Experimental overview of jets in heavy-ion collisions

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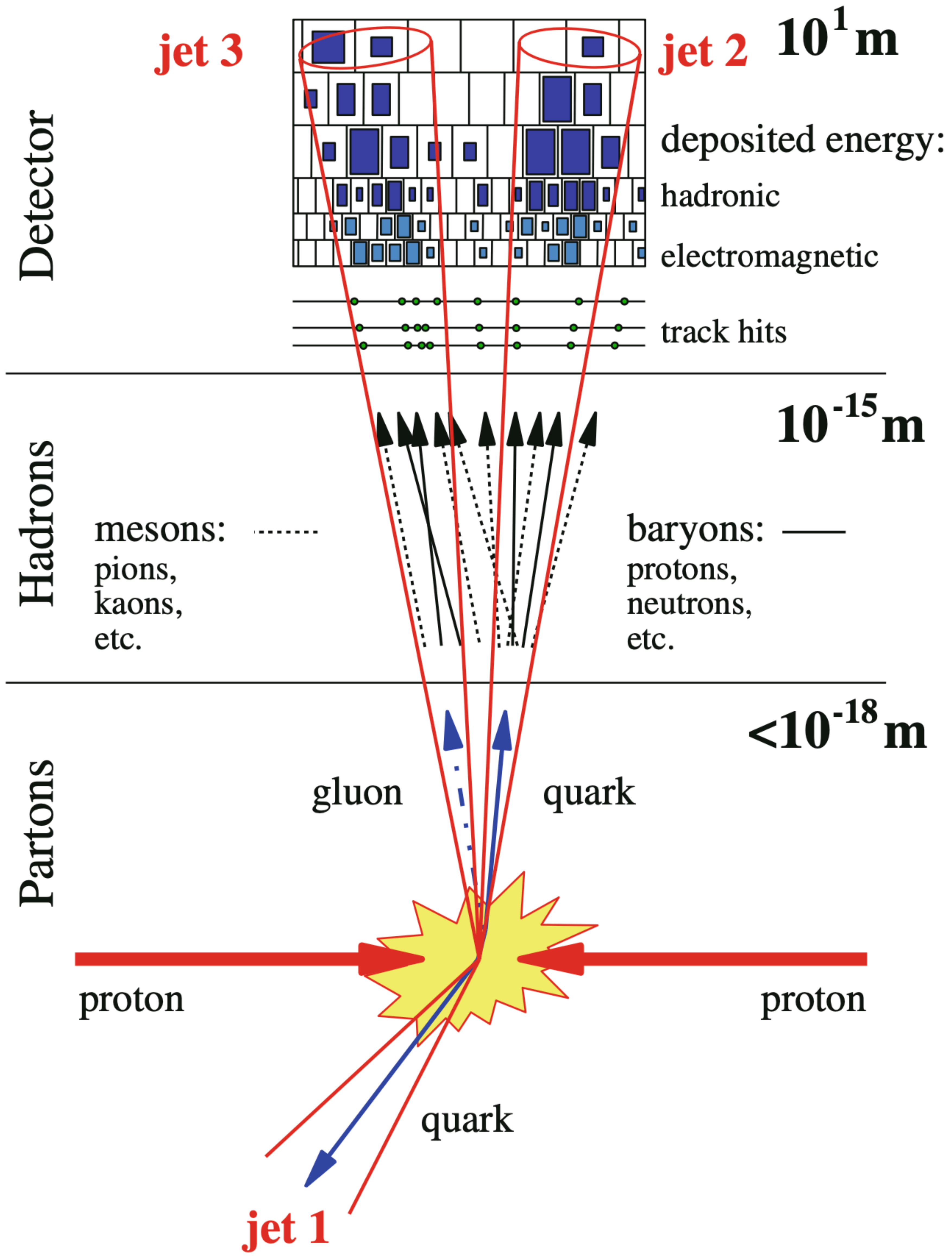
Jets in high energy experiments



R. A. Fernandez et al., The Large Hadron Collider: Harvest of Run1

deposited energy;

tracks

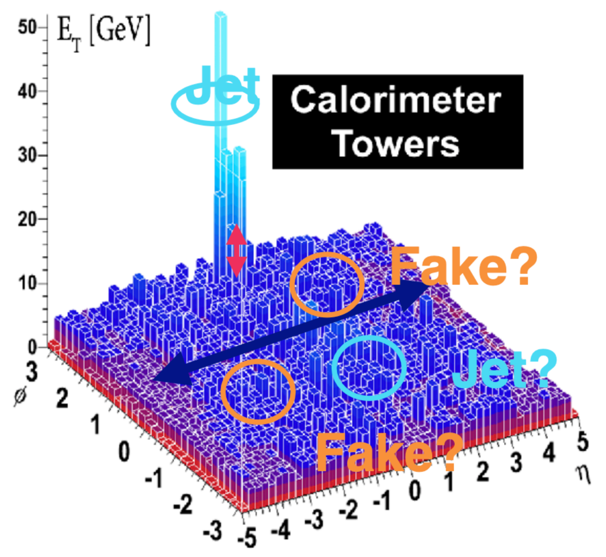
- **Experimental definition: Jet reconstructed via clustering algorithms, characterized by momentum (p_T) and size (R)…**

- **From theory to exp: Bridges the gap between perturbative parton showers and non-perturbative hadronization.**

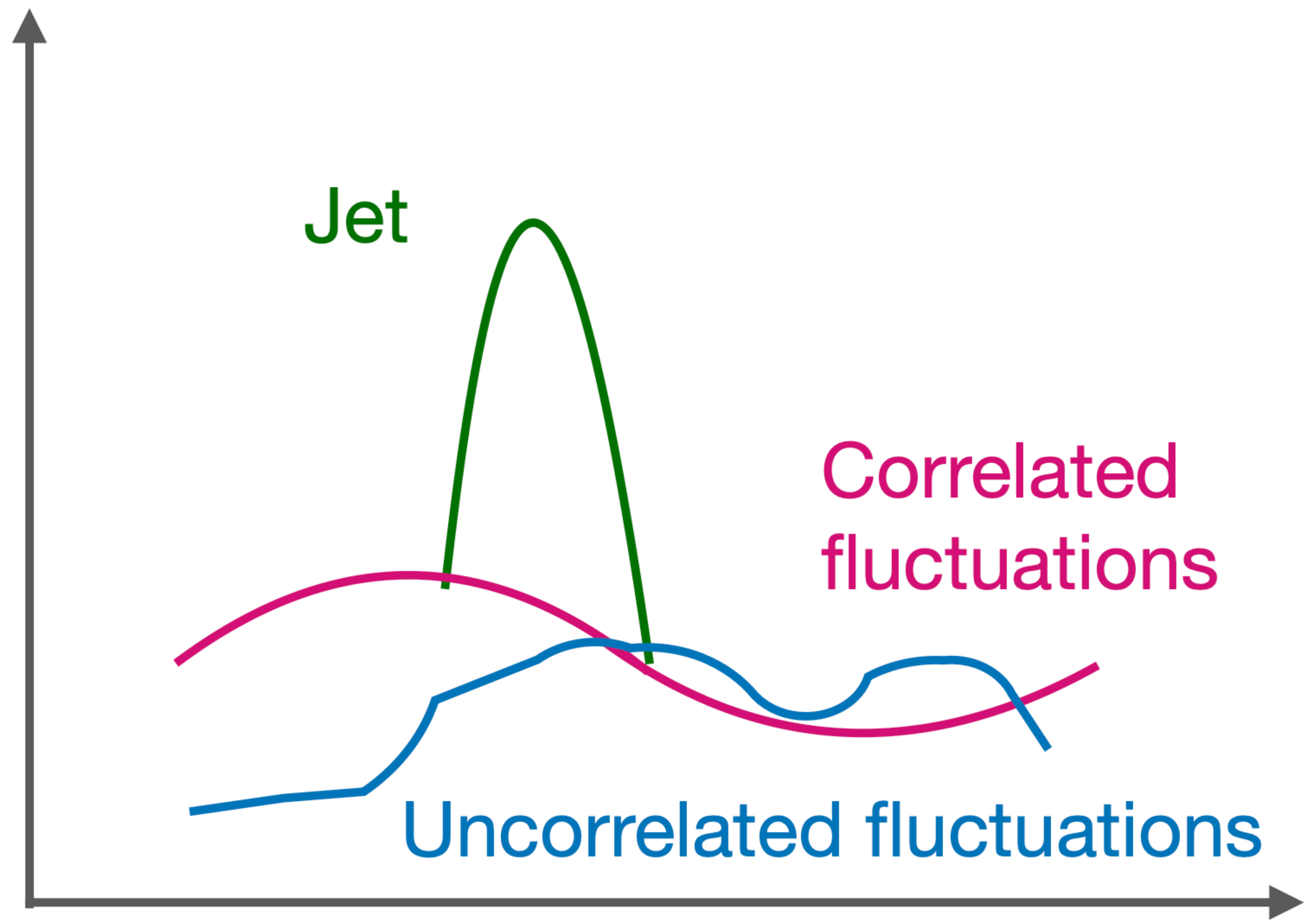
a collimated spray of hadron

Fastjet: rules to group hadrons

high energetic parton



Heavy-ion jets: background and biases



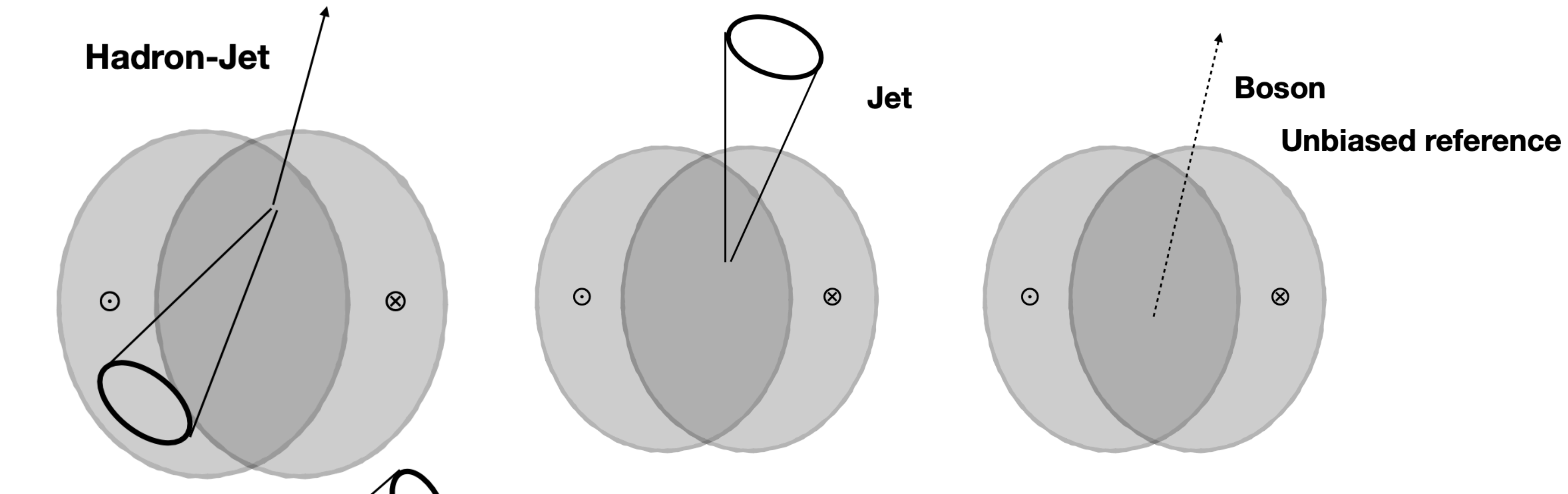
Raw jet spectra → Background subtraction → Sequential jet energy correction → Jet spectra

