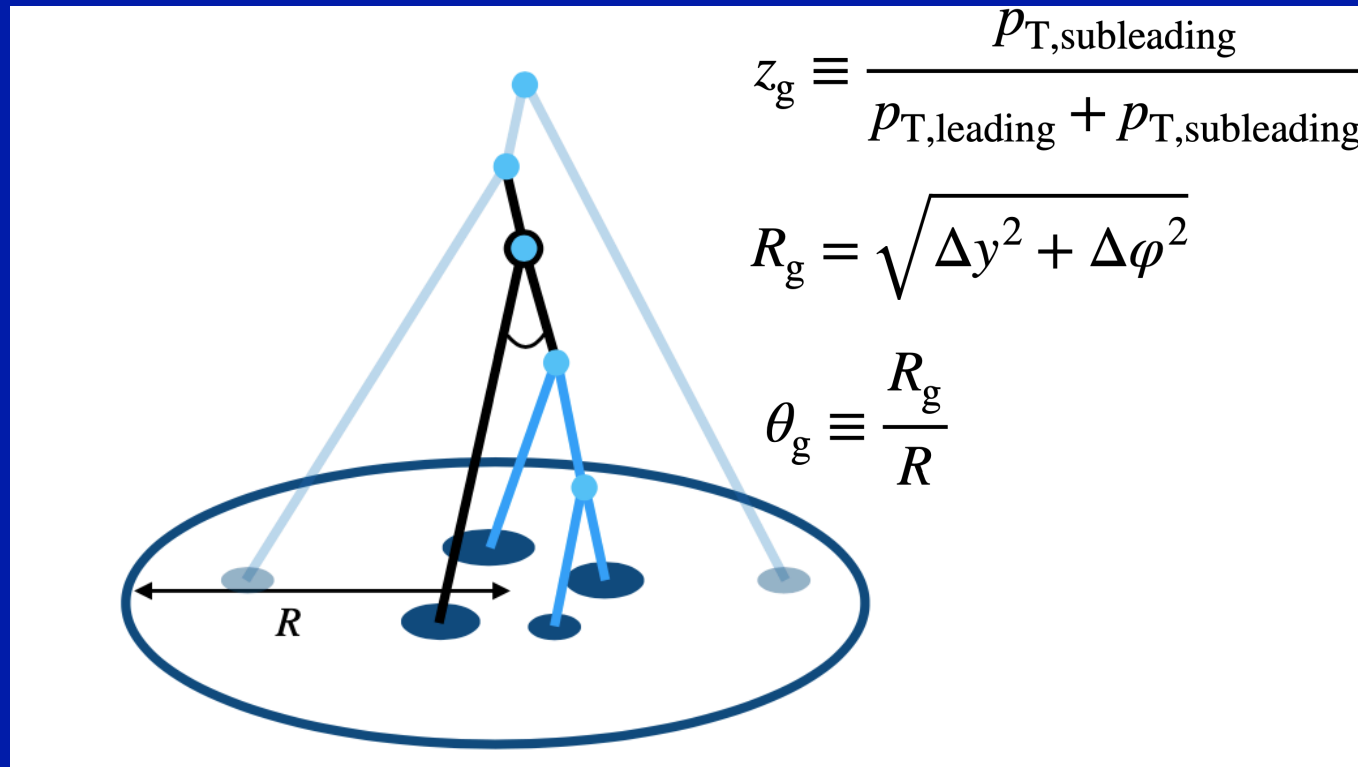
JETSCAPE compatible with exception for very low  $r_g$  (underestimates the suppression)

Caucal et al. overestimates the suppression for intermediate  $r_g$





# Jet substructure - $Z_g$



$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$R_g = \sqrt{\Delta y^2 + \Delta \phi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

SoftDrop conditions

ALICE:

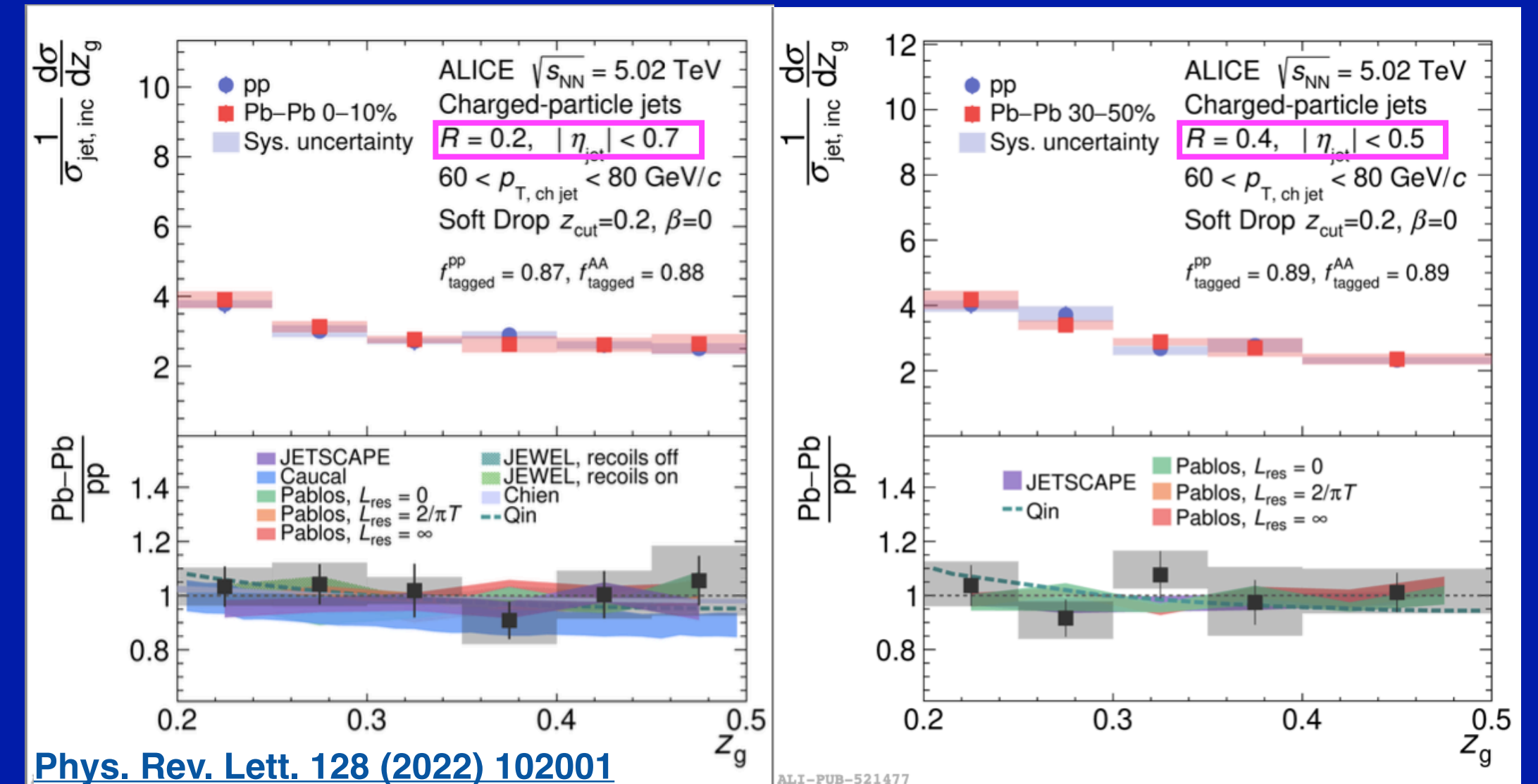
$z_{\text{cut}} = 0.2, \beta=0, R=0.2$  and  $0.4$

$60 < p_{T,\text{ch jets}} < 80 \text{ GeV}$

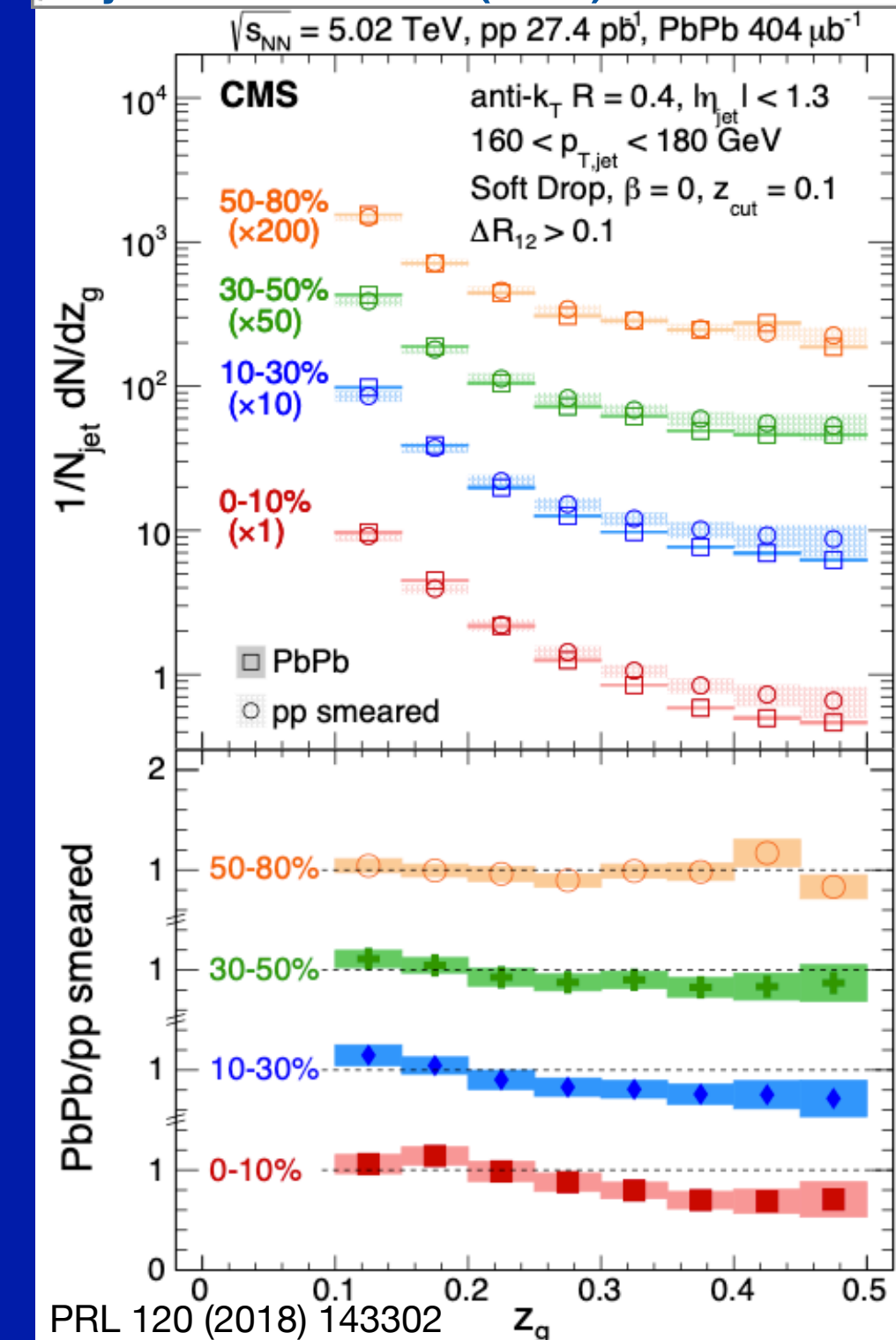
CMS:

$z_{\text{cut}} = 0.1, \beta=0, R=0.4$

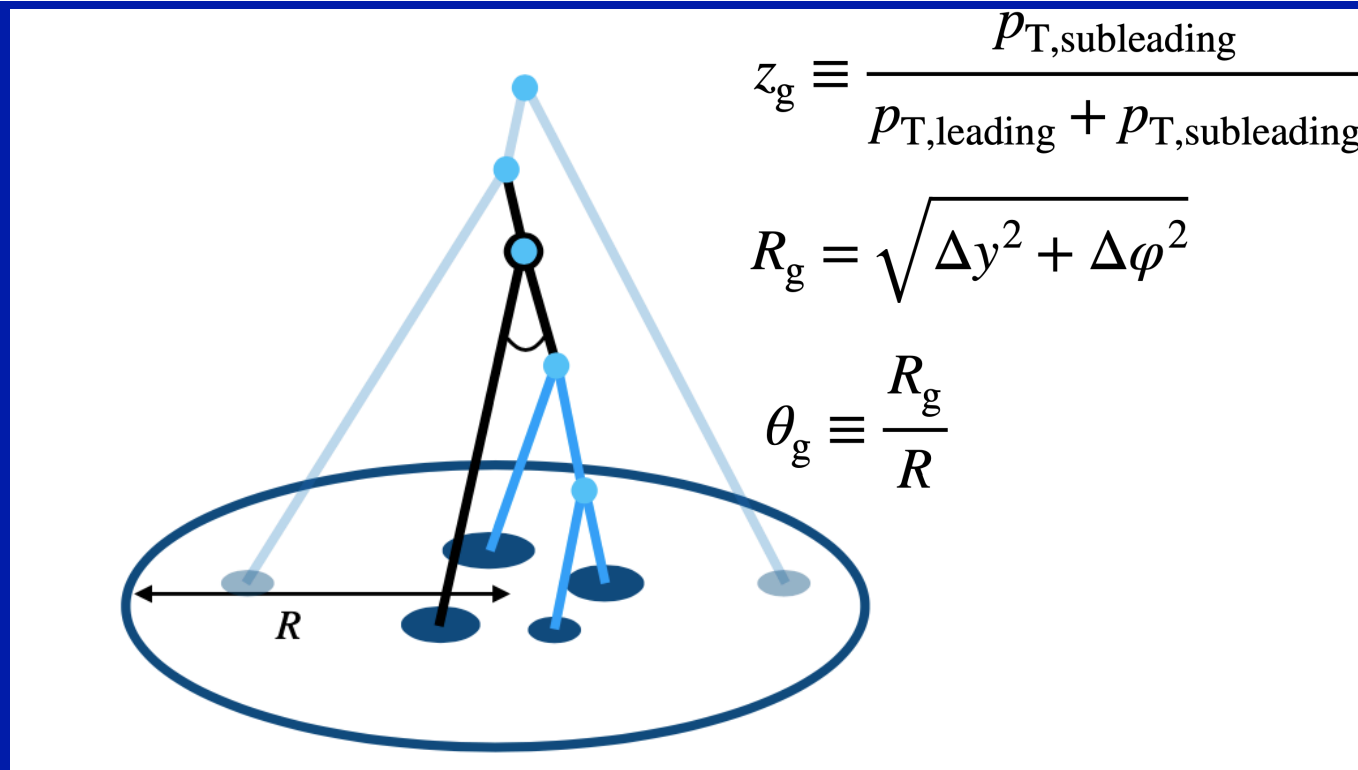
- when removing soft radiation under the grooming conditions no modifications on the  $p_T$  balance of the hardest subjets are seen.
- Reproduced by models that assume coherent or decoherent energy loss within uncertainties.



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PRL 120 (2018) 143302



SoftDrop conditions

ALICE:

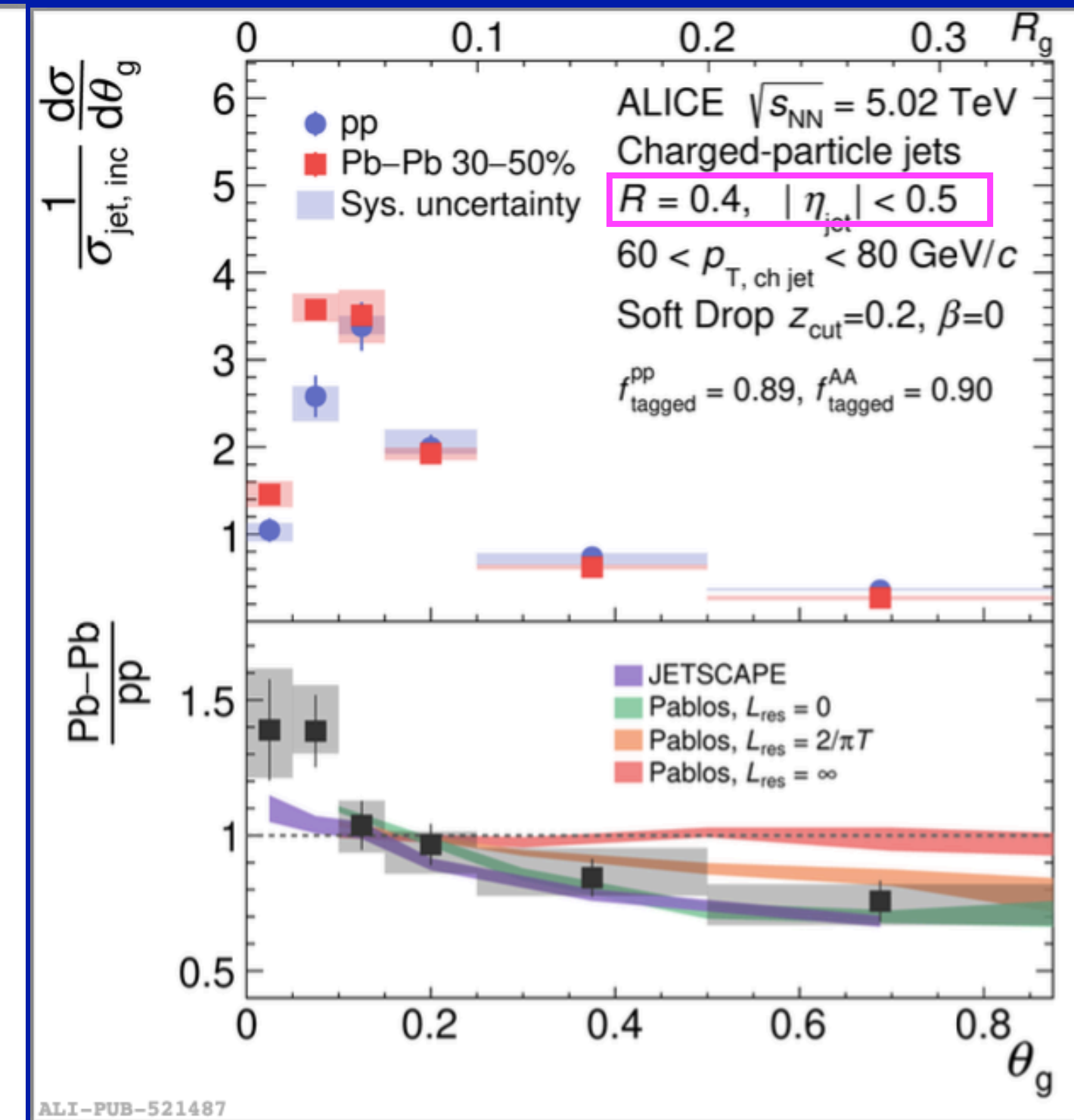
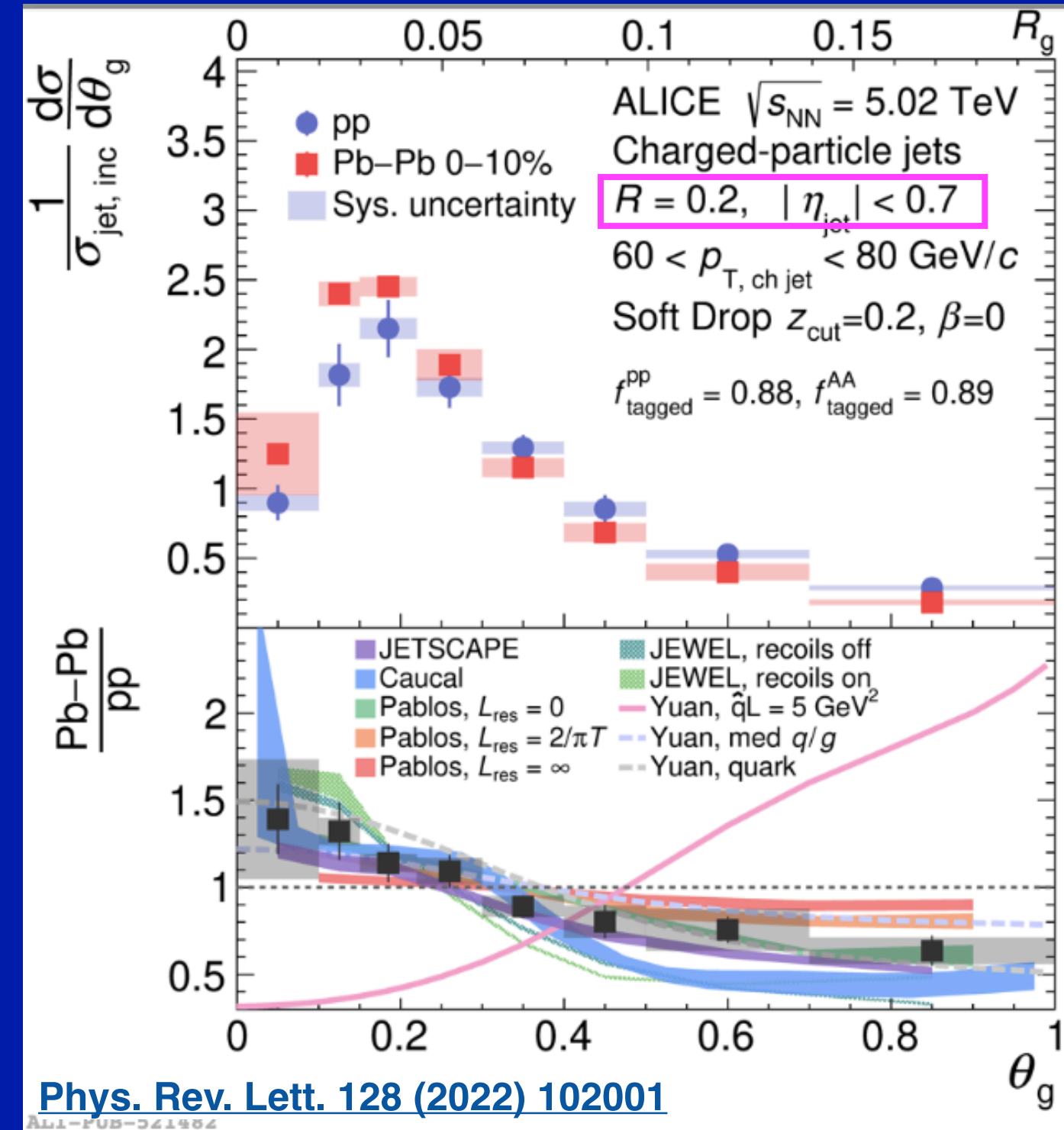
$z_{\text{cut}} = 0.2, \beta=0, R=0.2$  and  $0.4$

