Fundação
para a Ciência
e a Tecnologia

QGP tomography

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

Experimental observables reviewed in this talk

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

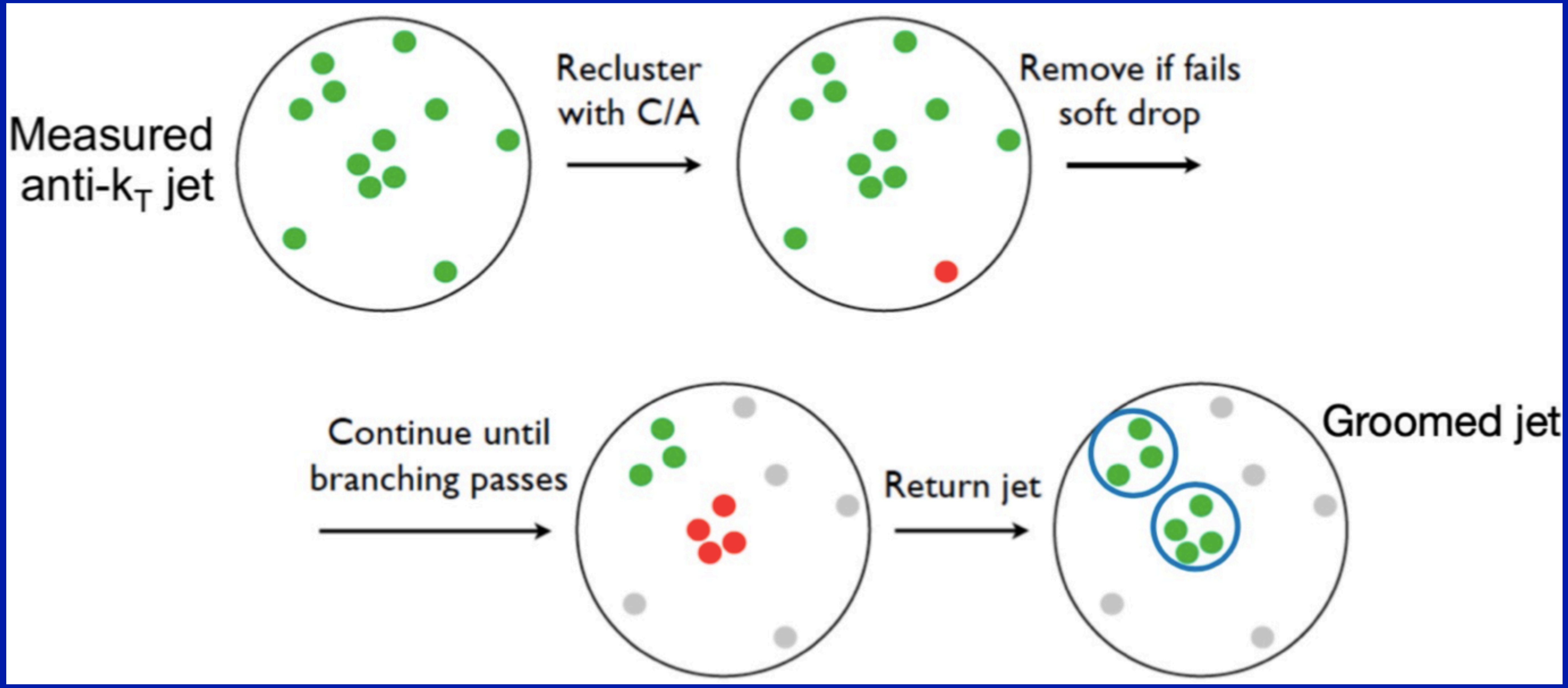
- Do jets disturb the QGP measurably?

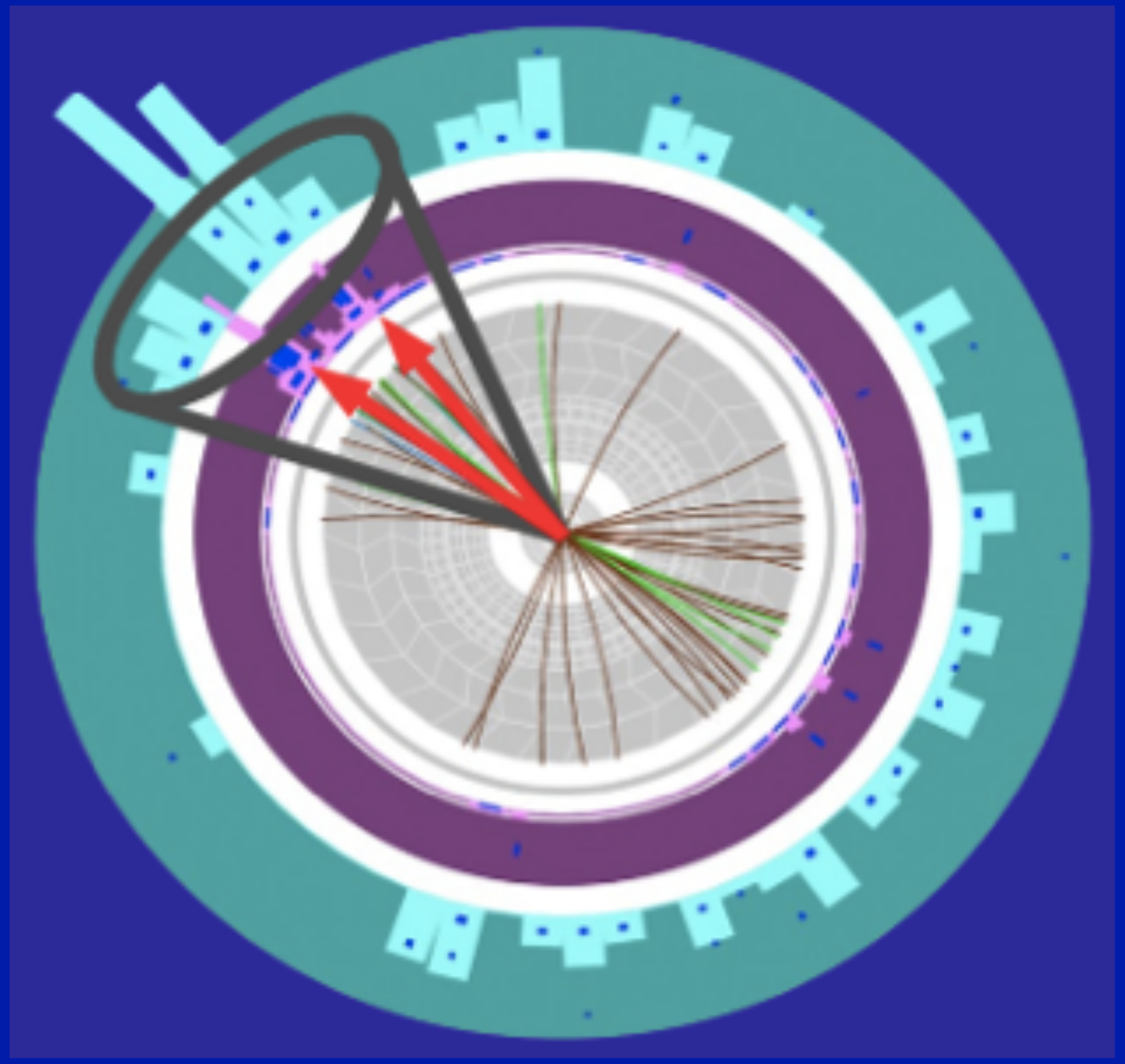
Explore:

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

Searching for the resolution scale

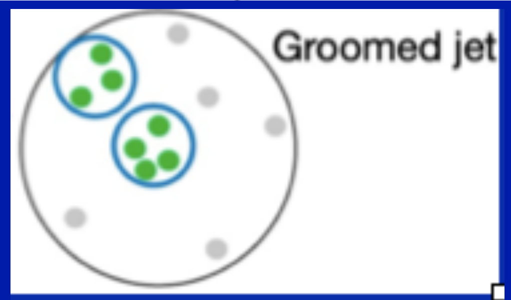
Substructure techniques like soft-drop or reclustering using subjets allow to experimentally access scales associated with individual branchings in the parton shower.





Jet substructure - r_g

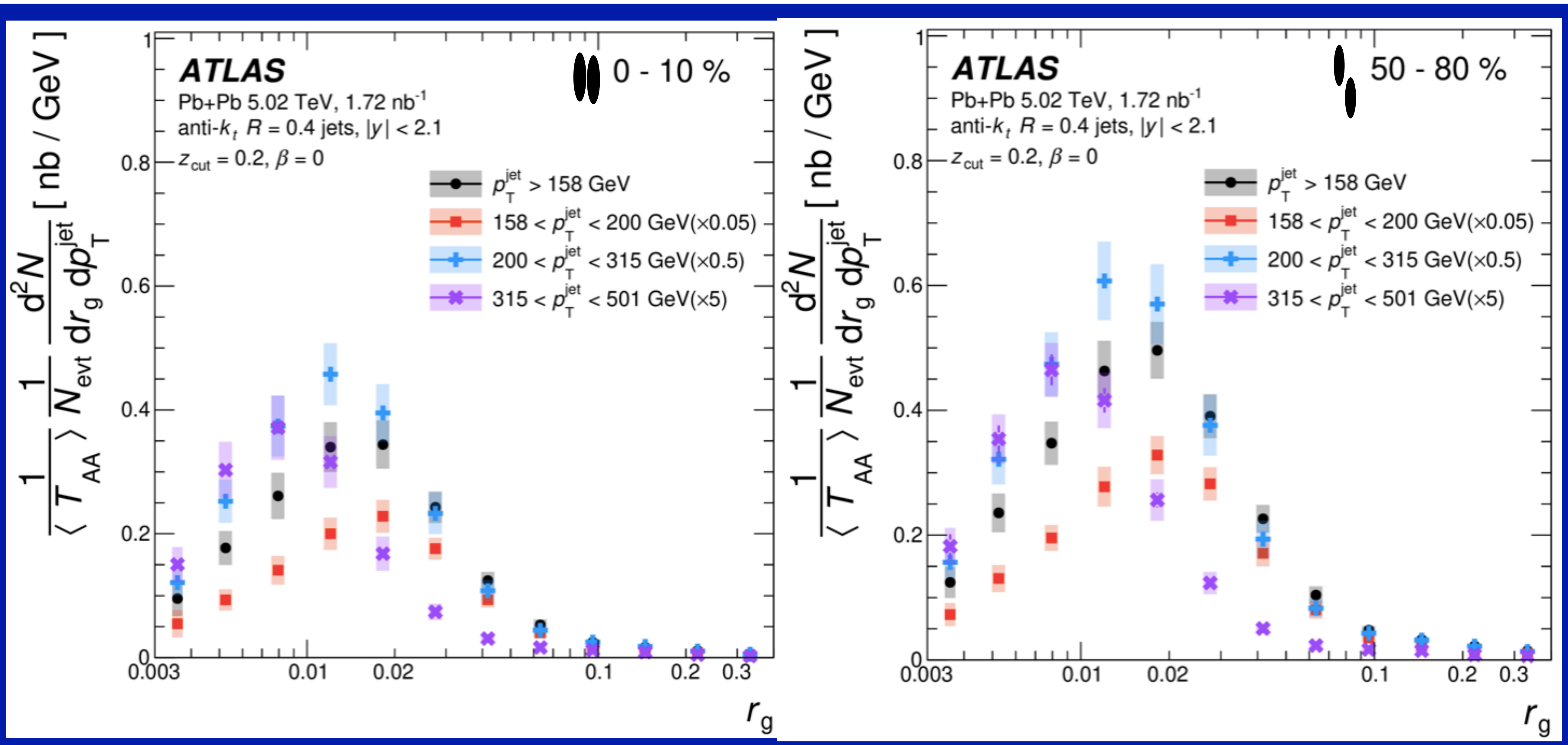
$$\frac{\min(p_T^{sj_1}, p_T^{sj_2})}{p_T^{sj_1} + p_T^{sj_2}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta} \qquad \Delta R_{12} = \sqrt{\Delta\eta_{12}^2 + \Delta\phi_{12}^2}$$



z_{cut}=0.2, β=0

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

- Jets are narrower with increasing p_T, independently on centrality



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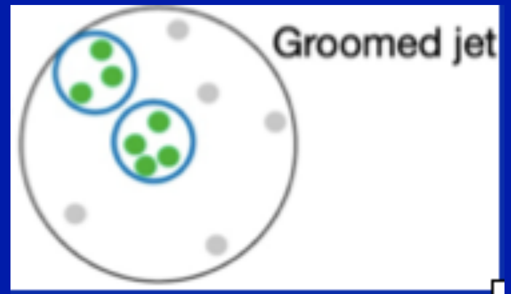


z_{cut}=0.2, β=0

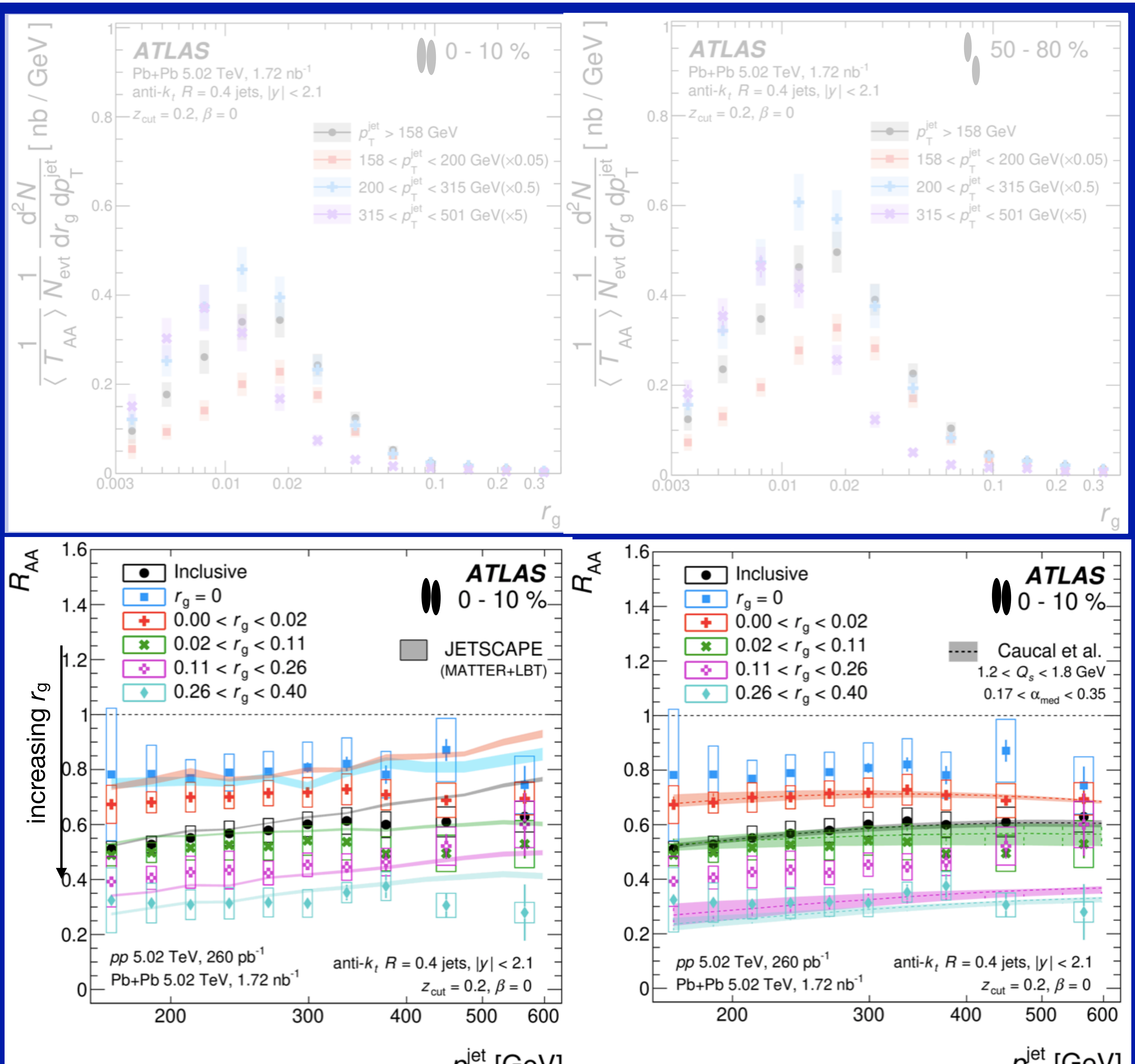
$r_g = \Delta R_{12}$ between the subjets from the first sppliting satisfying the soft drop condition

- 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

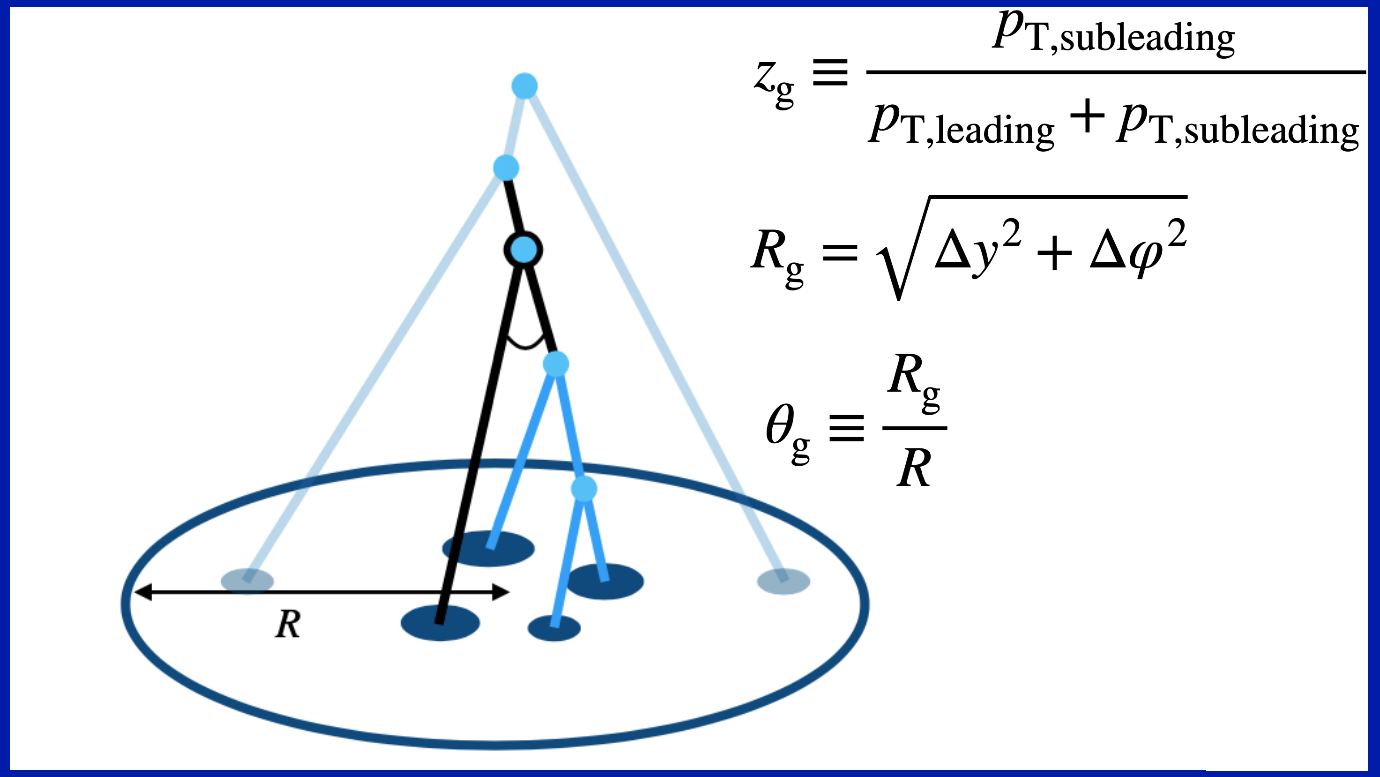
JETSCAPE compatible with exception for very low r_g (underestimates the suppression)