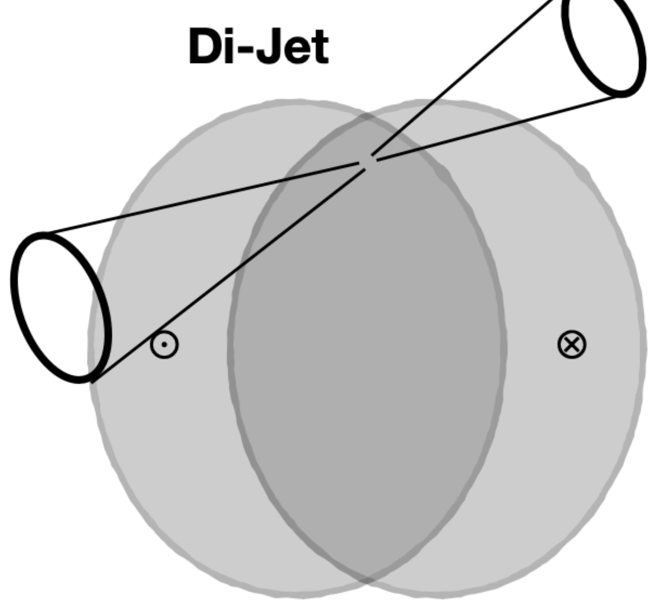
area-based, mix-event…

MC simulation

Unfolding

Credit: R. Elayavalli QM2023

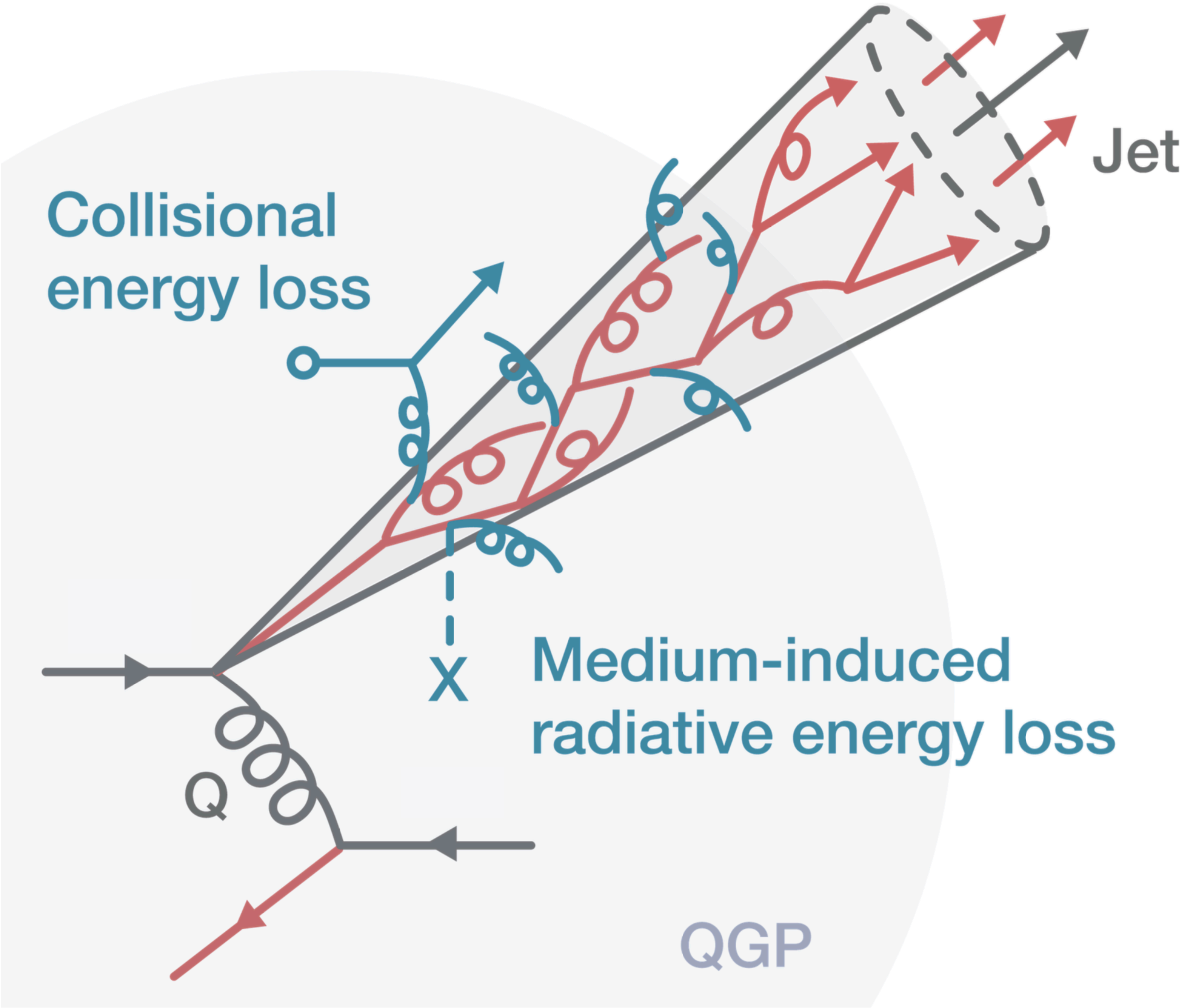




Surface bias, trigger bias, survival bias, event selection bias…

Crucial to understand their effects on experimental observables

Jets in heavy-ion collisions



Credit: J. Wang, Light Ion Workshop 2025

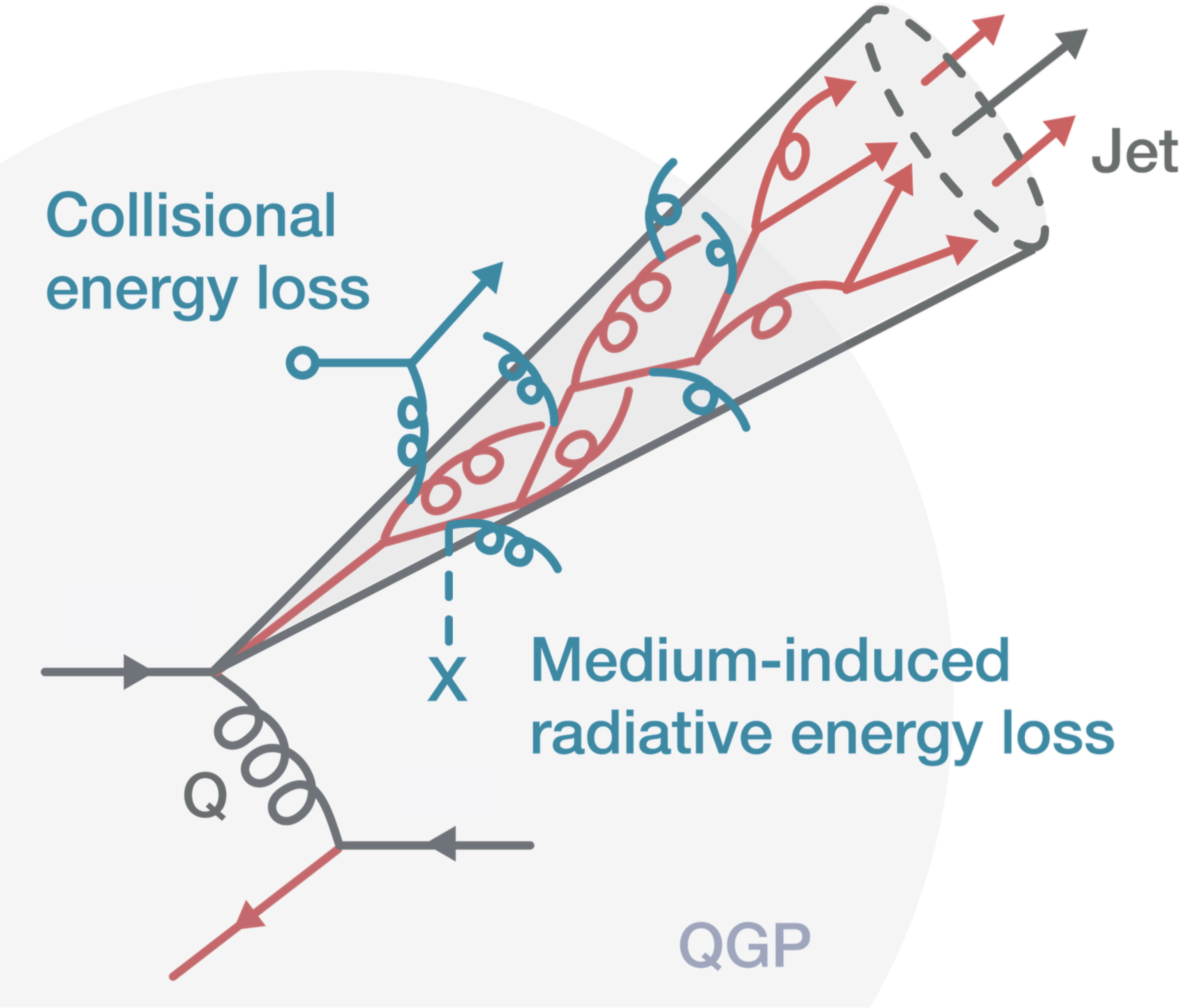
Jet quenching

Jet substructure

Non-perturbative & hadronization

Critical system size of jet quenching

Jets in heavy-ion collisions



Jet quenching

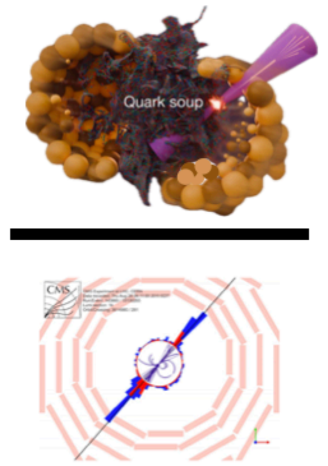
Jet substructure

Non-perturbative & hadronization

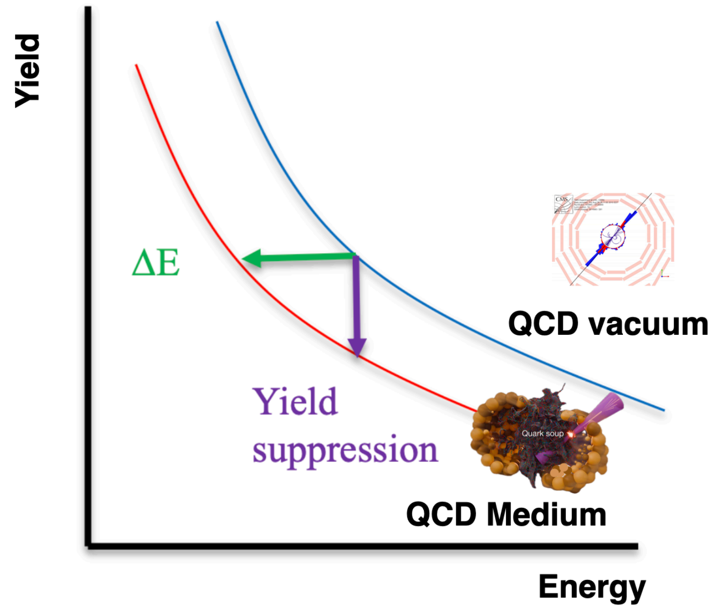
Critical system size of jet quenching

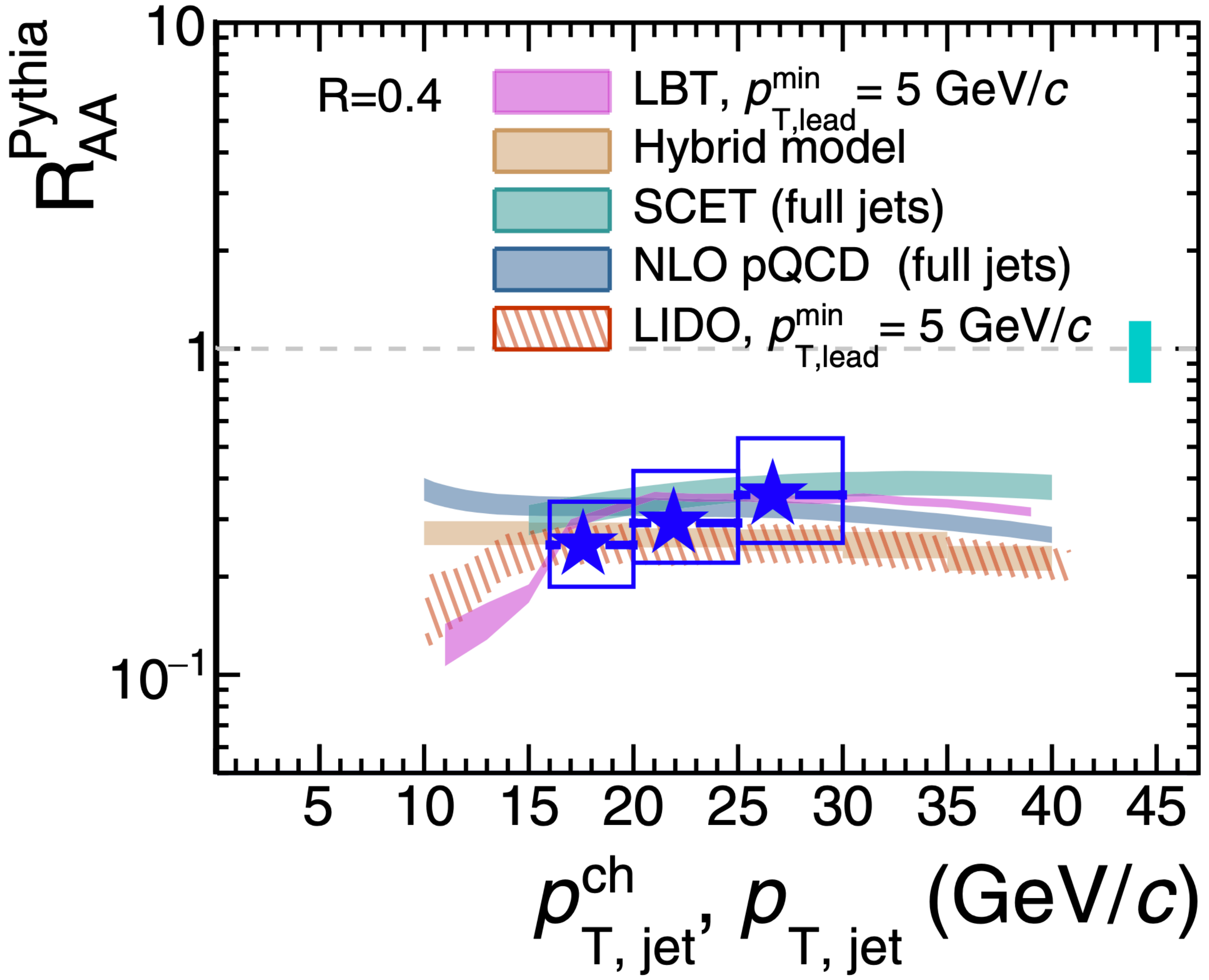
Inclusive jet suppression at RHIC and LHC

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{N_{coll}} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim$$

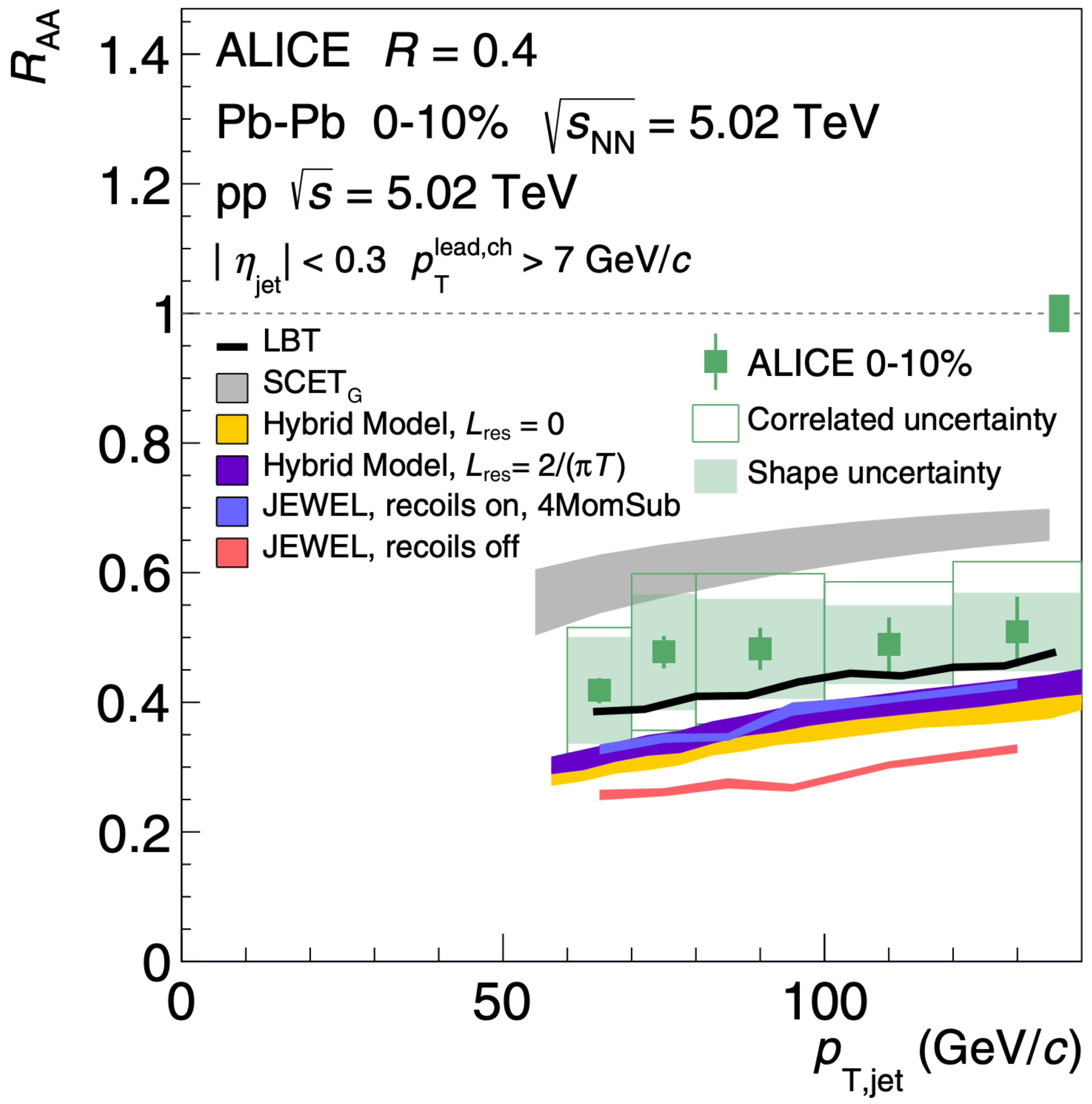


$$\begin{cases} R_{AA} > 1 & \text{(enhancement)} \\ R_{AA} = 1 & \text{(no medium effect)} \\ R_{AA} < 1 & \text{(suppression)} \end{cases}$$