$60 < p_{T,\text{ch jets}} < 80 \text{ GeV}$

- Enhancement of narrow splittings and suppression of wider ones. No difference for  $R=0.4$  jets

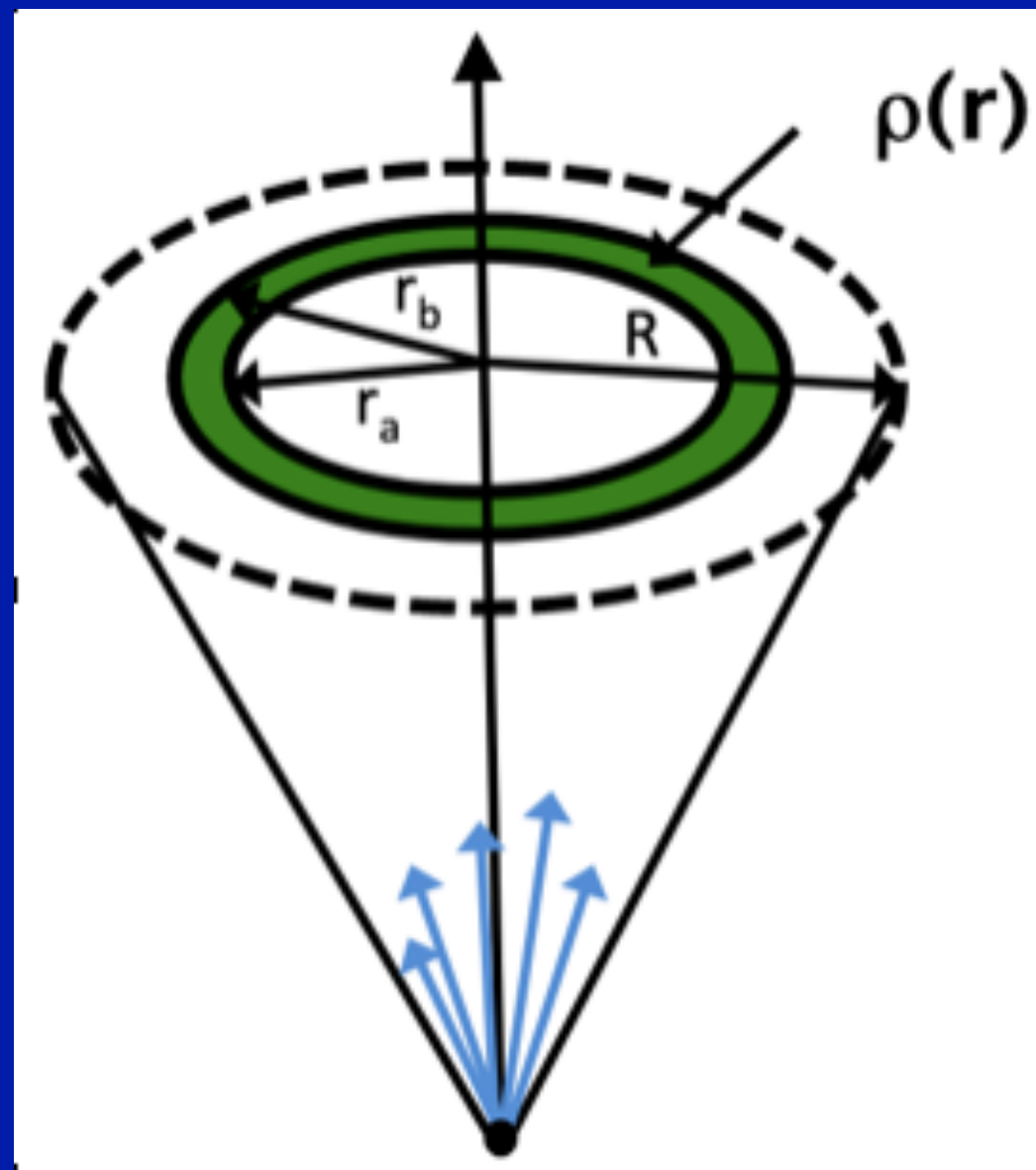
Hybrid model assuming fully incoherent energy loss reproduces the data for  $\theta_g > 0.2$

Yuan (quark only) describes the data as well



# Sensitivity to medium response

JHEP 05 (2021) 116



Jet radial momentum distributions

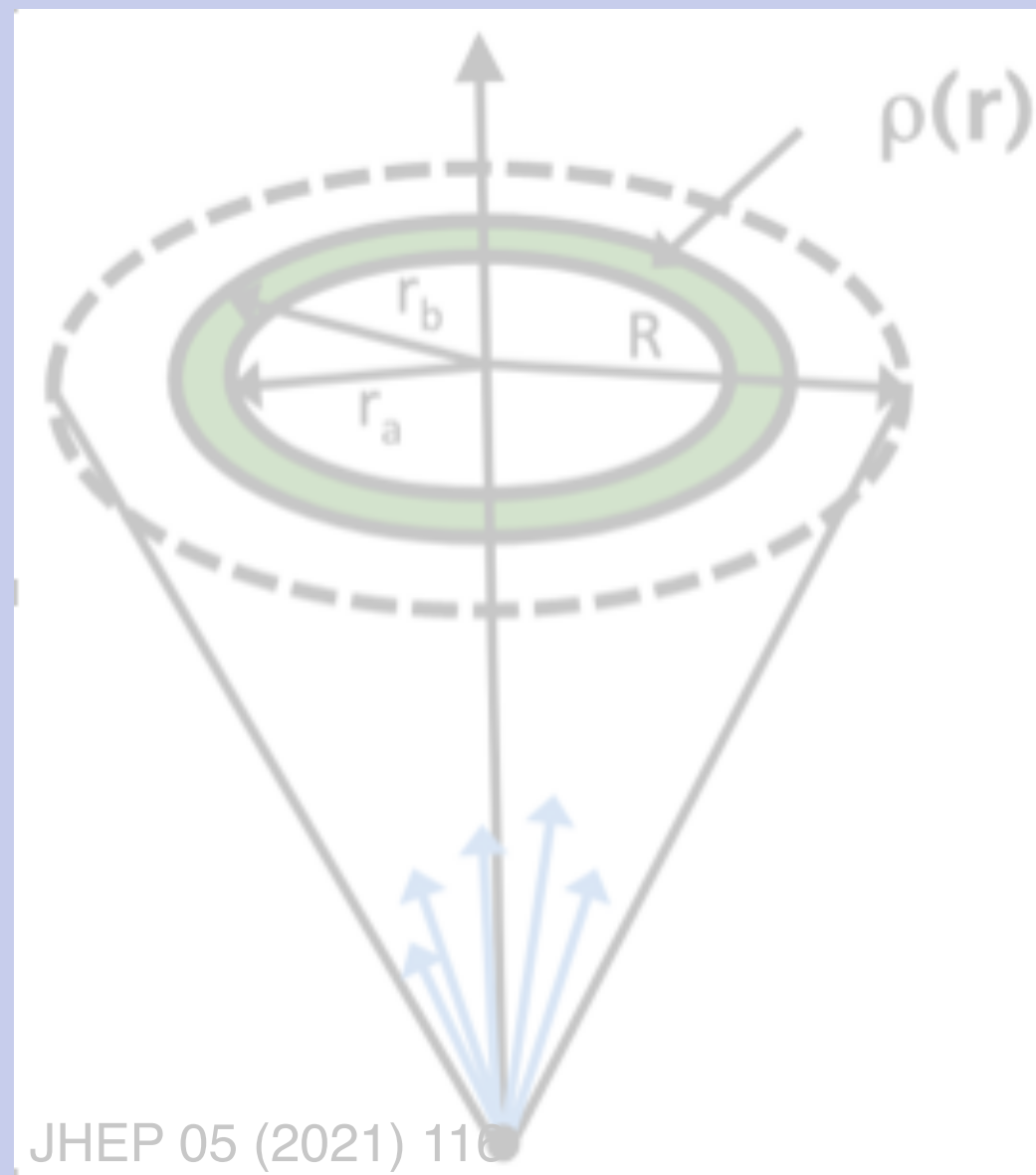
$$P(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_T^{\text{trk}}$$

Jet shapes

$$\rho(\Delta r) = \frac{P(\Delta r)}{\sum_{\text{jets}} \sum_{\text{tracks} \in \Delta r < 1} p_T^{\text{ch}}}$$



# Sensitivity to medium response

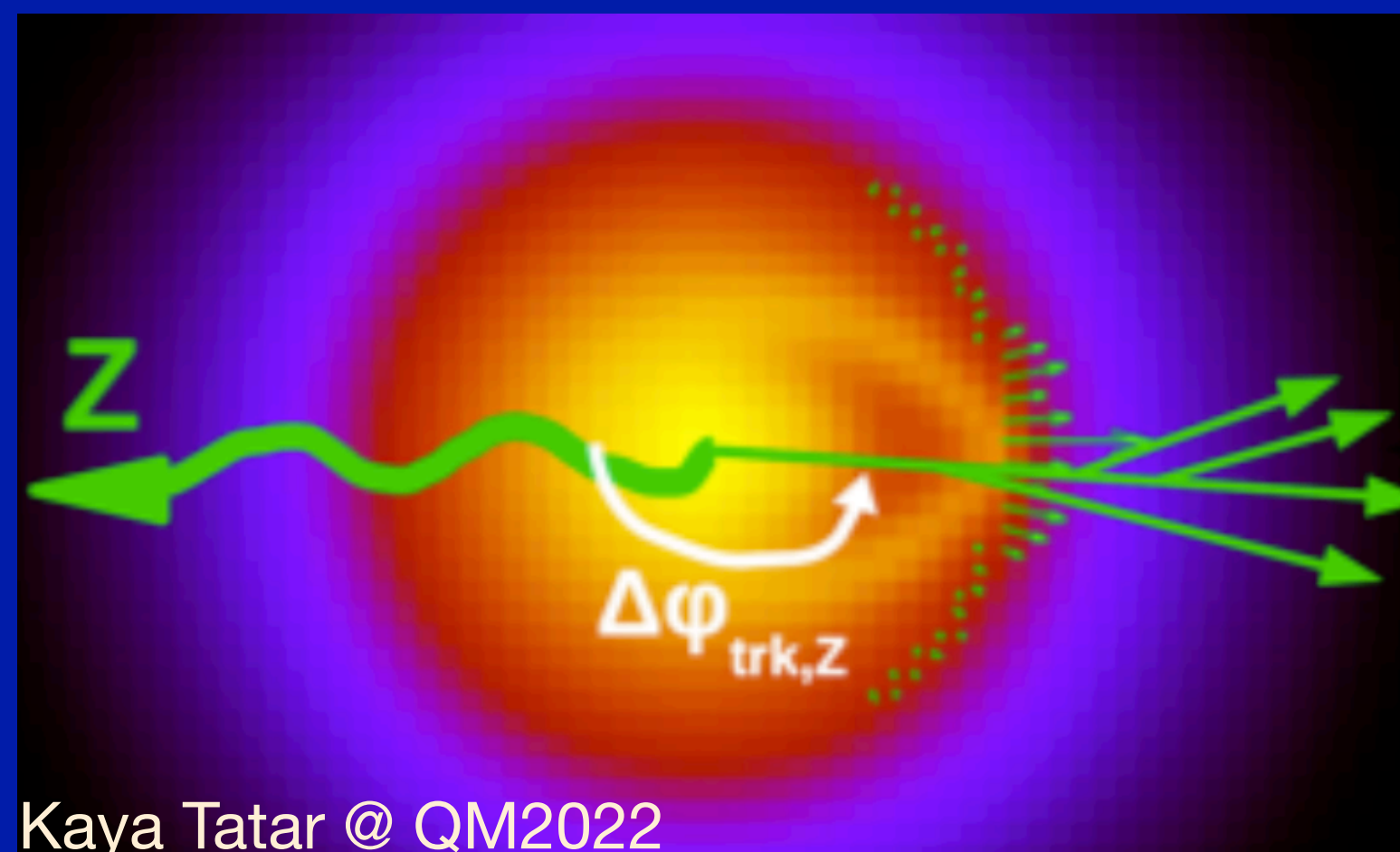


Jet radial momentum distributions

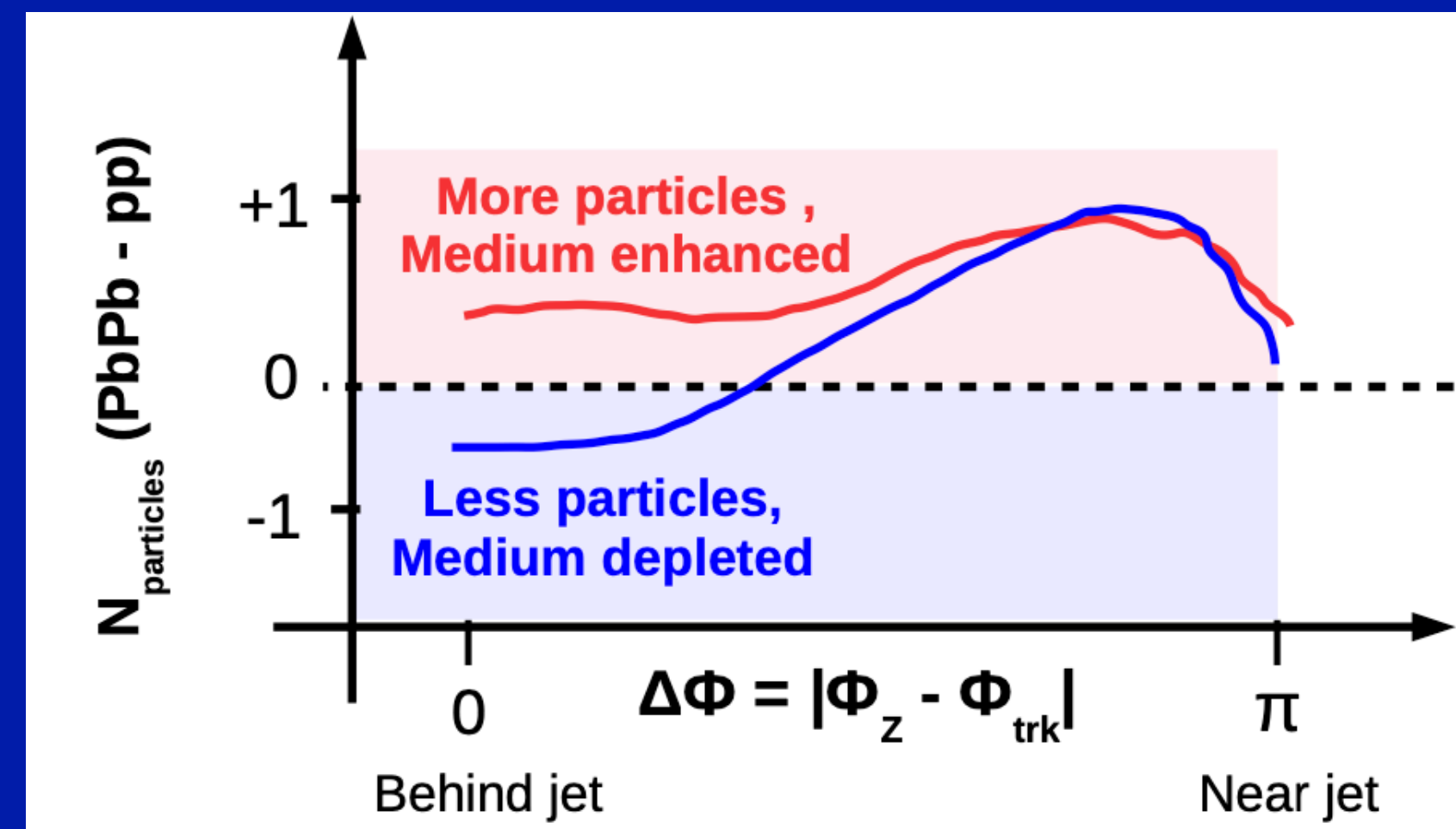
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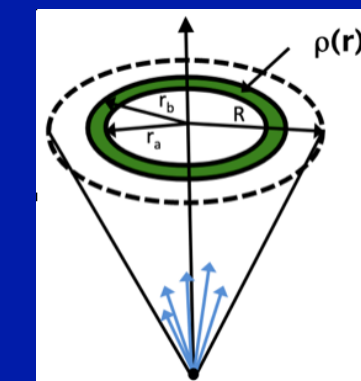
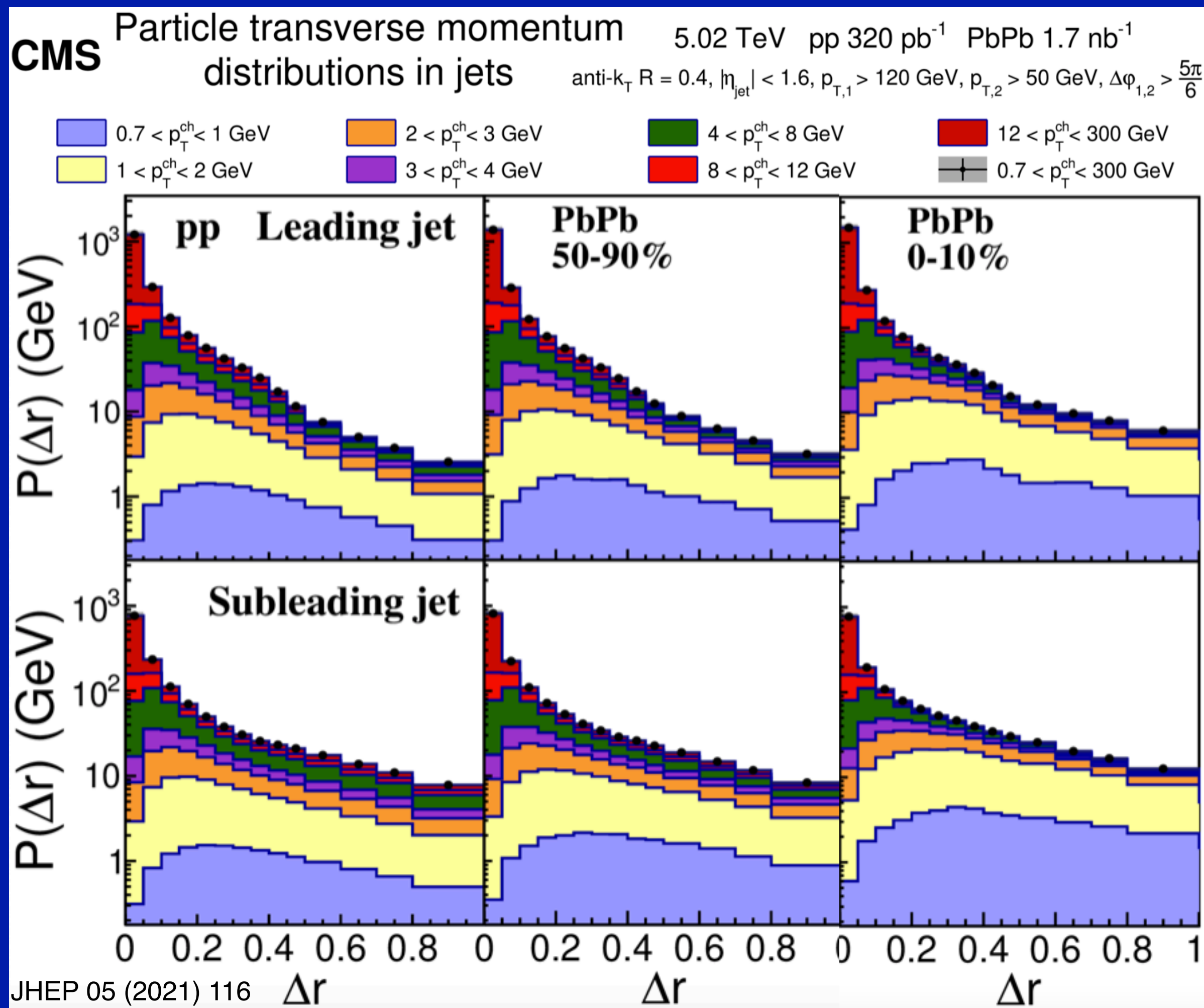
$$\rho(\Delta r) = \frac{P(\Delta r)}{\sum_{\text{jets}} \sum_{\text{tracks} \in \Delta r < 1} p_T^{\text{ch}}}$$