Caucal et al. overestimates the suppression for intermediate r_g



Phys. Rev. C 107 (2023) 054909

Jet substructure - z_g



SoftDrop conditions

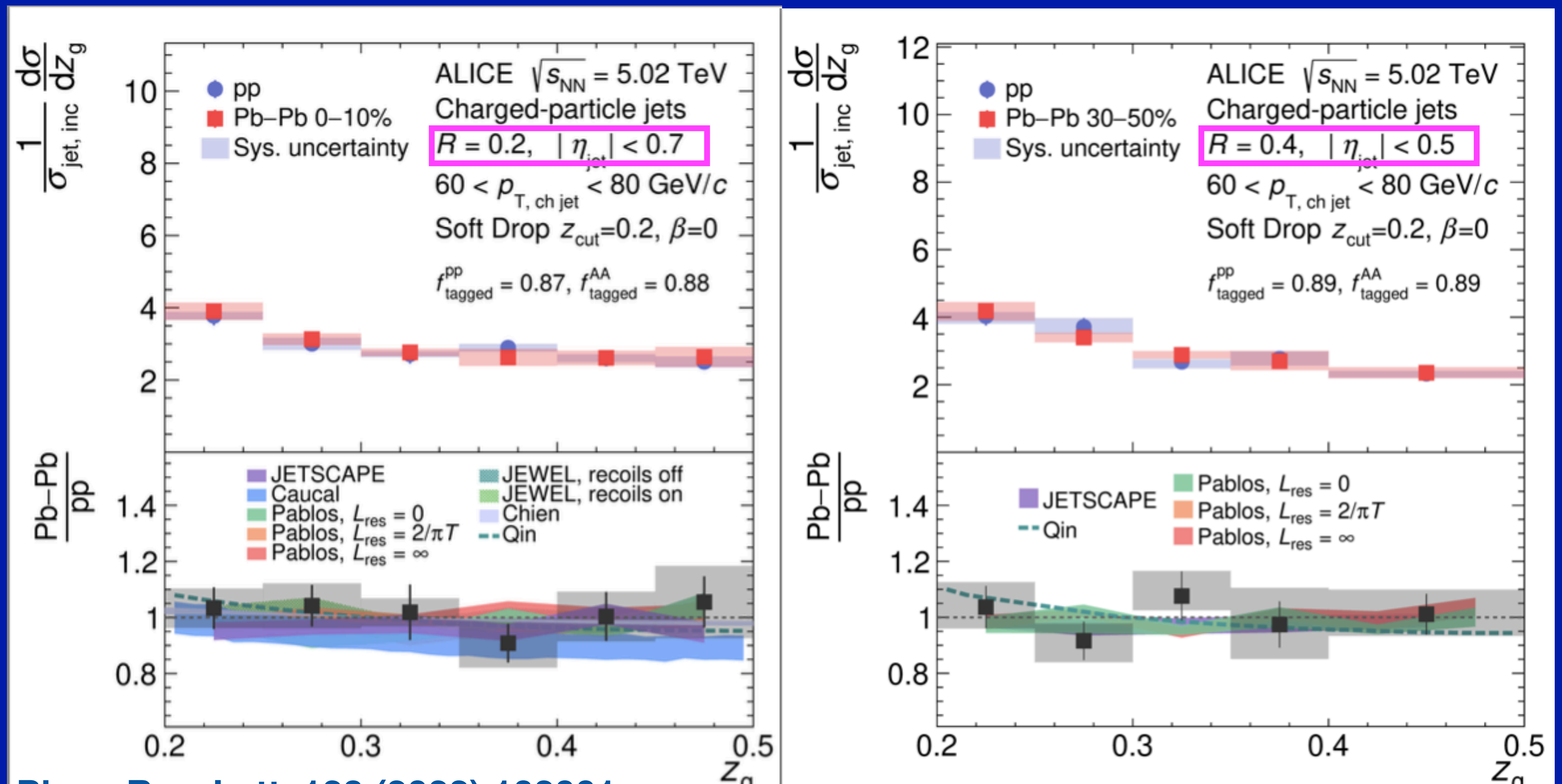
ALICE:

z_{cut} = 0.2, β=0, R=0.2 and 0.4

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

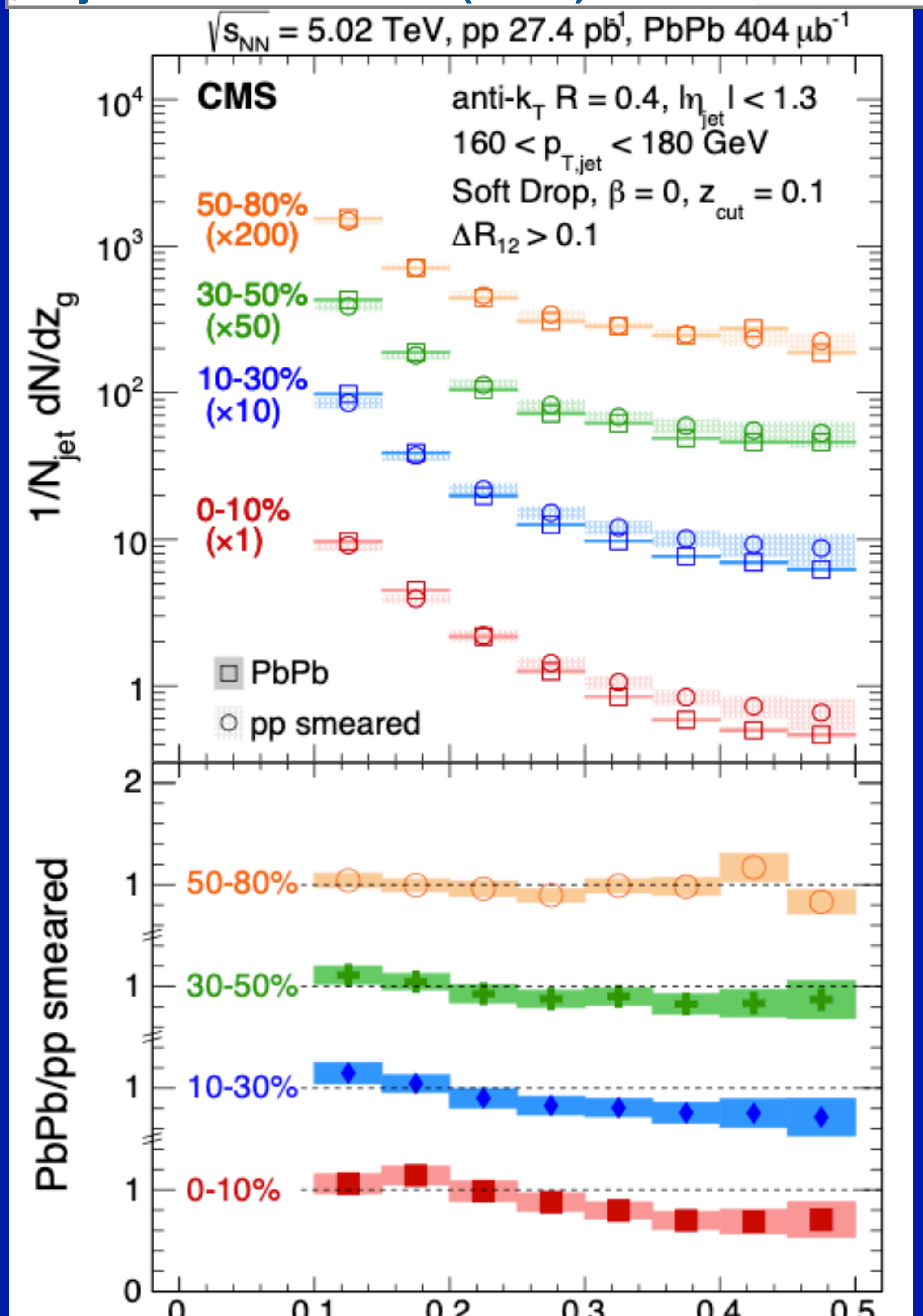
CMS:

z_{cut} = 0.1, β=0 R=0.4



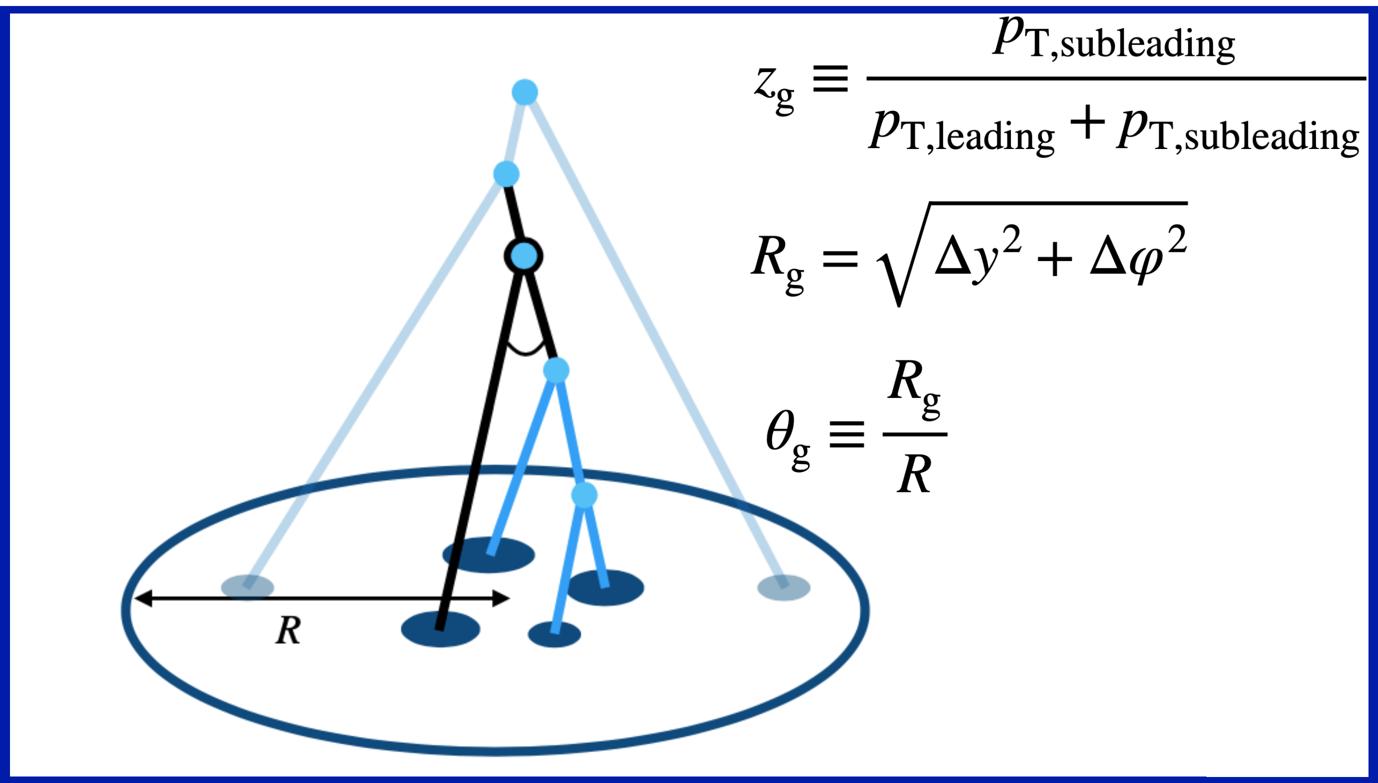
Phys. Rev. Lett. 128 (2022) 102001

- 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.



PRL 120 (2018) 143302

Jet substructure - θ_g



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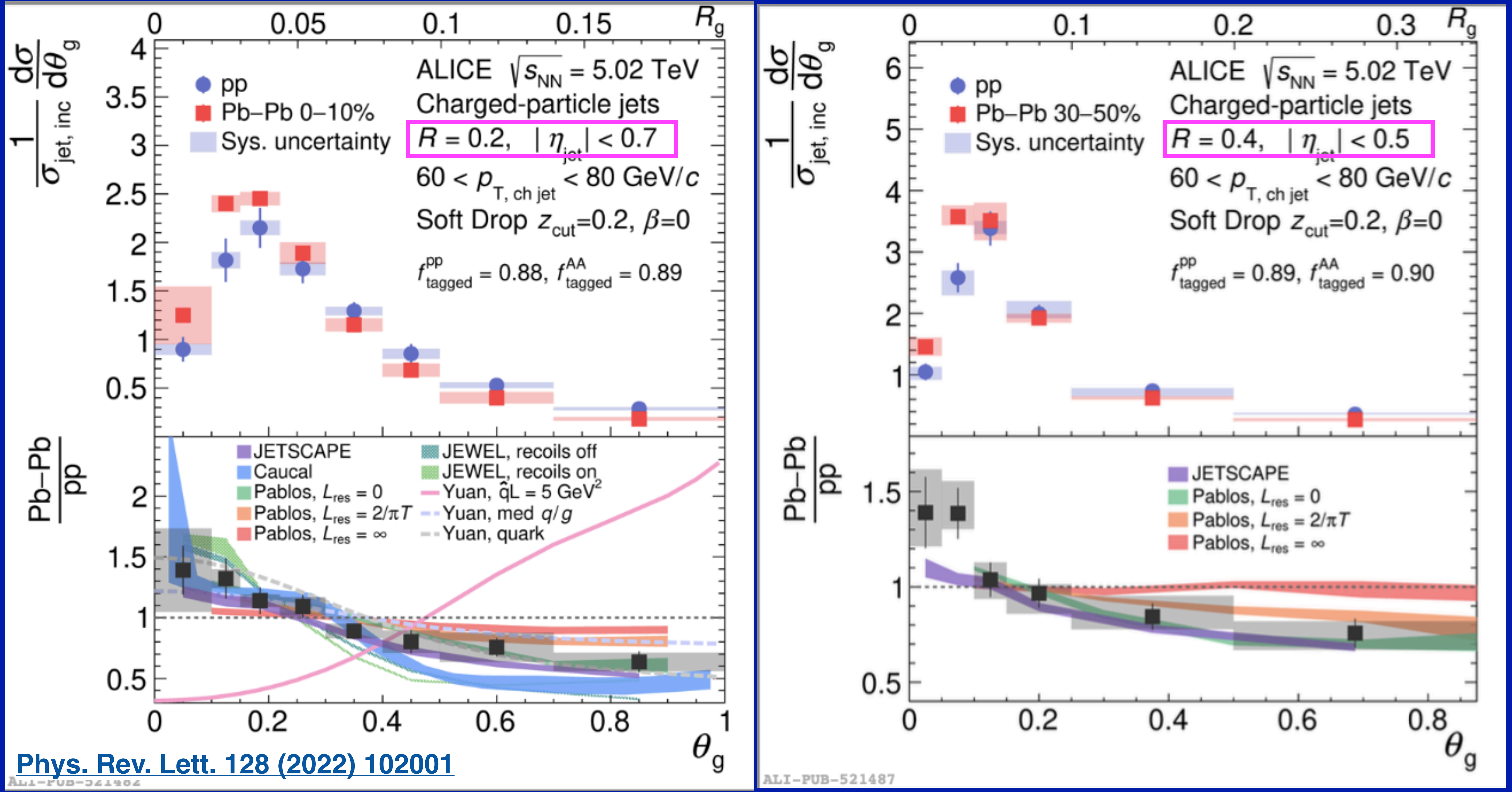

- Enhancement of narrow splittings and suppression of wider ones. No difference for R=0.4 jets

Hybrid model assuming fully incoherent energy loss reproduces the data for θ_g > 0.2

Yuan (quark only) describes the data as well

Sensitivity to medium response

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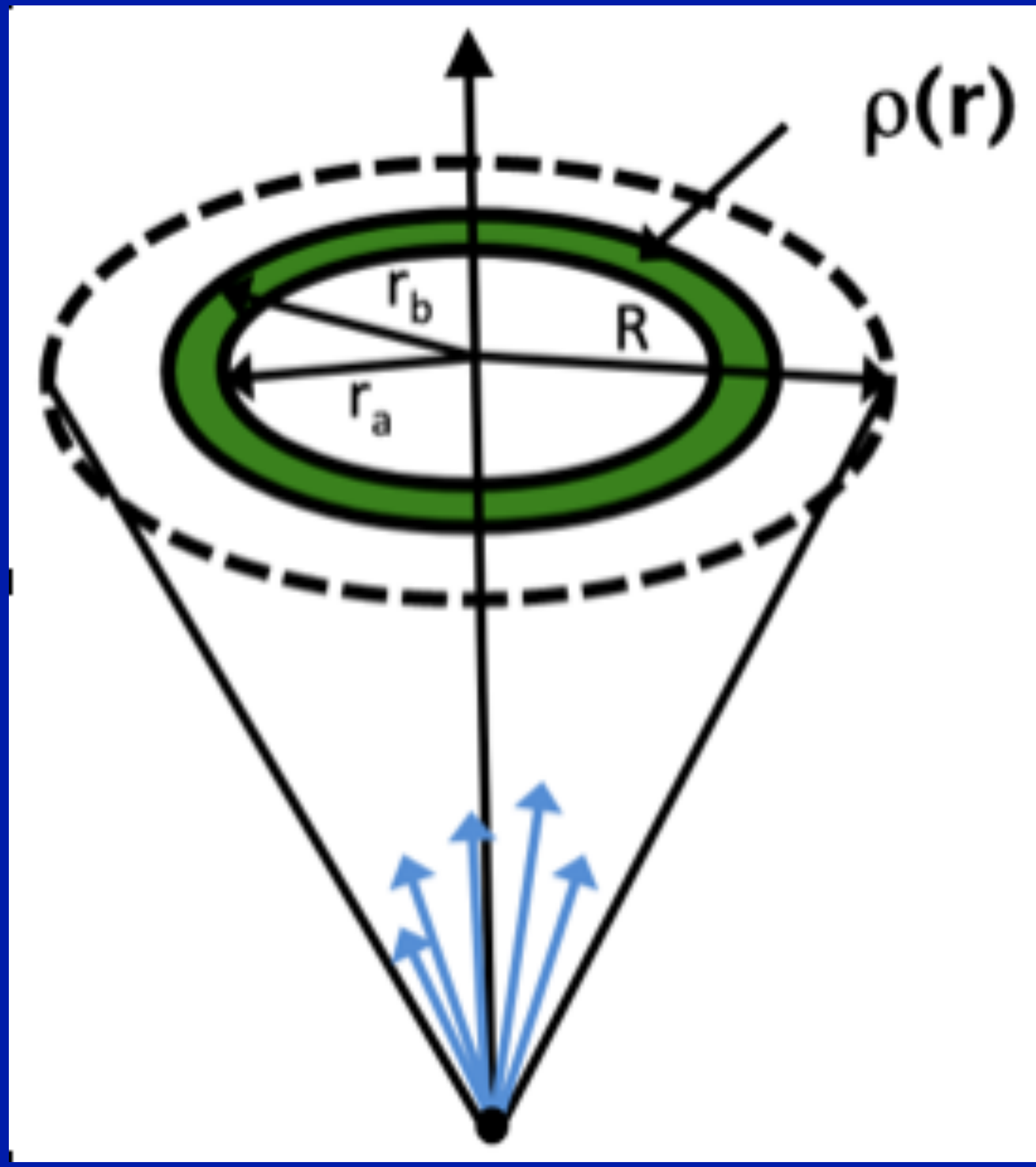


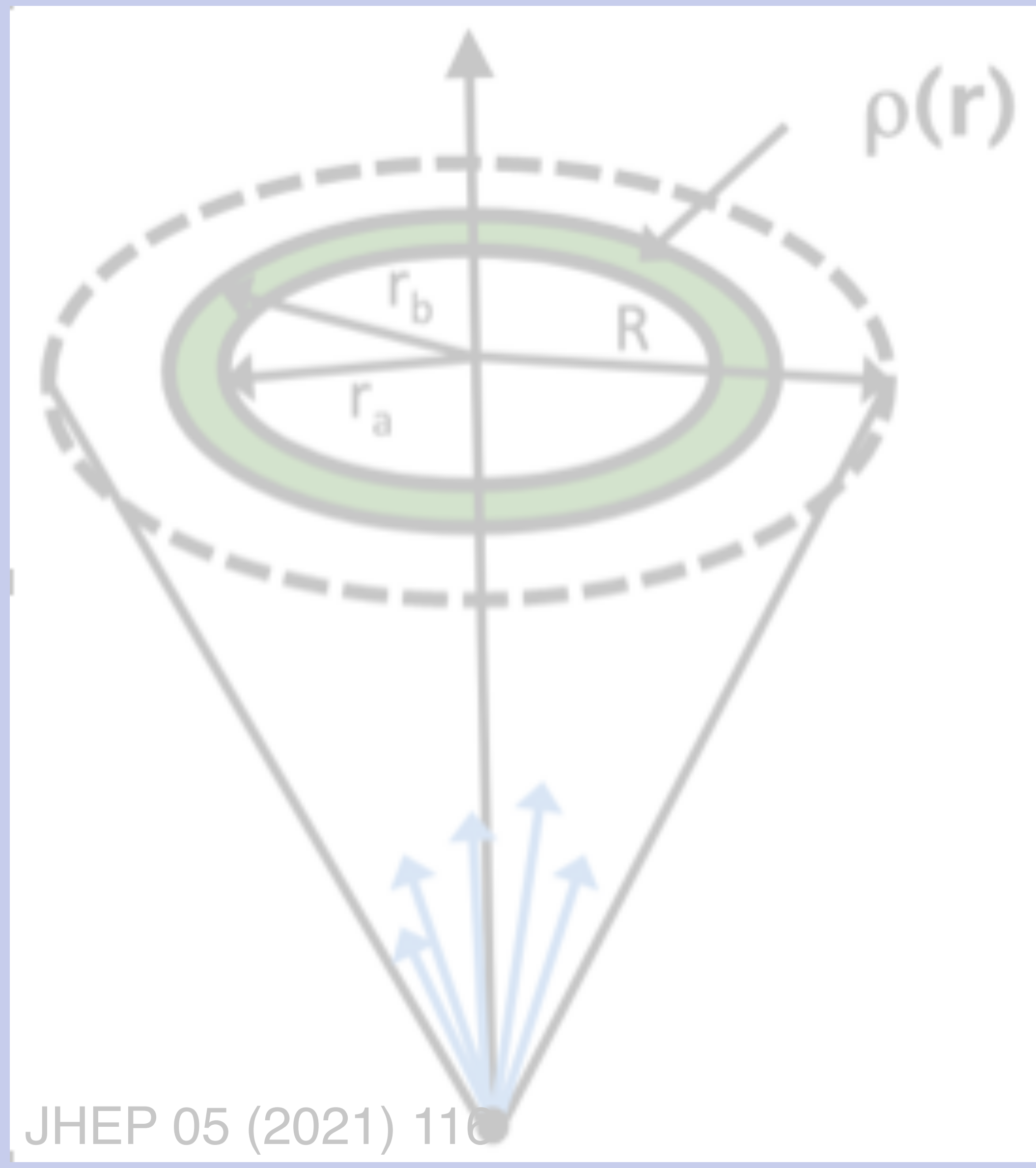
Jet radial momentum distributions

$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\Sigma_{\mathrm{jets}}\Sigma_{\mathrm{trk}\in(\Delta r_{\mathrm{a}},\Delta r_{\mathrm{b}})}\, p_{\mathrm{T}}^{\mathrm{trk}}$$

Jet shapes

$$\rho(\Delta r) = \frac{\mathrm{P}(\Delta r)}{\Sigma_{\mathrm{jets}}\Sigma_{\mathrm{tracks}\in\Delta r<1}\, p_{\mathrm{T}}^{\mathrm{ch}}}$$