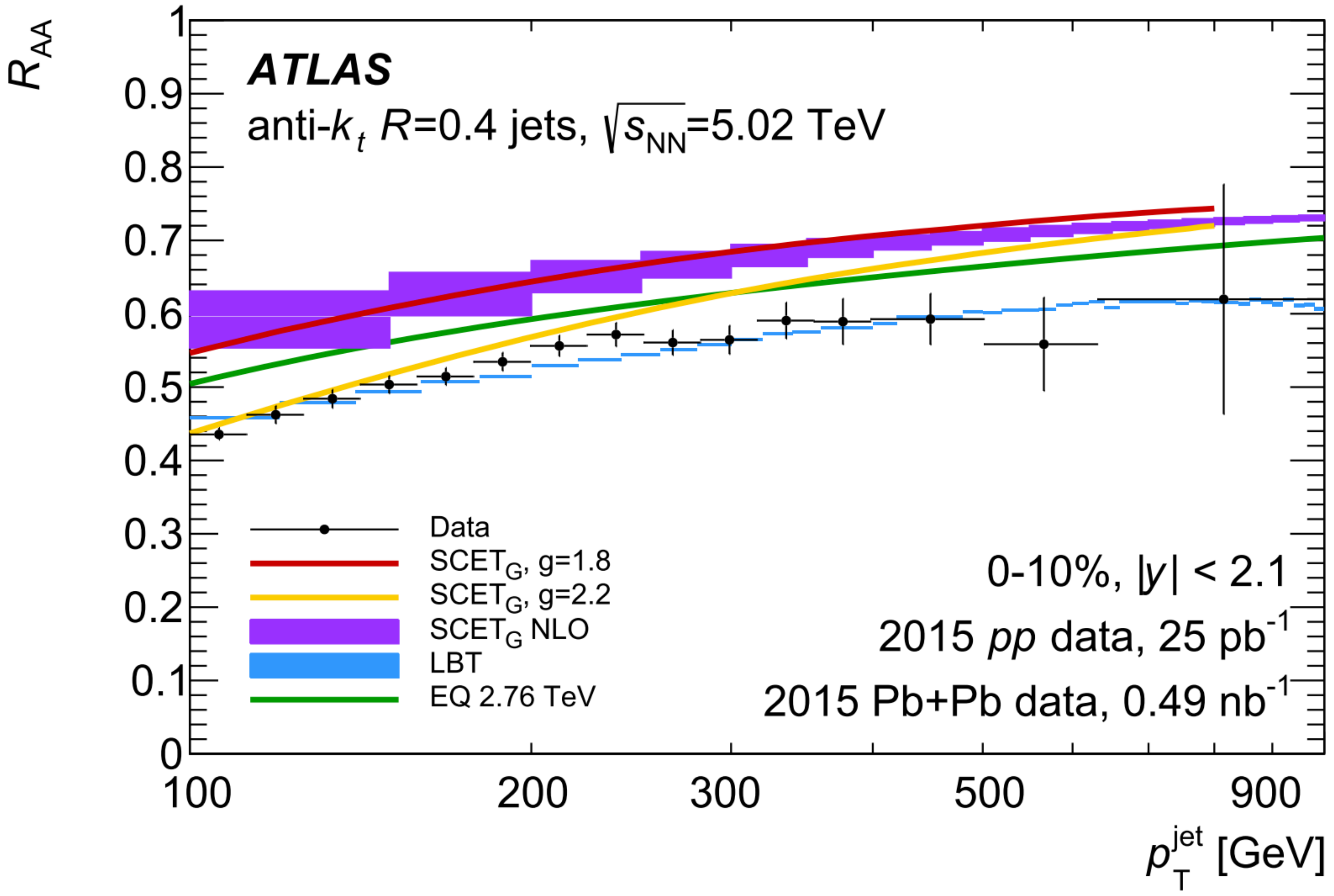




STAR, Phys. Rev. C 102, 054913 (2020)



ALICE, Phys. Rev. C 102, 054913 (2020)



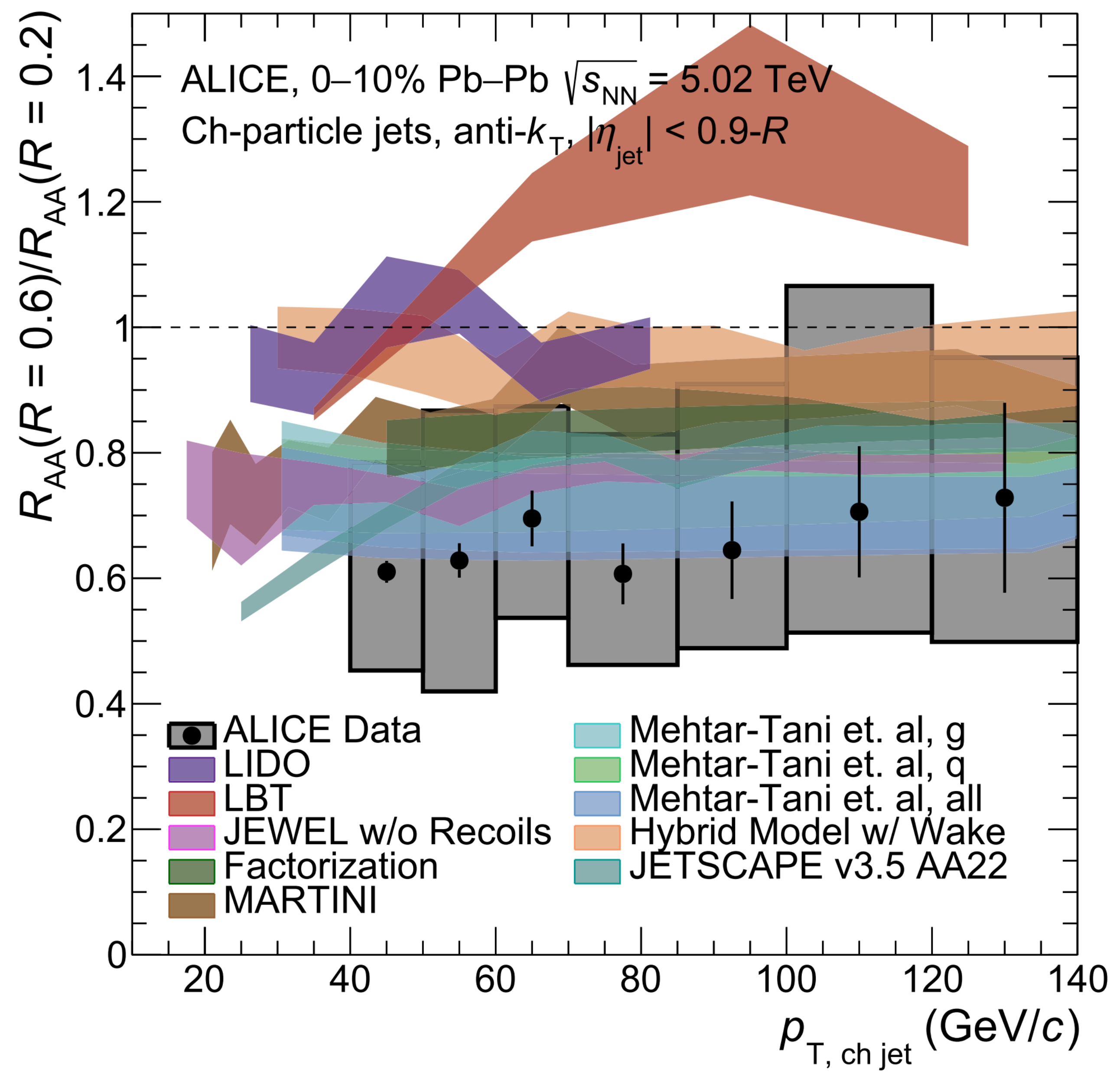
ATLAS, Phys. Lett. B 790 (2019) 108–128

- **Jet quenching models can describe experimental data well.**

Radius dependent Jet R_{AA}

Jet energy recovered with increasing of jet radius?

$R_{AA}(R = 0.6)/R_{AA}(R = 0.2)$



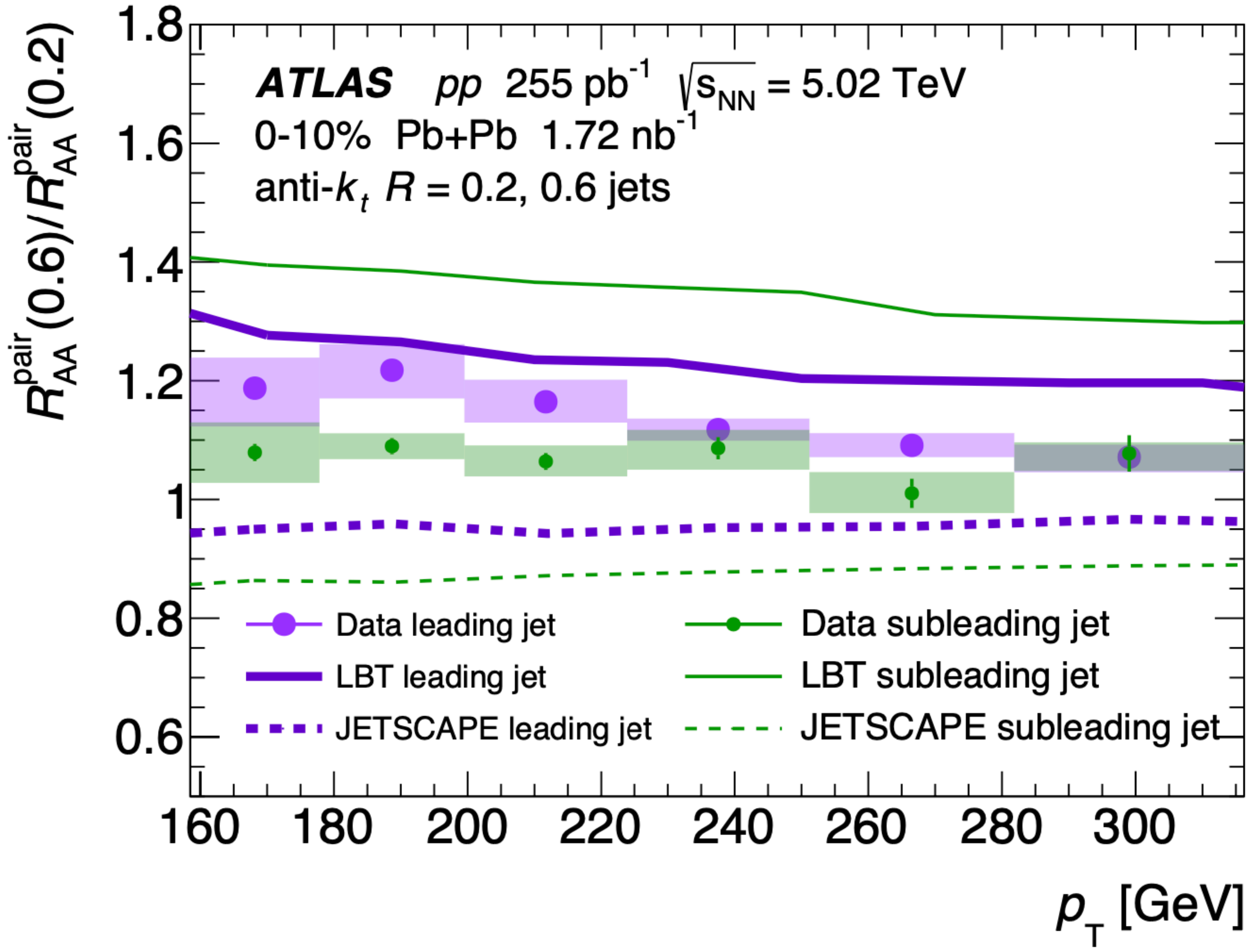
ALICE, Phys. Lett. B 849 (2024) 138412

ML based method is used

Wider jets are more suppressed

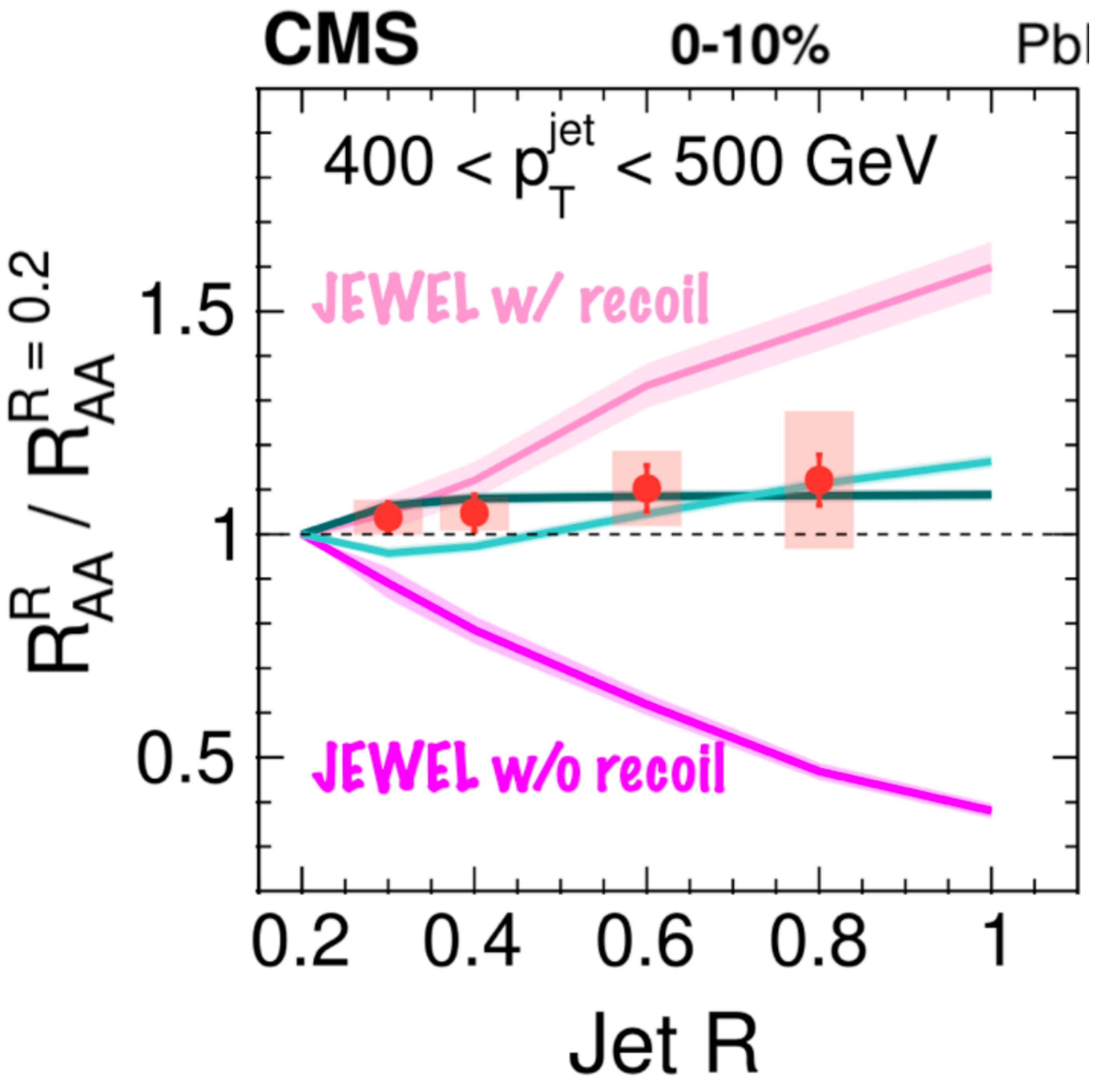
Yilun Du's talk

R = 0.6 / R = 0.2



ATLAS, Phys. Rev. C 110, 054912 (2024)