Kaya Tatar @ QM2022



Angular scan of jet-QGP interactions

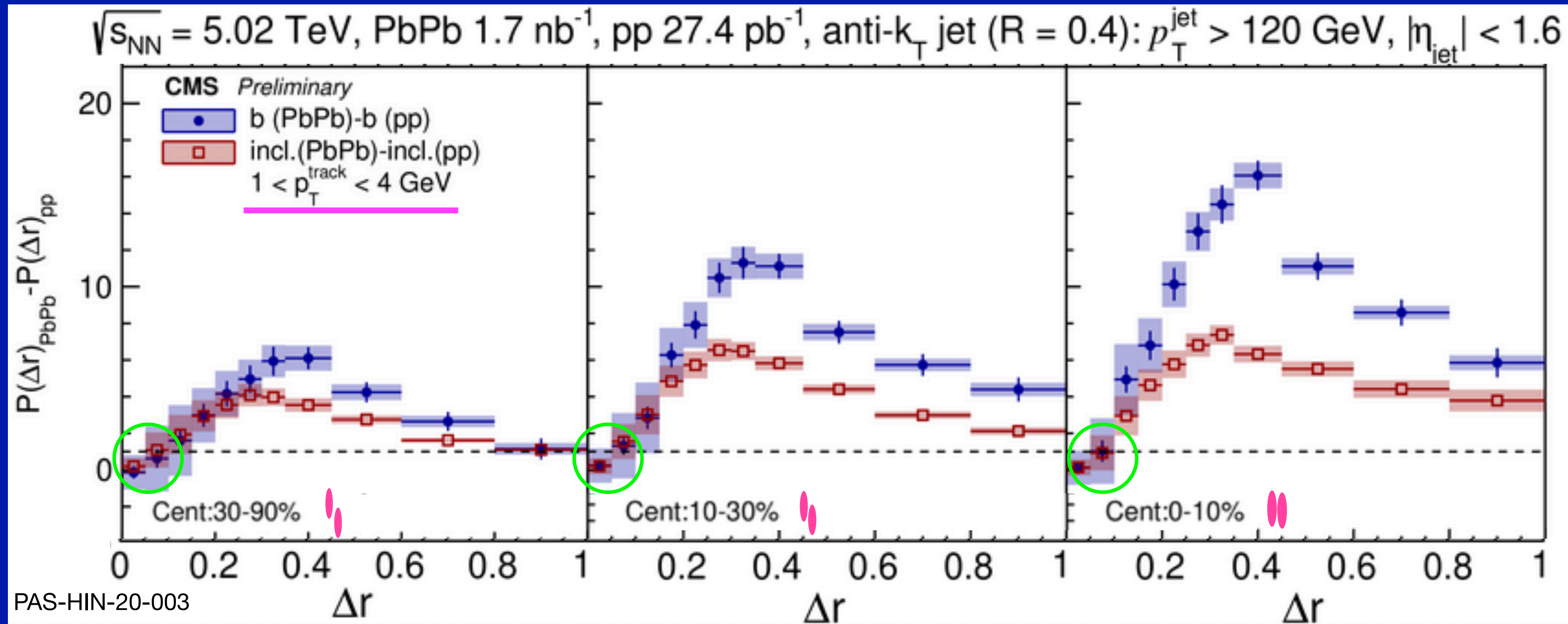
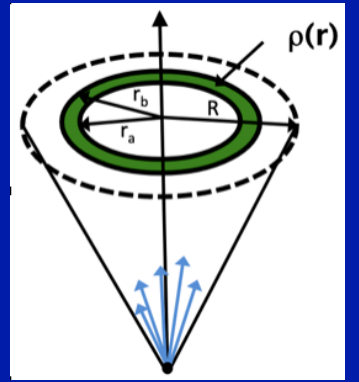


Enhancement of low- $p_T$  charged particles in central PbPb relative to  $pp$  at large angular distance from the jet axis.

One common explanation is that the energy lost at high  $p_T$  resulting from interactions between partons of both jet and QGP reappears in the form of low- $p_T$  particles far away from the jet axis.



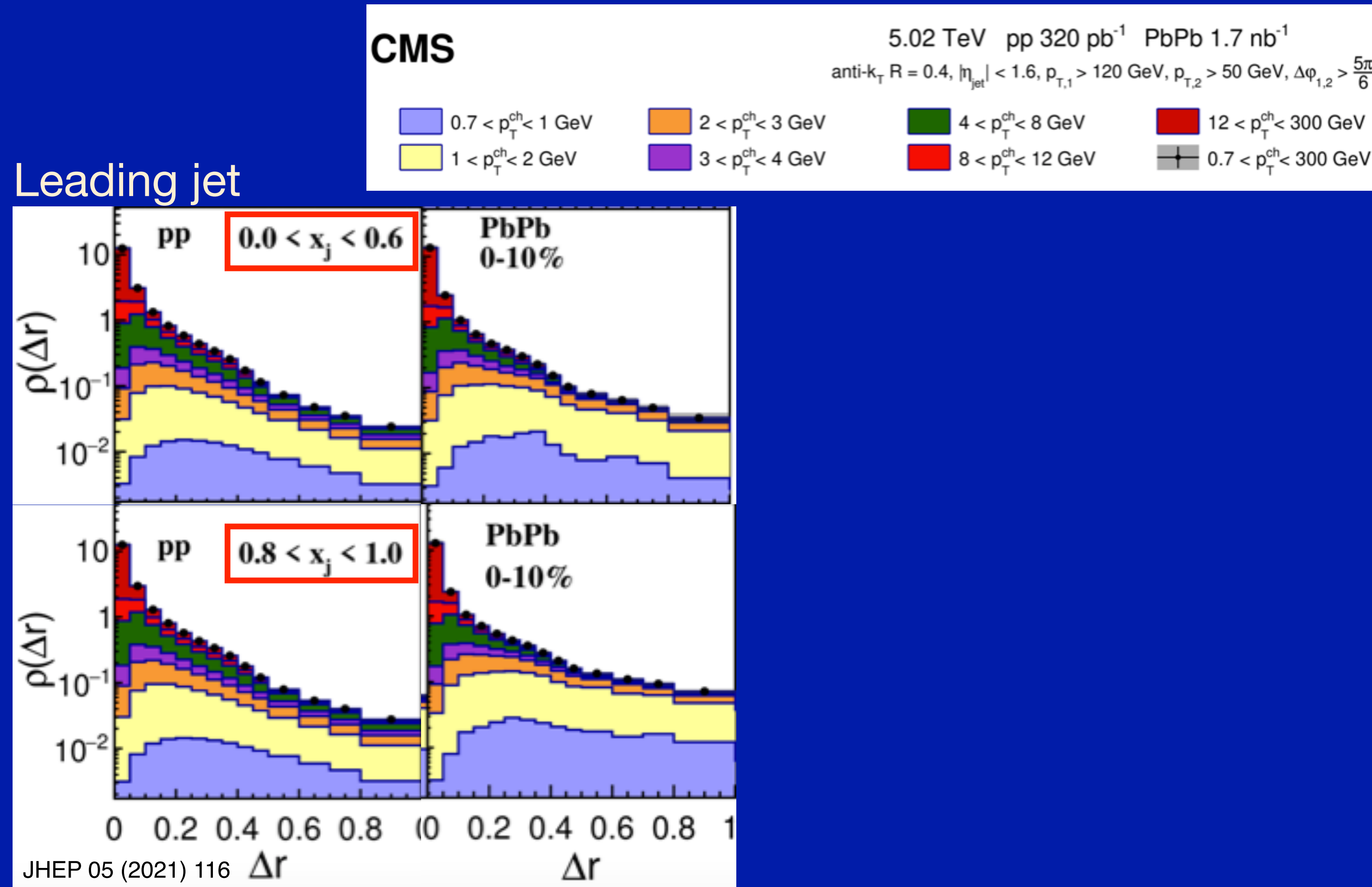
For **inclusive** and  **$b$ -jets**



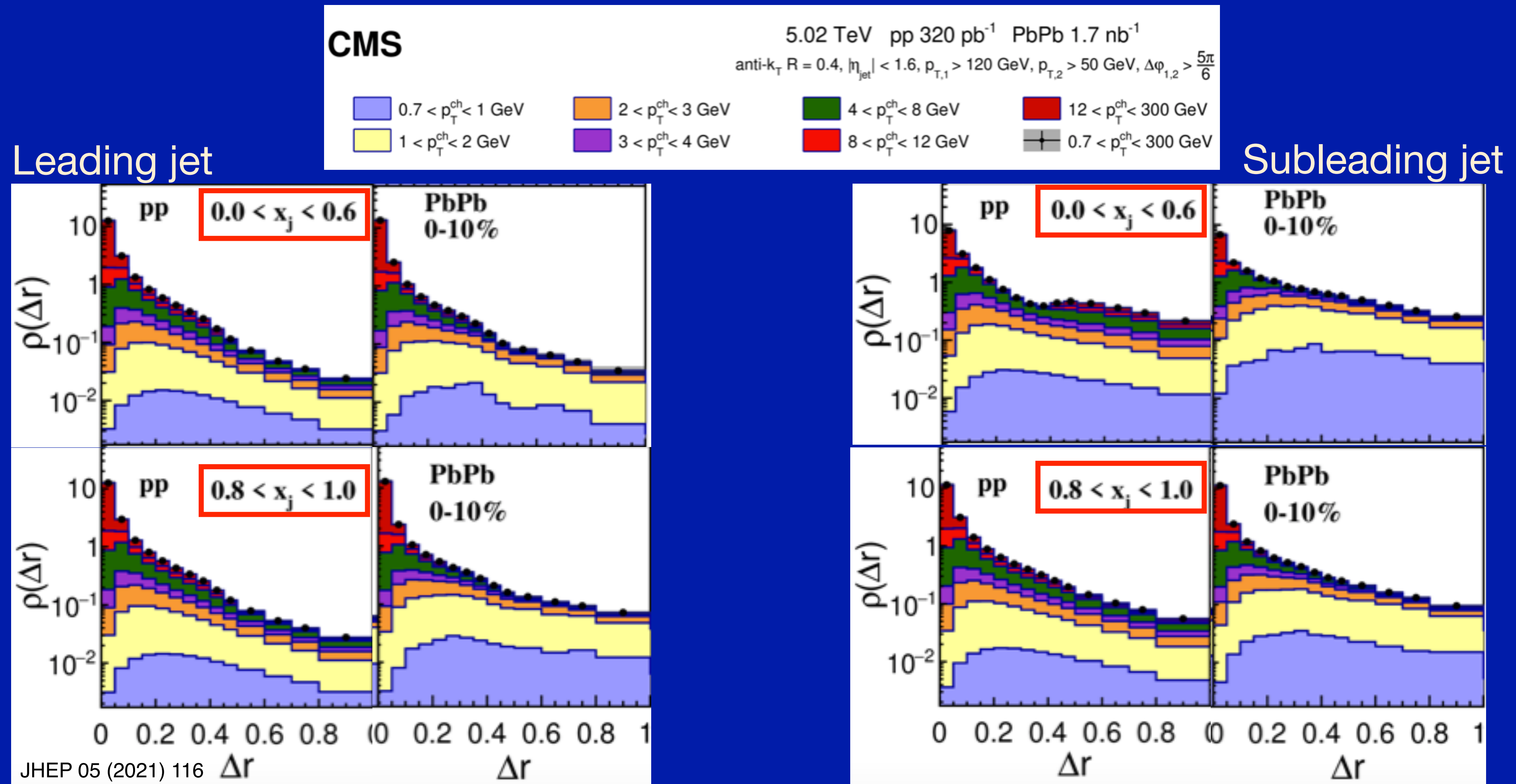
- In PbPb more  $p_T$  from **low momentum particles** is accumulated at the edge of the jet ( $\Delta r \sim 0.3 - 0.4$  for  $R=0.4$  jets).
- **Core of the jet is unmodified**, independently on the flavour, but then the redistribution is strongly enhanced for  $b$ -jets



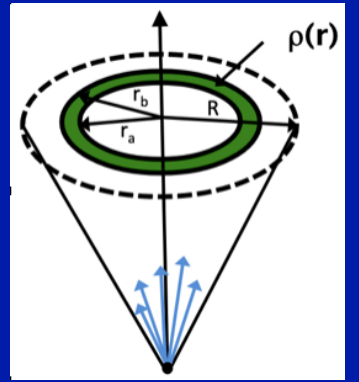
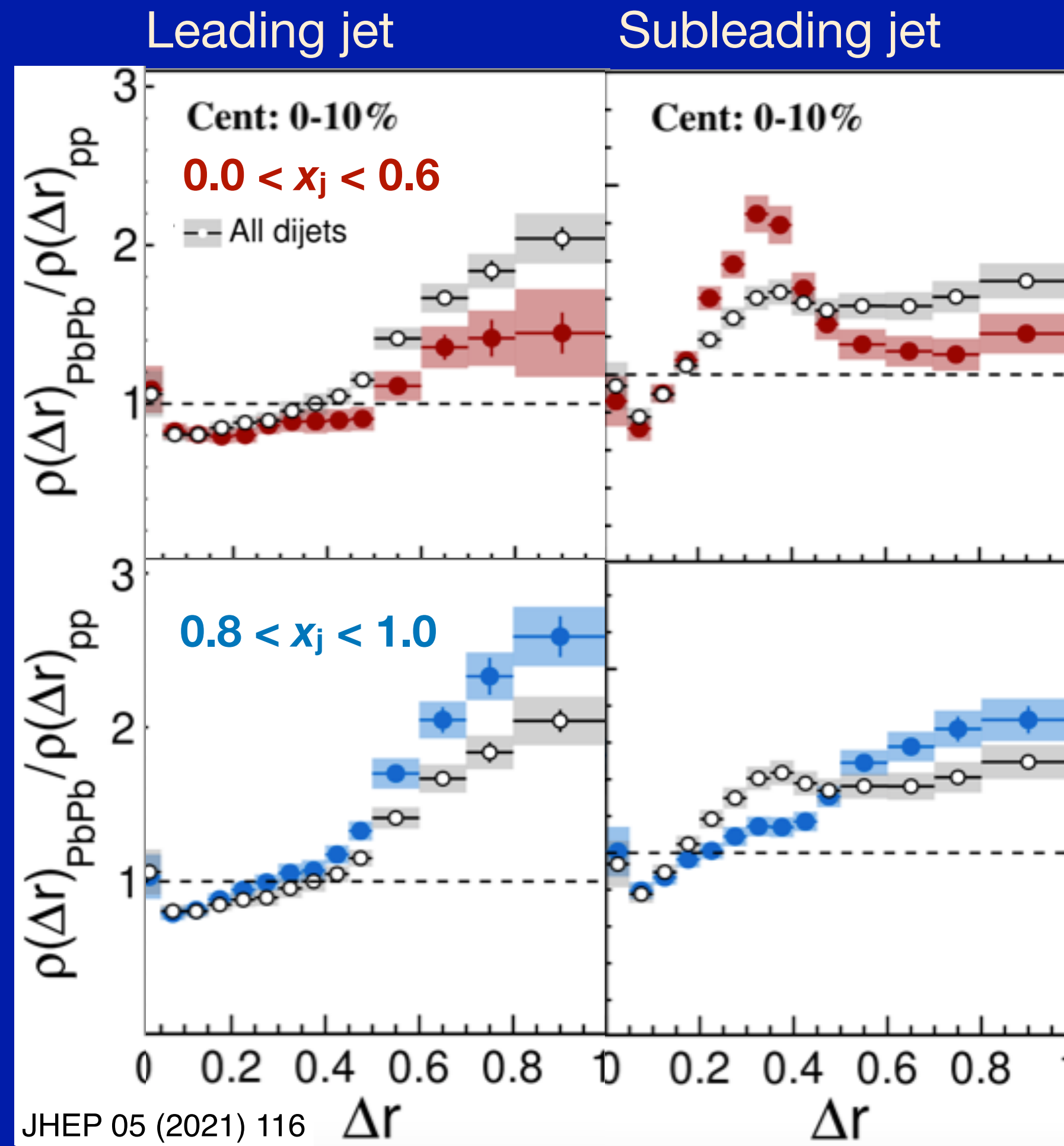
Leading jet



- Enhancement of low- $p_T$  charged particles in central PbPb relative to  $pp$  at large  $\Delta r$ .
- For leading jets the enhancement is larger for balanced dijets (no surface bias).



- Enhancement of low- $p_T$  charged particles in central PbPb relative to  $pp$  at large  $\Delta r$ .
- For leading jets the enhancement is larger for balanced dijets (no surface bias).
- Higher modification for sub-leading jets in unbalanced dijets.