Sensitivity to medium response



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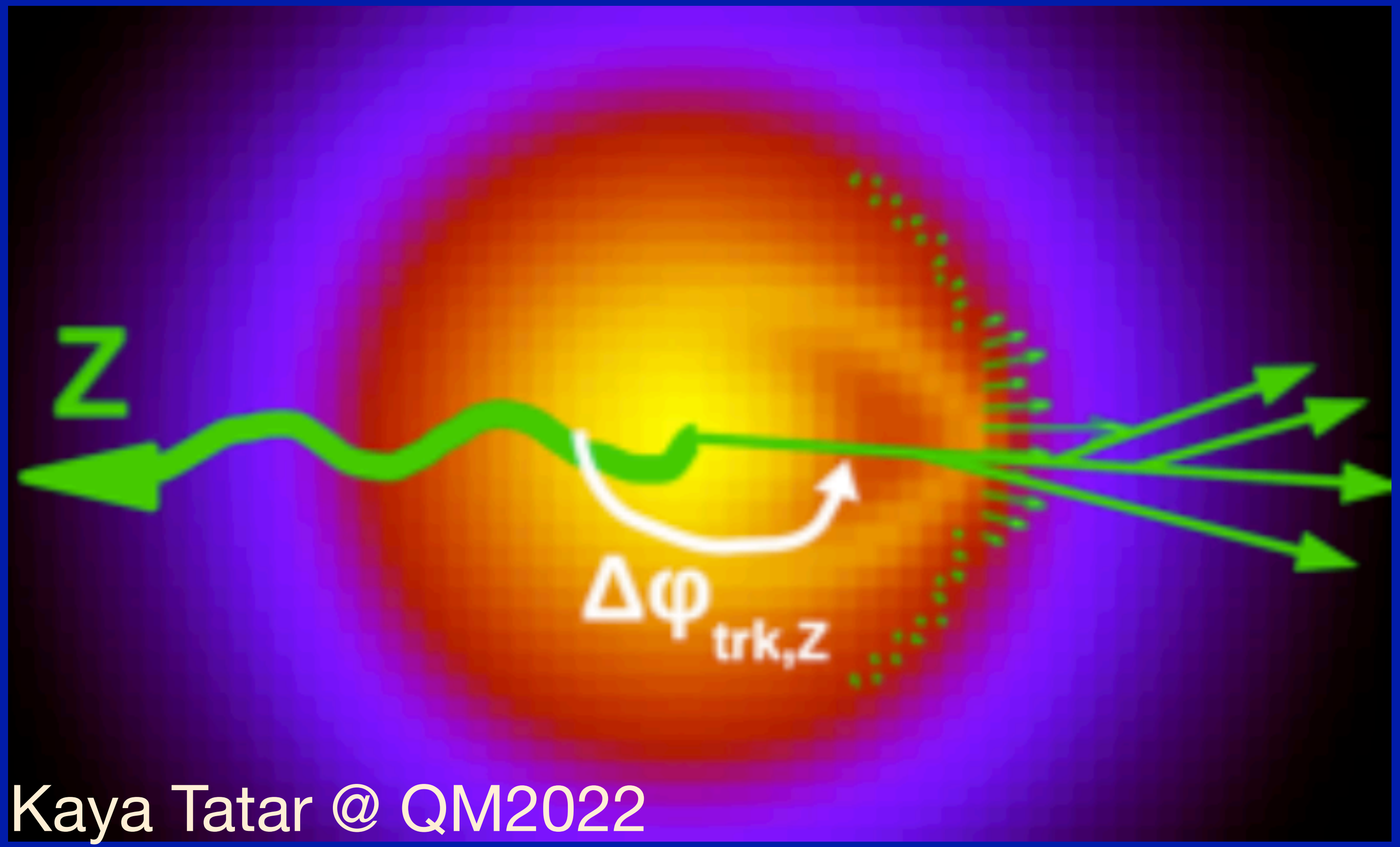
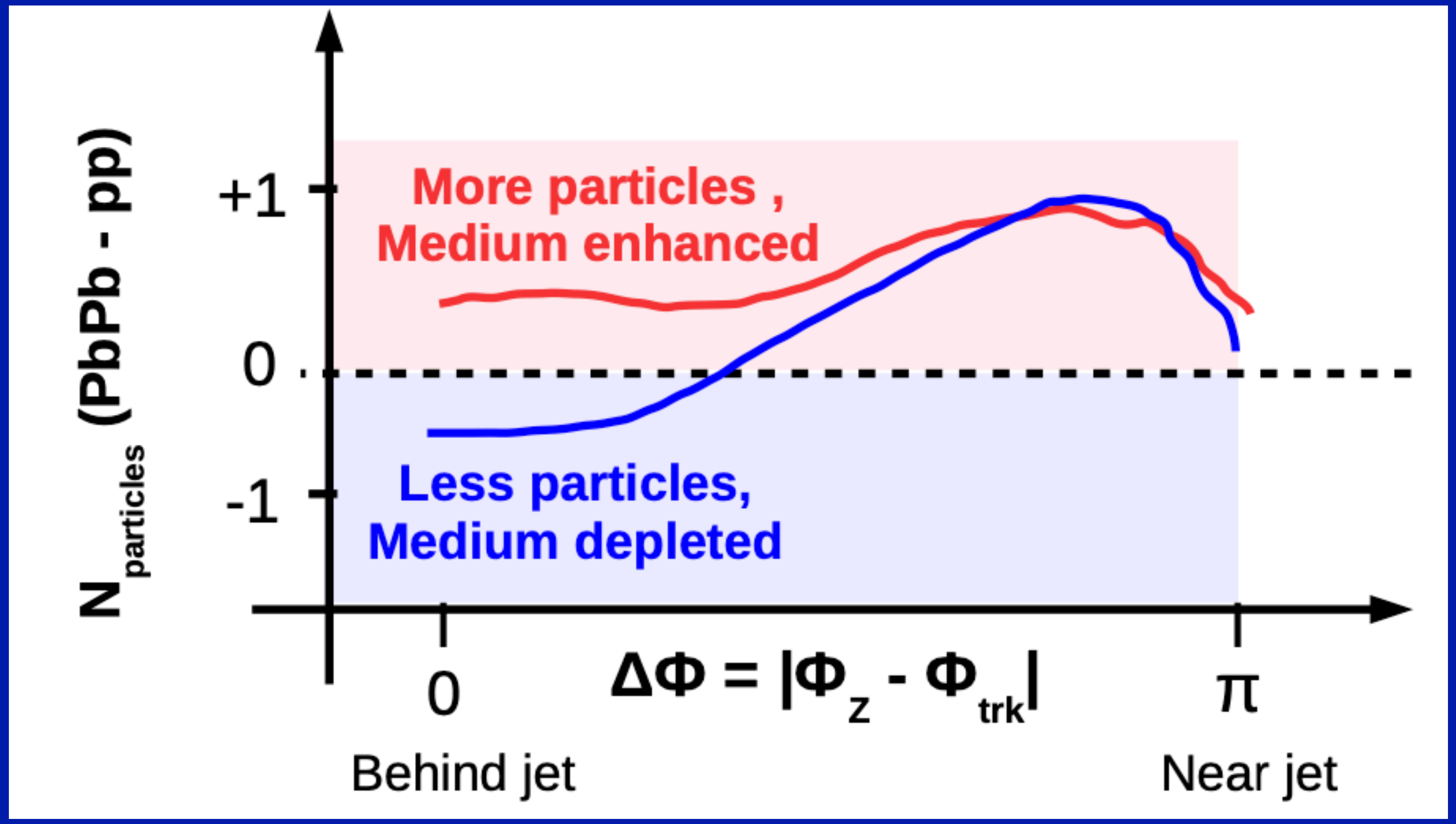
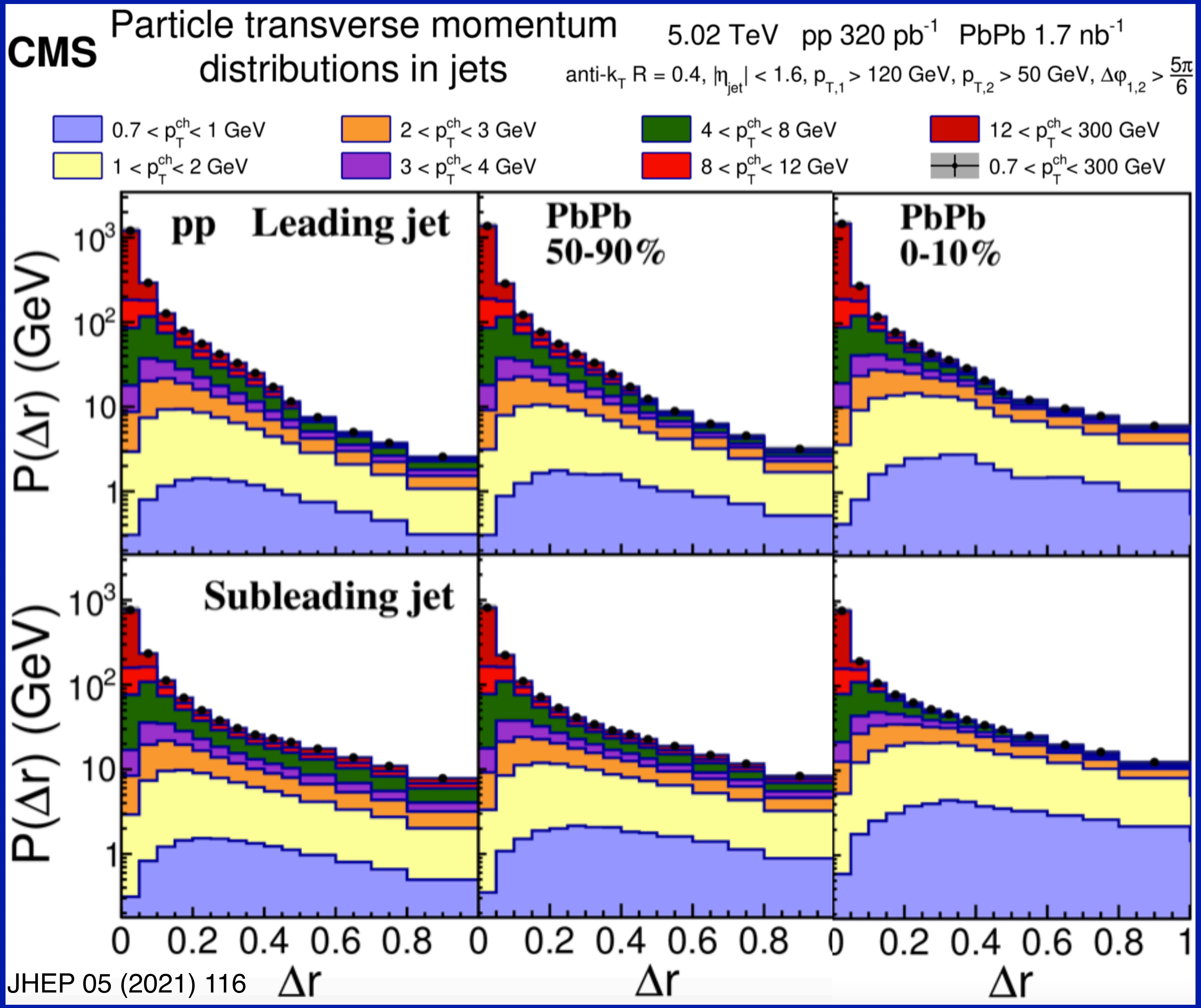
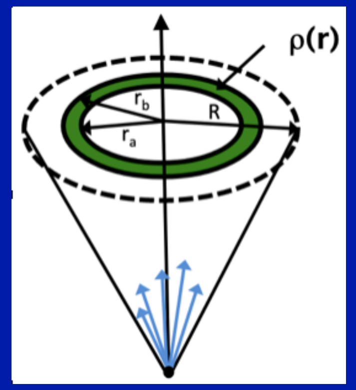




Angular scan of jet-QGP interactions

Jet radial momentum flow



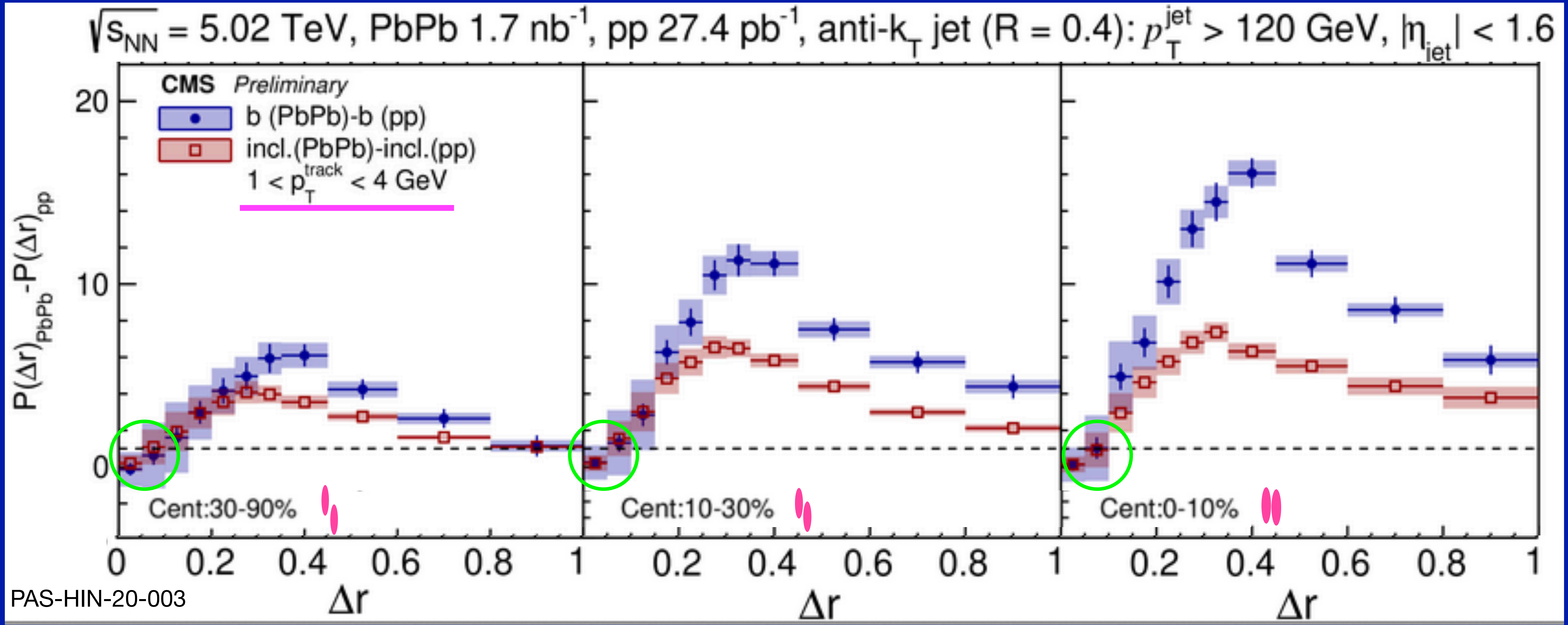


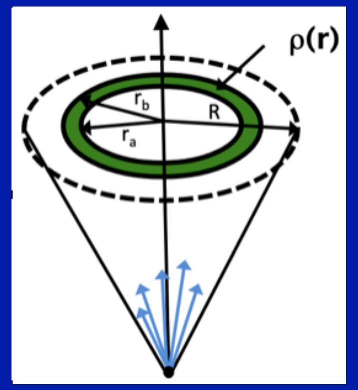
Enhancement of low-p_T charged particles in central PbPb relative to *pp* at large angular distance from the jet axis.

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-pT particles far away from the jet axis.

Difference of p_T profiles in *pp* and PbPb

For inclusive and *b*-jets

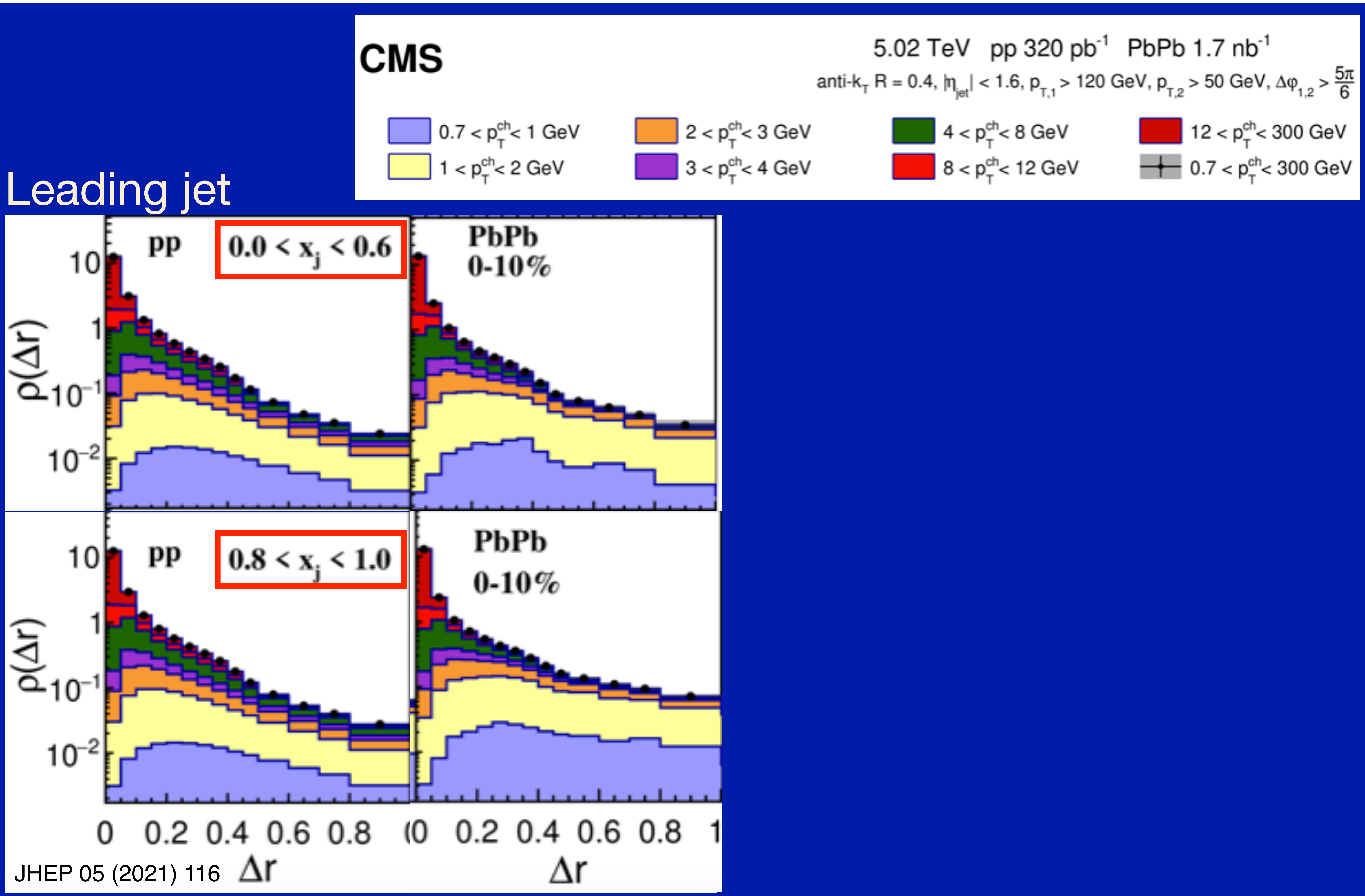




- In PbPb more p_T from low momentum particles is accumulated at the edge of the jet (Δr~0.3—0.4 for R=0.4 jets).
- Core of the jet is unmodified, independently on the flavour, but then the redistribution is strongly enhanced for *b*-jets