Narrow jets are more suppressed

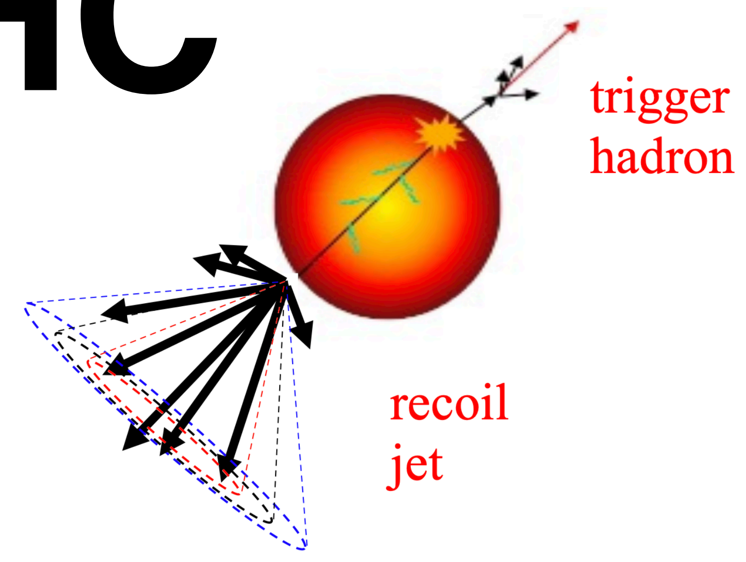


CMS, JHEP 05 (2021) 284

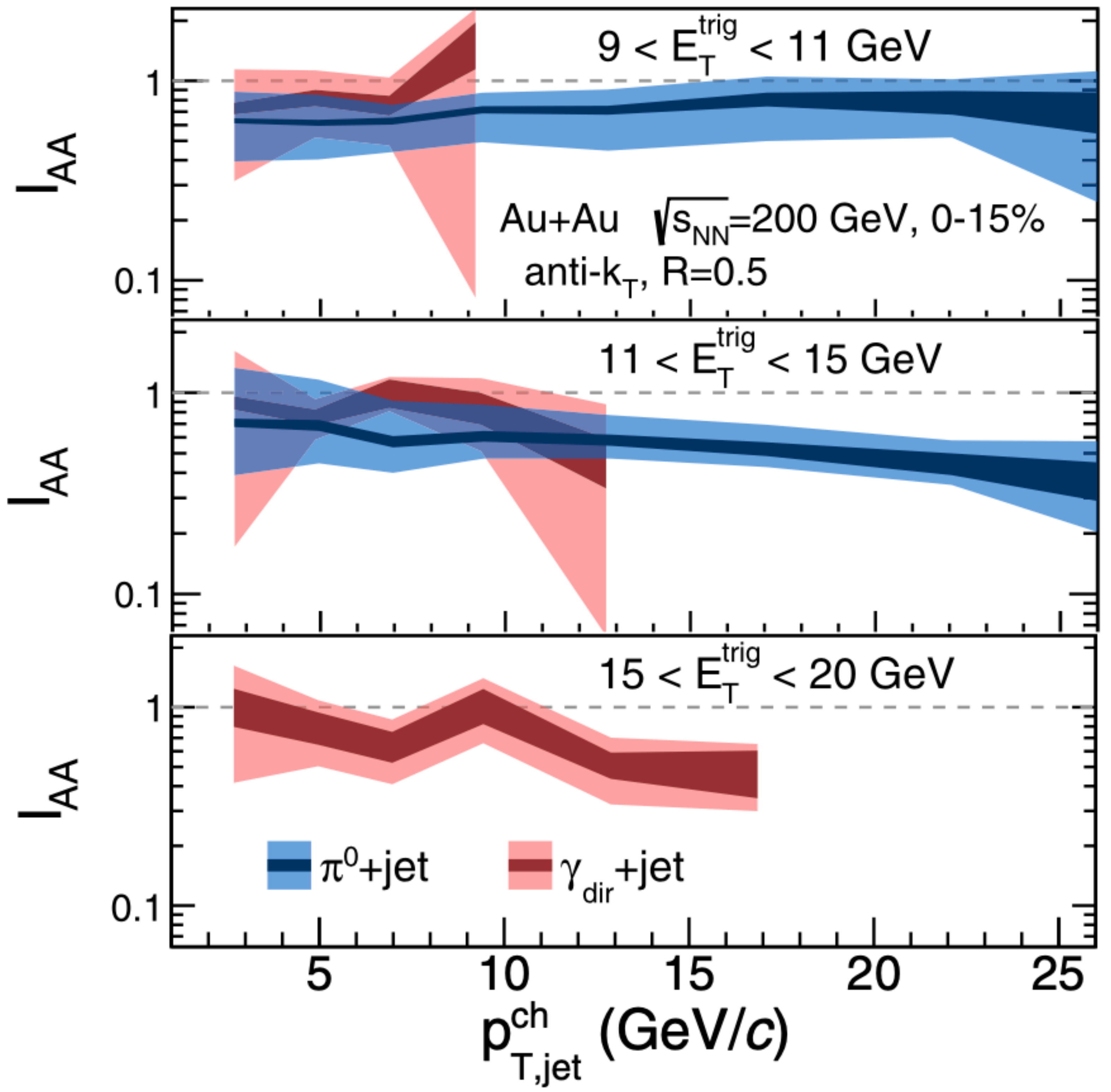
No significant R dependence

- **Different jets and kinematic ranges in different experiments.**

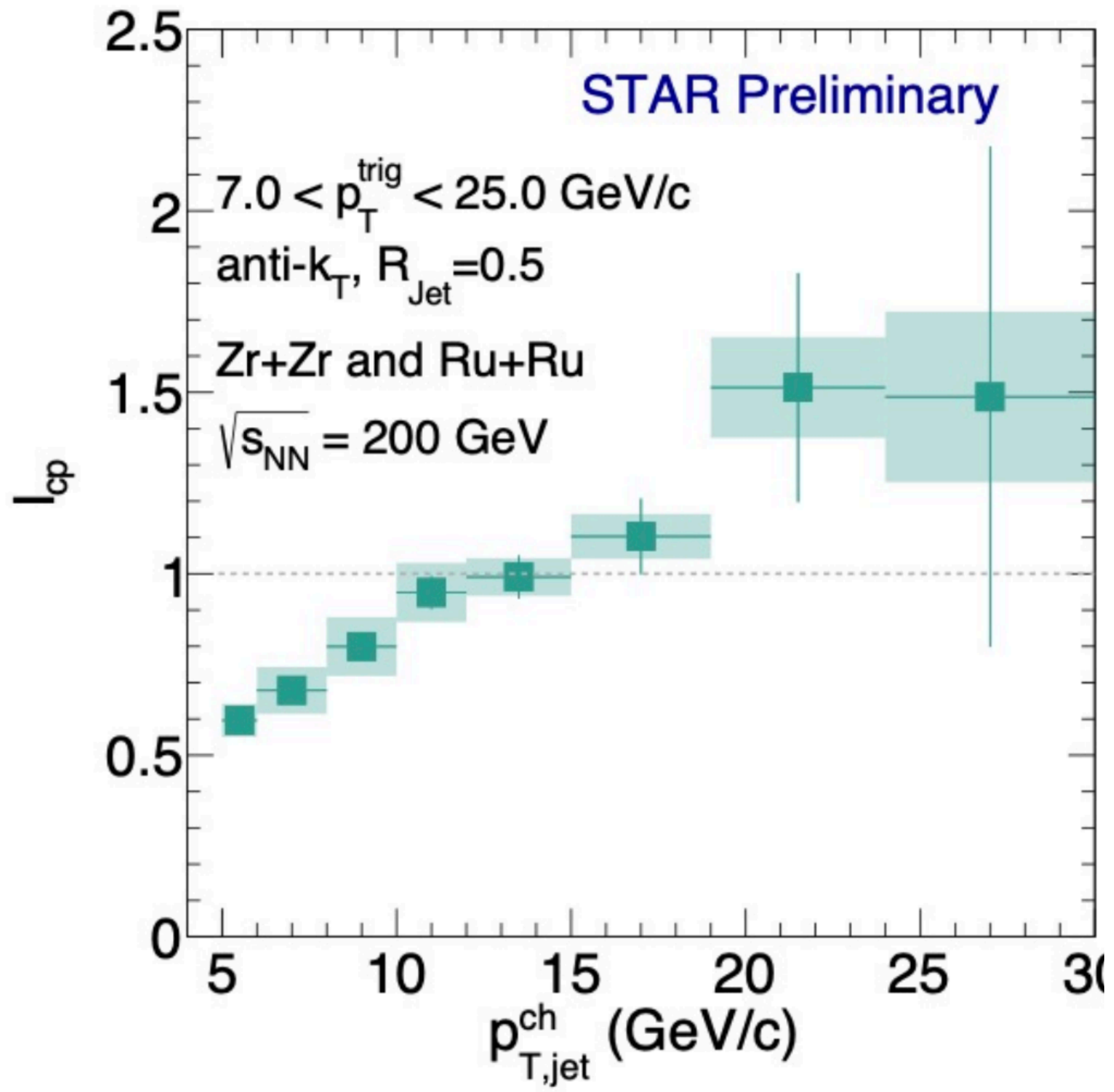
Semi-inclusive h-jet at RHIC and LHC

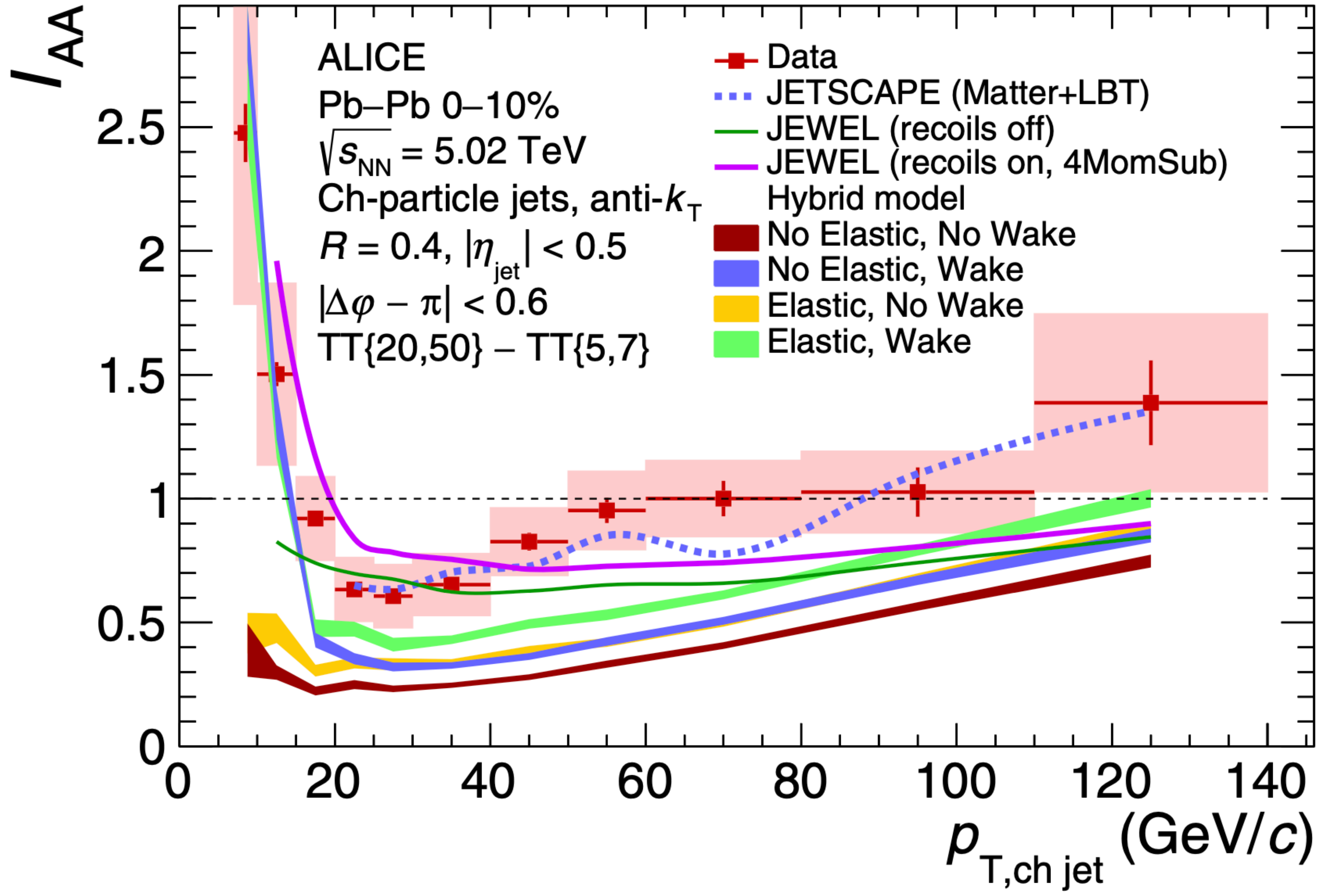


Extended to large jet R and low jet p_T with the advantage of mix-event.



STAR, Phys. Rev. C 111, 064907 (2025)





ALICE, Phys. Rev. C 110, 014906 (2024)

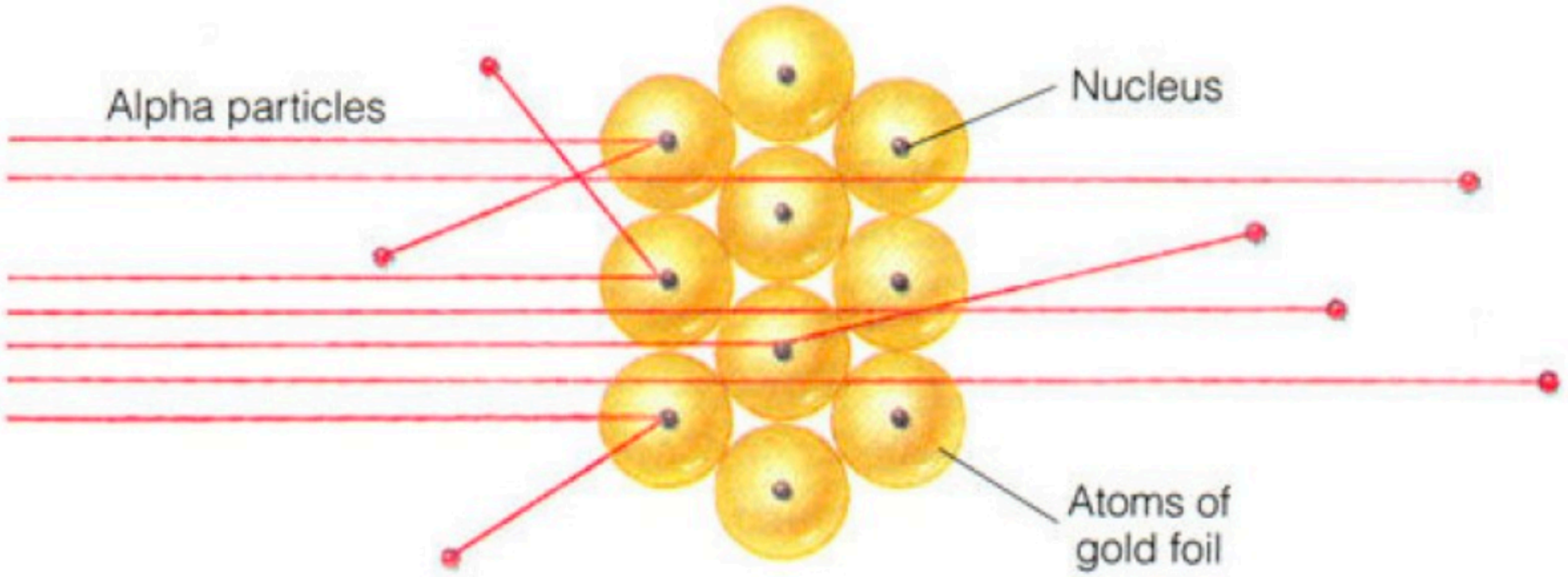
- **Clear recoil jet suppression, excess above unity at high pT due to trigger hadron energy loss.**