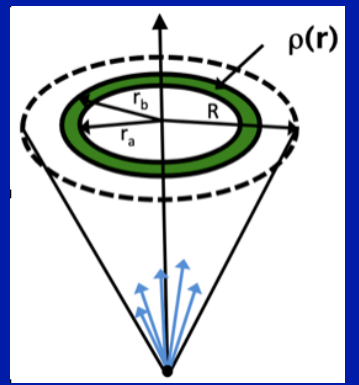
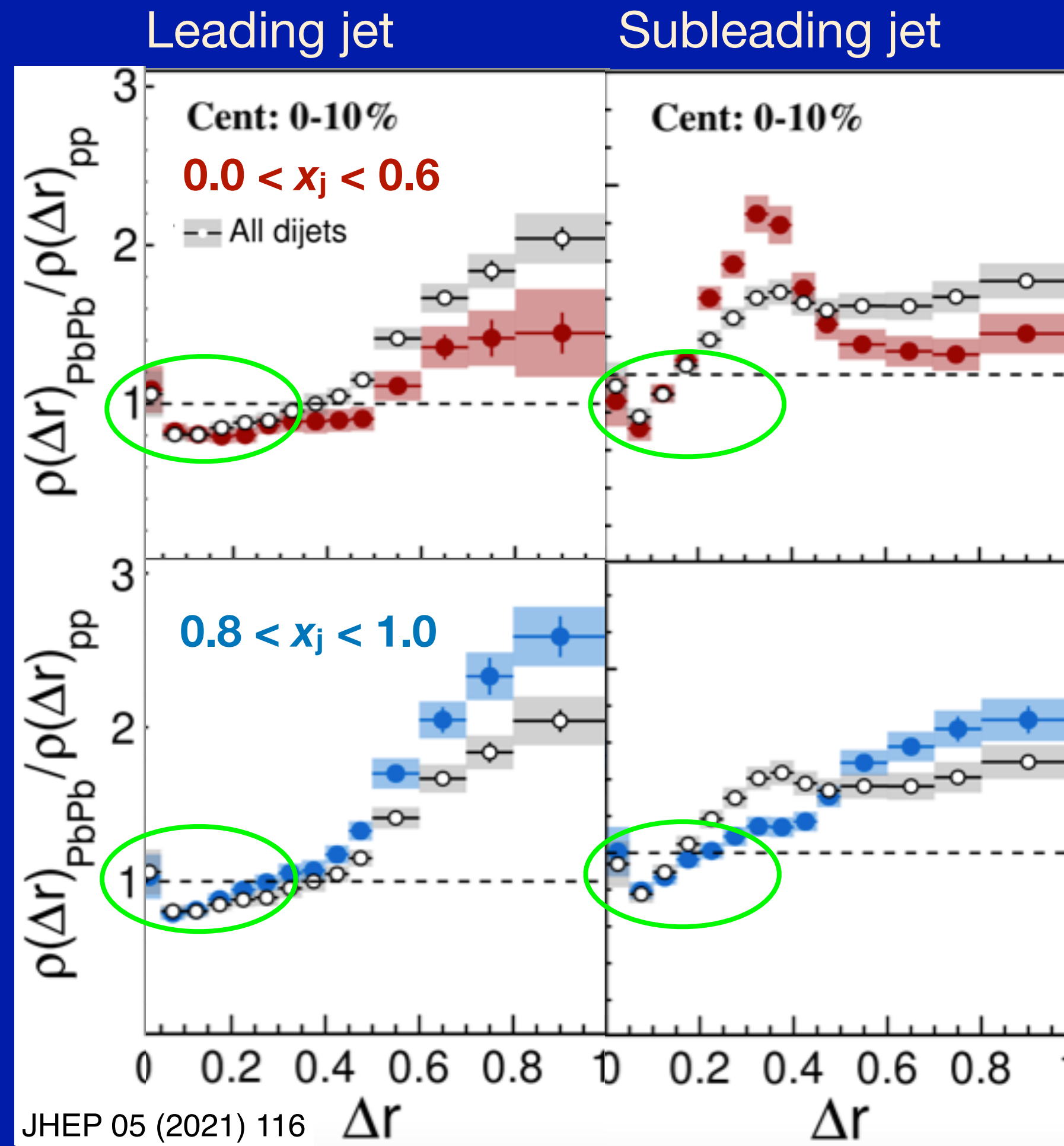


For subleading jets a clear effect at  $\Delta r \approx 0.3$  is observed, explained by the presence of a 3<sup>rd</sup> recoiled jet in  $pp$  that eventually disappeared in PbPb.

Enhancement of the PbPb leading (and subleading) jet shape modification at large  $\Delta r$  in balanced dijets.

Significant effects from different path length crossed.





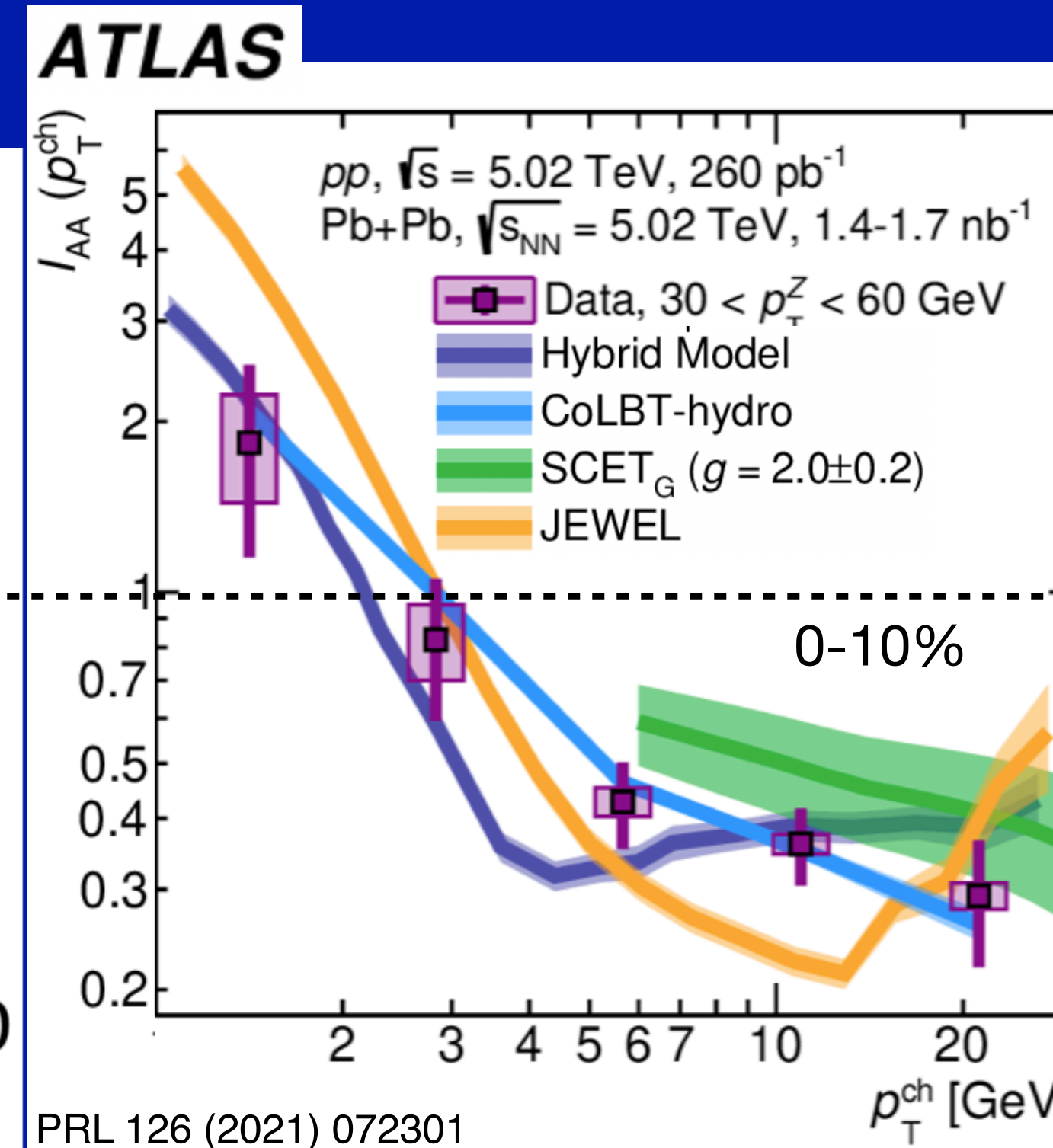
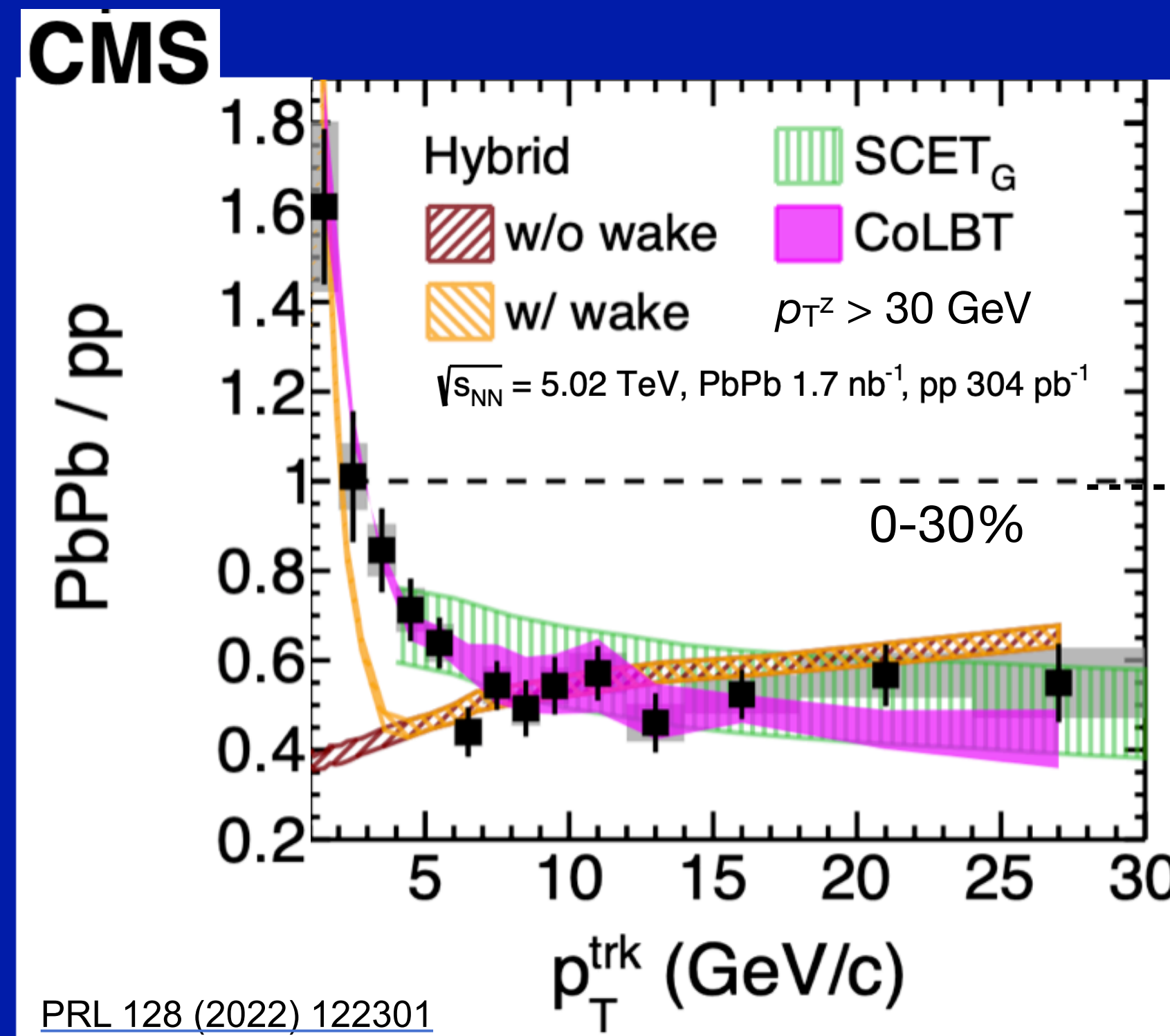
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Enhancement of the PbPb leading (and subleading) jet shape modification at large  $\Delta r$  in balanced dijets.

Significant effects from different path length crossed.

Besides, the jet core remains unmodified.

Then depletion of particles at low radial region. This depletion is there independently on centrality (backup).



The  $p_T$  spectrum of charged particles recoiling against Z is strongly modified in PbPb.

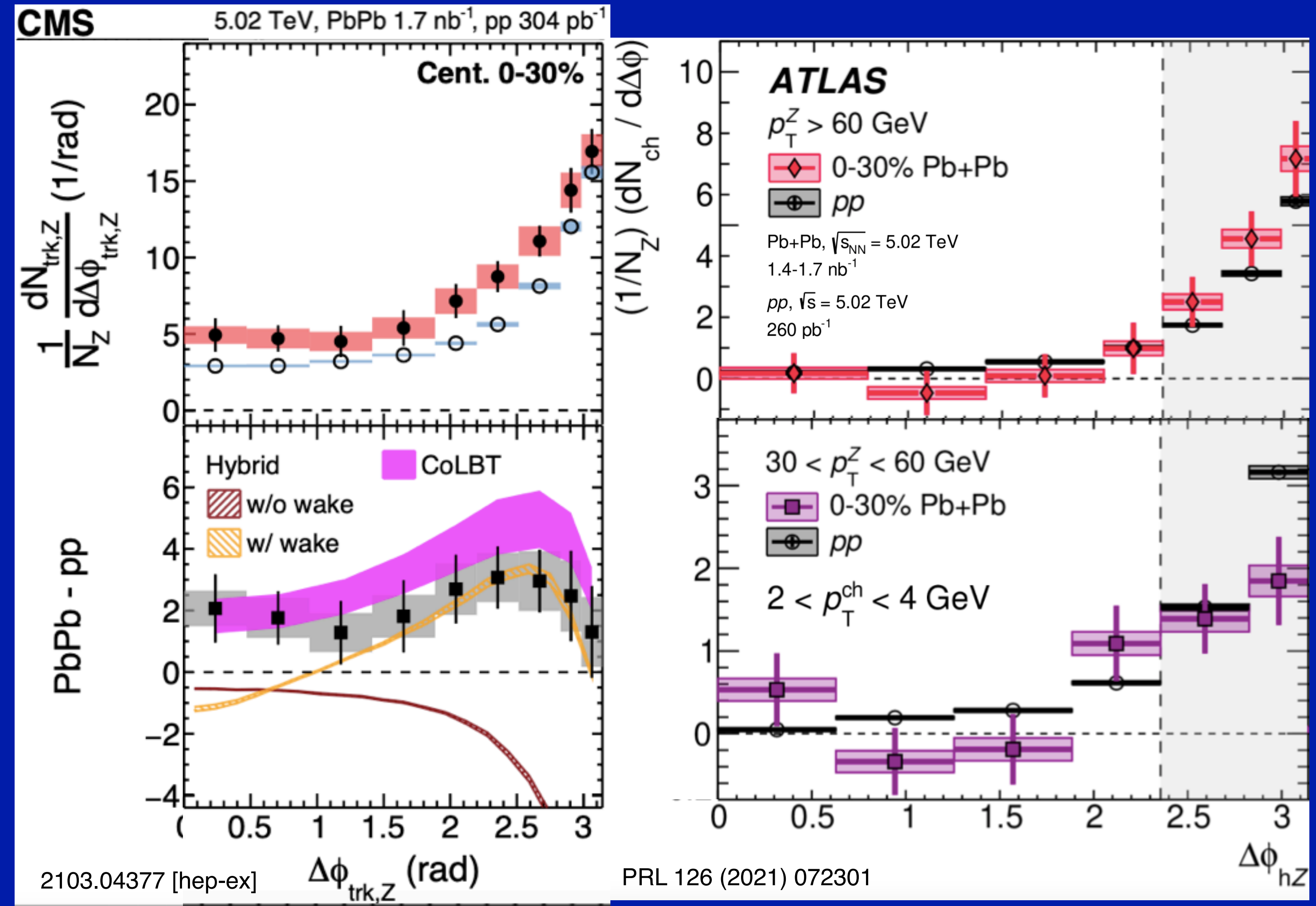
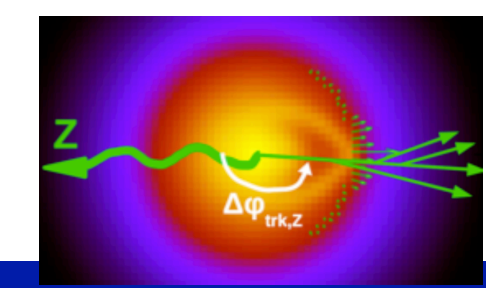
SCET<sub>G</sub> (no medium response) describes CMS data but not available at low- $p_T^{trk}$ .

Hybrid w/o wake disagrees. Global improvement if including wake.

CoLBT (medium feeds back the quenched energy deposited) describes well CMS and ATLAS.

Medium response is needed to describe the excess at low- $p_T^{trk}$ .





Enhancement of recoiling particles for  $p_{T^{ch}} > 1 GeV$  in CMS and  $p_{T^{ch}} > 2 GeV$  in ATLAS (for  $p_{T^Z} > 60 GeV$  only).

CMS data supports medium response predicted by CoLBT. Hybrid with wake describes the data in the away-side region but not in the near side, for which predicts a depletion of particles in PbPb.

Looking forward to jet-hadron correlations in  $\gamma/Z$ +jet events



- LHC data show evidence for decoherent energy loss. Jet quenching depends strongly on the branching width.
- Enhancement of low- $p_T$  particles at the edge of the jet supporting medium response is observed. Jet core remains unmodified.

We are starting to relate the jet modifications observed in the experiments with the properties of the QGP.

But

In a steep falling  $p_T$  spectrum ( $\sigma \sim p_T^{-6}$ ) the population in each bin is composed essentially by jets that suffered few or no energy loss (e.g. 1812.05111 and references therein).

Comparing observables as a function of reconstructed jet  $p_T$  ranges imply:

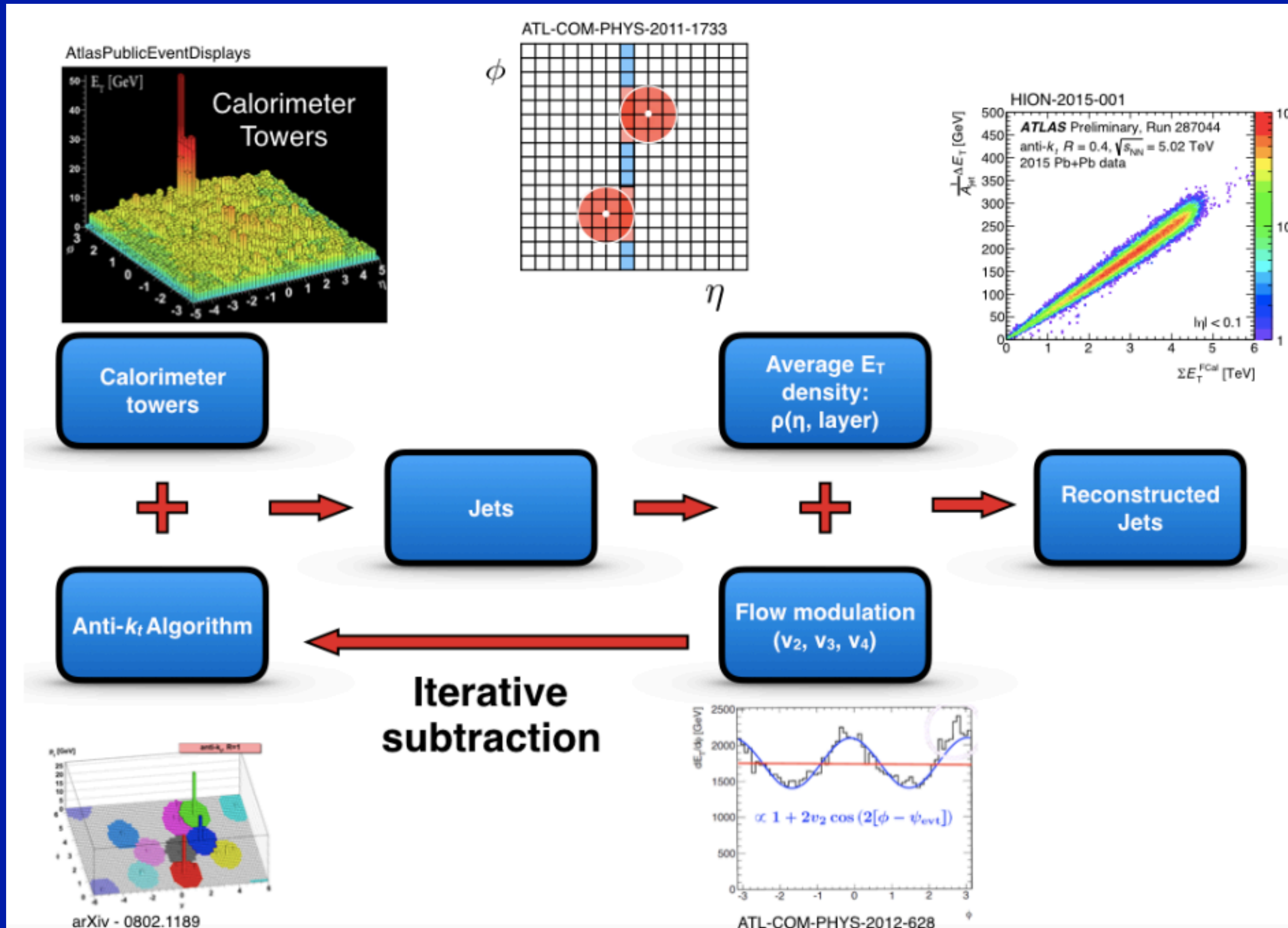
- lower  $p_T$  ranges have larger mixing of jets that born differently. More than a physics feature, it is a mess and makes data interpretation very model dependent.