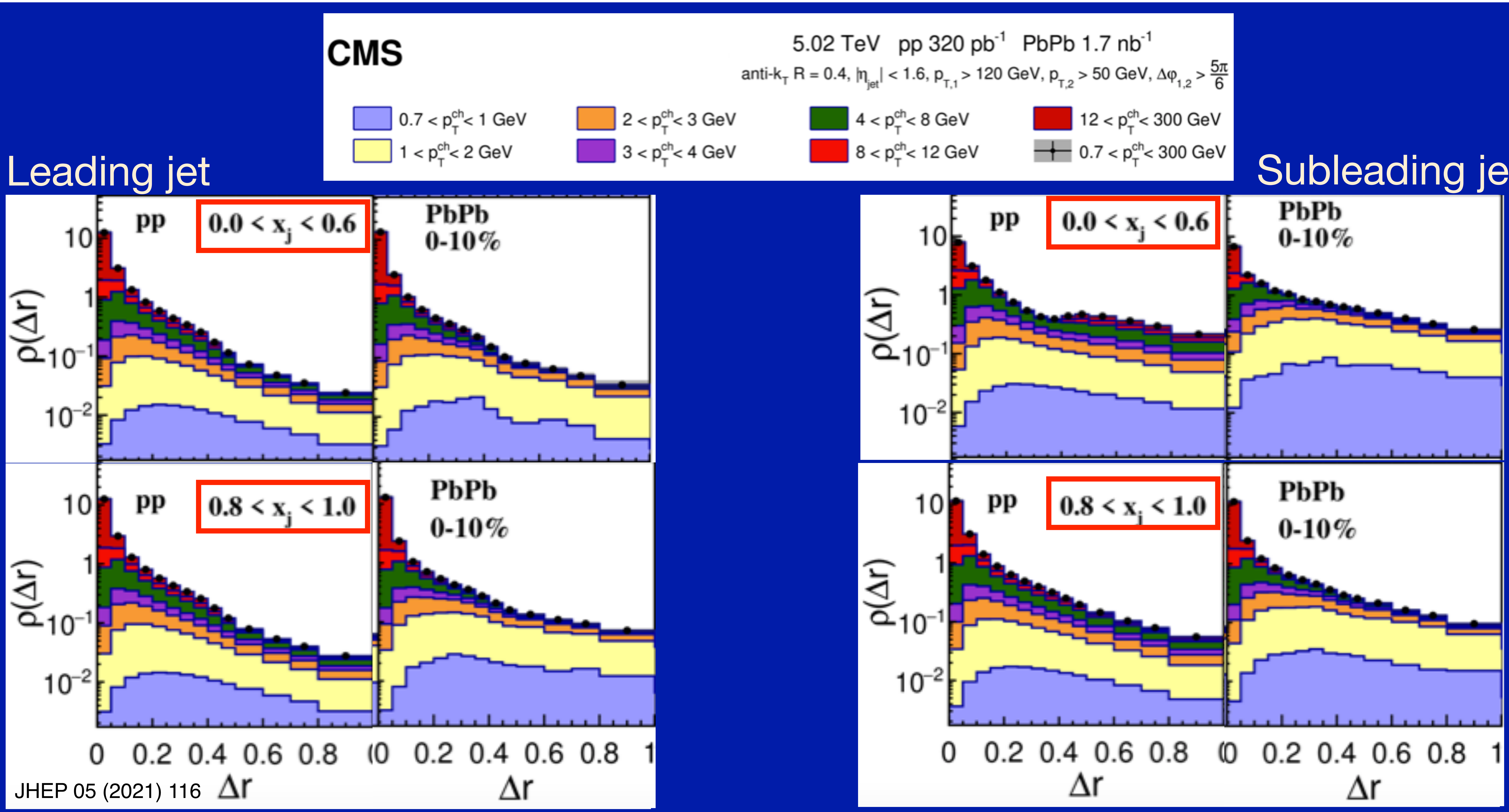
Jet shape in dijets as a function of x_j

Leading jet



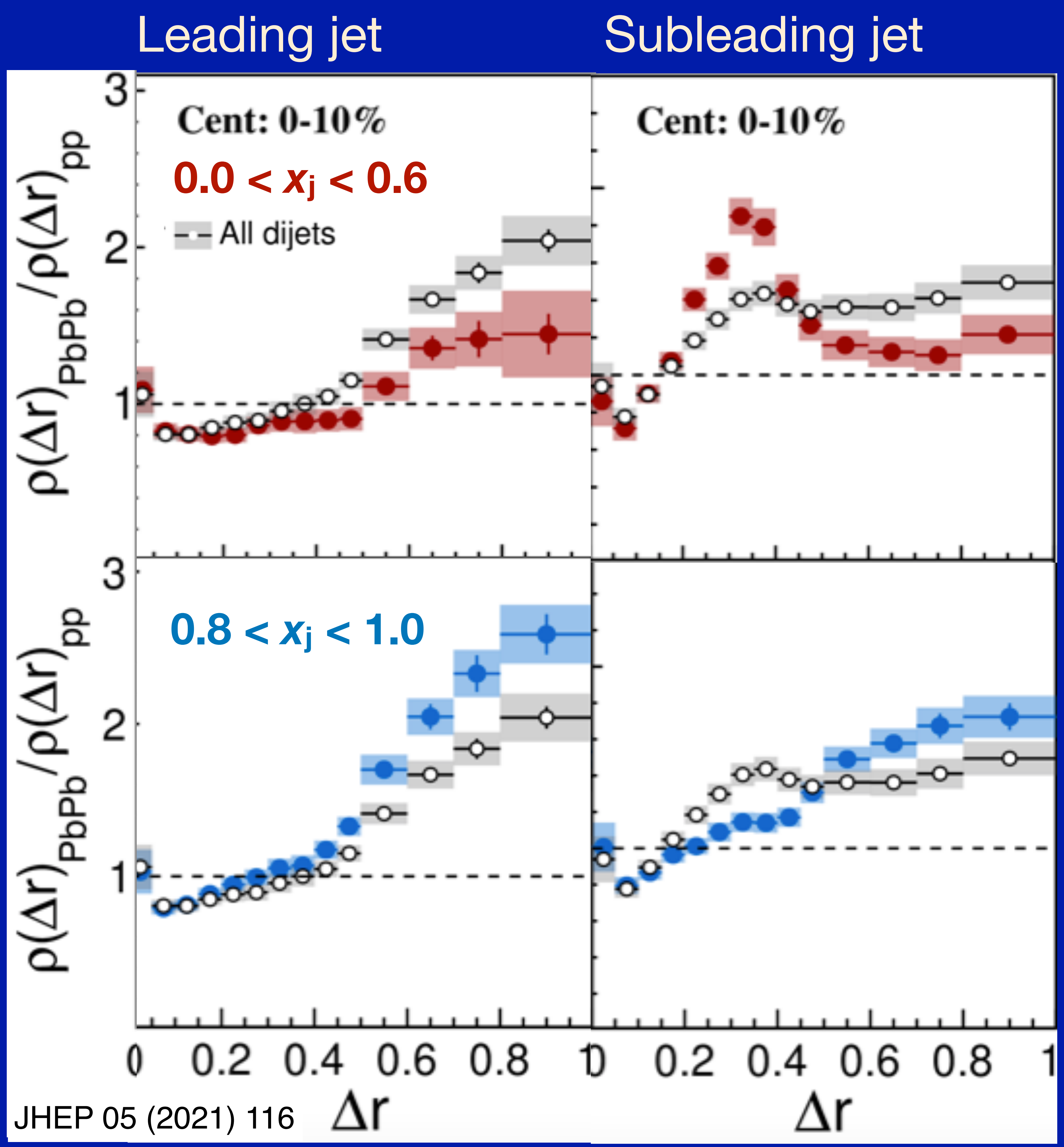
- Enhancement of low-p_T charged particles in central PbPb relative to *pp* at large Δr.
- For leading jets the enhancement is larger for balanced dijets (no surface bias).

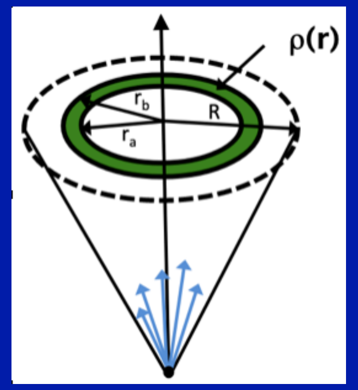
Jet shape in dijets as a function of x_j



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

Jet shape ratios as a function of x_j



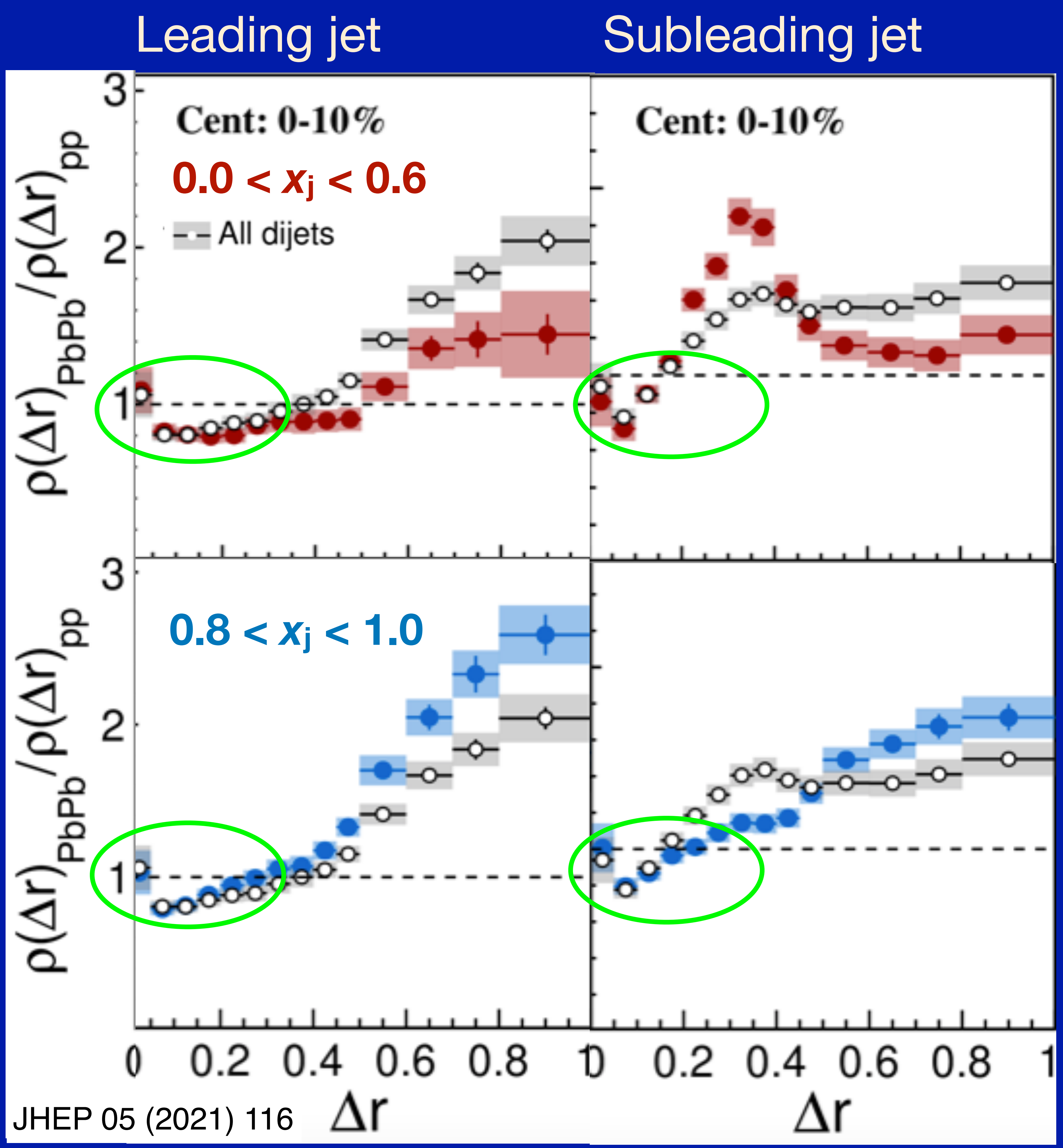


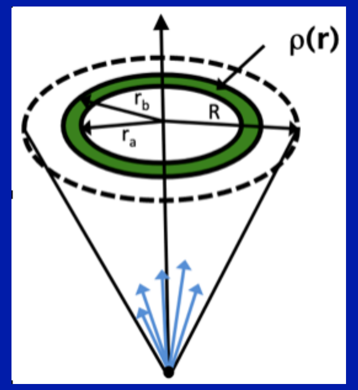
For subleading jets a clear effect at $\Delta r \simeq 0.3$ is observed, explained by the presence of a 3rd recoiled jet in *pp* that eventually disappeared in PbPb.

Enhancement of the PbPb leading (and subleading) jet shape modification at large Δr in balanced dijets.

Significant effects from different path length crossed.

Jet shape ratios as a function of x_j





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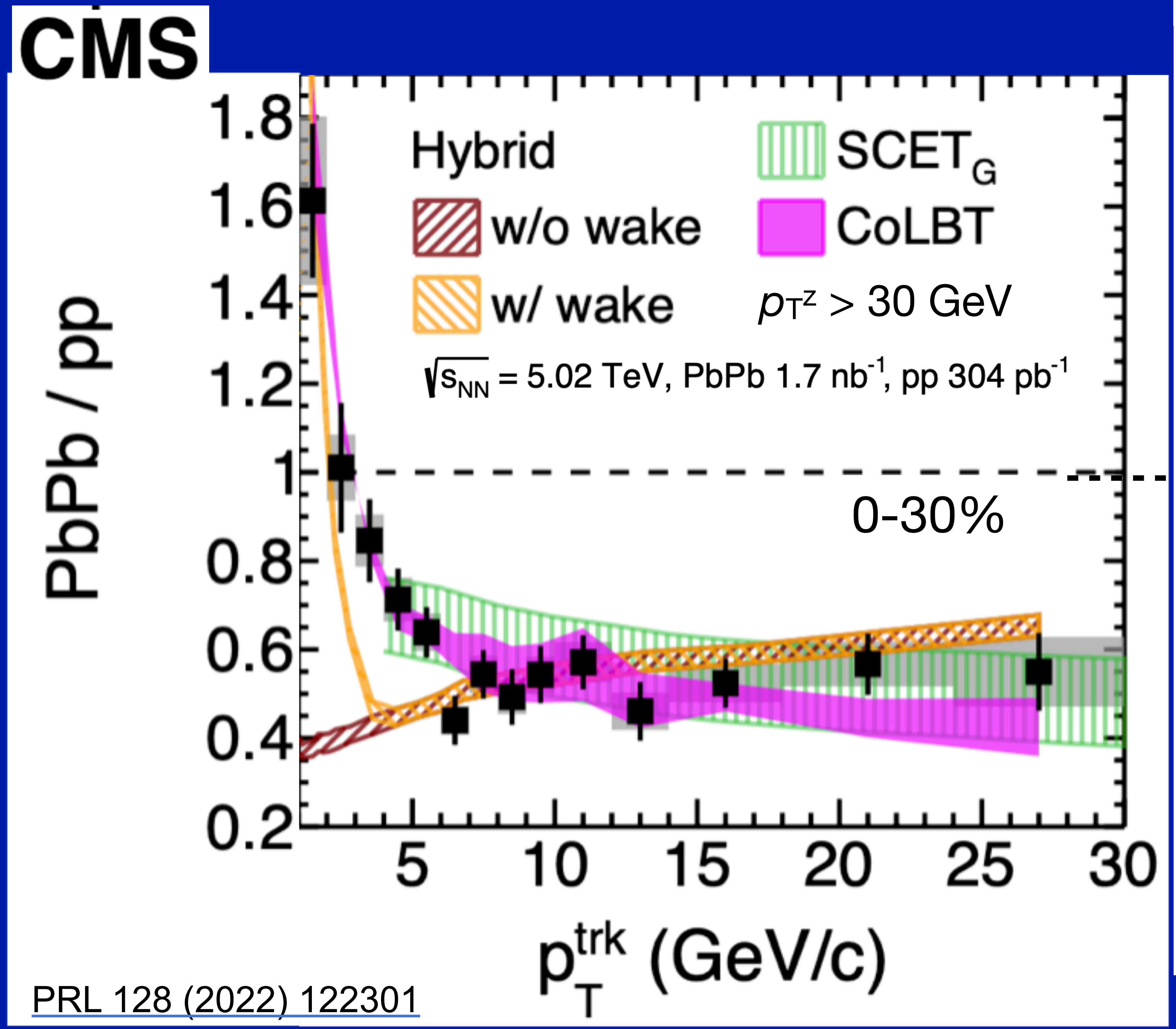
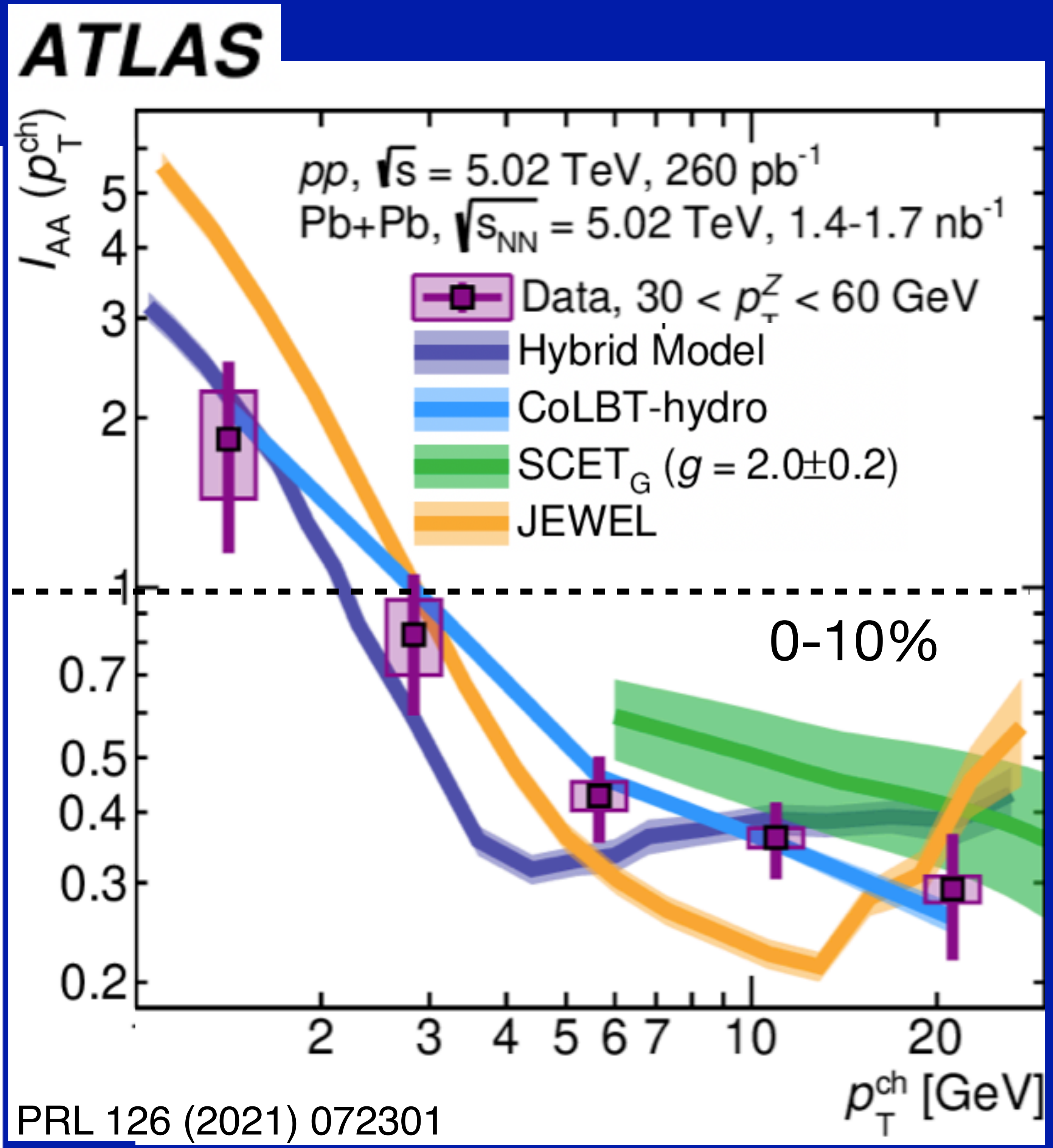
Enhancement of the PbPb leading (and subleading) jet shape modification at large Δr in balanced dijets.

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).

Z-recoil particles - I_{AA} as a function of p_T^{ch}





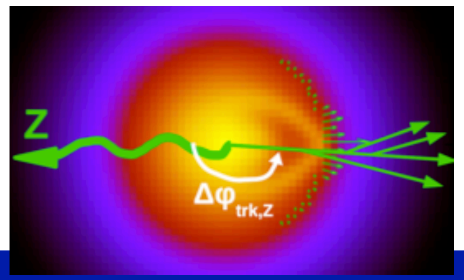
The p_T spectrum of charged particles recoinling against Z is strongly modified in PbPb.

SCET$_G$ (no medium response) describes CMS data but not available at low-p_T^{trk}.

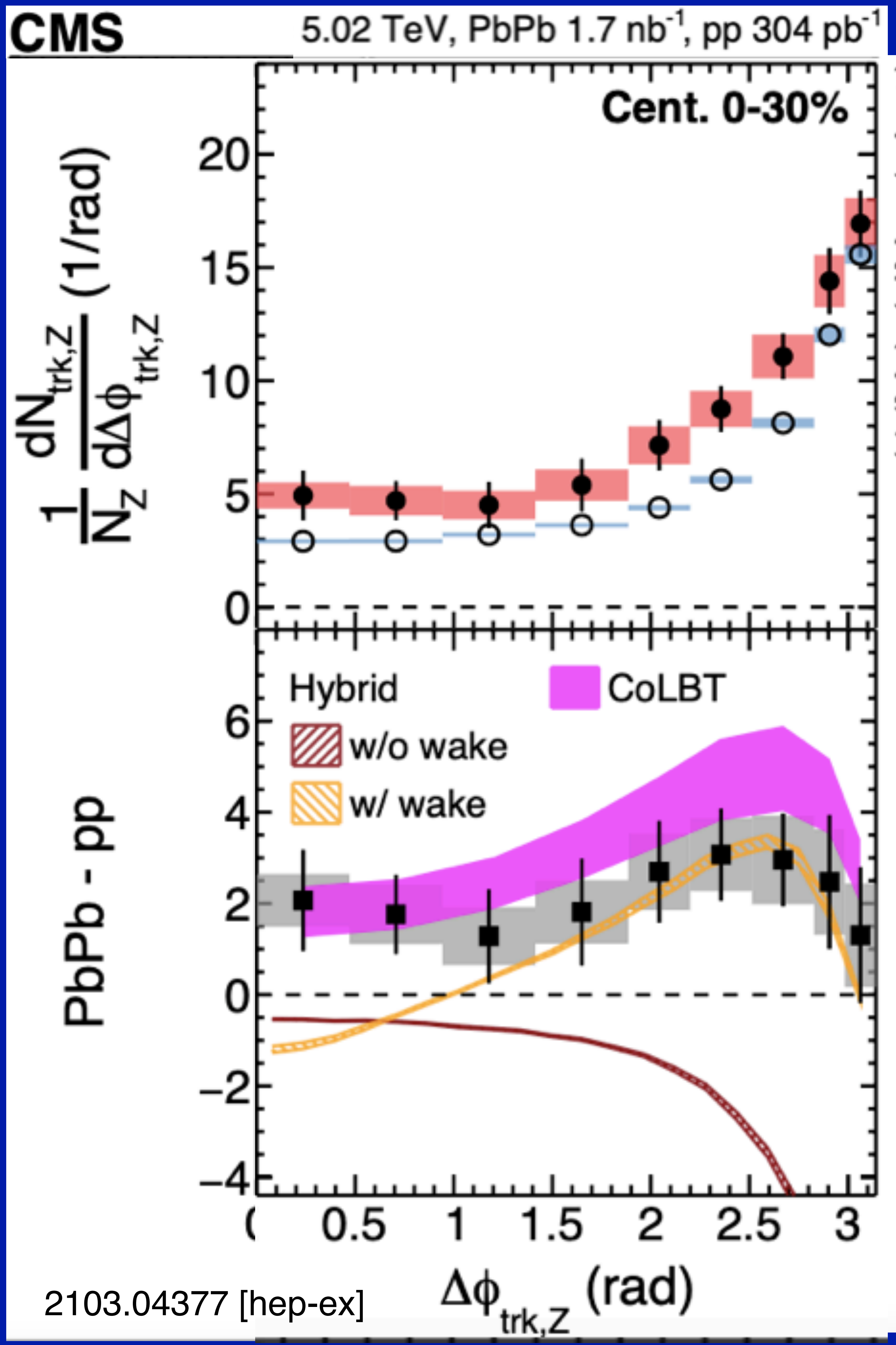
Hybrid w/o wake disagrees. Global improvement if including wake.