Yichao Dang's talk

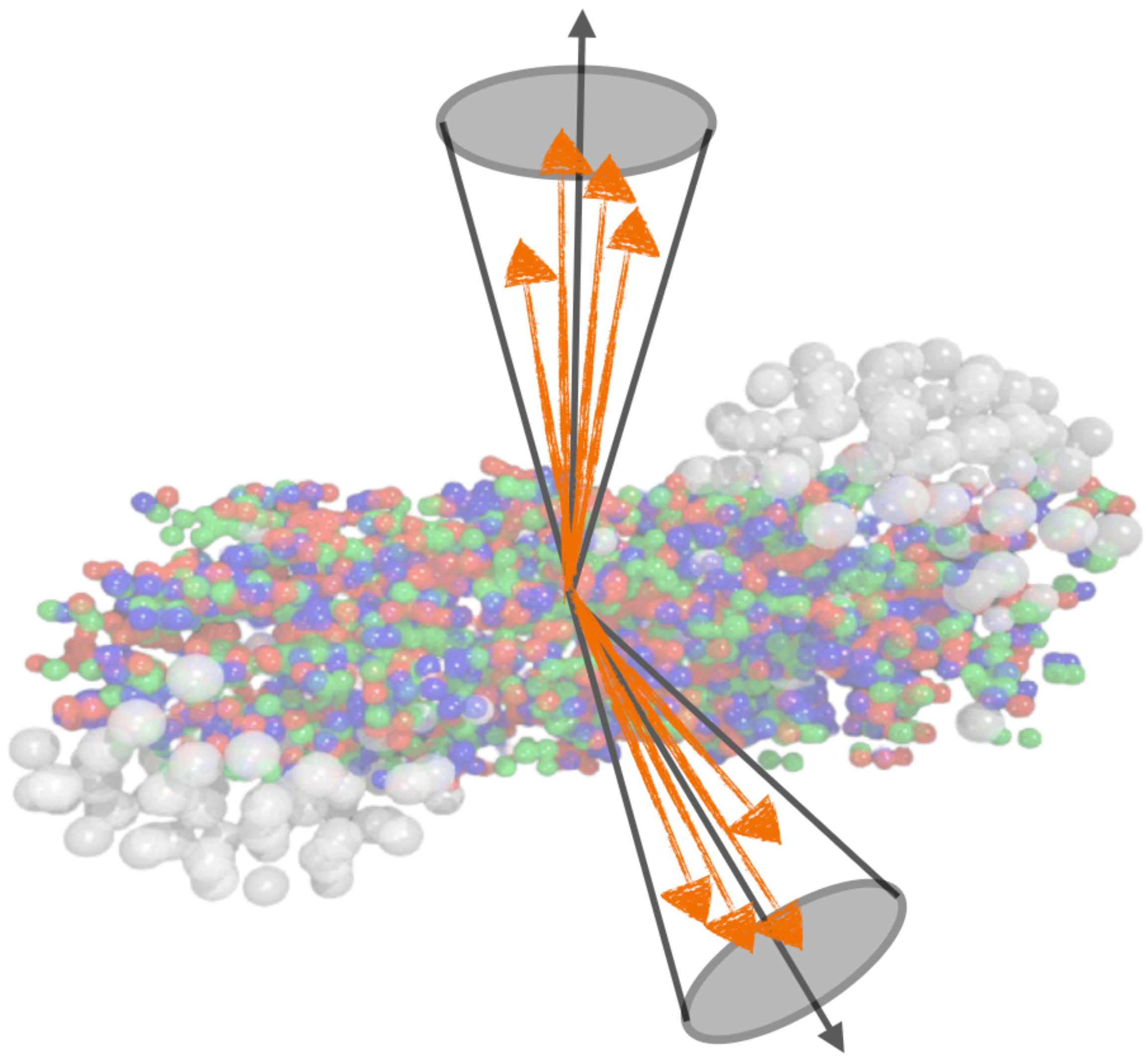
- **Low p_T region: enhancement at LHC (medium response), thermal recoil jet?**

Search for quasi-particles in QGP: jet acoplanarity

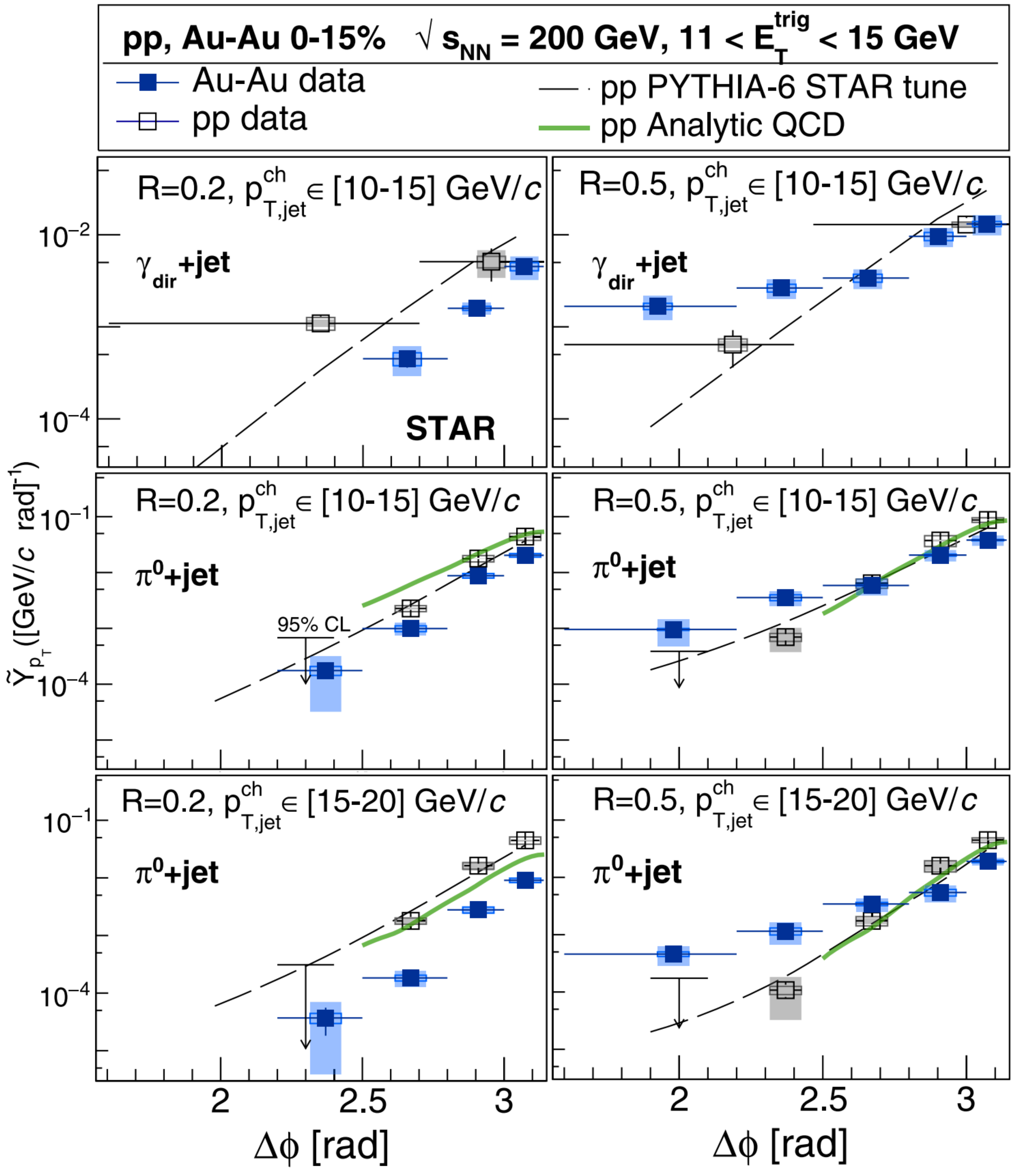
Rutherford experiment



Rutherford experiment in QGP



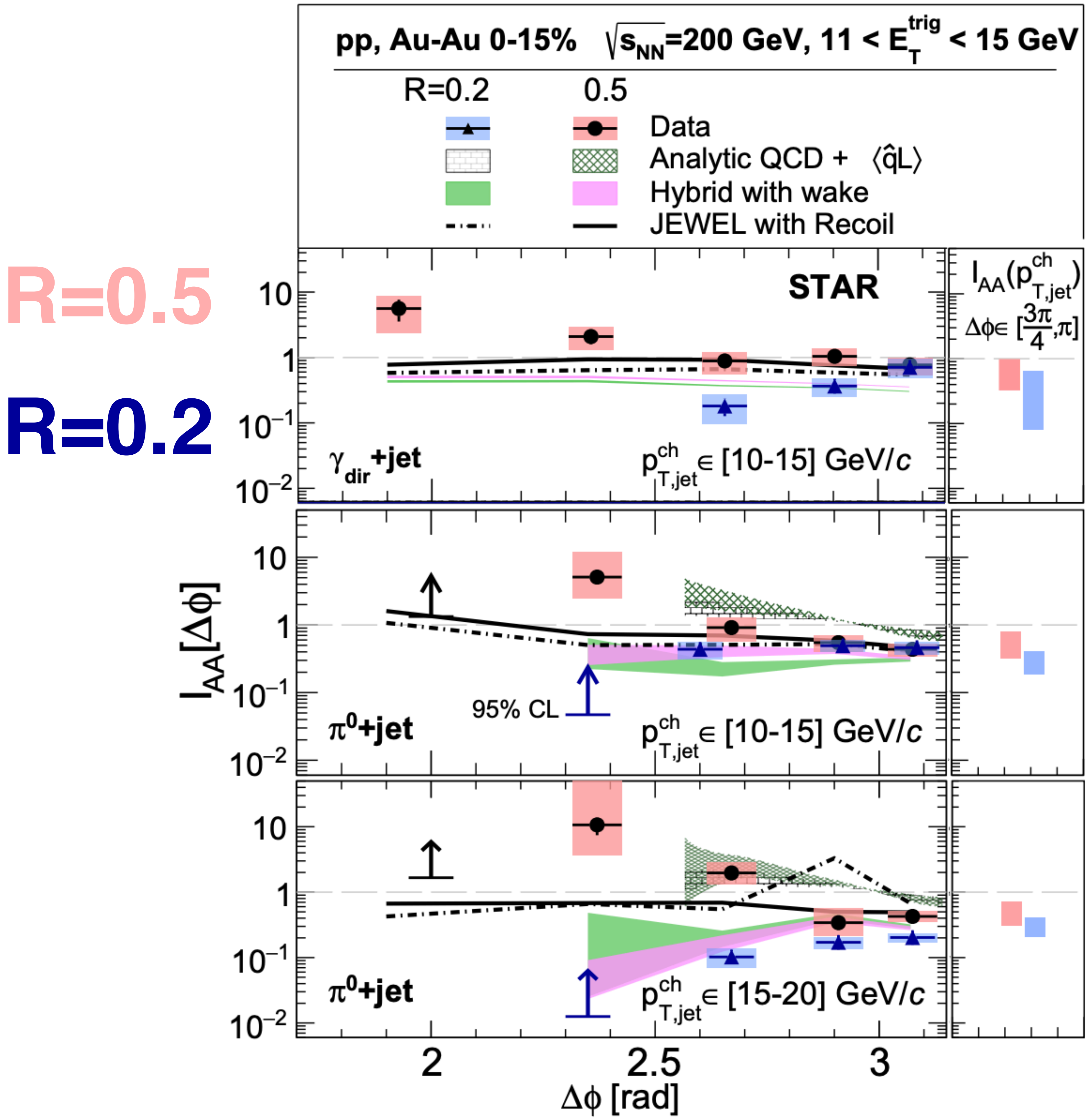
Jet deflection—soft multiple scatterings or single hard scatterings?



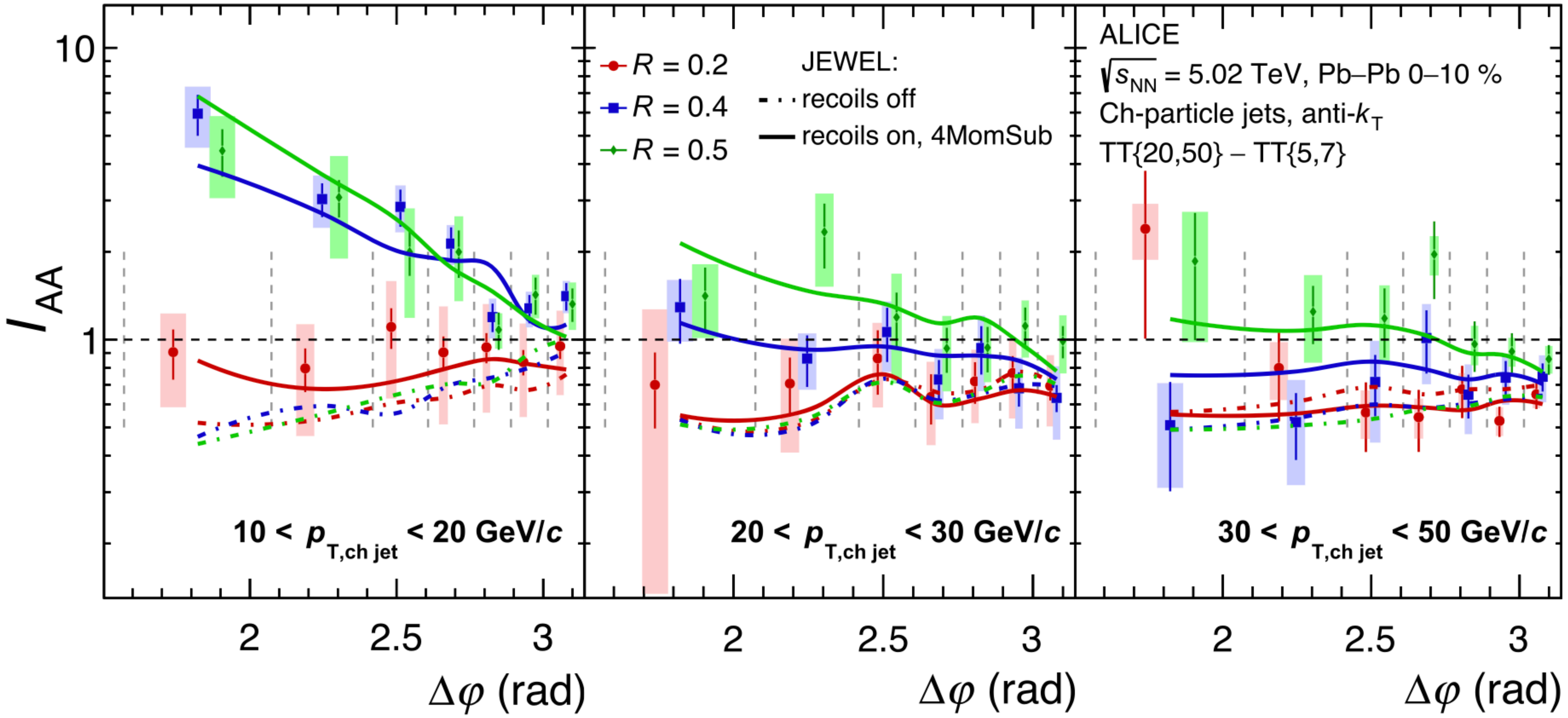
STAR, Phys. Rev. C 113, 014902 (2026)

Enhancement at large jet R with large acoplanarity.