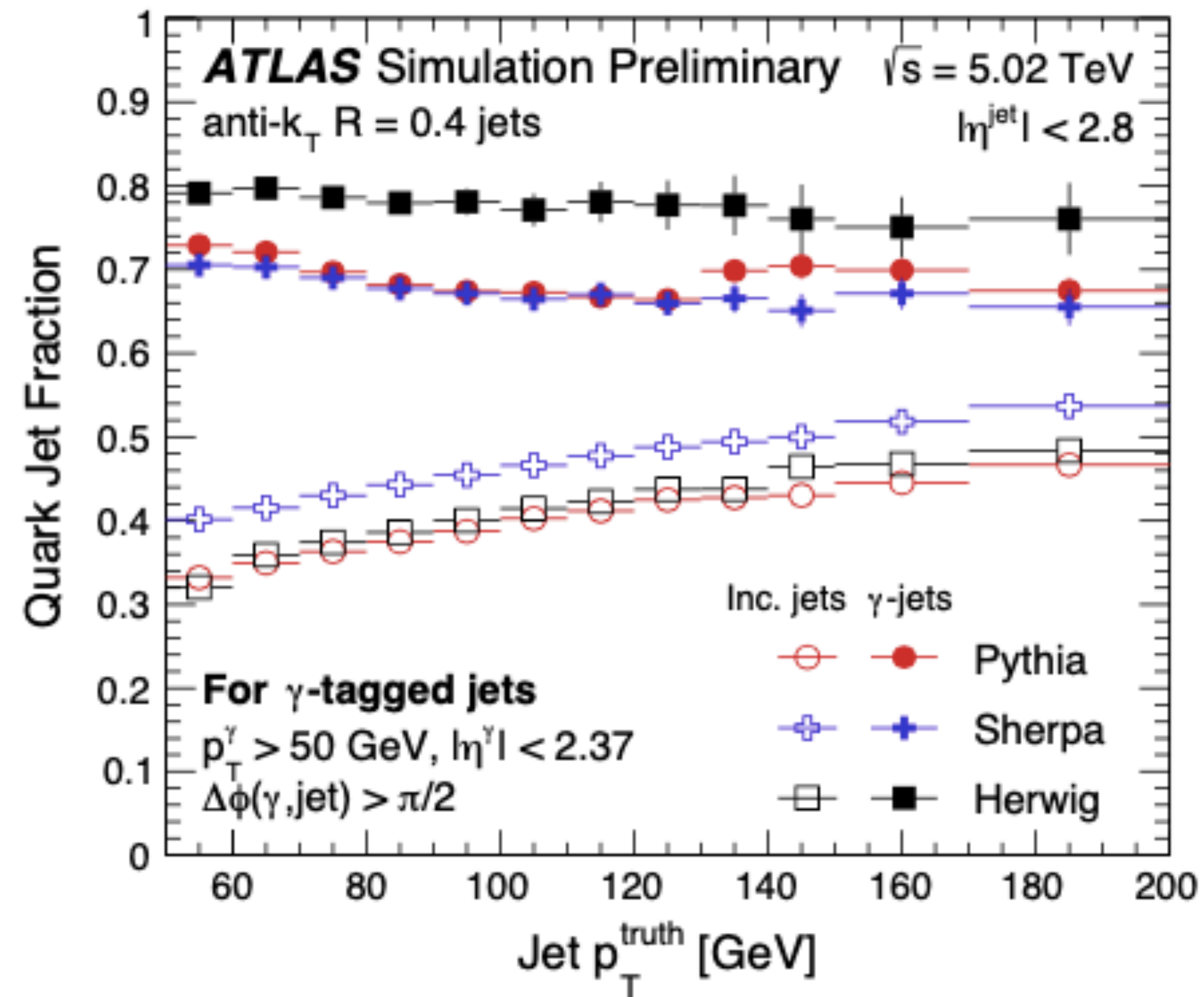
- ...

—> enriched samples of jets that were modified are needed for complex observables.





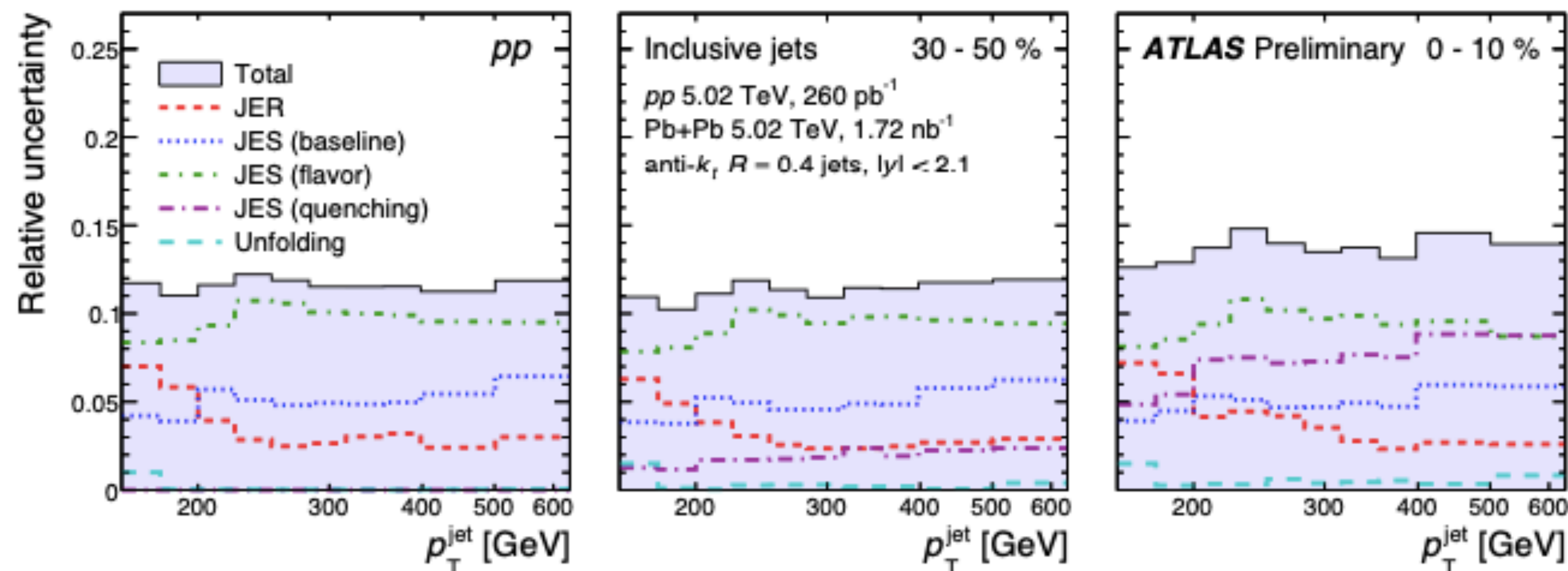




ATLAS-CONF-2022-019

Figure 1: Fraction of photon-tagged jets (filled markers) and inclusive jets (open markers) initiated by a quark, as a function of  $p_T^{\text{jet}}$ , in the PYTHIA (red), HERWIG (black), and SHERPA (blue) event generators.





ATLAS-CONF-2022-026

Figure 2: The relative systematic uncertainties on inclusive  $p_T^{\text{jet}}$  cross-section and per-event jet yield measurements in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV (left) and for different event centralities in Pb+Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV (second and third panels). The legend applies to all the panels.

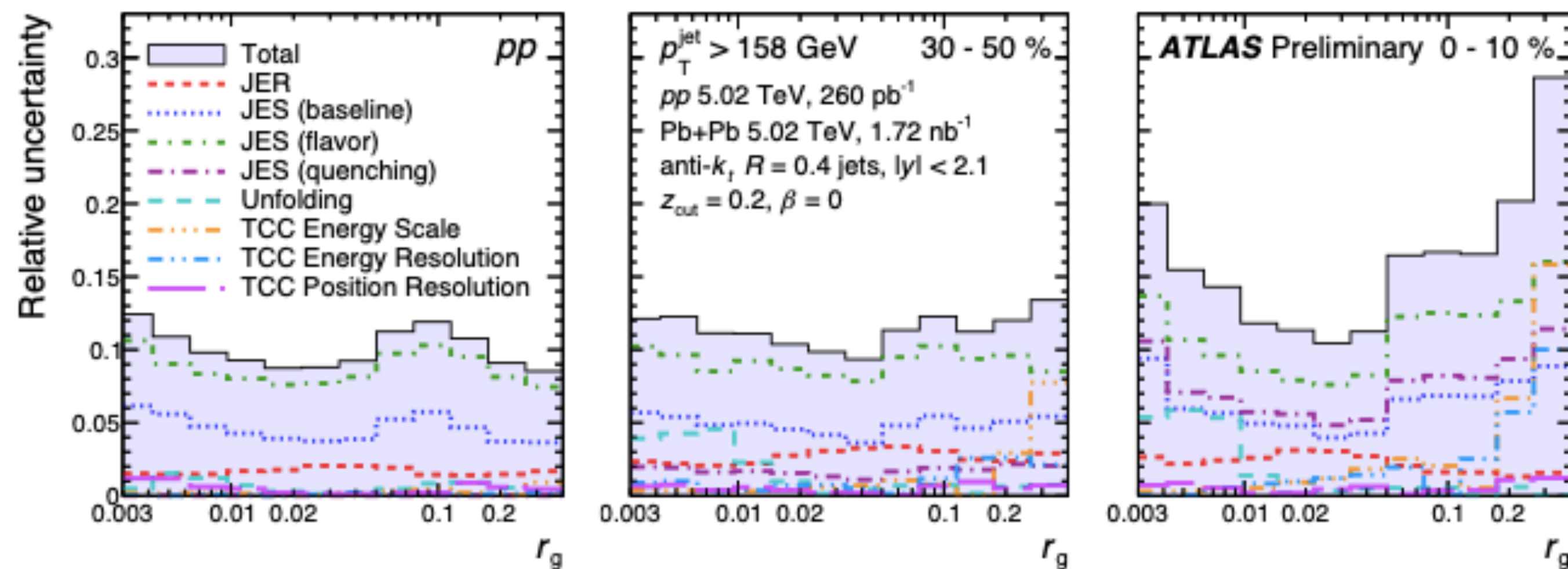


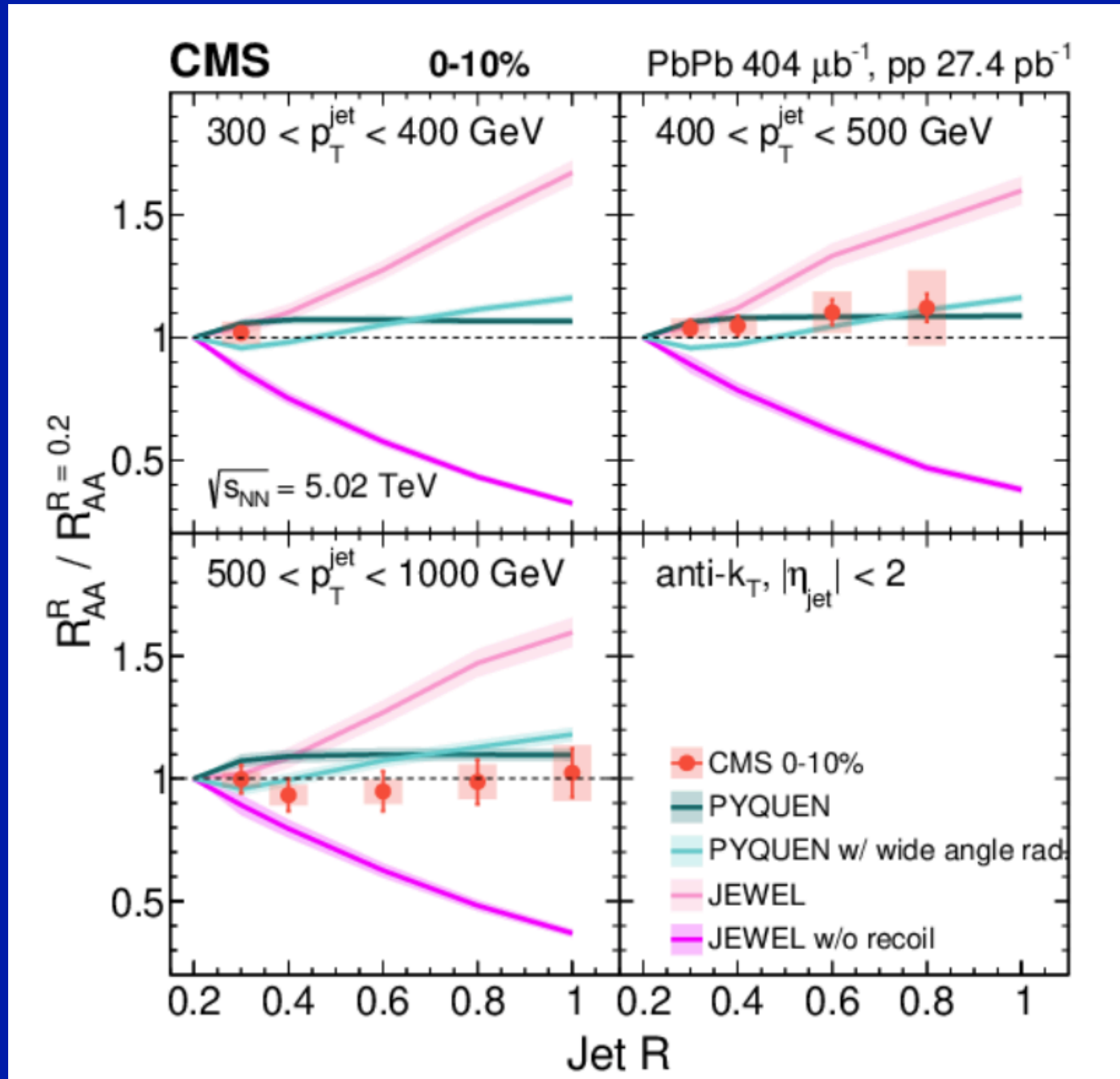
Figure 3: The relative systematic uncertainties on inclusive  $r_g$  cross-section and per-event jet yield measurements in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV (left) and for different event centralities in Pb+Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV (second and third panels) shown for soft-drop parameters  $z_{\text{cut}} = 0.2$  and  $\beta = 0$ . The legend applies to all the panels.



# Jet substructure

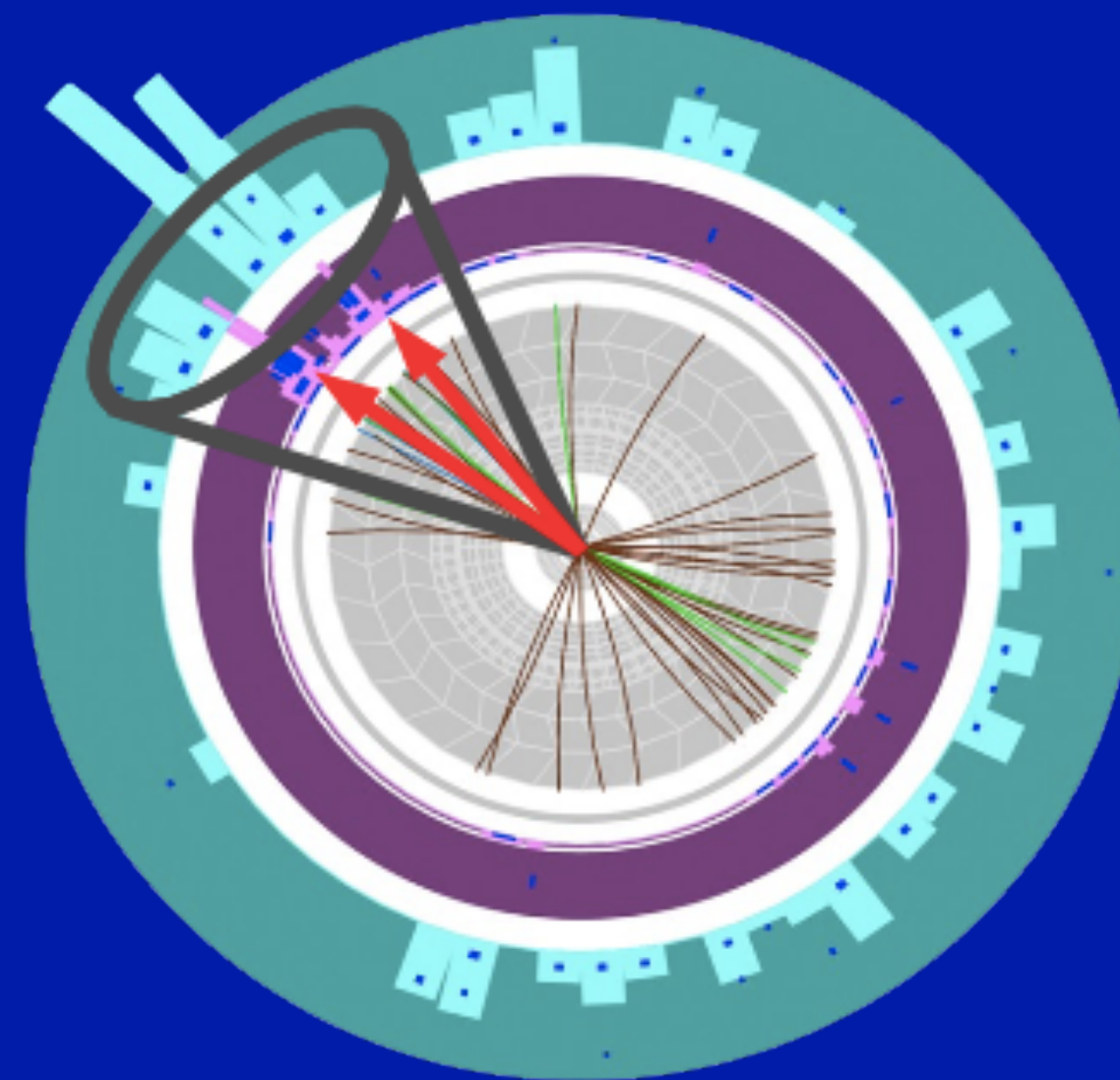
Inclusive jets

$R_{AA}/R_{AA}^{0.2}$  for  $R=0.3, 0.4, 0.6, 0.8, 1.0$

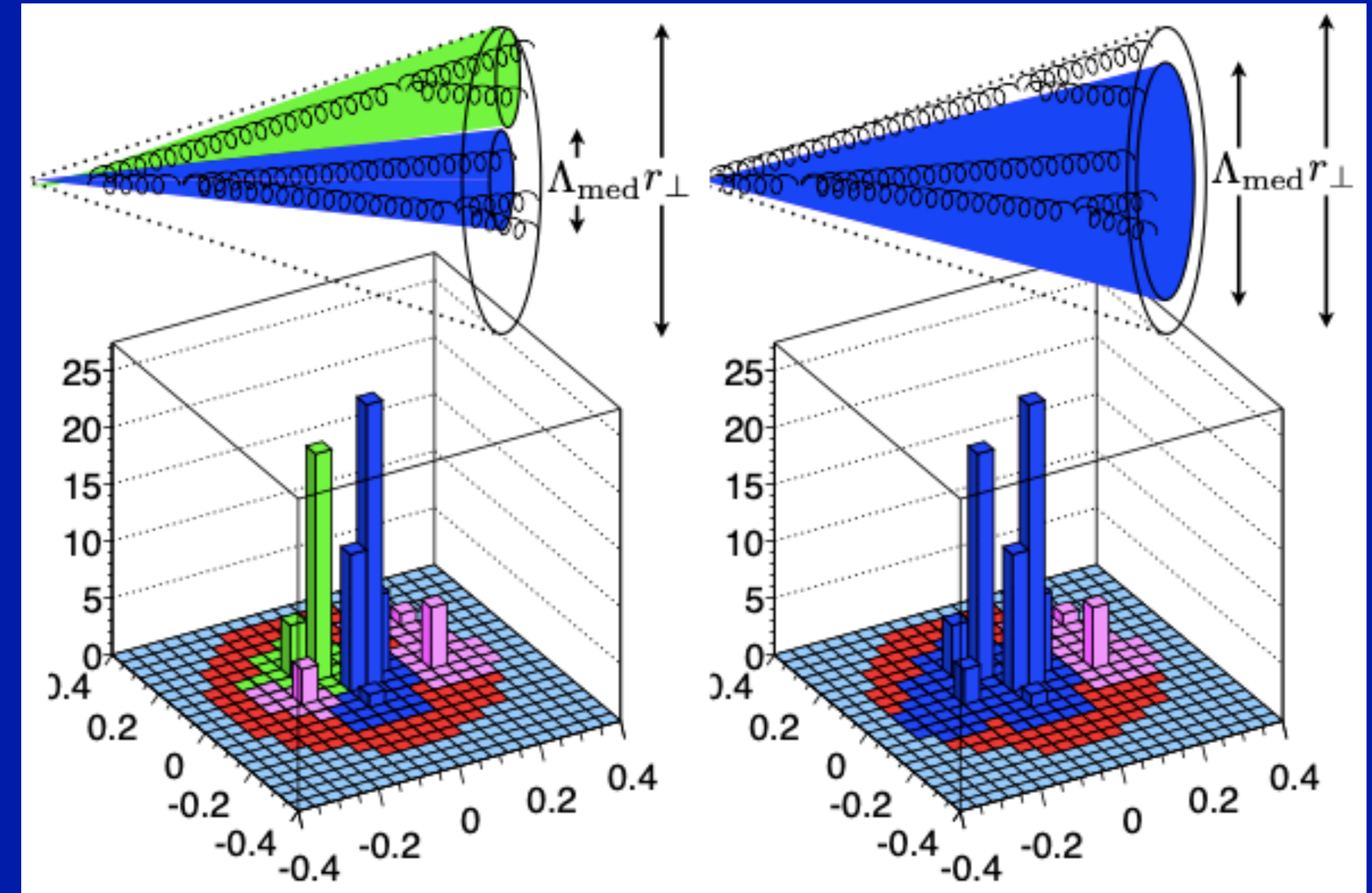


The suppression for jet  $p_T > 300$  GeV does not depend on jet radii.