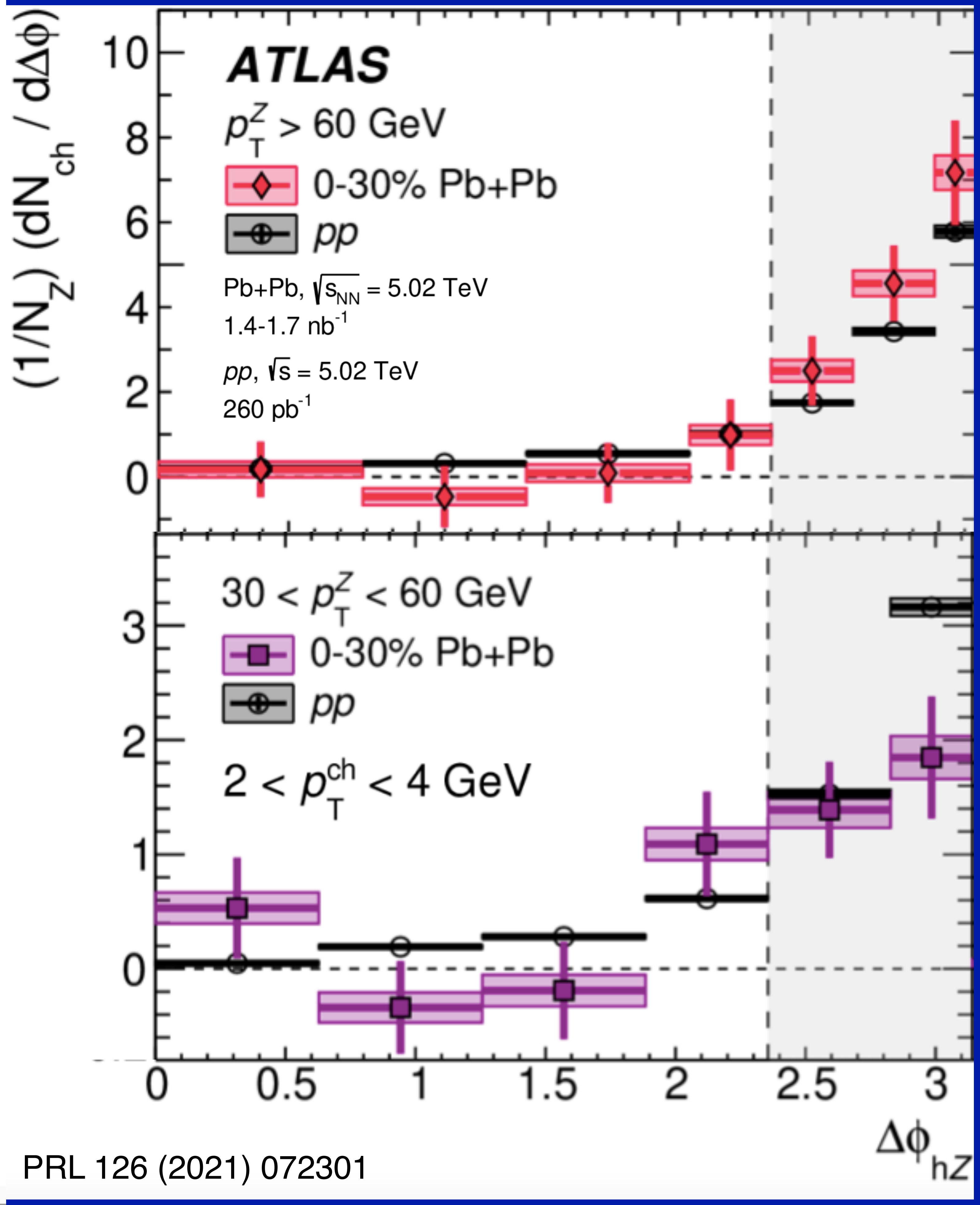
ColLBT (medium feeds back the quenched energy deposited) describes well CMS and ATLAS.

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



Sensitivity to the wake and diffusion wake — $\Delta\varphi_{hZ}$





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 ColLBT. 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 γ/Z+jet events

Conclusions and outlook

- 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).

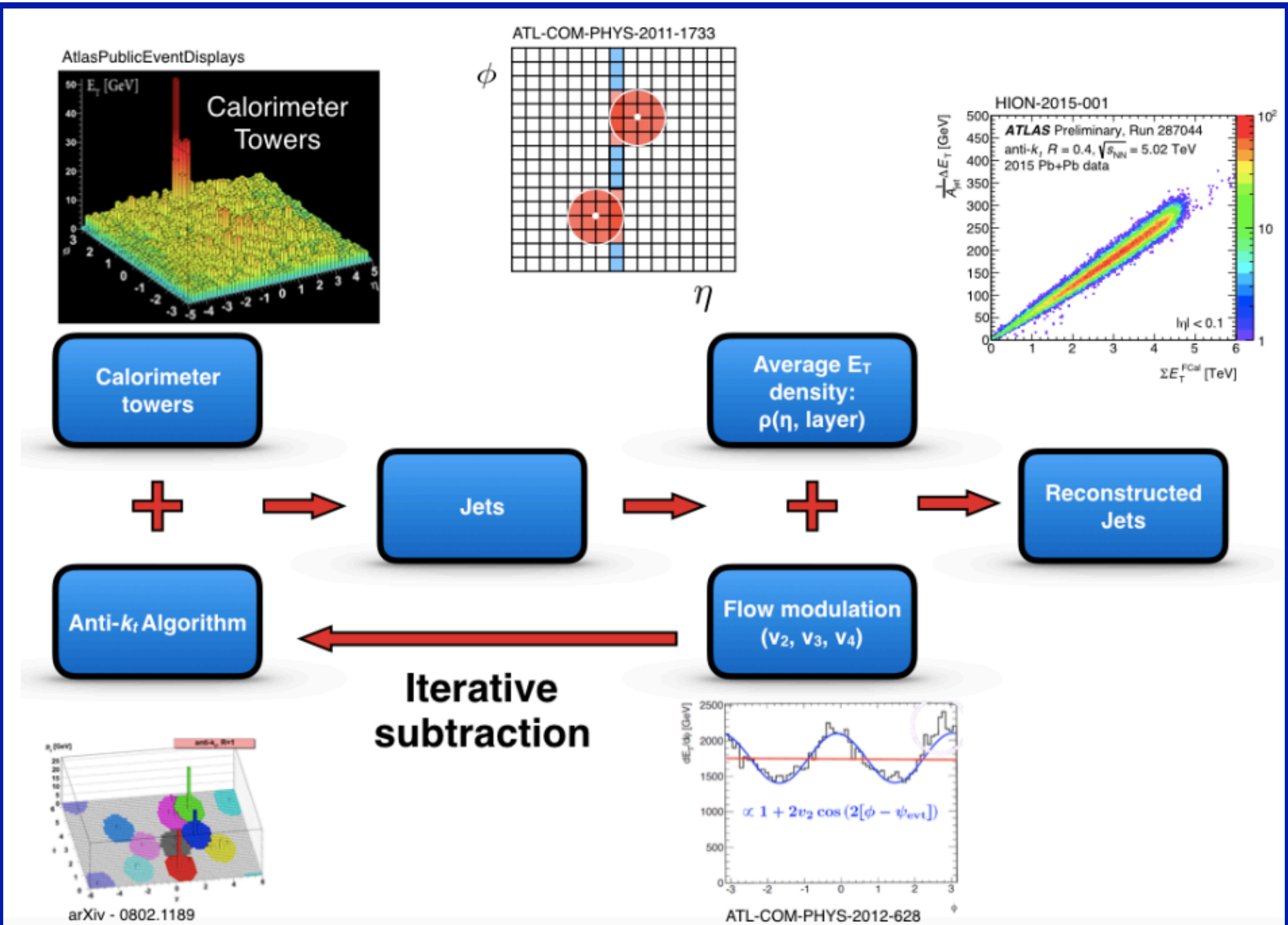
Comparing observables as a function of reconstructed jet p_T ranges imply:

- 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.

Backup

Jet reconstruction in Pb+Pb collisions



Quark jet fraction

ATLAS-CONF-2022-019

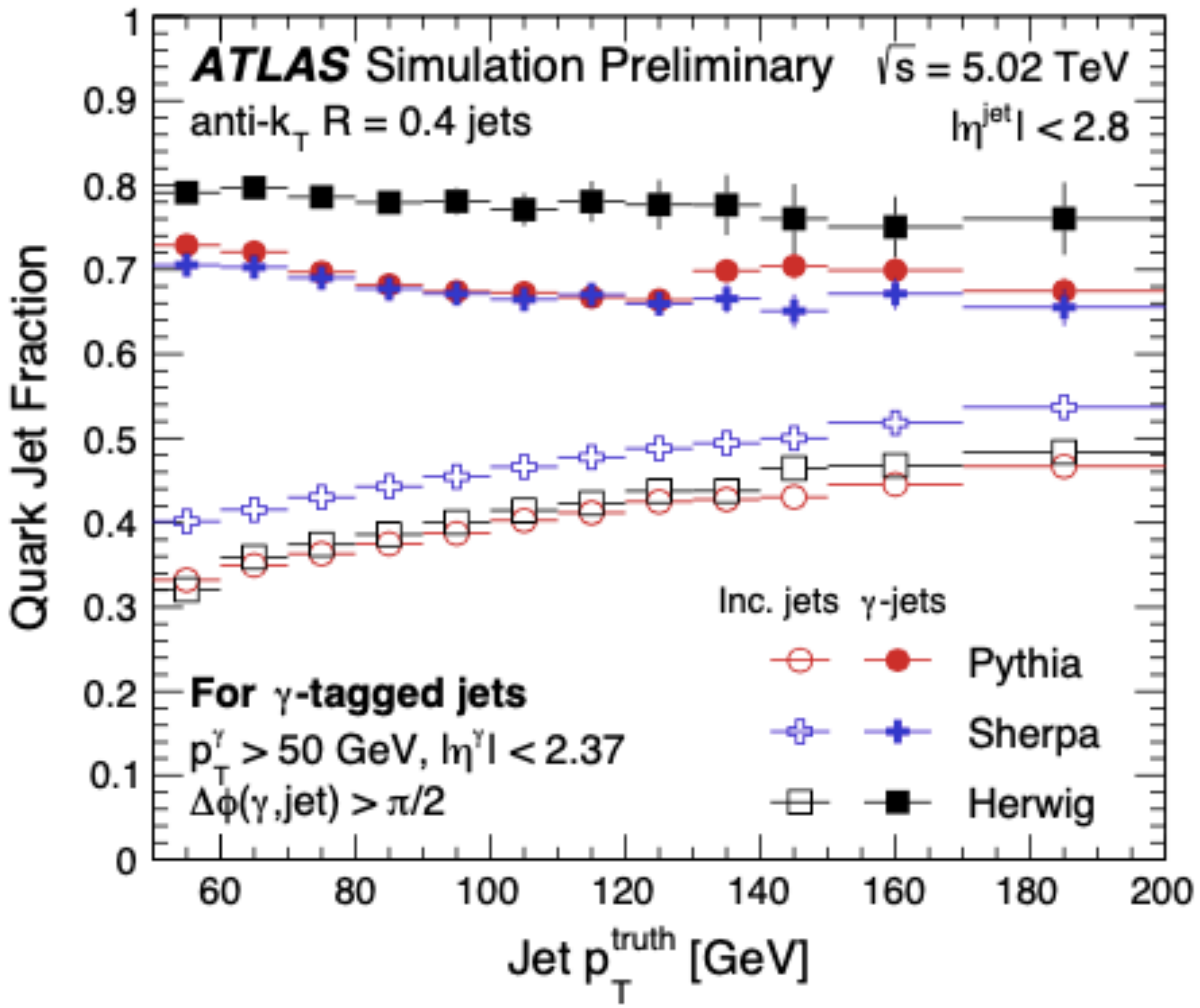
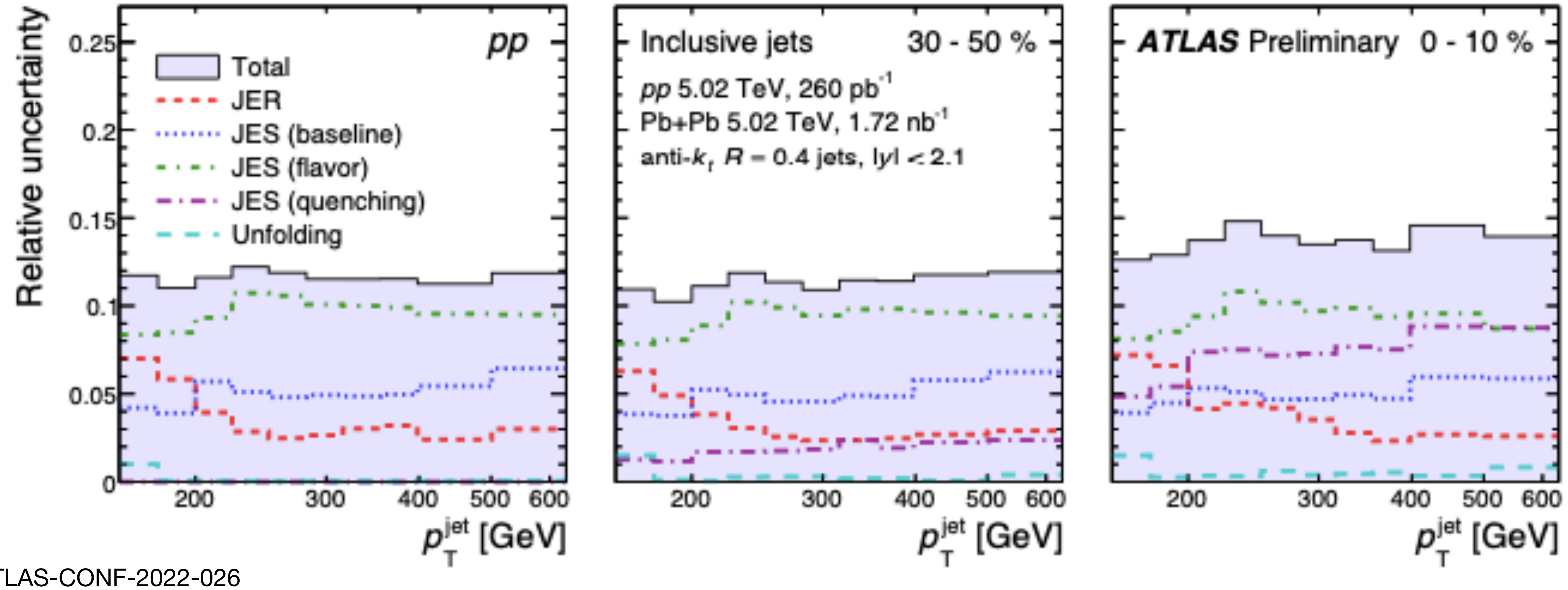


Figure 1: Fraction of photon-tagged jets (filled markers) and inclusive jets (open markers) initiated by a quark, as a function of p_T^{jet}, in the PYTHIA (red), HERWIG (black), and SHERPA (blue) event generators.

Jet substructure uncertainties



ATLAS-CONF-2022-026

Figure 2: The relative systematic uncertainties on inclusive p_T^{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 $\sqrt{s_{NN}}$ = 5.02 TeV (second and third panels). The legend applies to all the panels.

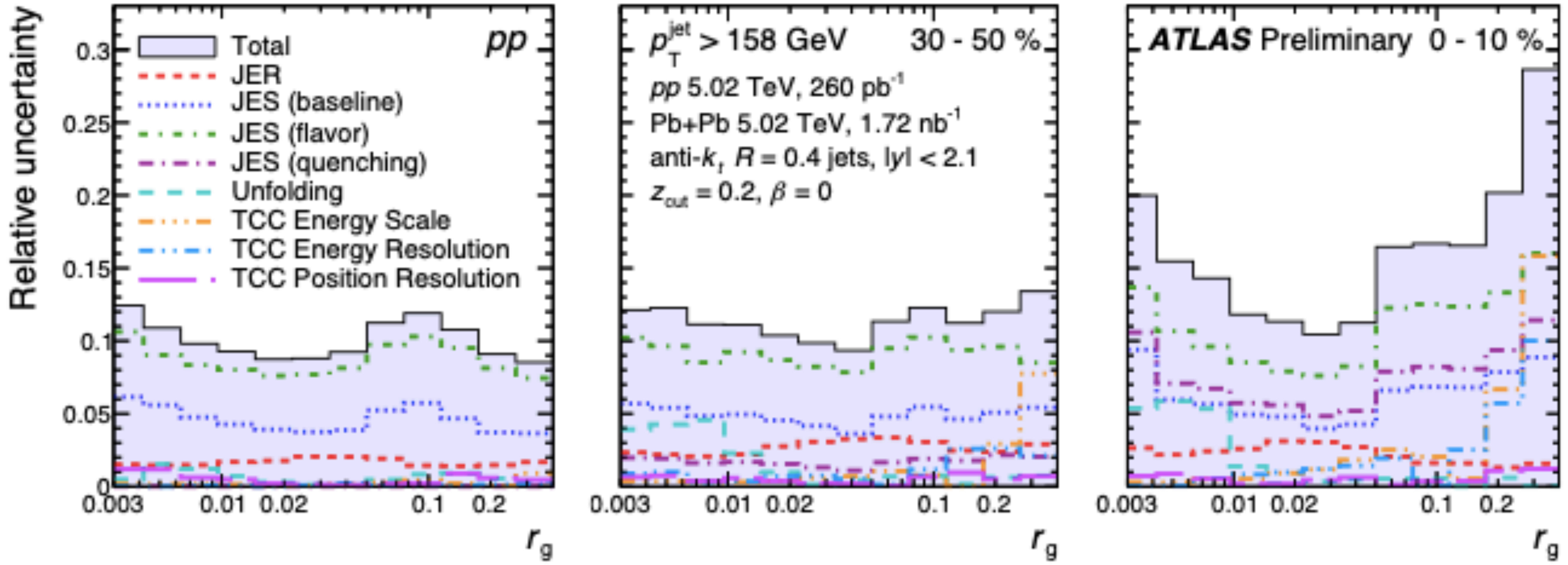


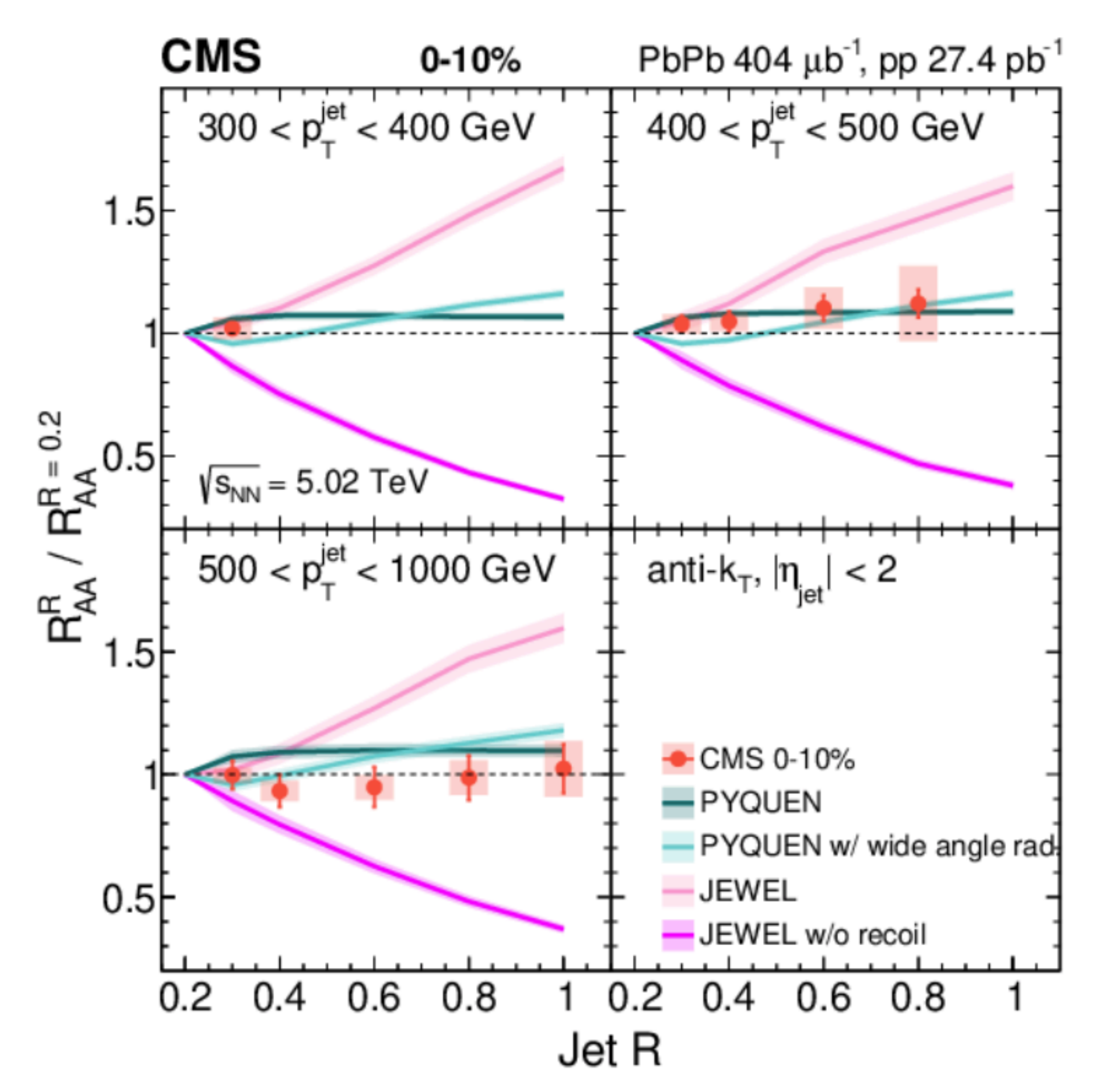
Figure 3: The relative systematic uncertainties on inclusive r_g cross-section and per-event jet yield measurements in pp collisions at $\sqrt{s}$ = 5.02 TeV (left) and for different event centralities in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (second and third panels) shown for soft-drop parameters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