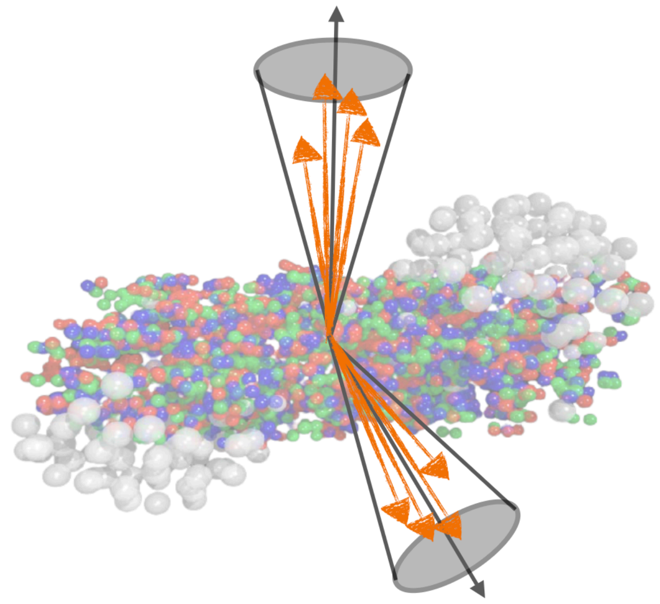
Jet acoplanarity



STAR, Phys. Rev. C 113, 014902 (2026)



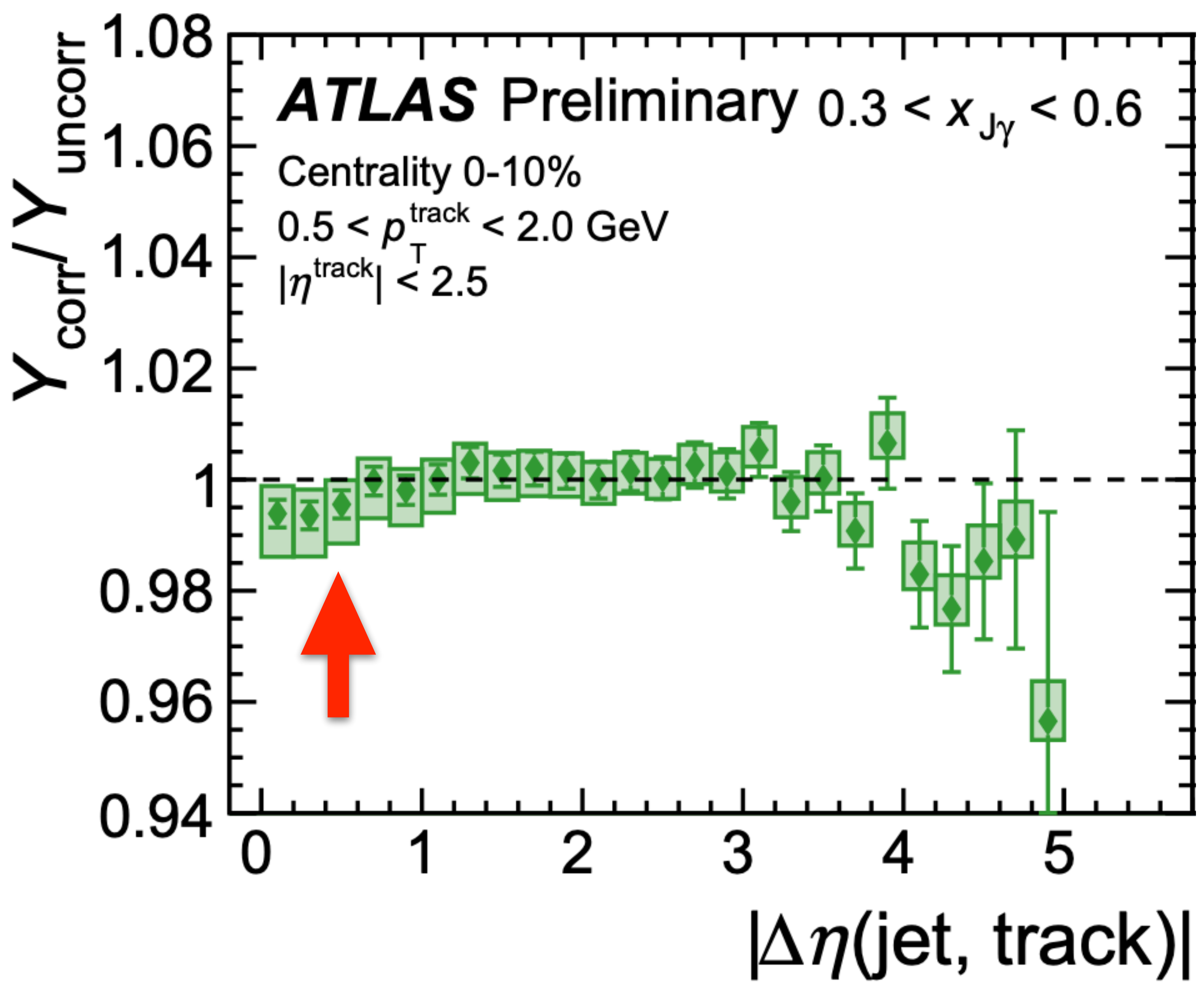
ALICE, Phys. Rev. Lett. 133, 022301 (2024)



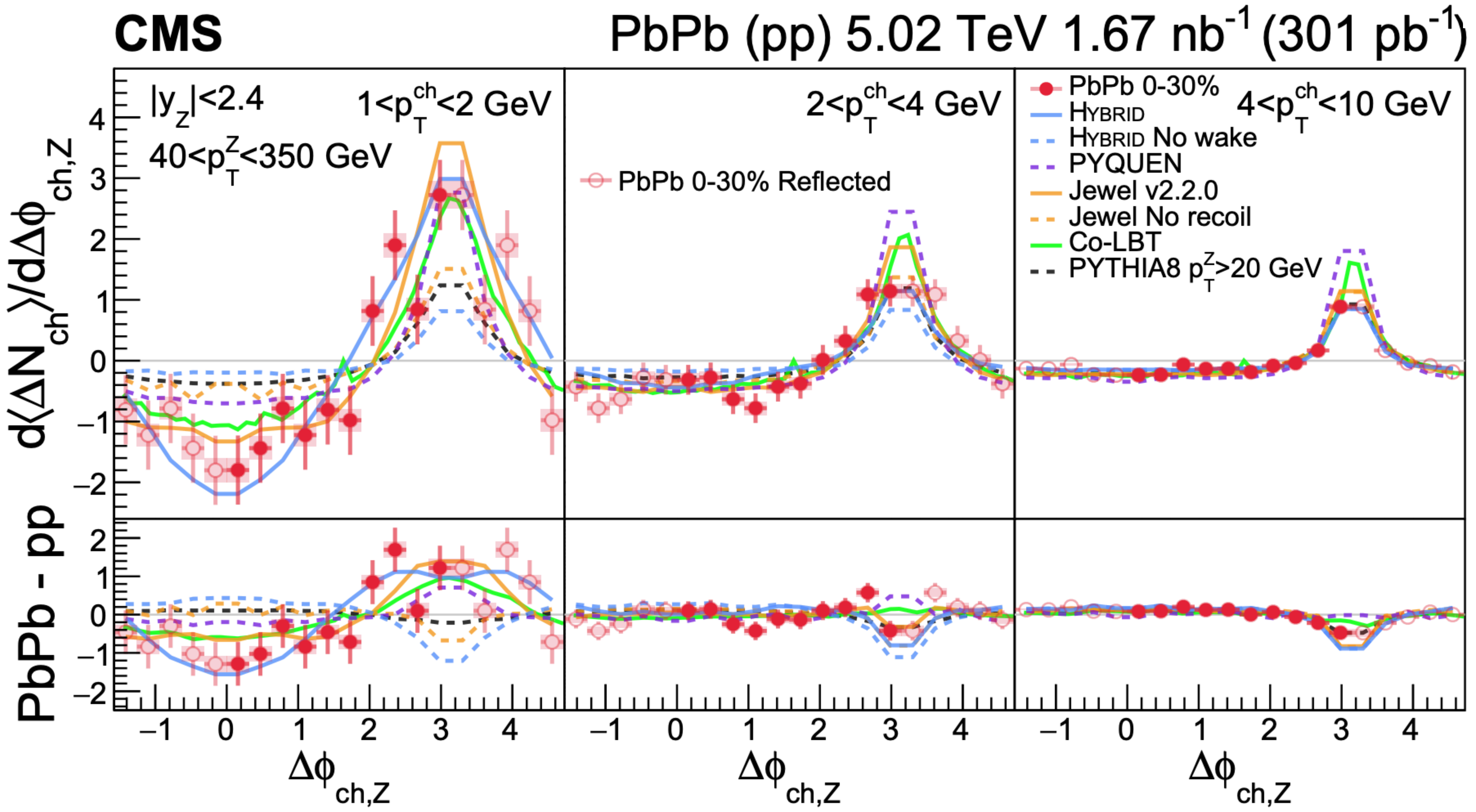
- **Enhancement of large R and low p_T jets with large acoplanarity.**

Yichao Dang's talk

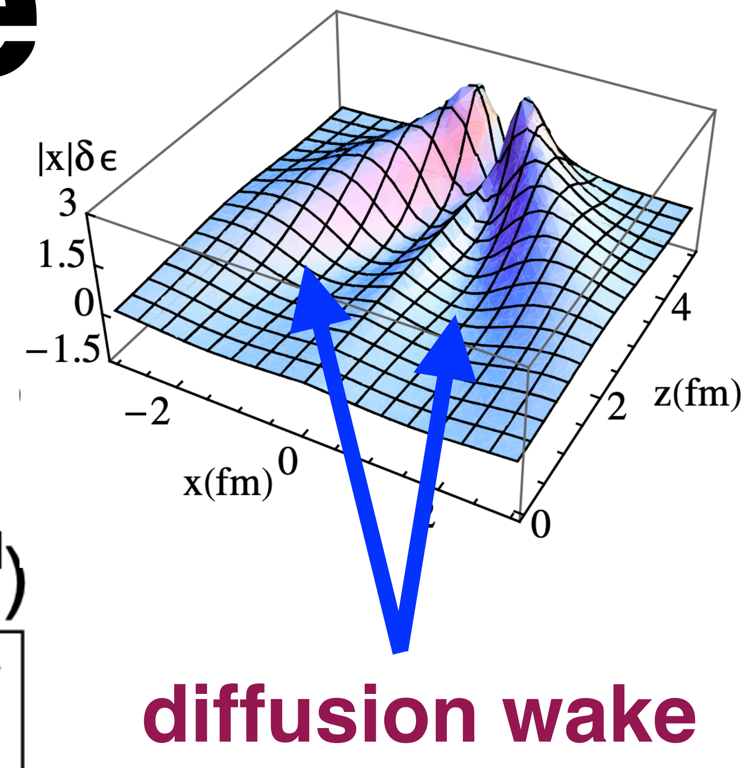
Medium response: diffusion wake



ATLAS, Phys. Rev. C 111, 044909 (2025)

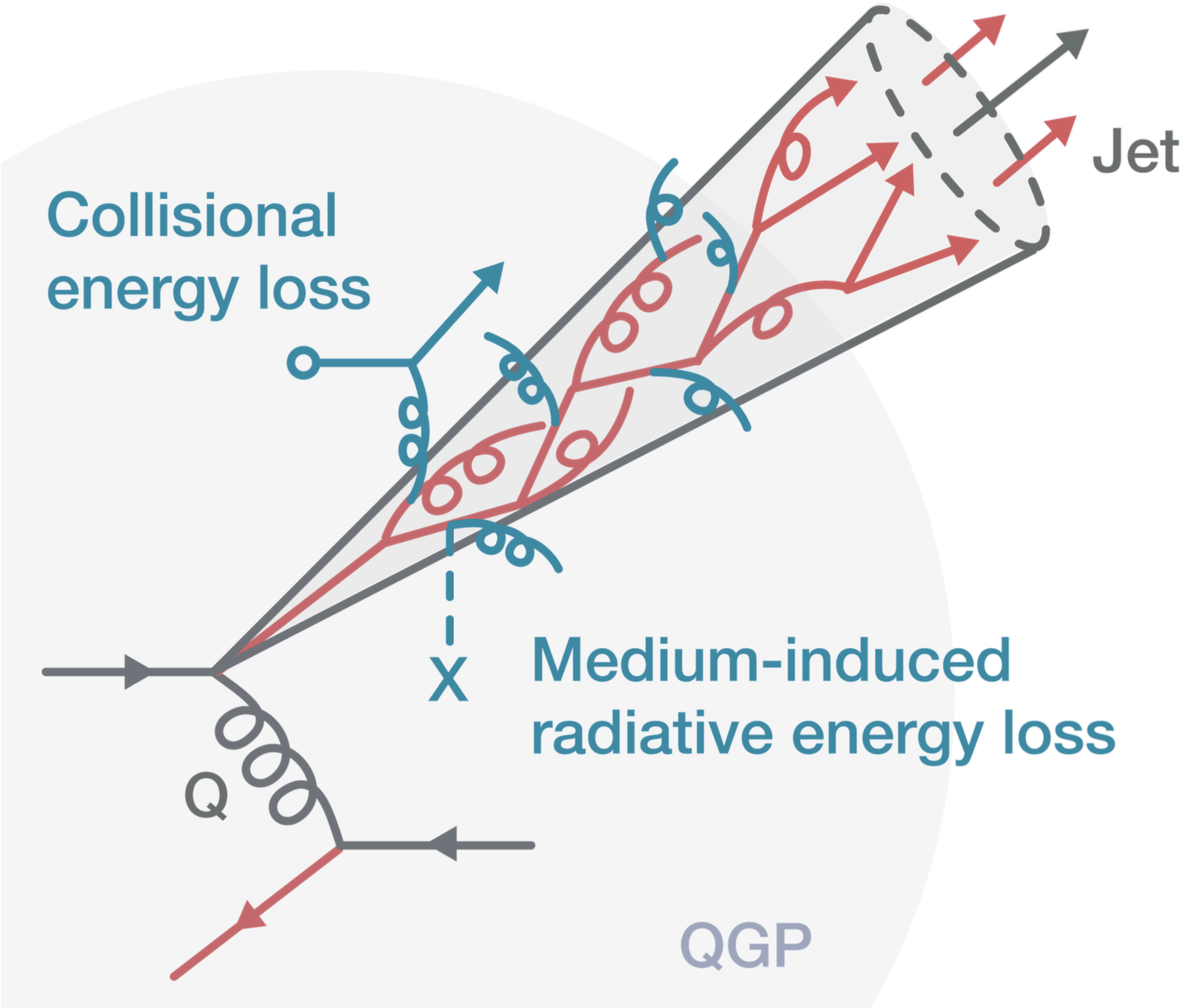


CMS, arXiv:2507.09307



- **ATLAS: Hint of small diffusion wake signal in the asymmetric γ-jet events.**
- **CMS: First direct evidence of medium response Z^0-hadron correlations.**