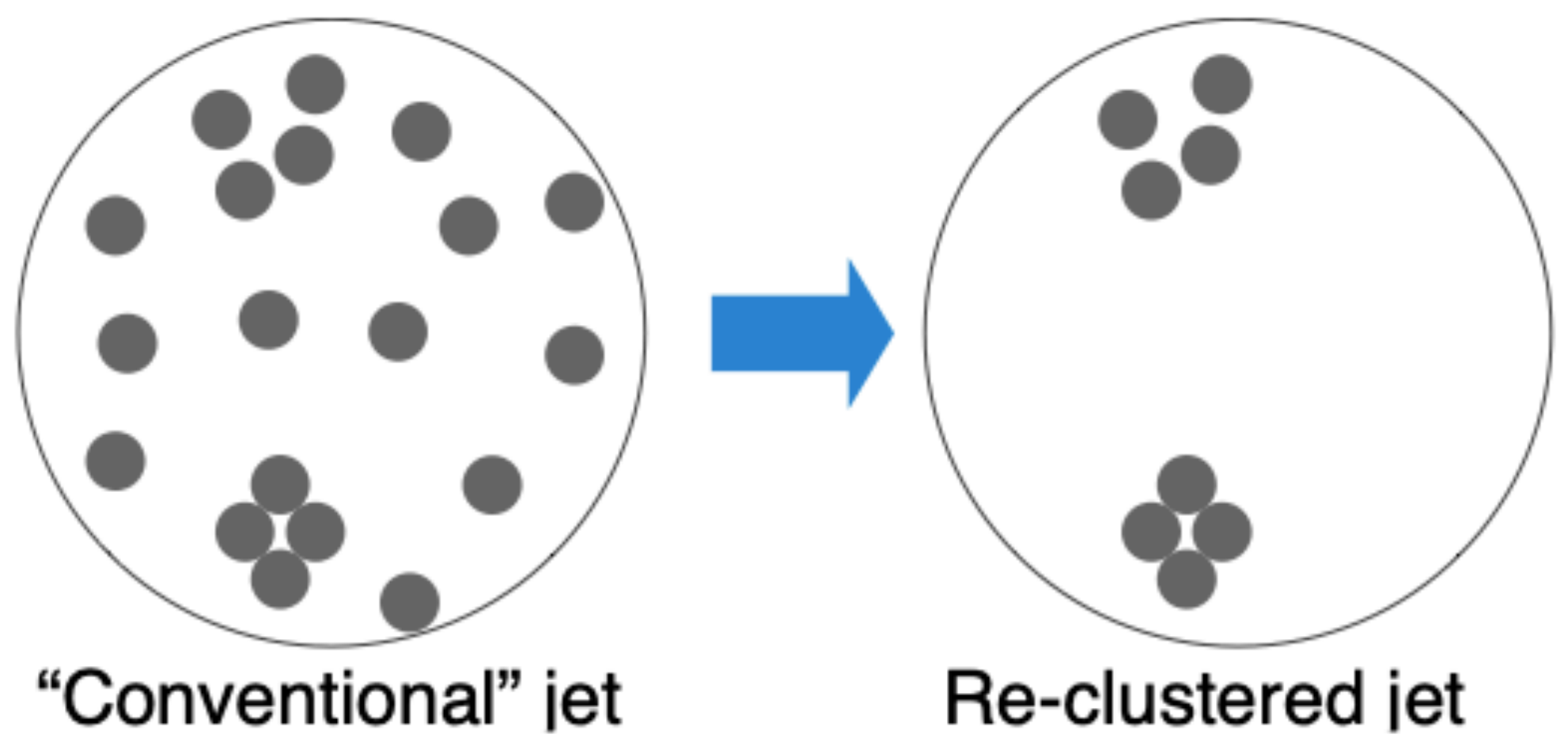
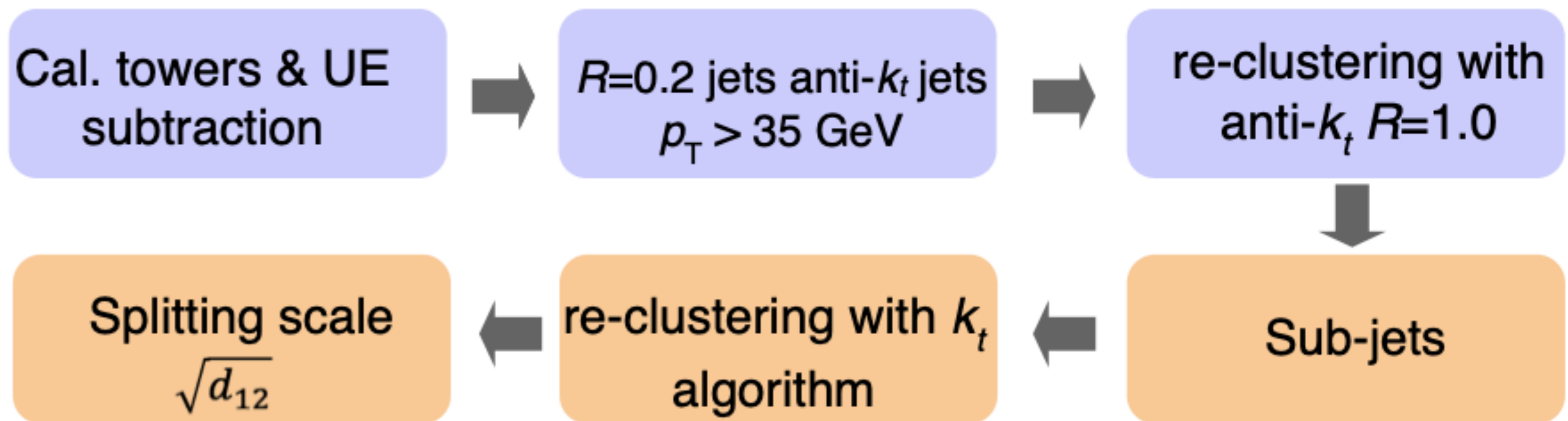
—> Look for two-prong structures as they might be sensitive to coherence effects in the QGP.



Recluster jets and remove soft contributions





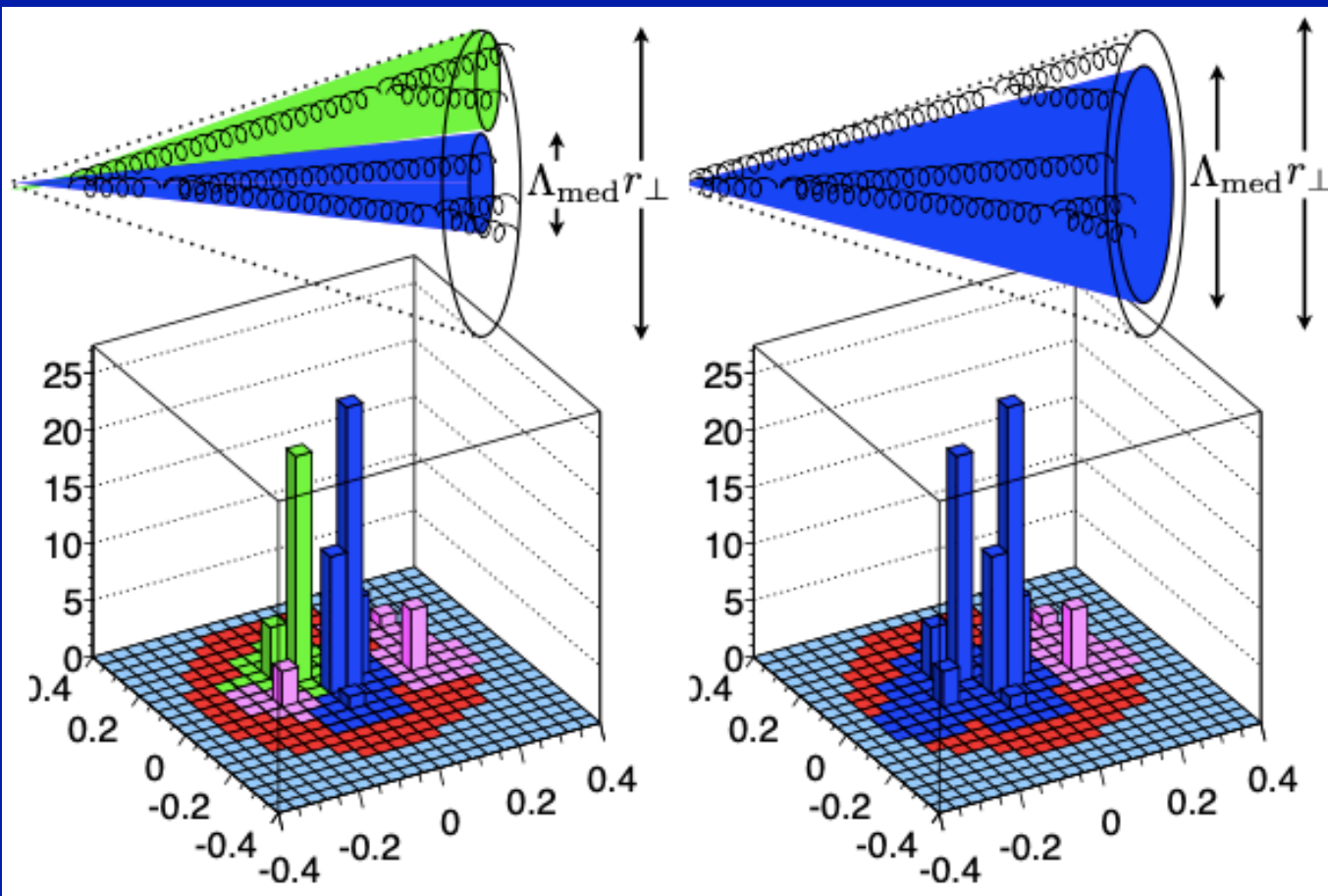
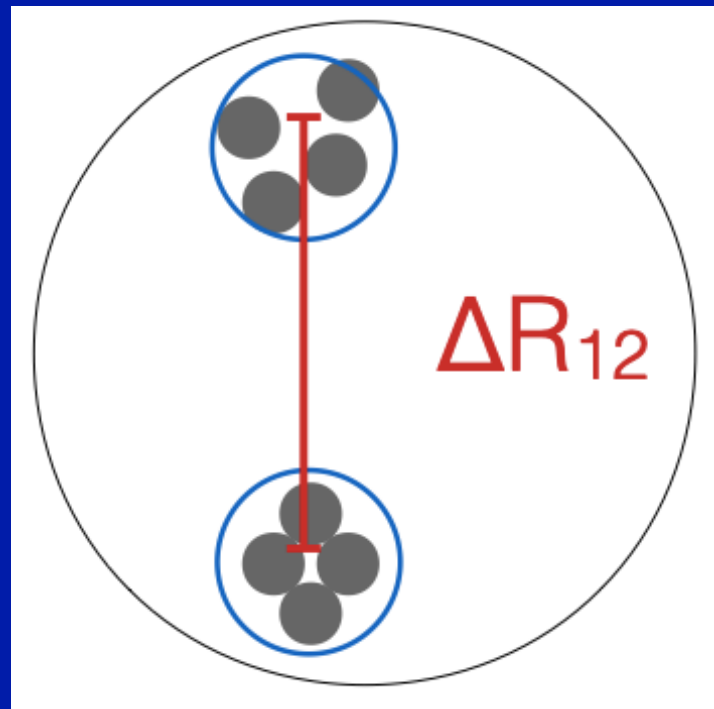


Different jets than the conventional  $R=1.0$ .  
Trimming & 35 GeV threshold remove soft components.

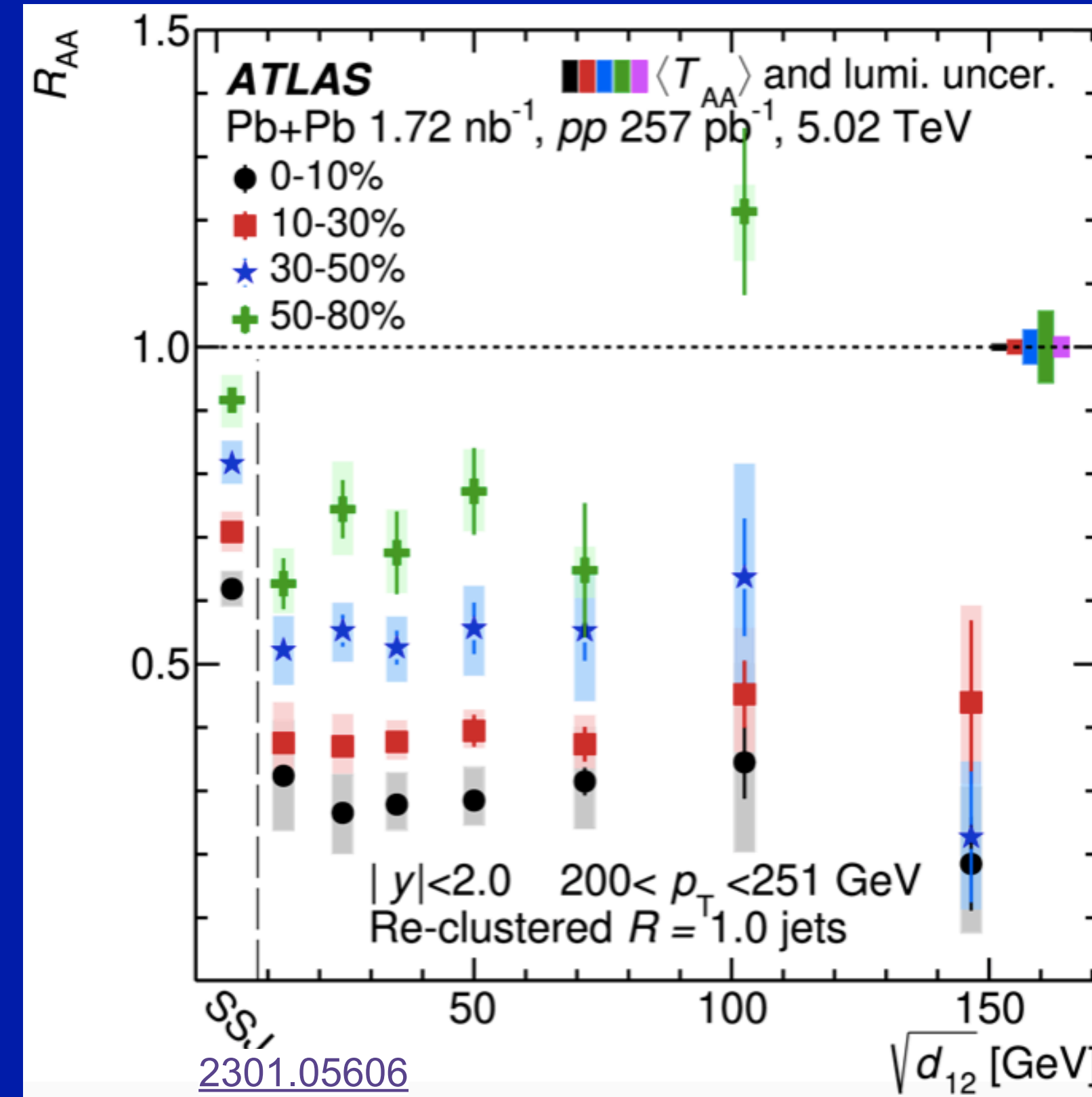
$R = 0.2$  jets with  $p_T > 35$  GeV reclustered into anti- $k_t$   $R = 1.0$

study of  $k_t$  splitting scale

$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \cdot \Delta R_{12}$$



Recluster jets and remove soft contributions

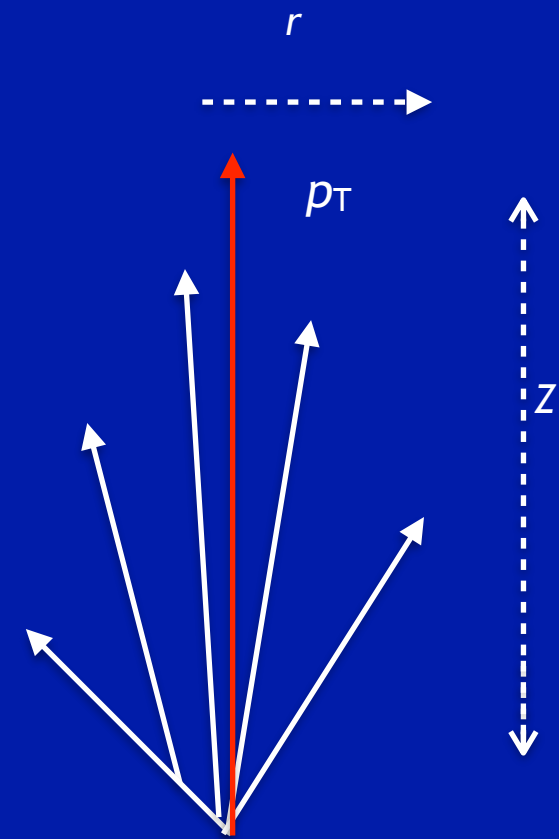


- Significant change of the  $R_{AA}$  magnitude between jets with SSJ and those with more complex substructure
- Then  $R_{AA}$  is not dependent on  $\sqrt{d_{12}}$
- Result points to decoherent energy loss



# How do particles redistribute within the jet and beyond? 26

Study  $FF$  as a function of the angular distance between the charged particle and the jet axis.