Jet substructure

2102.12080 [hep-ex]

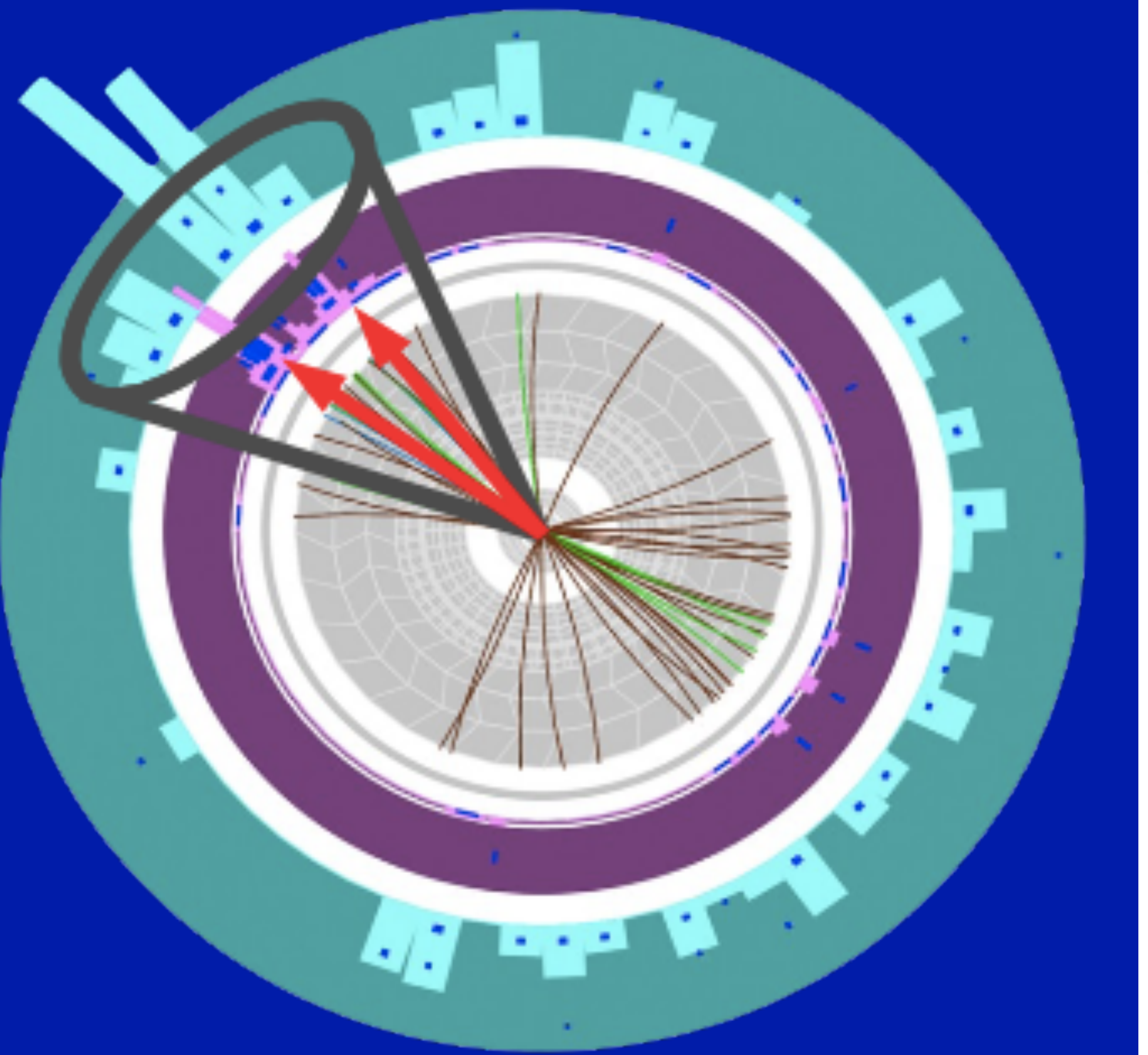
Inclusive jets

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

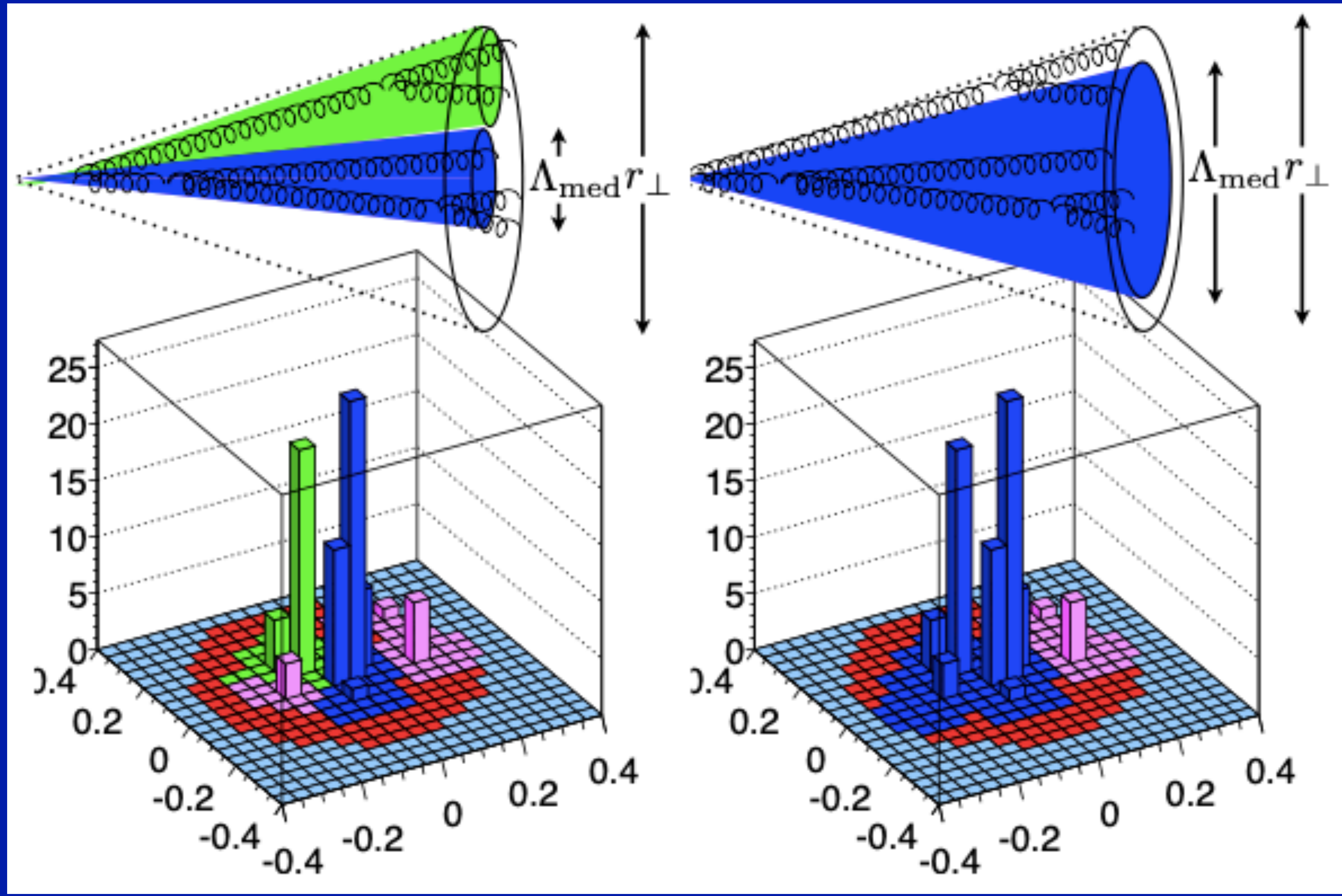


The suppression for jet p_T > 300 GeV does not depend on jet radii.

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



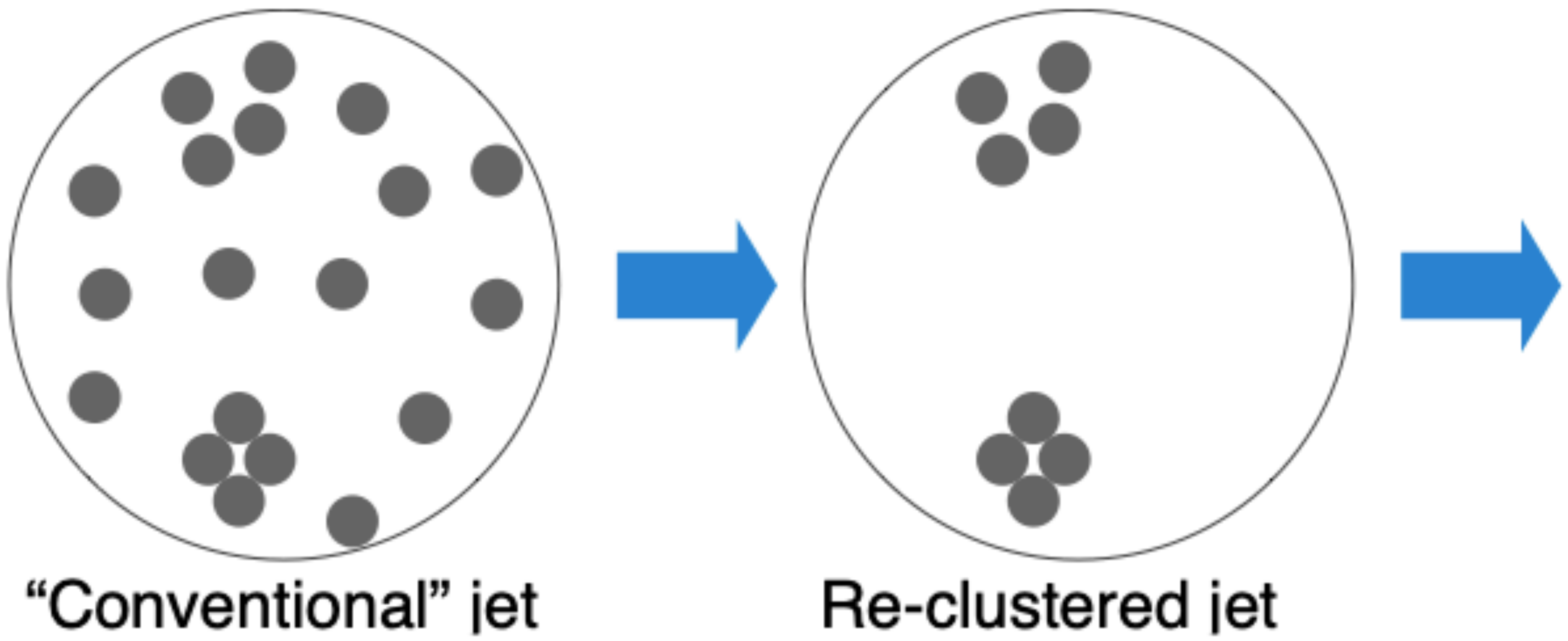
Recluster jets and remove soft contributions



J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, PLB725 (2013) 357

Large R jets reconstructed from R = 0.2 jets

Cal. towers & UE subtraction → R=0.2 jets anti-k_t jets $p_T > 35$ GeV → re-clustering with anti-k_t R=1.0 → Sub-jets → re-clustering with k_t algorithm → Splitting scale $\sqrt{d_{12}}$



Different jets than the conventional R=1.0.

Trimming & 35 GeV threshold remove soft components.

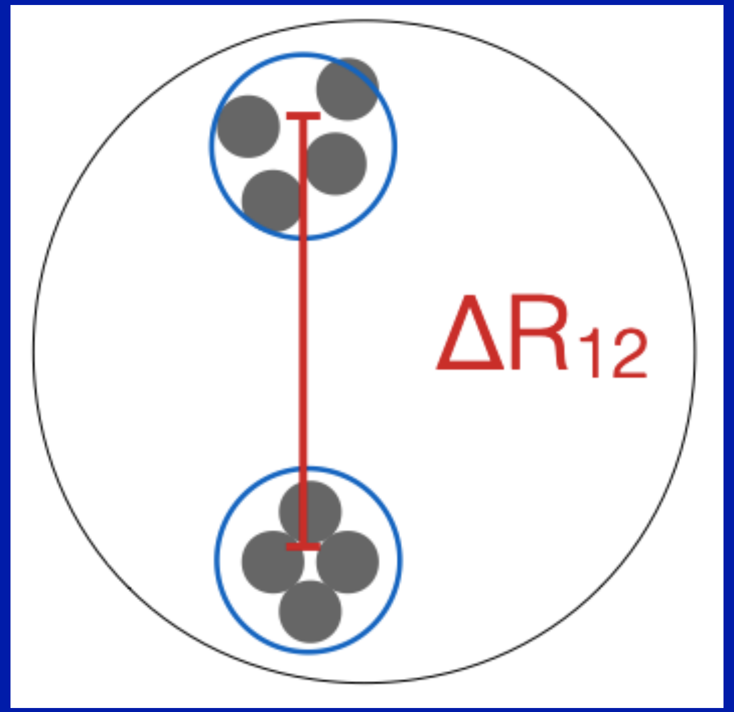
M. Rybar QM19

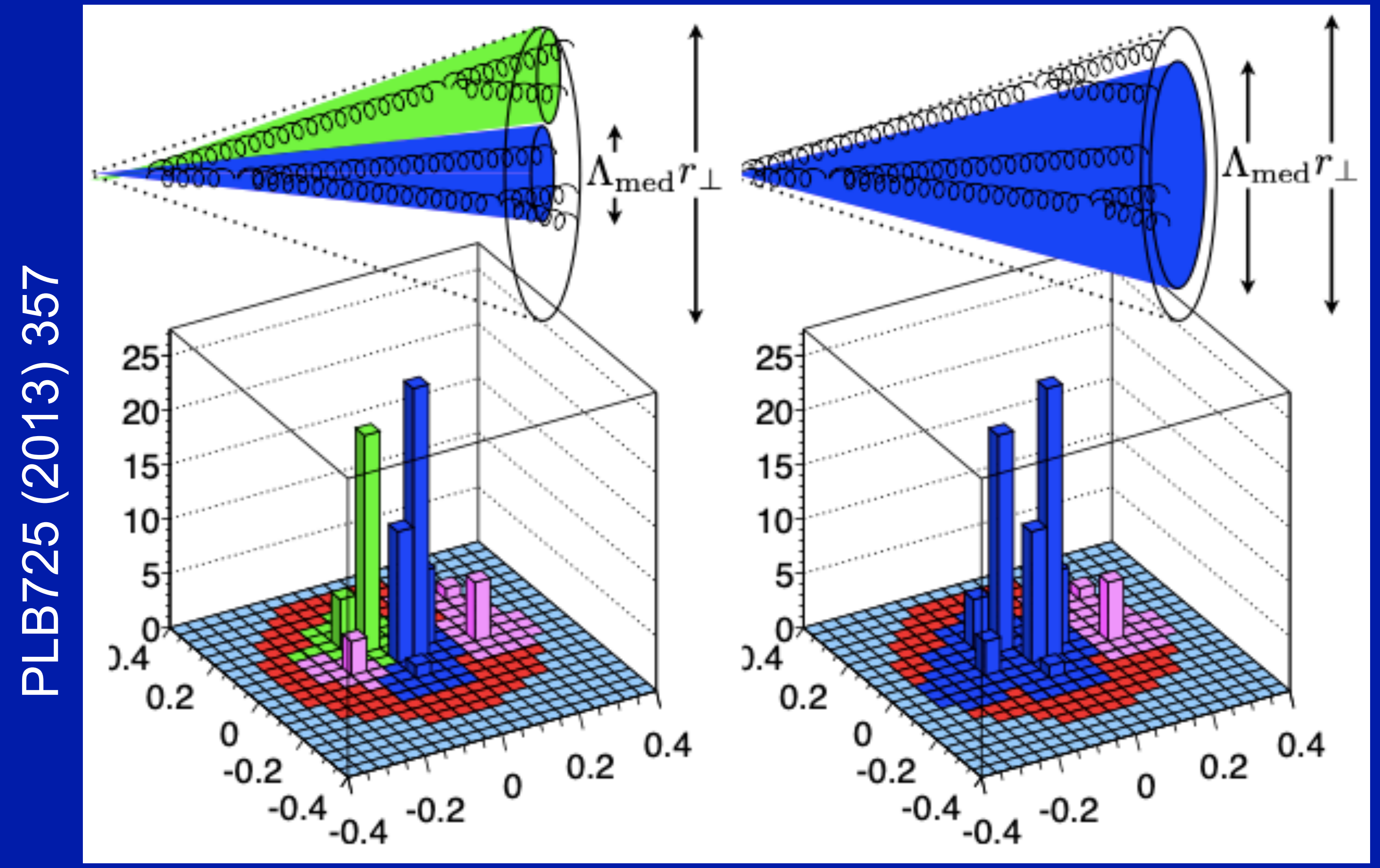
Jet substructure - reclustered large jets ($R = 1.0$)

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

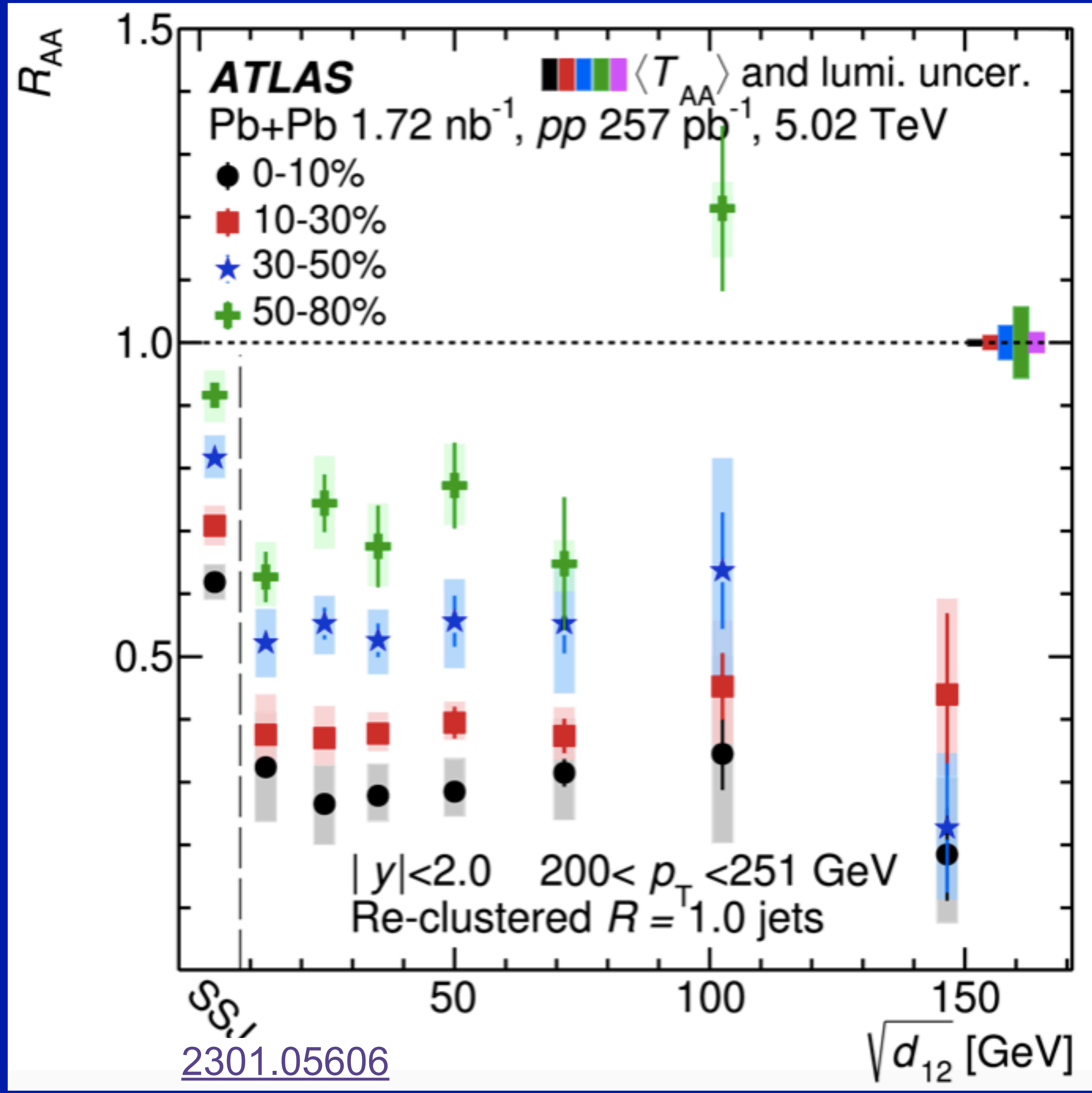
study of k_t splitting scale

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





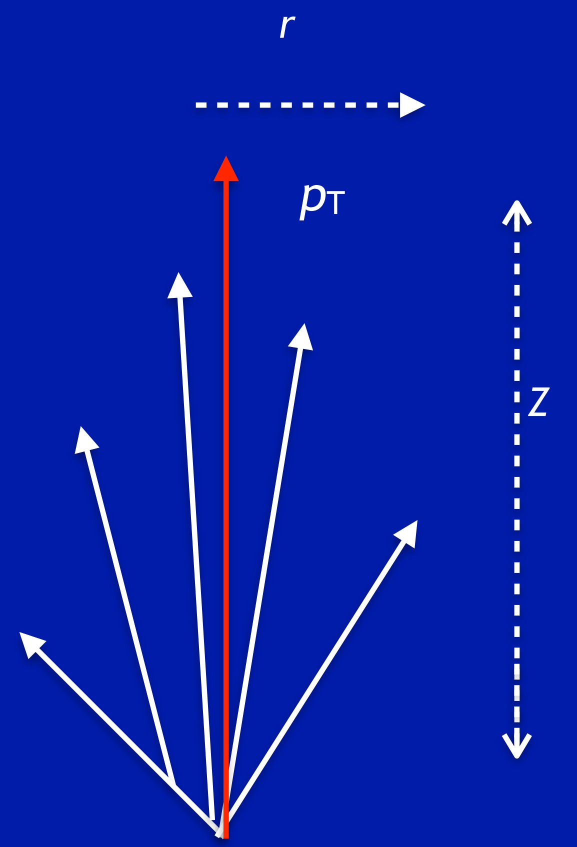
Recluster jets and remove soft contributions