Jets in heavy-ion collisions



Jet quenching
Jet yield suppression; jet acoplanarity; medium response

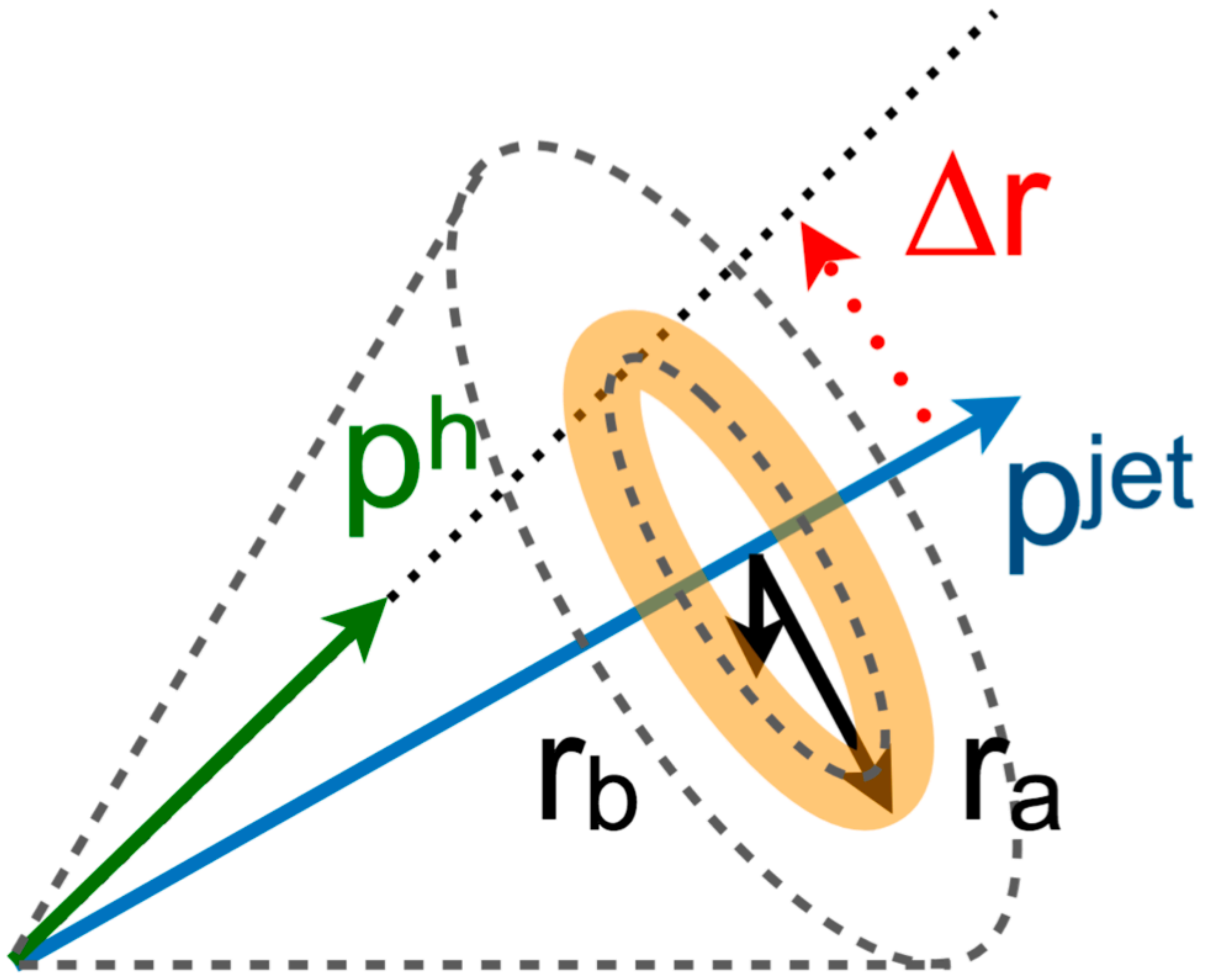
Jet substructure

Non-perturbative & hadronization

Critical system size of jet quenching

Jet substructure: shape & FF

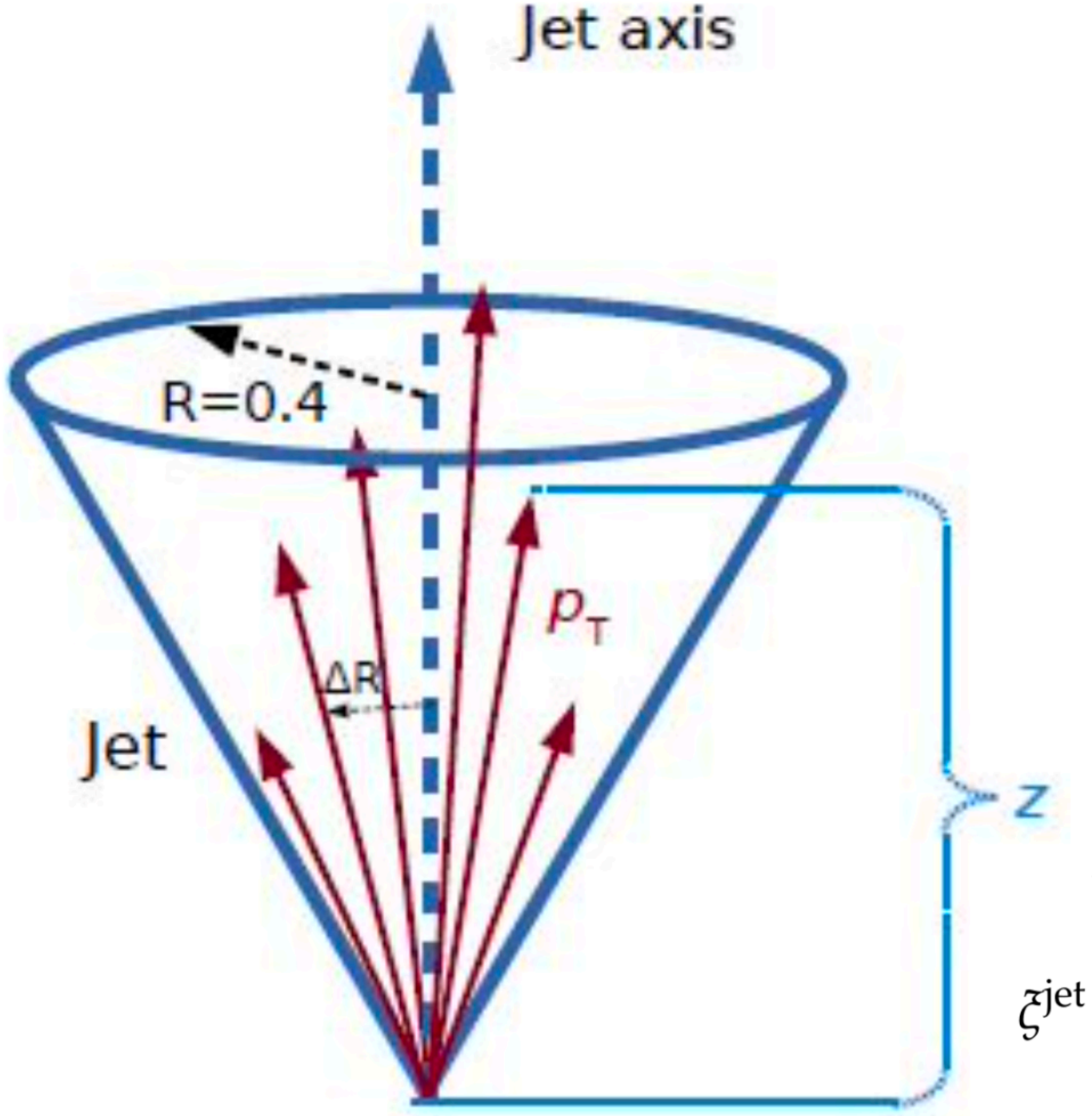
Jet shape: radial profile



$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\rm jets}}\sum_{\rm jets}\frac{\sum_{{\rm track}\in(r_a,r_b)} p_{\rm T}^{\rm track}}{p_{\rm T}^{\rm jets}}$$

Jet energy distribution as a function of R

Jet fragmentation function: longitudinal profile



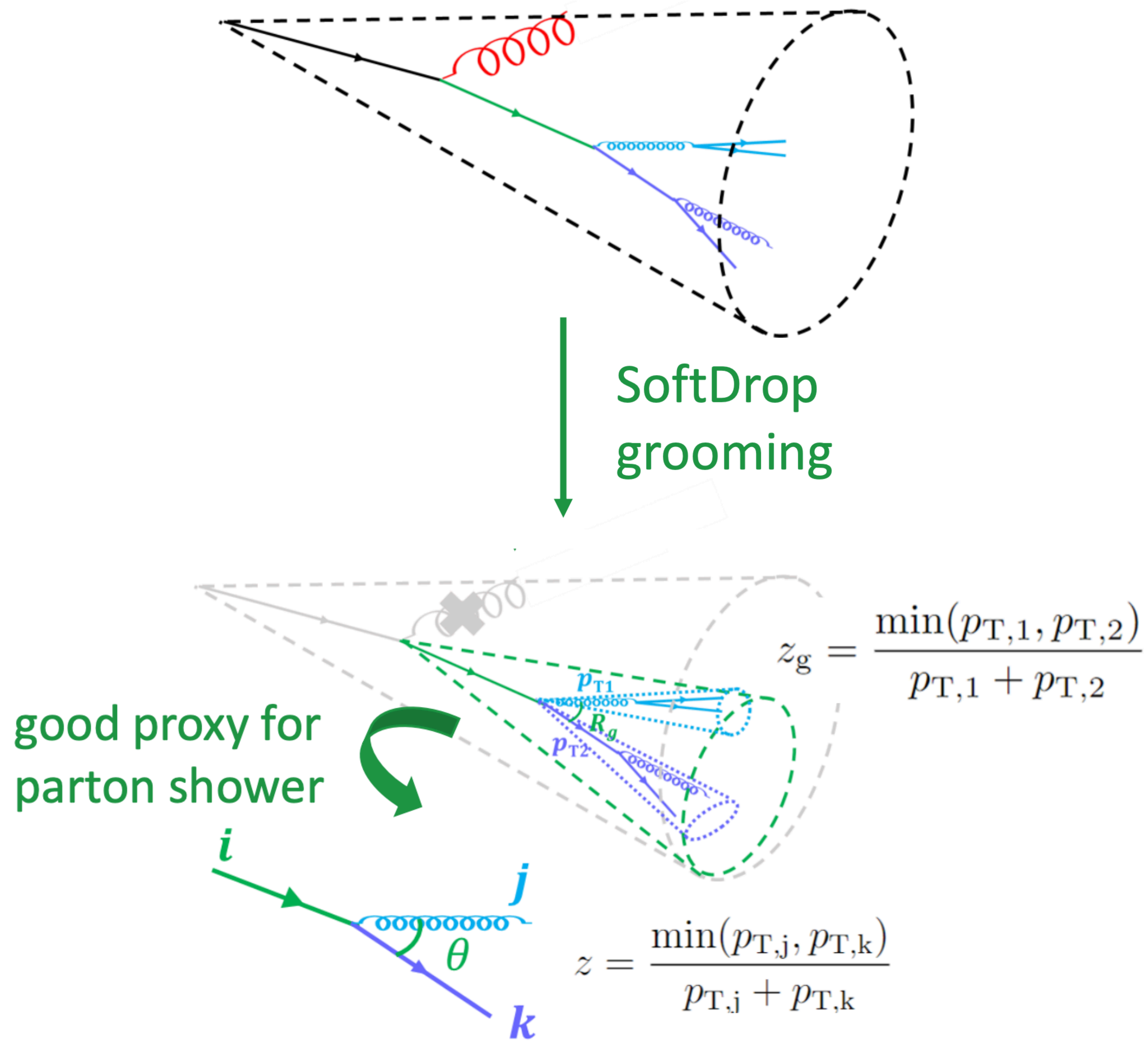
$$z \equiv p_{\rm T}\cos\Delta R \,/\, p_{\rm T}^{\rm jet}$$

$$\xi^{\rm jet} = \ln\frac{|\mathbf{p}^{\rm jet}|^2}{\mathbf{p}^{\rm trk}\cdot\mathbf{p}^{\rm jet}} = -\ln Z$$

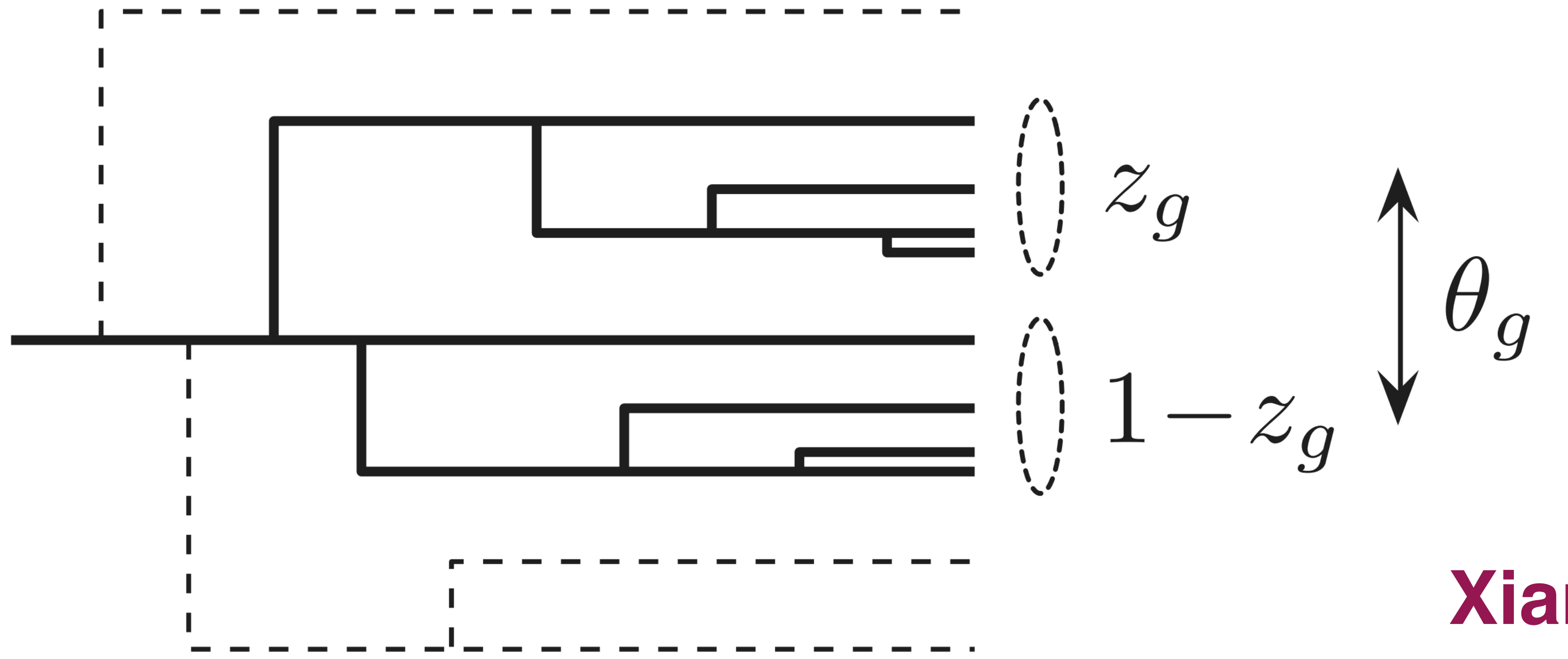
How transverse momentum is distributed inside the jet cone

Jet substructures with grooming

Use subscript “g” to denote observables obtained through SoftDrop grooming which removes soft and wide-angle radiation from the jet