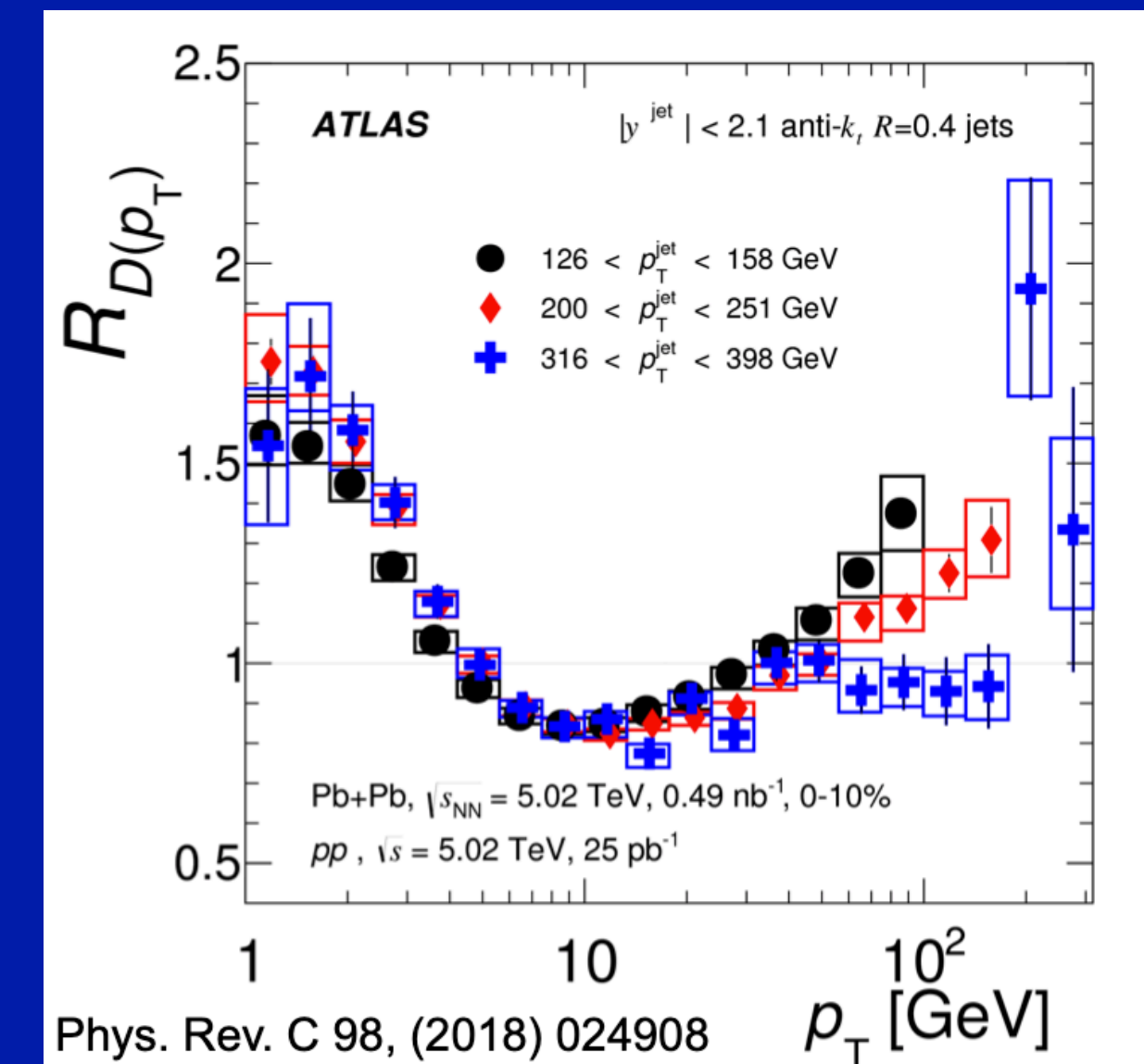
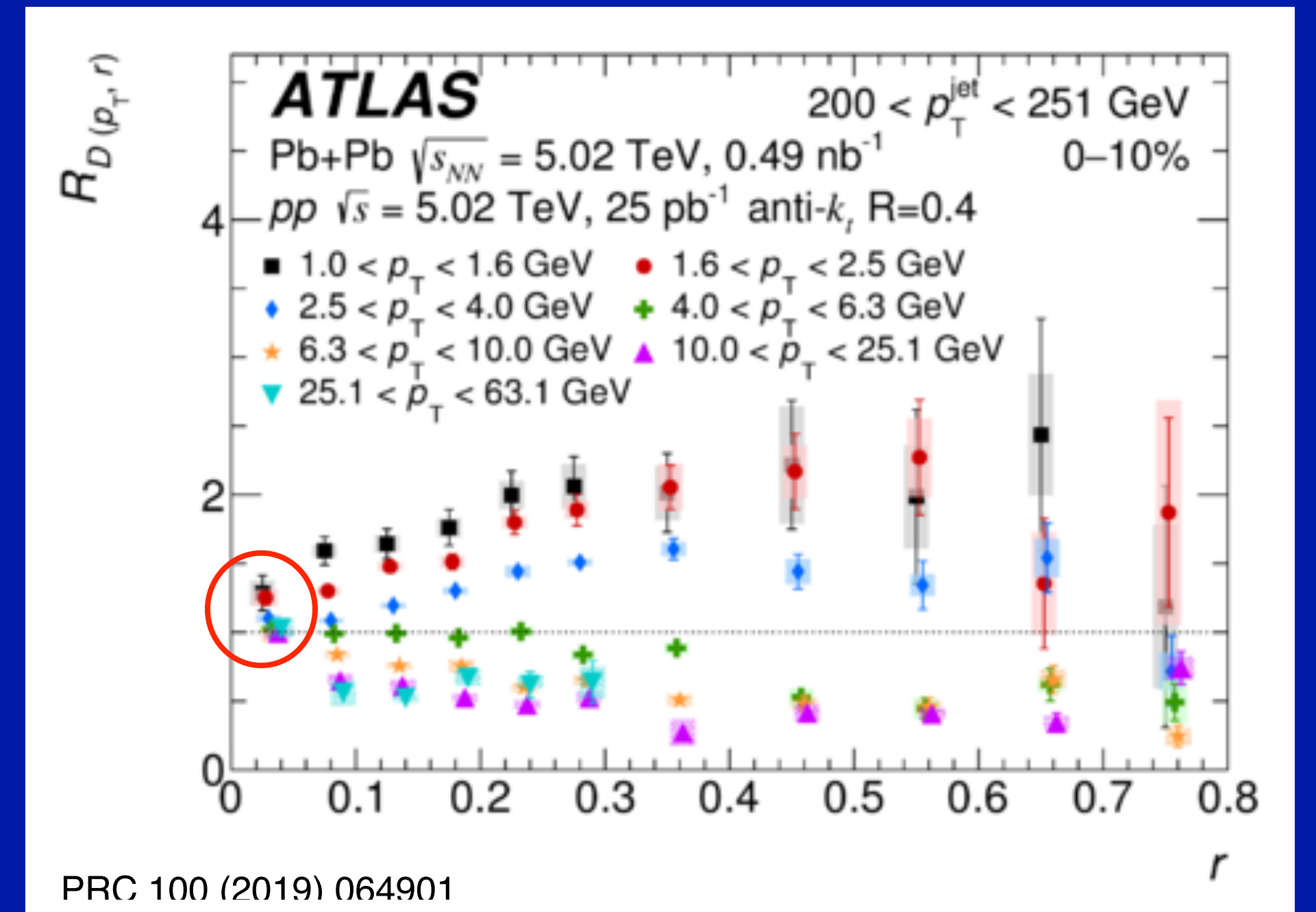
$$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{d^2 n_{\text{ch}}(r)}{dr dp_T}$$

$$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

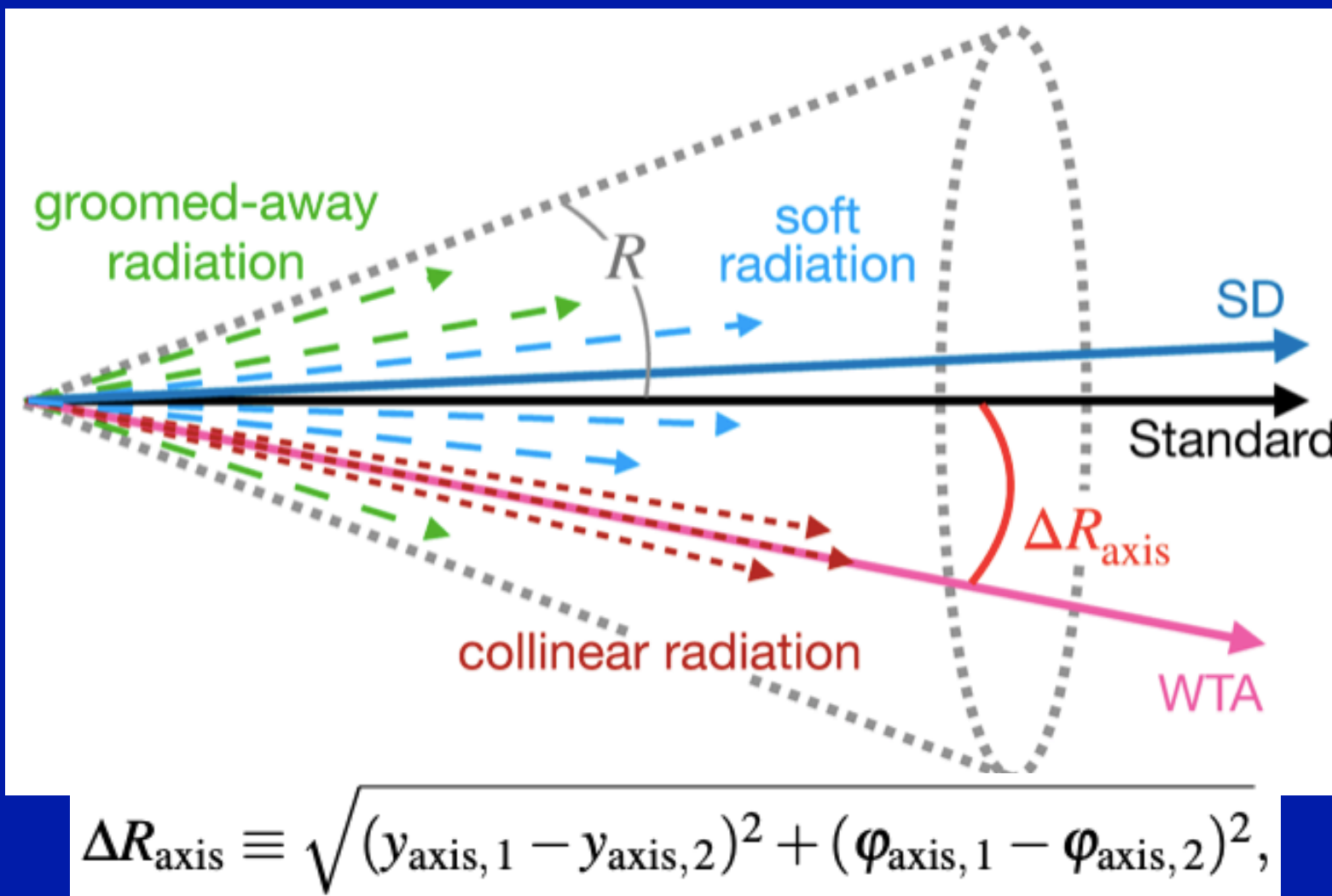
In central collisions  $R_{D(p_T, r)}$  is above unity at all  $r$  for all  $p_T < 4$  GeV  $\rightarrow$  Energy lost by jets is being transferred to particles with  $p_T < 4$  GeV with larger radial distance. Expected from jet  $FF$ .

Depletion of high- $p_T$  particles over all range.

Jet core remains unmodified.

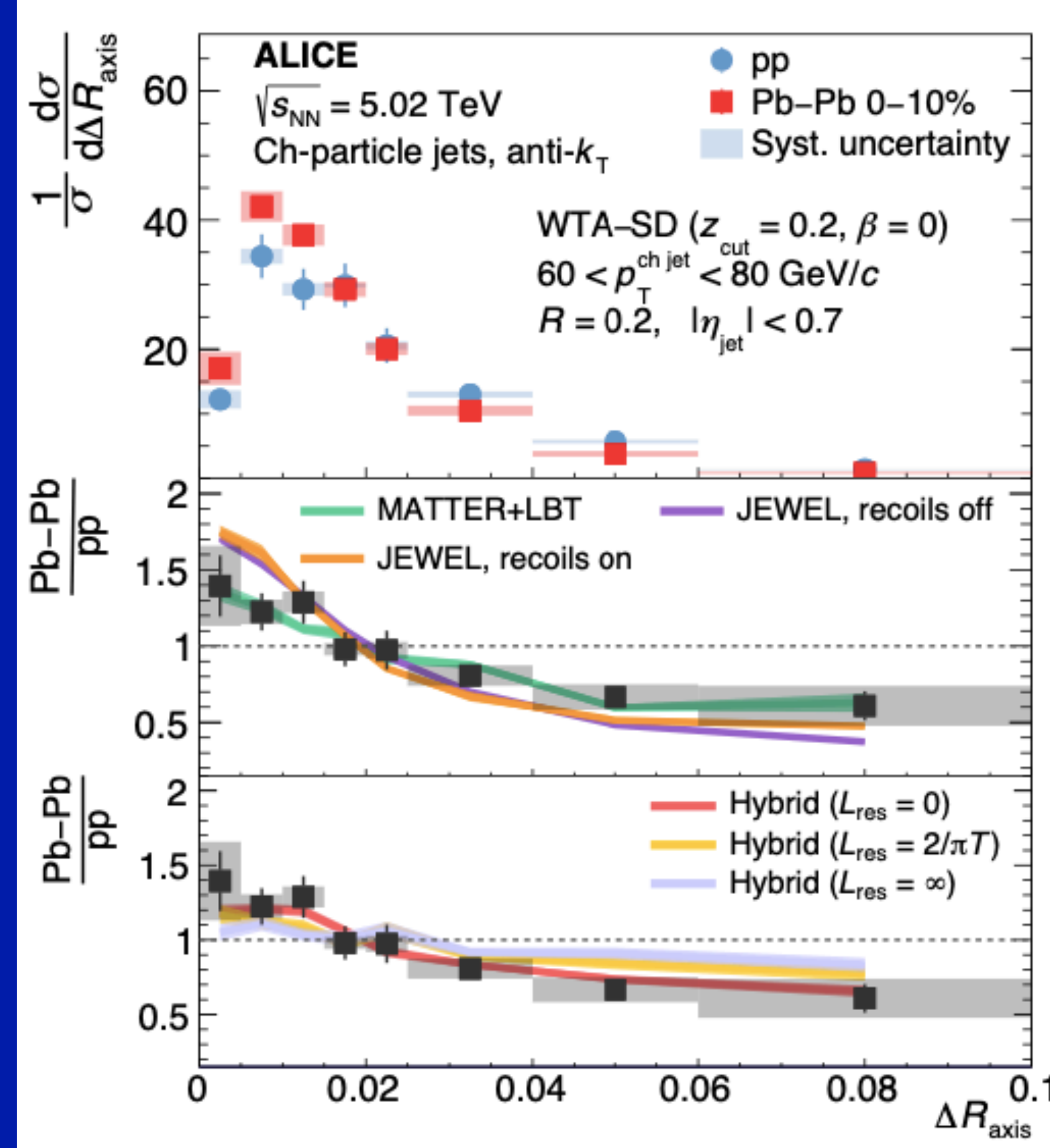
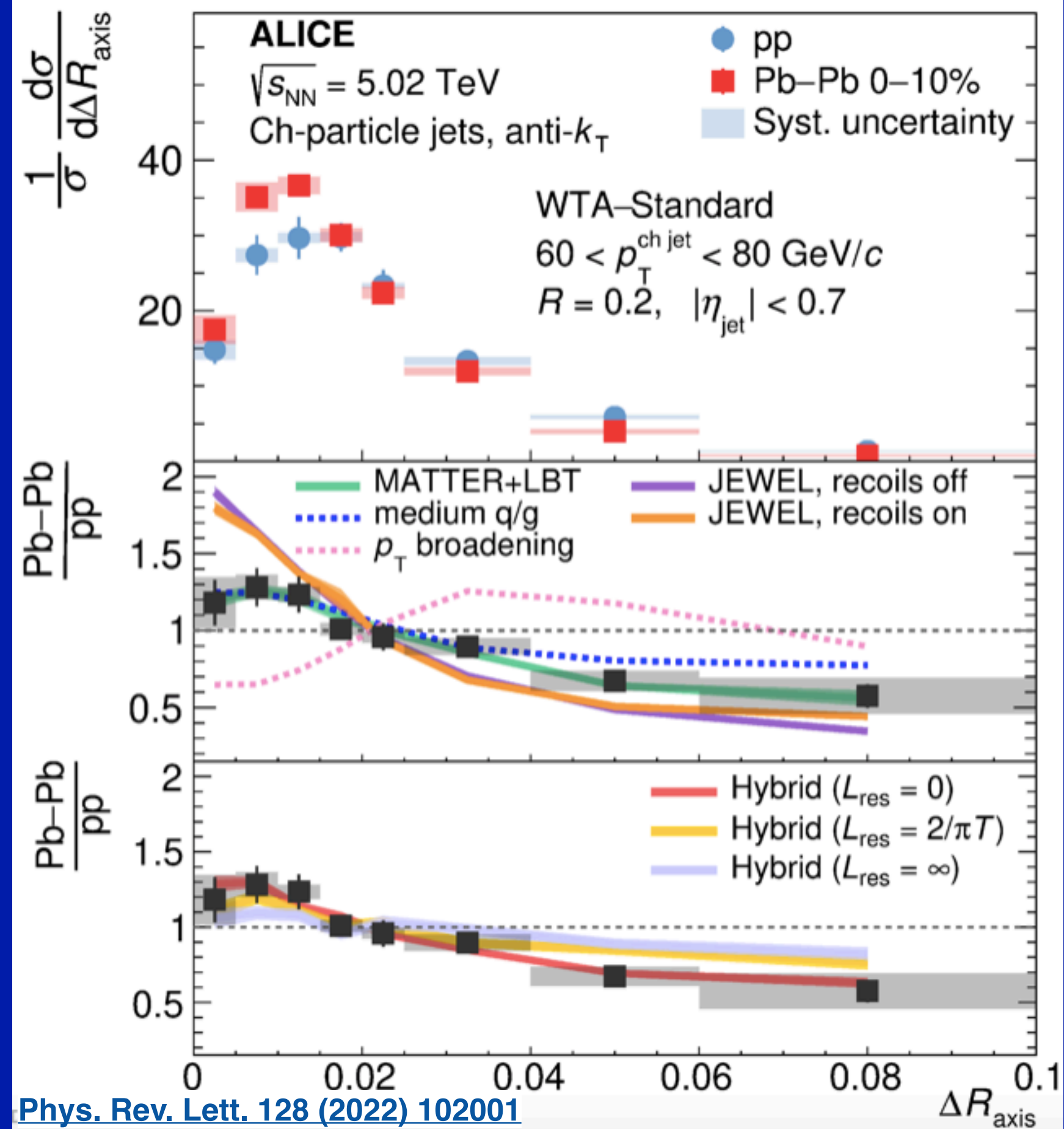






SD: axis defined by the particles left after grooming.

WTA: merged branch takes the  $p_T$  sum of the two sub-branches and the direction of the hardest one. Insensitive to soft radiation.