- 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

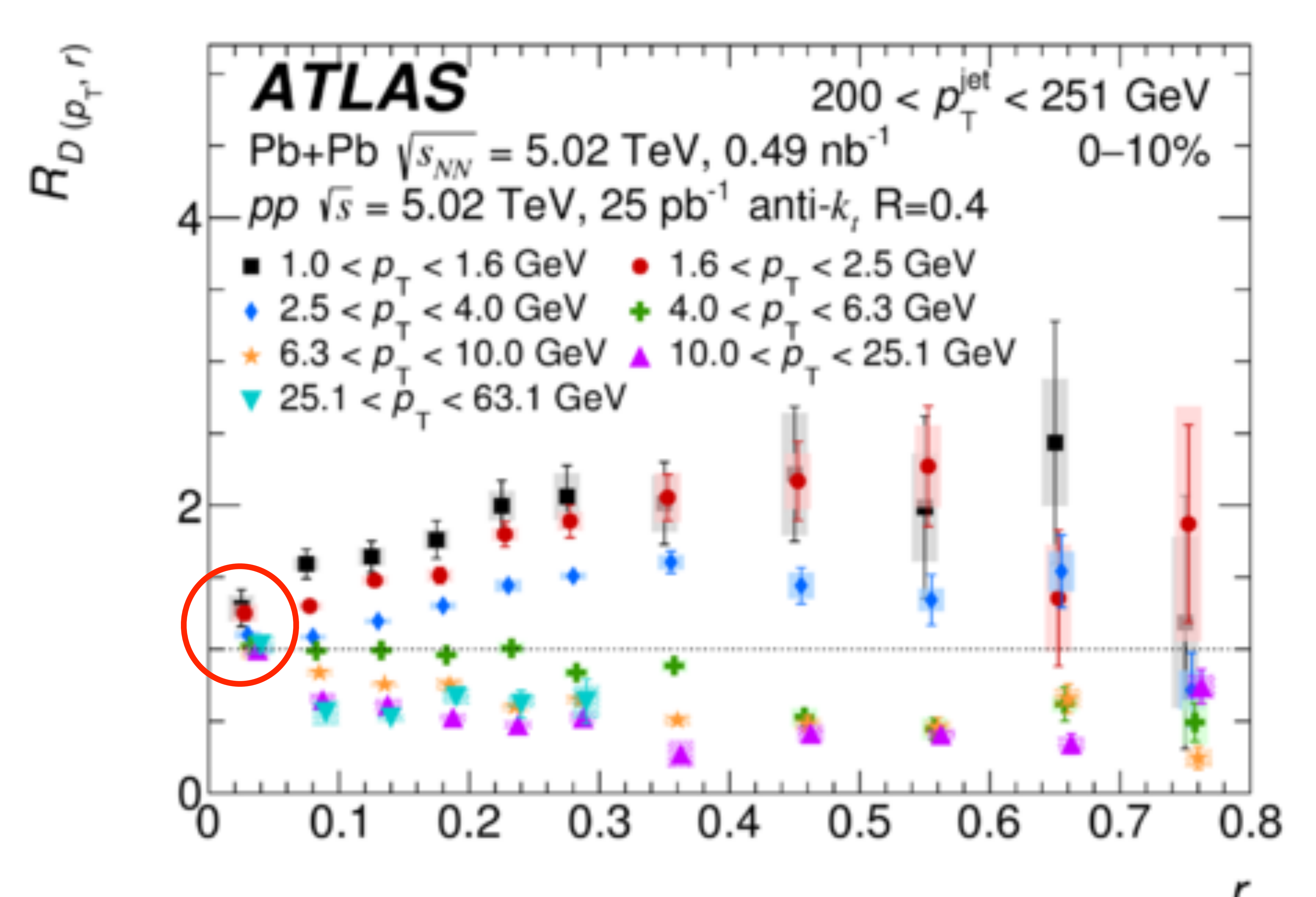
How do particles redistribute within the jet and beyond?

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



$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\,\mathrm{d}p_{\mathrm{T}}}$$

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

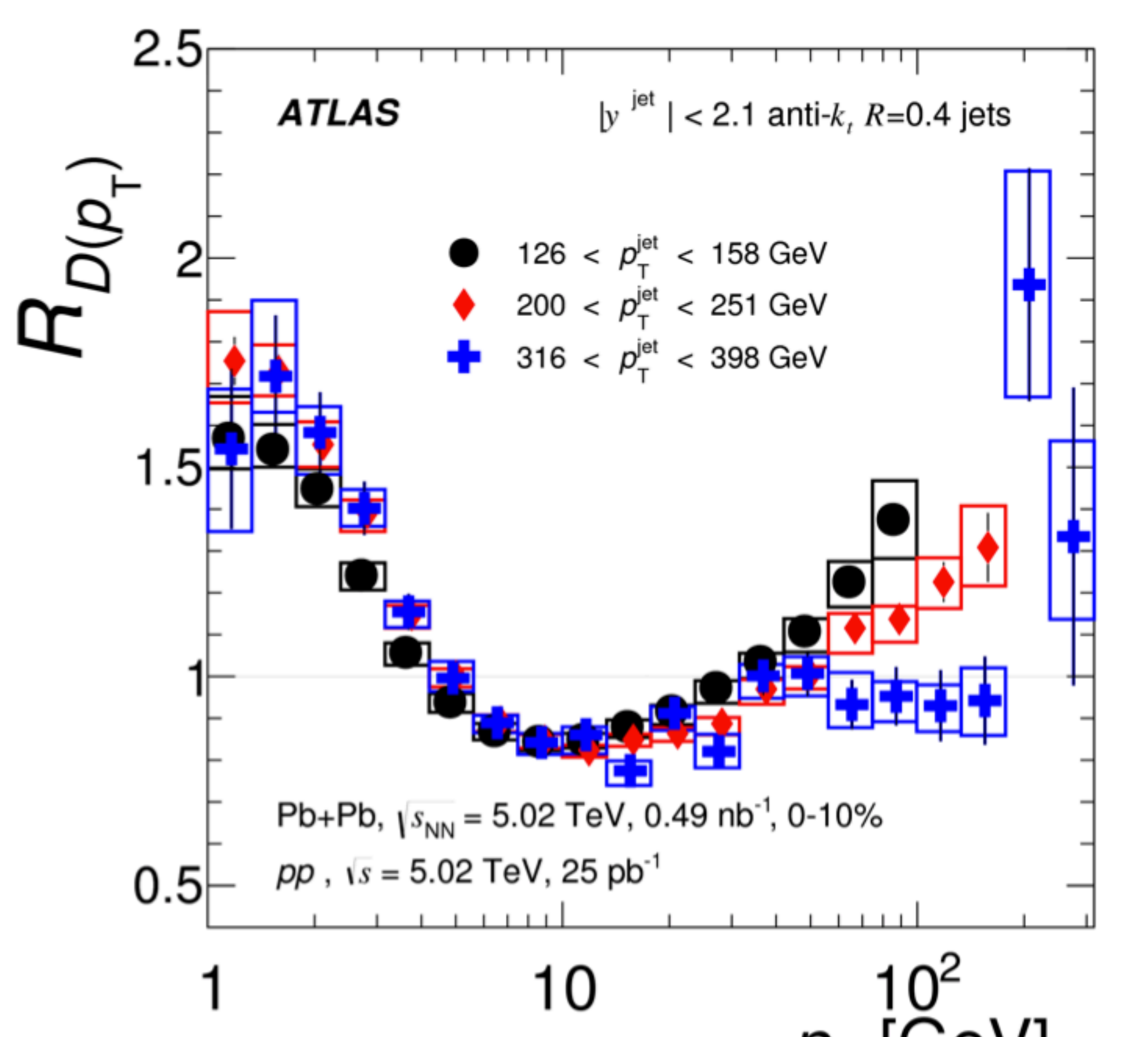


PRC 100 (2019) 064901

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

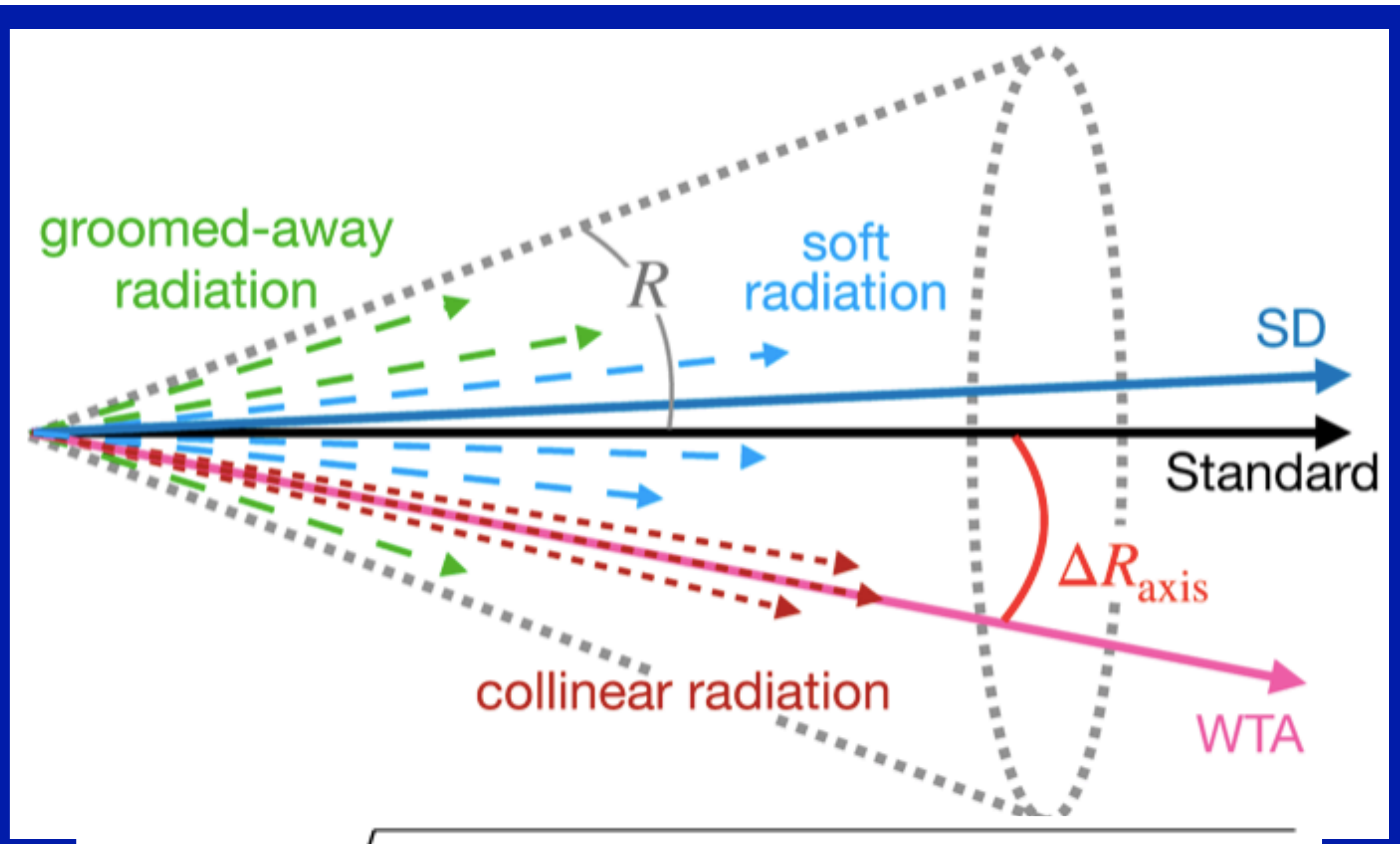
Depletion of high-p_{T} particles over all range.

Jet core remains unmodified.



Phys. Rev. C 98, (2018) 024908

Sensitivity to angle between jet axes

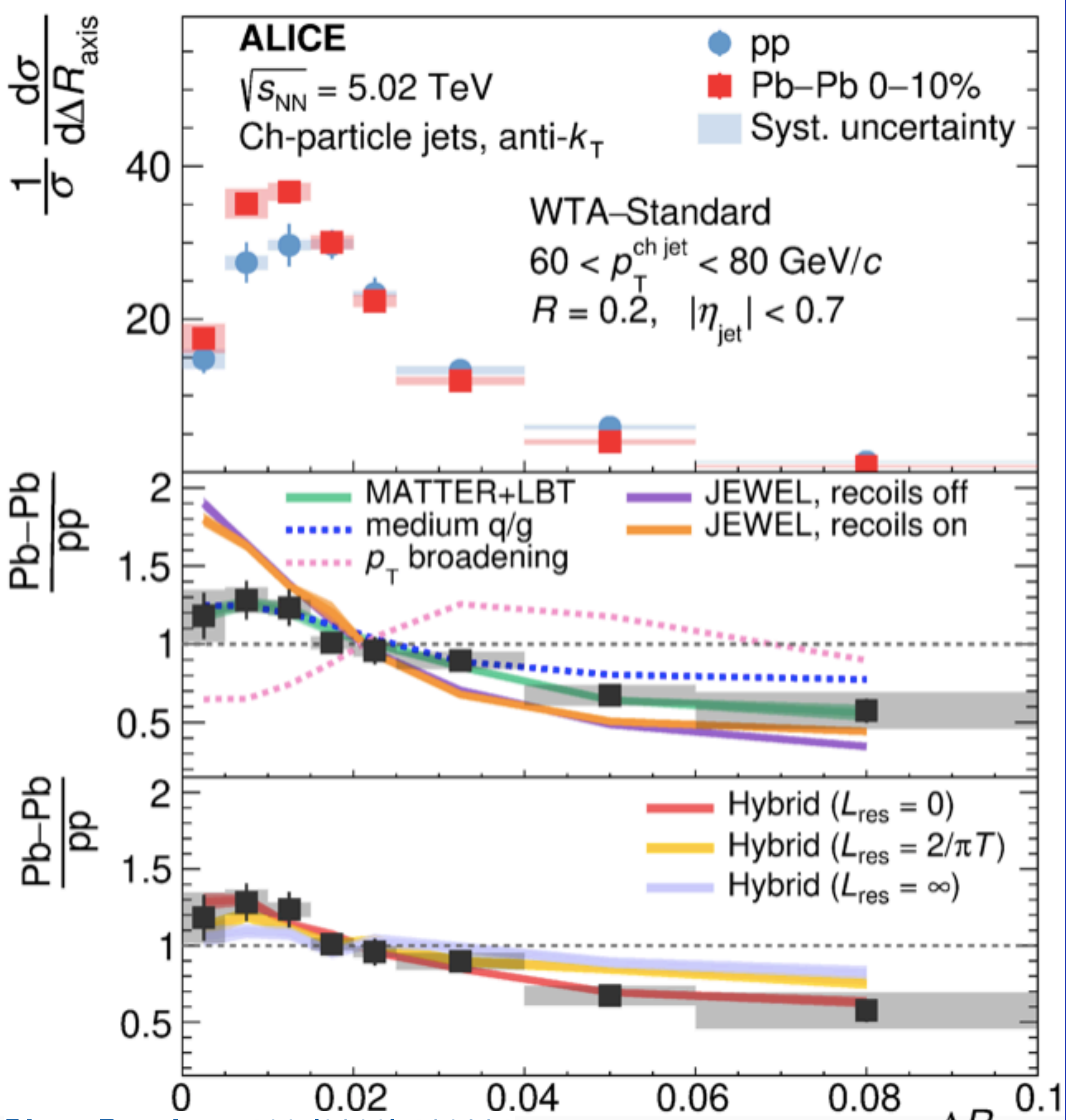


$$\Delta R_{\mathrm{axis}} \equiv \sqrt{(y_{\mathrm{axis},1} - y_{\mathrm{axis},2})^2 + (\varphi_{\mathrm{axis},1} - \varphi_{\mathrm{axis},2})^2},$$

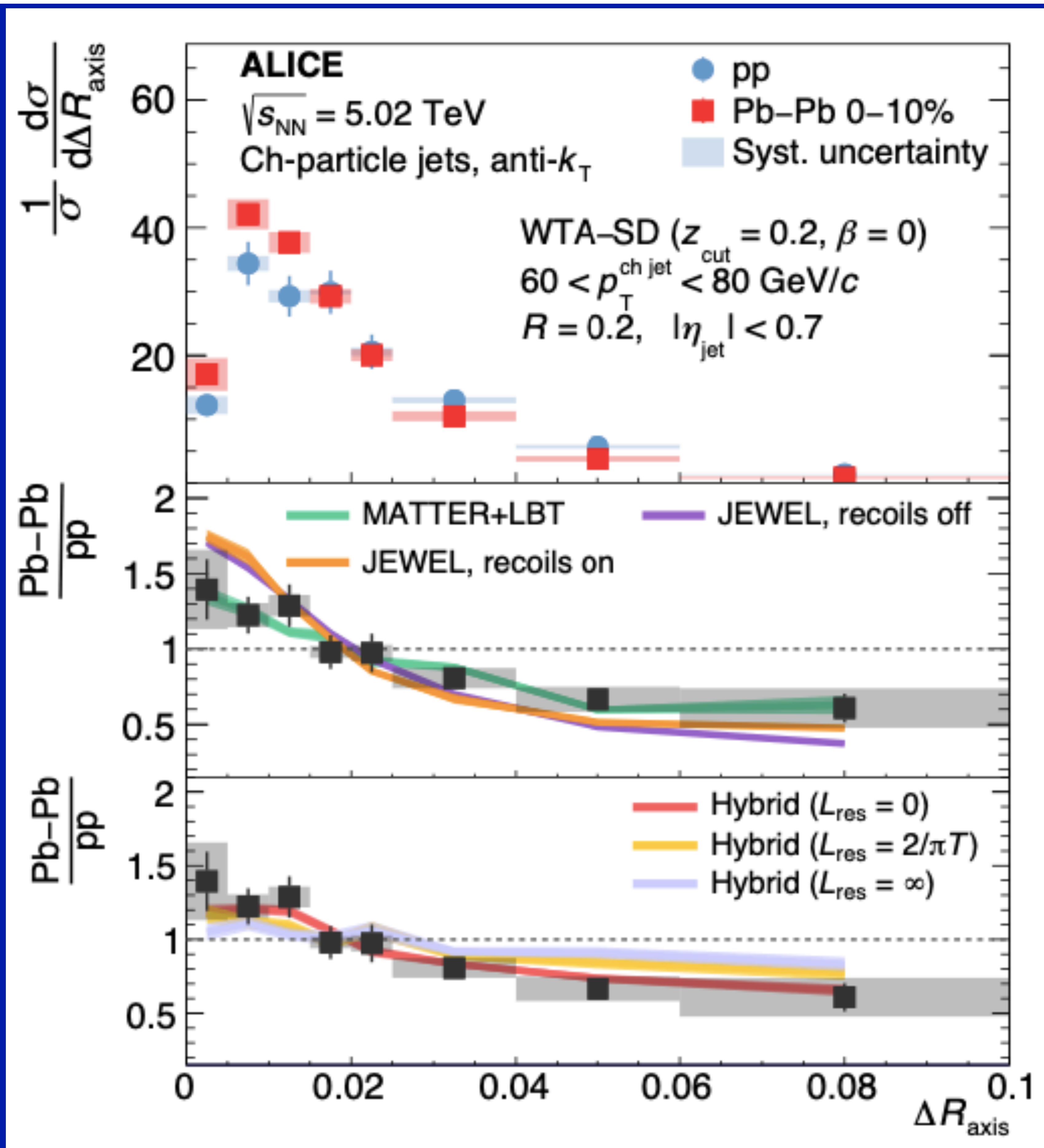
SD: axis defined by the particles

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.