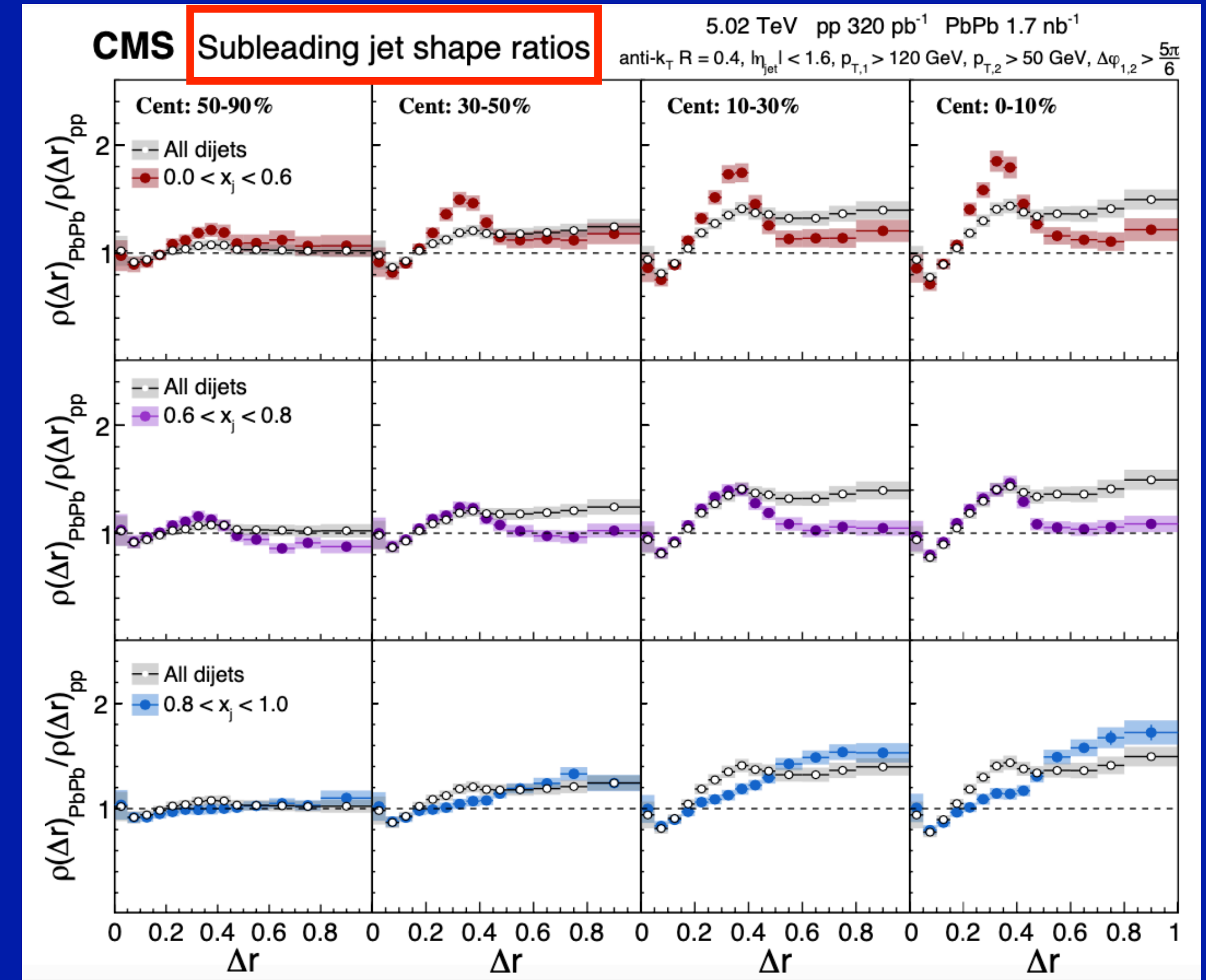
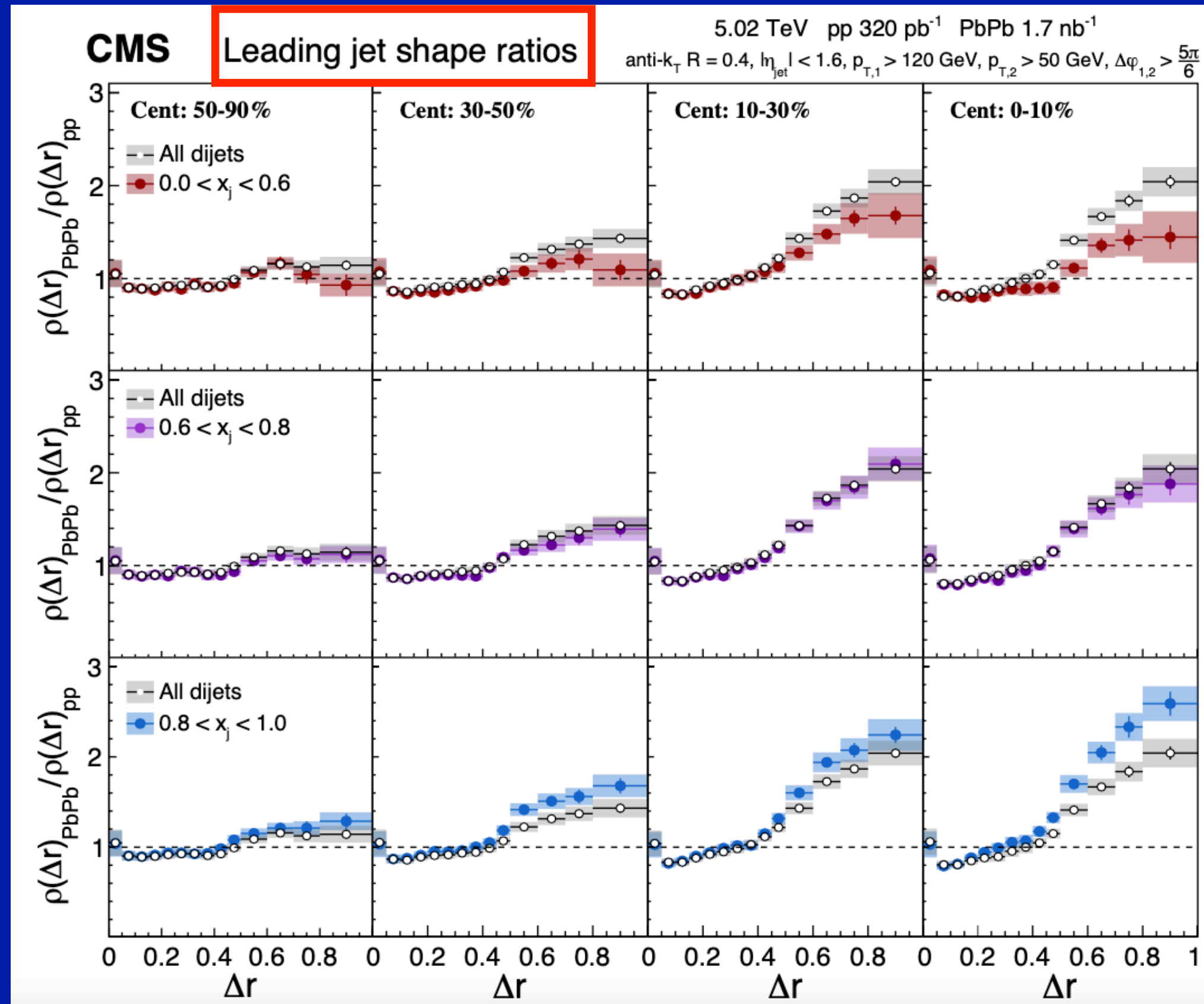


$\Delta R$  distributions are narrower in PbPb

Grooming ( $z_{\text{cut}} = 0.2, \beta=0$ ) doesn't change the jet axis visibly. Not sensitive to grooming.

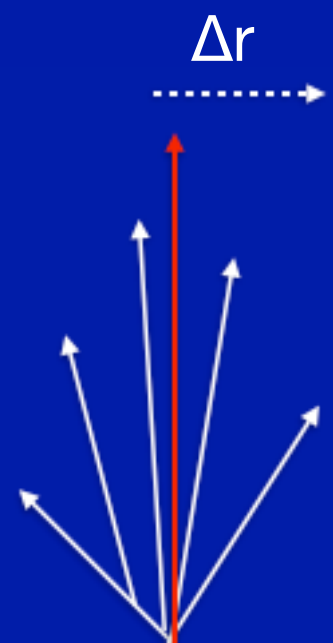
MATTER+LBT and Hybrid ( $L_{\text{res}}=0$ ) consistent with the data. Intra-jet  $p_T$  broadening ruled out.

Leading and subleading jet shape ratios  $\rho(\Delta r)_{\text{PbPb}}/\rho(\Delta r)_{\text{pp}}$ , in different centrality and  $x_j$  ranges



imbalanced  
 $0.0 < x_j < 0.6$

Balanced  
 $0.8 < x_j < 1.0$

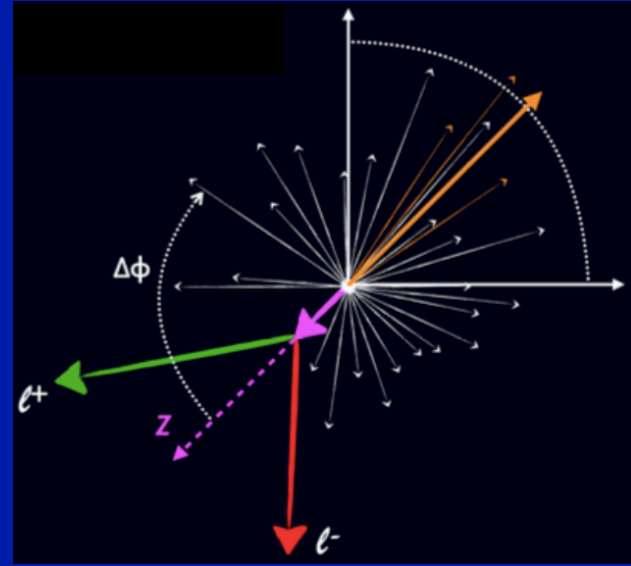


Enhancement of the PbPb jet shape modification at large  $\Delta r$  in balanced dijets and with increasing centrality.

Significant effects from different path length crossed.

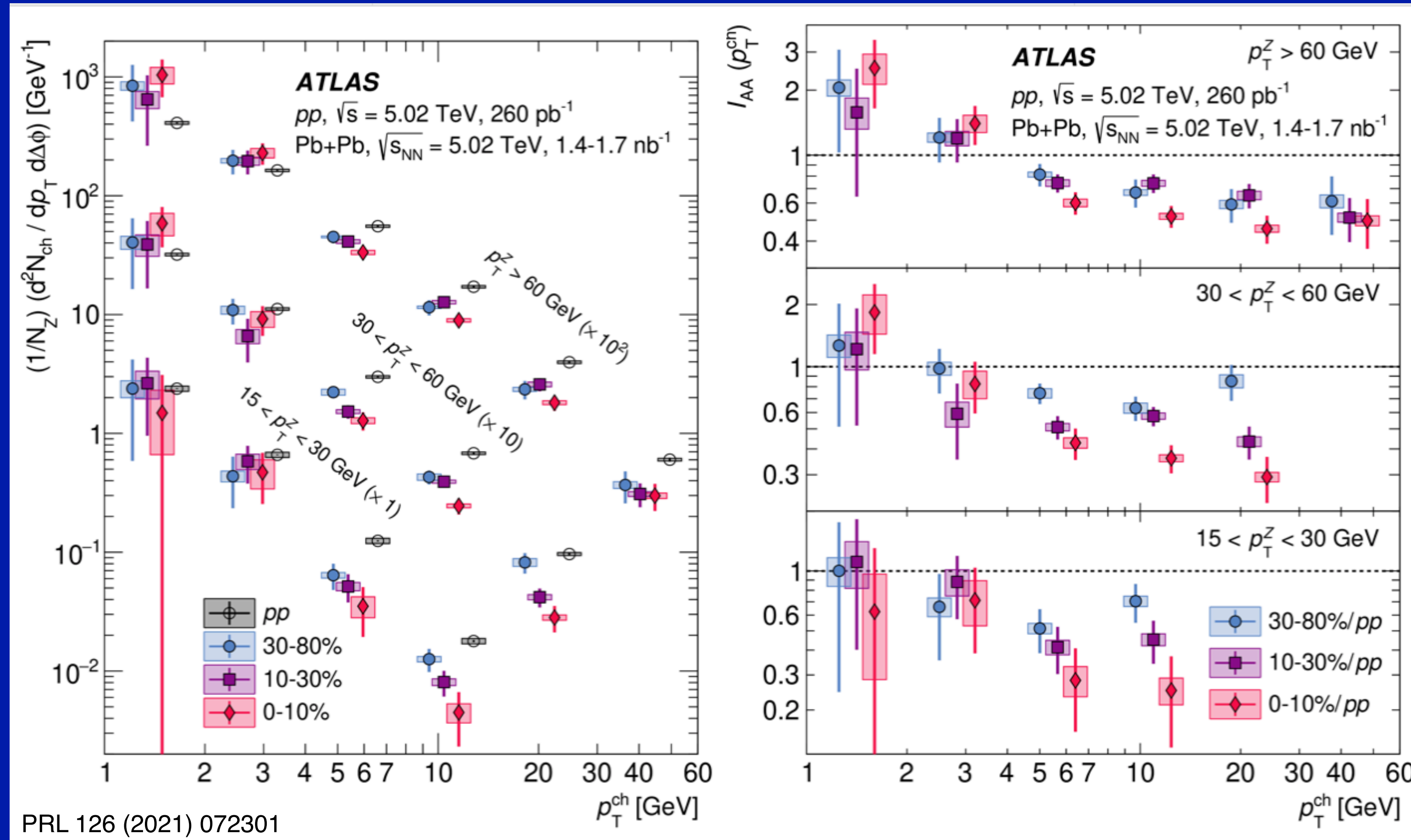
Clear effect at  $\Delta r \approx 0.3$ , and for imbalance dijets ( $x_j < 0.8$ ). Enhancement at large  $\Delta r$  less pronounced in imbalanced dijets. Opposite effect in balanced.





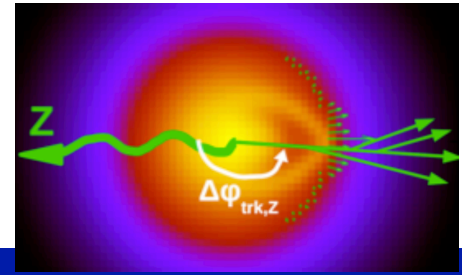
#charged particles per Z

yield in PbPb / yield in pp



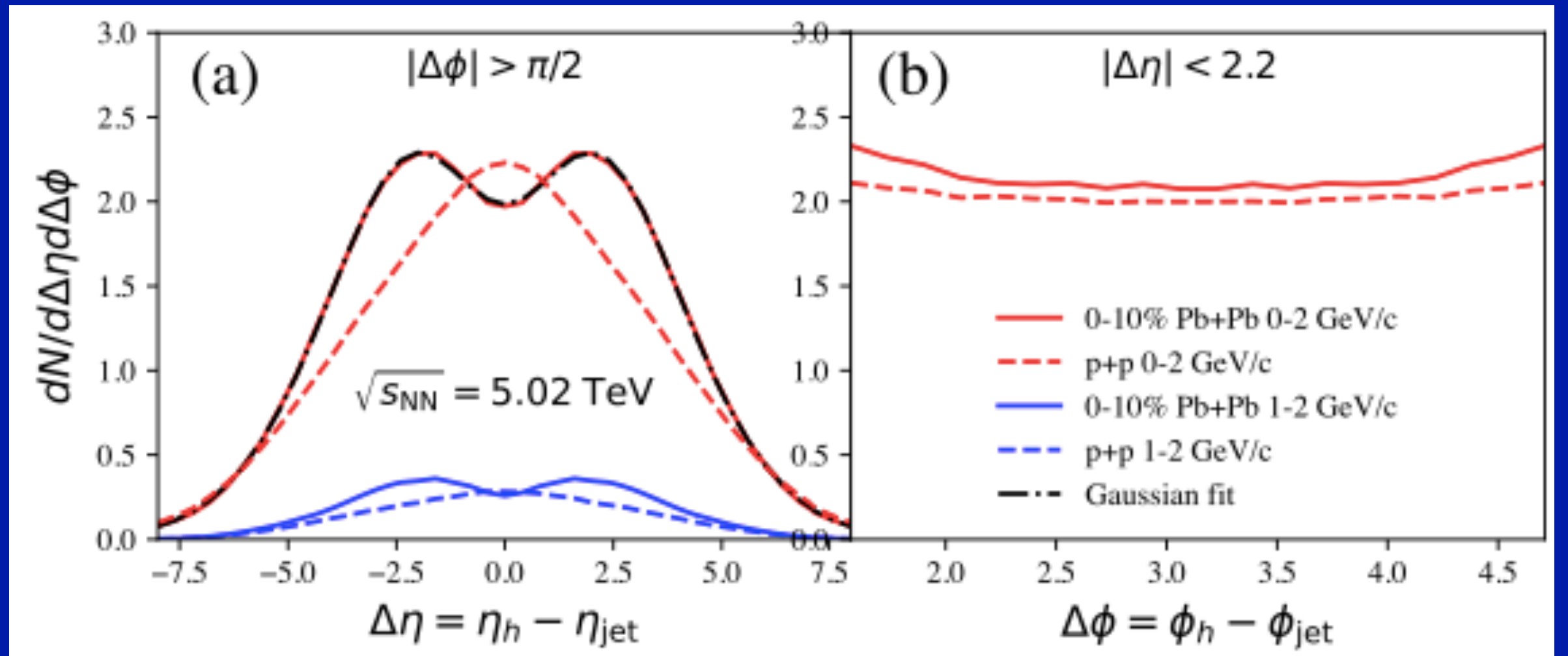
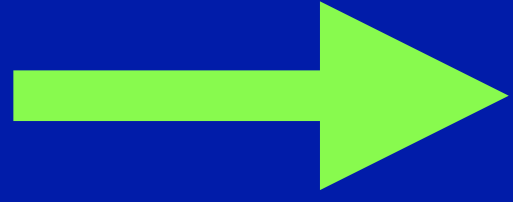
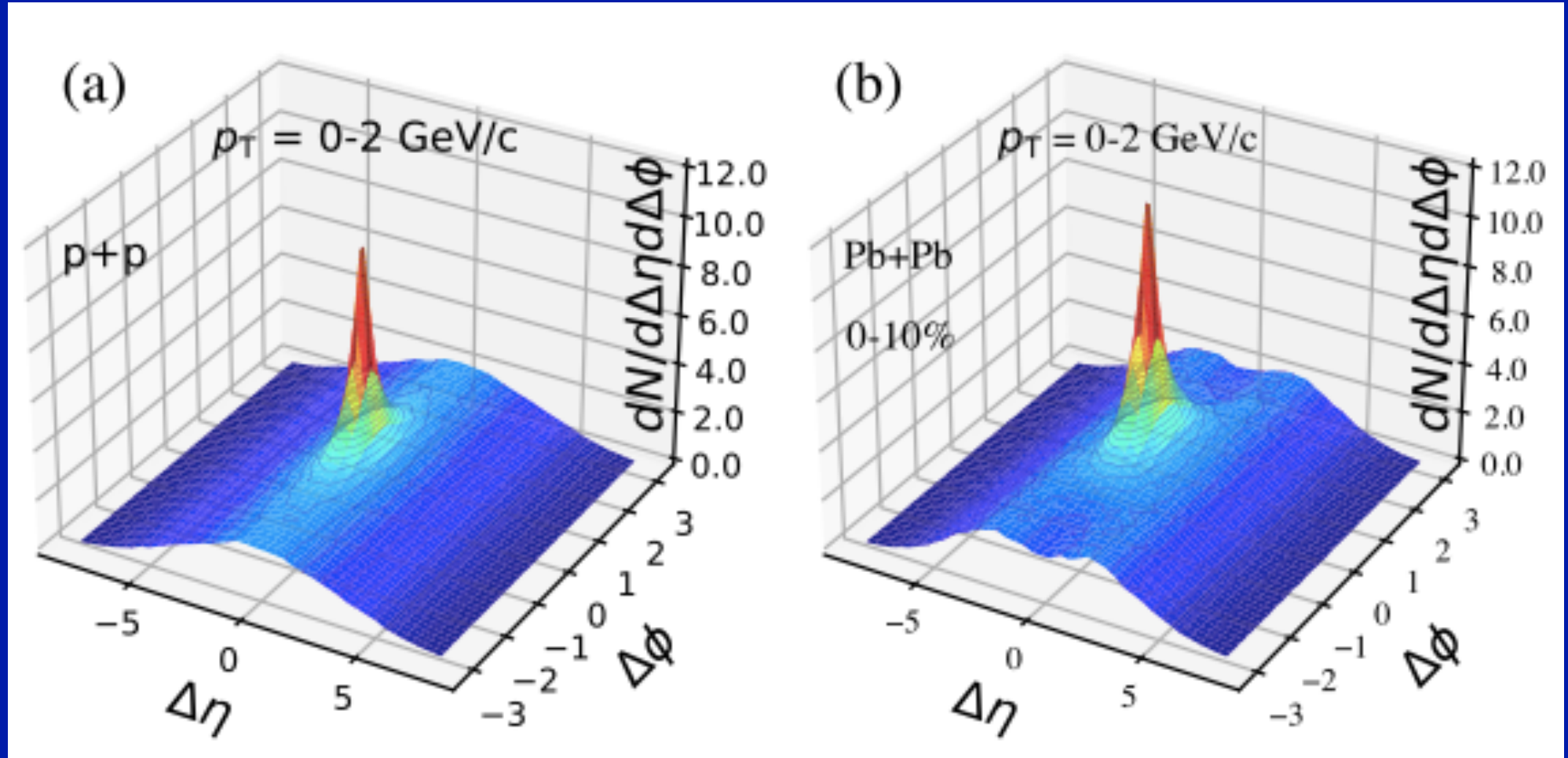
Enhancement of low- $p_T^{\text{ch}}$  recoiling particles for  $p_T^Z > 60 \text{ GeV}$ . Less pronounced as  $p_T^Z >$  decreases. Then clear suppression of high- $p_T^{\text{ch}}$  particles with increasing centrality.





Looking forward to jet-hadron correlations in  $\gamma/Z$ +jet events

at the photon side



CoLBT, Xin-Nian et al, PRL 130, 052301 (2023)

The DF-wake valley on top of the MPI ridge gives rise to a double peak feature in the rapidity distribution of the jet-hadron correlation.