[Phys. Rev. Lett. 128 (2022) 102001]



ΔR distributions are narrower in PbPb

Grooming (zcut = 0.2, β=0) doesn't change the jet axis visibly. Not sensitive to grooming.

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

Jet shape ratios in dijets

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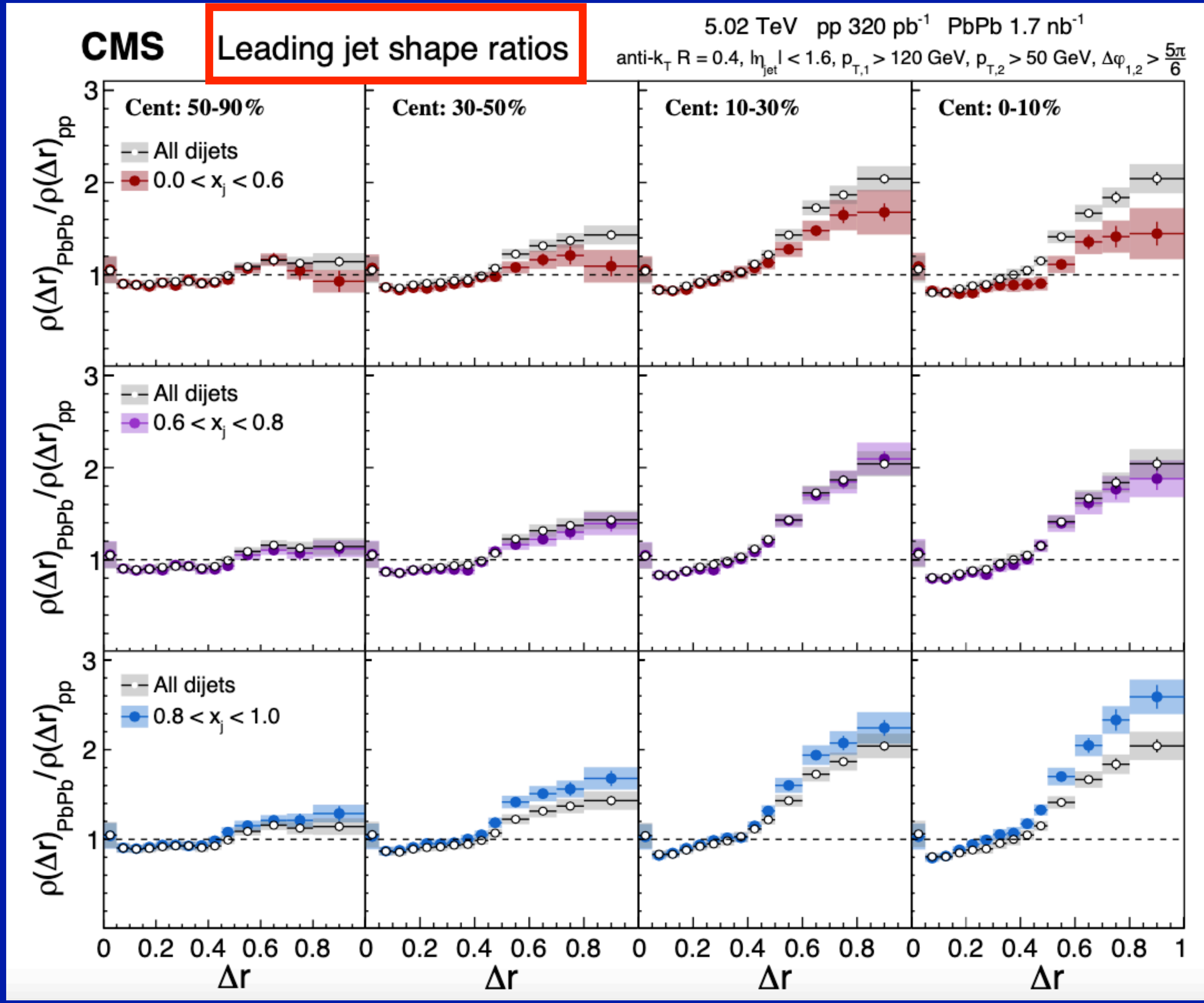
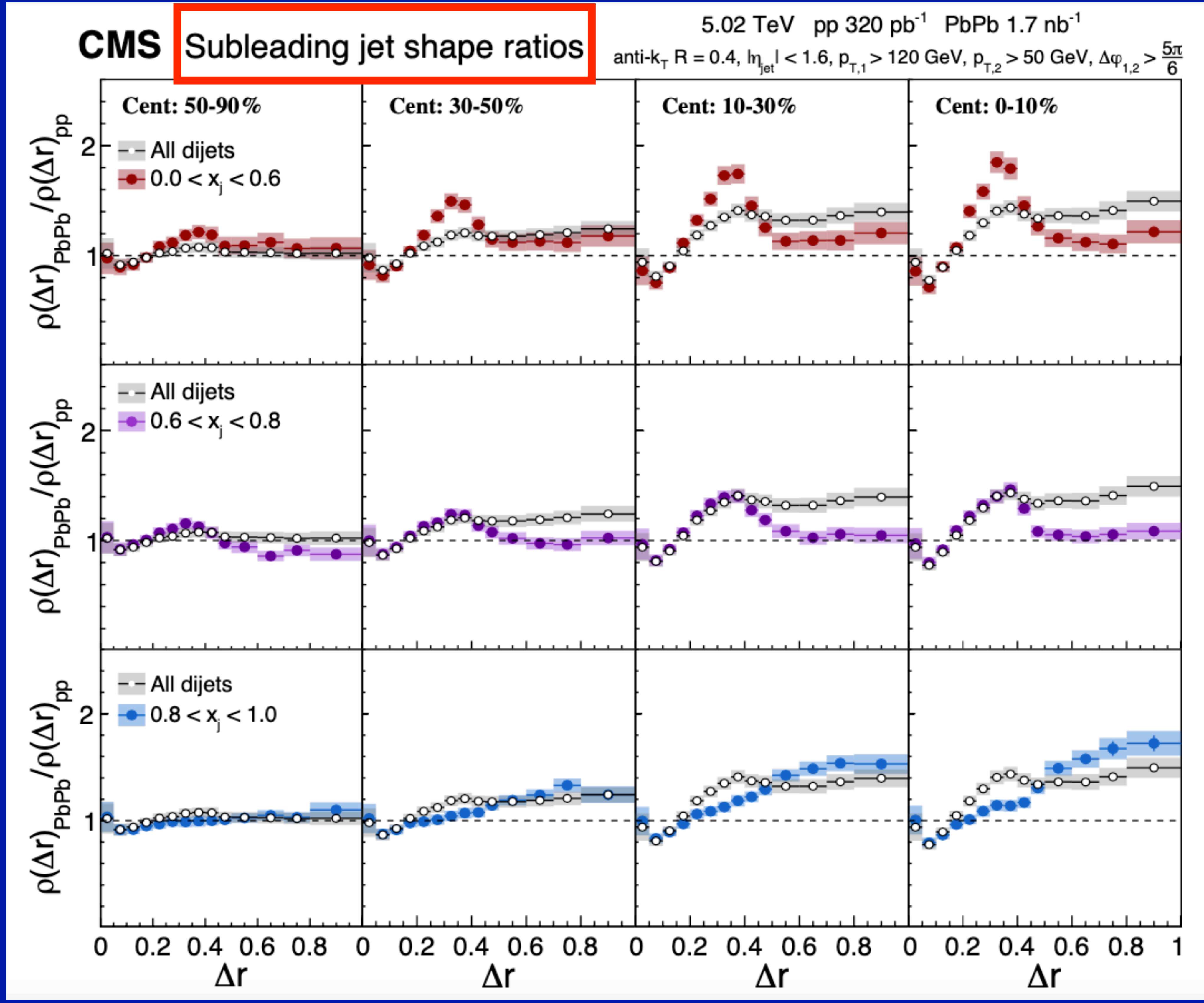
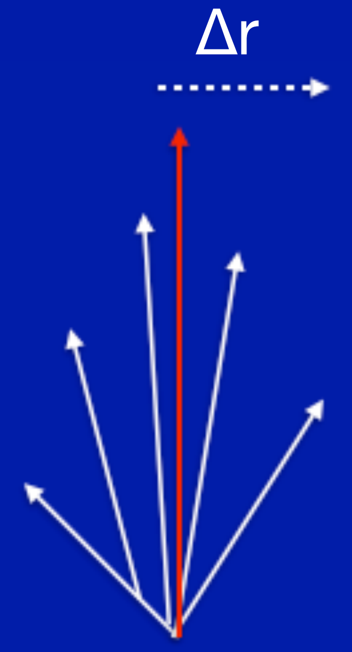
Leading and subleading jet shape ratios ρ(Δr)PbPb/ρ(Δr)pp, in different centrality and x_j ranges

imbalanced
$0.0 < x_j < 0.6$

Balanced
$0.8 < x_j < 1.0$





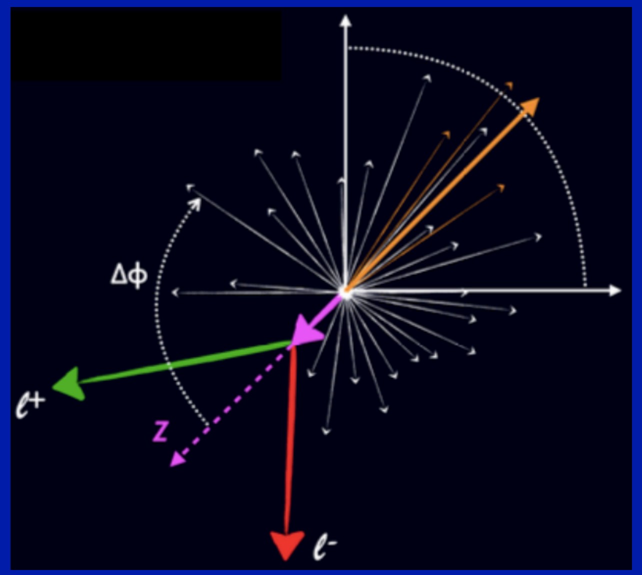


Enhancement of the PbPb jet shape modification at large Δr in balanced dijets and with increasing centrality.

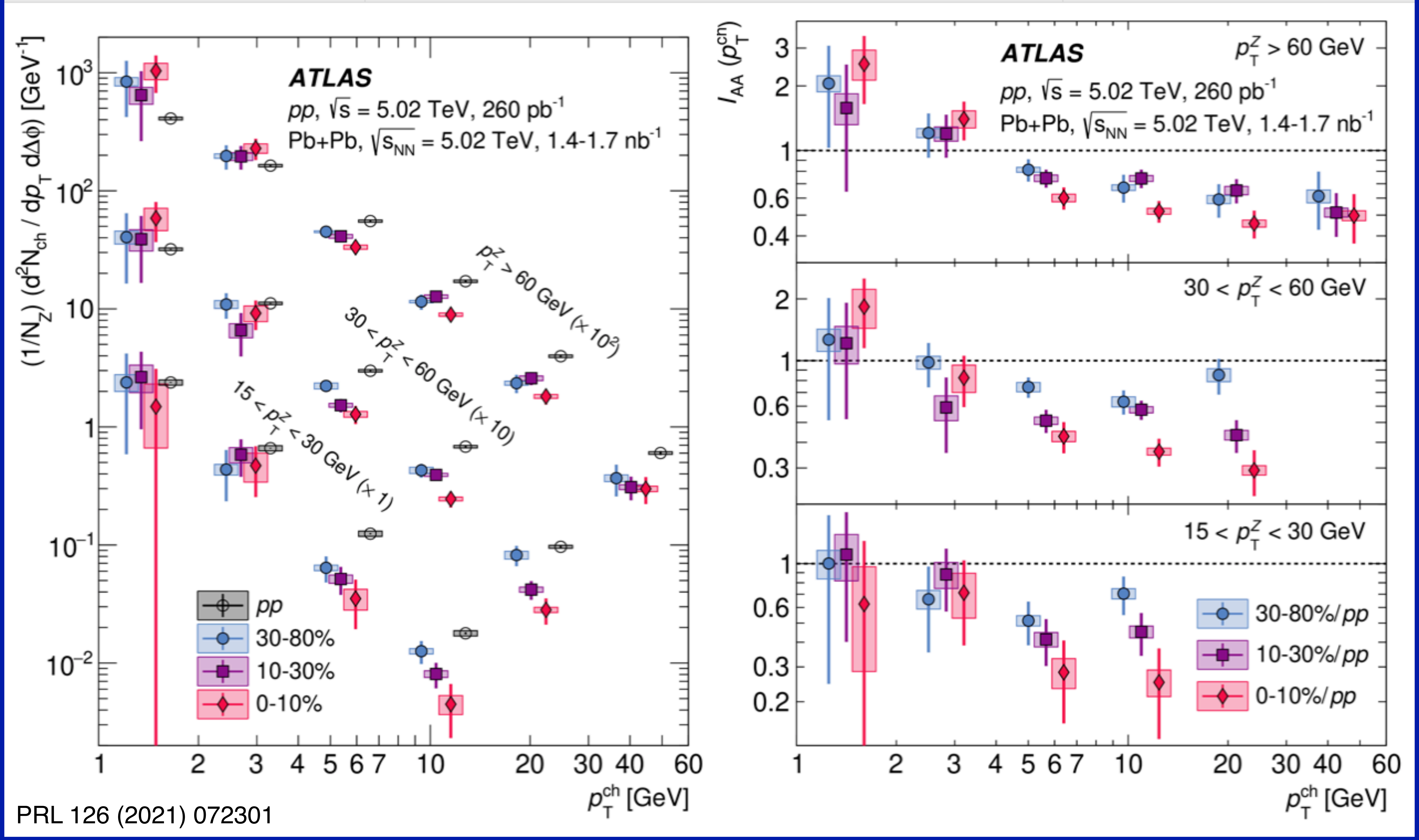
Clear effect at Δr ≃ 0.3, and for imbalance dijets ($x_j < 0.8$). Enhancement at large Δr less pronounced in imbalanced dijets. Opposite effect in balanced.

Significant effects from different path length crossed.

Z-recoil particles - I_{AA} as a function of p_T^{ch}



#charged particles per *Z* yield in PbPb / yield in pp

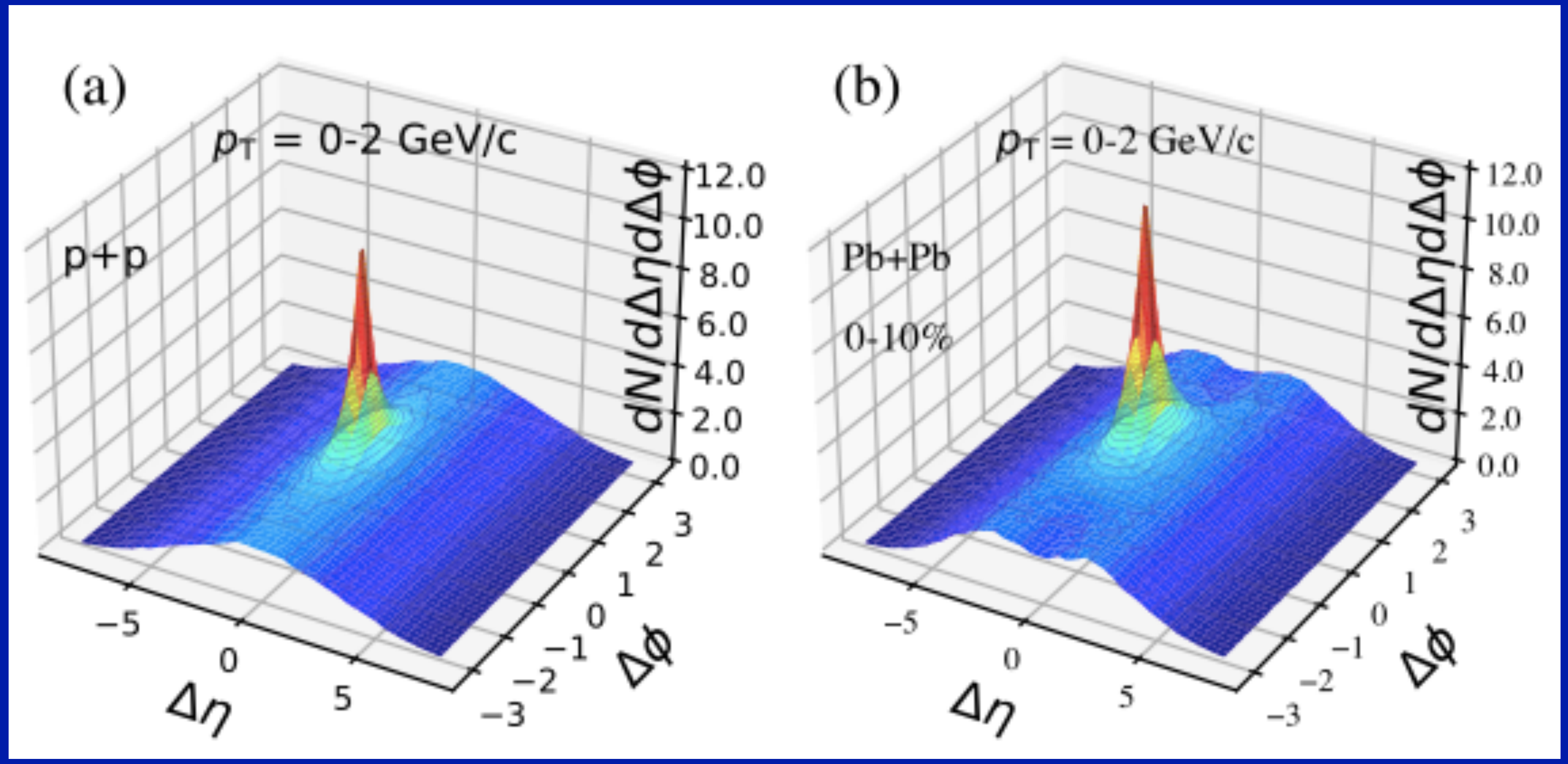


Enhancement of low-p_T^{ch} recoiling particles for $p_T^Z > 60$ GeV. Less pronounced as p_T^Z > decreases.

Then clear suppression of high-p_T^{ch} particles with increasing centrality.

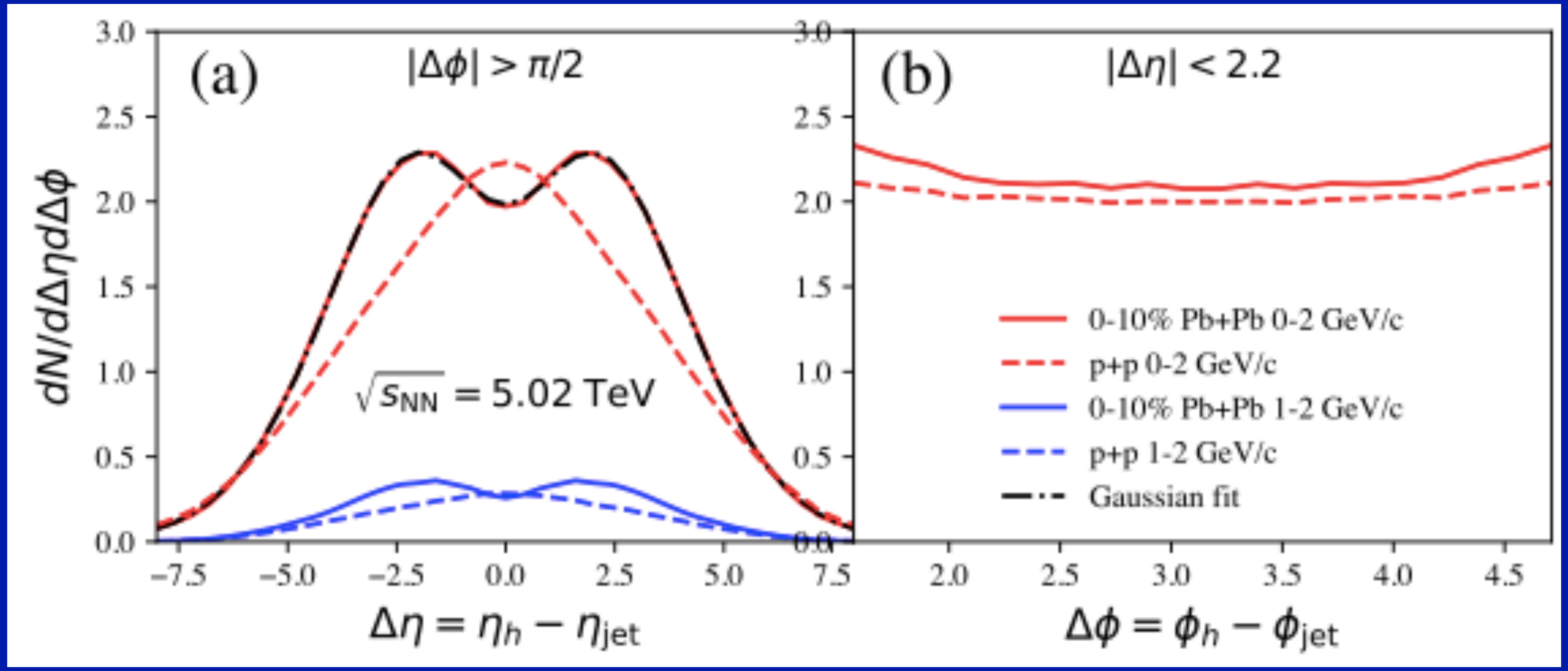
Sensitivity to the wake and diffusion wake — $\Delta\varphi_{hZ}$

Looking forward to jet-hadron correlations in γ/Z+jet events



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

at the photon side



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.