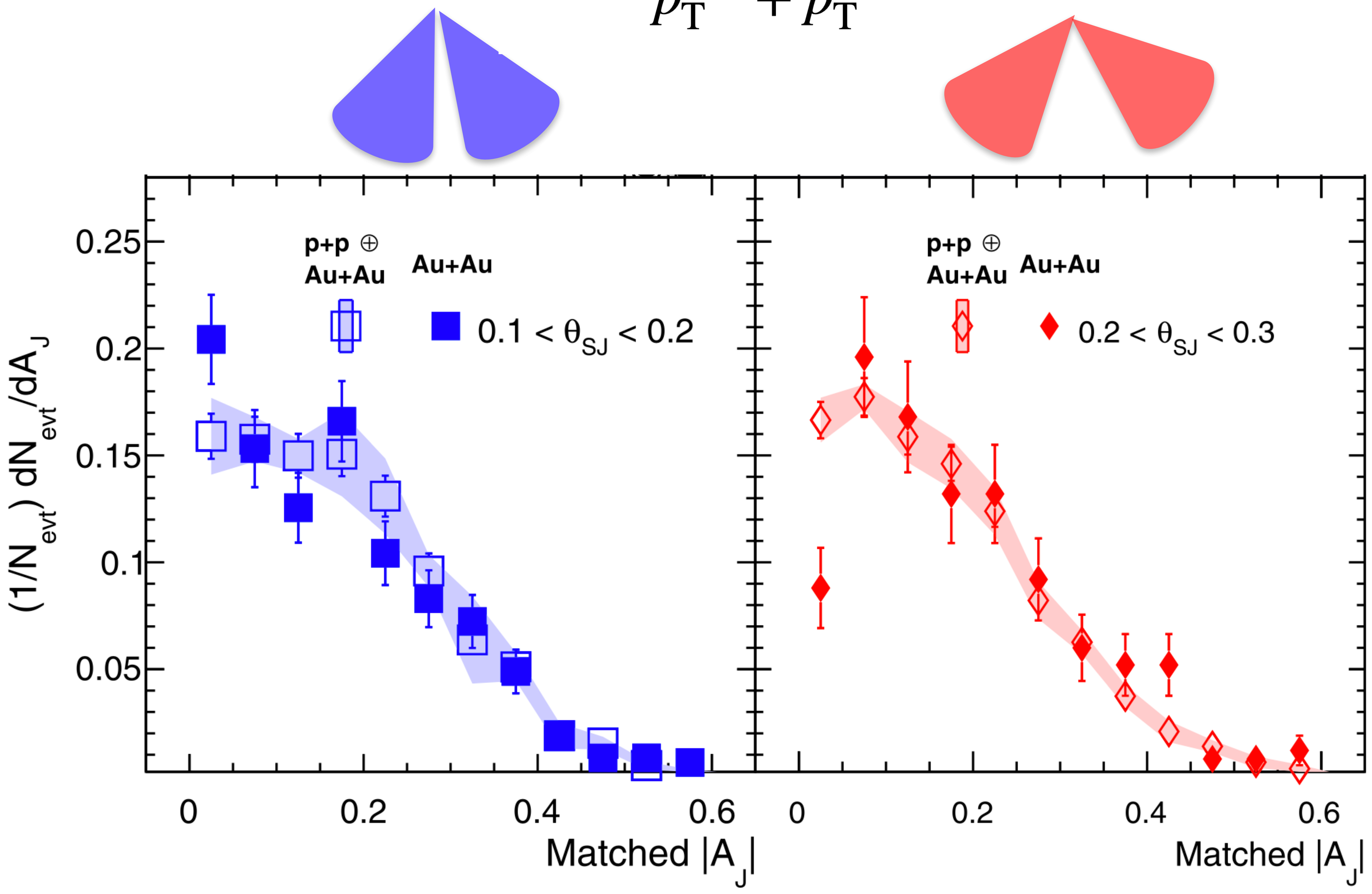
- **Structures within jets — built via correlations or algorithms**
- **SoftDrop — Utilizing the clustering information to build a tree**
- **Partonic energy loss via a differential study in momentum scale and angular scale**



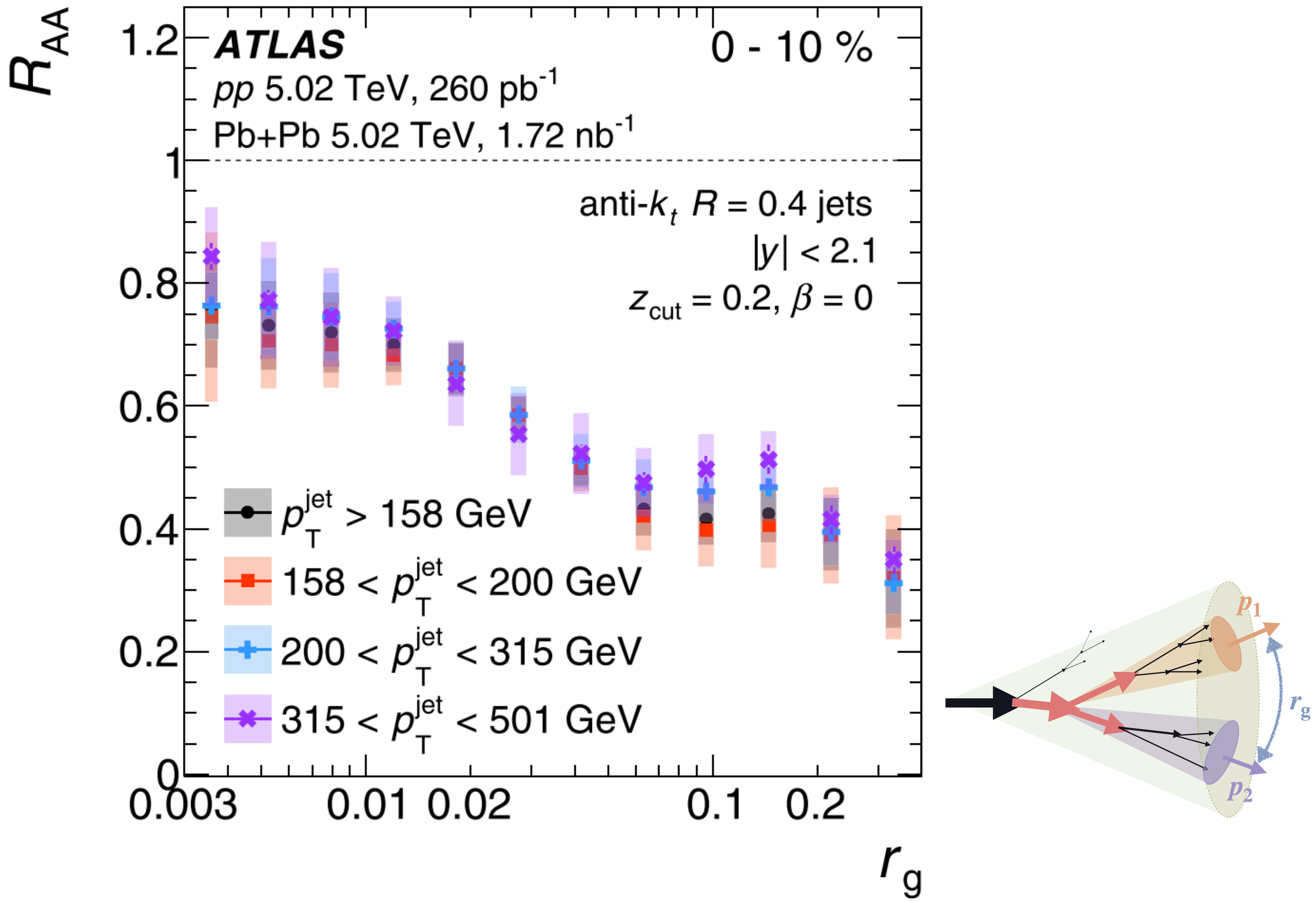
Xiangpan Duan’s talk

Differential measurements of jet suppression

$$A_J = \frac{p_T^{trig} - p_T^{recoil}}{p_T^{trig} + p_T^{recoil}}$$



STAR, Phys. Rev. C 105, 044906 (2022)



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

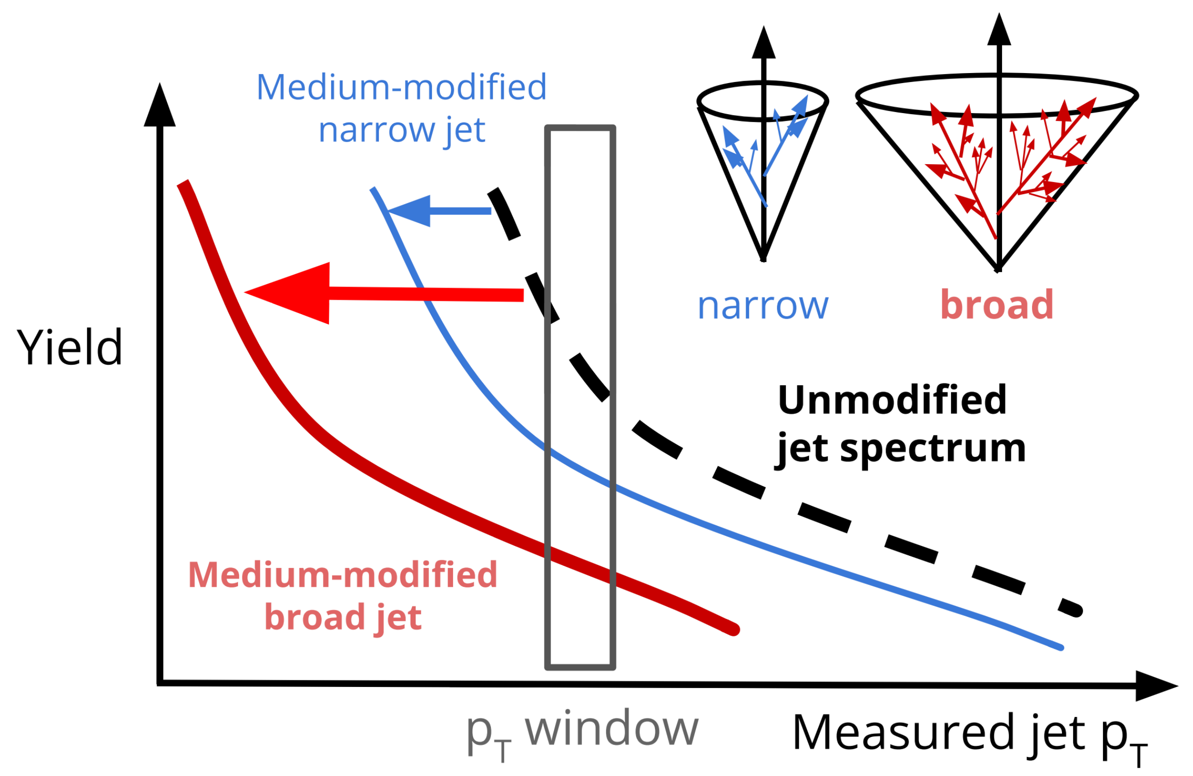
No significant difference between wide/narrow jets in matched A_J.

Wide jets quenched more than narrow jets.

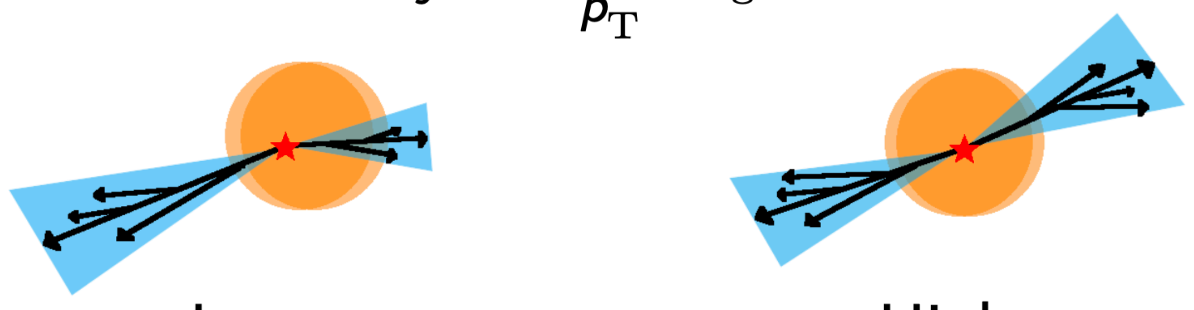
Selection bias?

γ+jet substructure to reduce bias

CMS, Phys. Lett. B B 861 (2025) 139088



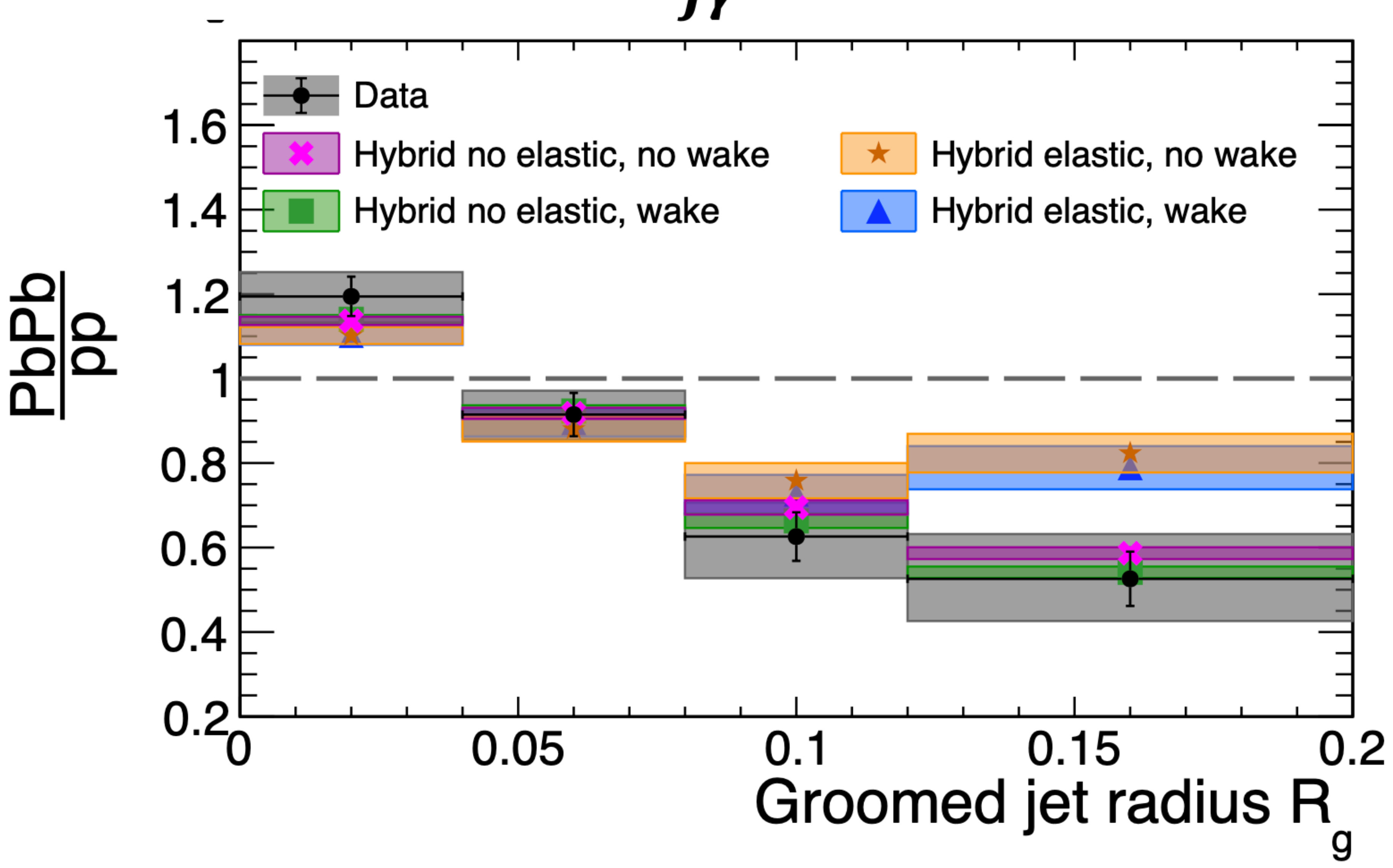
$$x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$



Low x_j
Unbalanced dijet

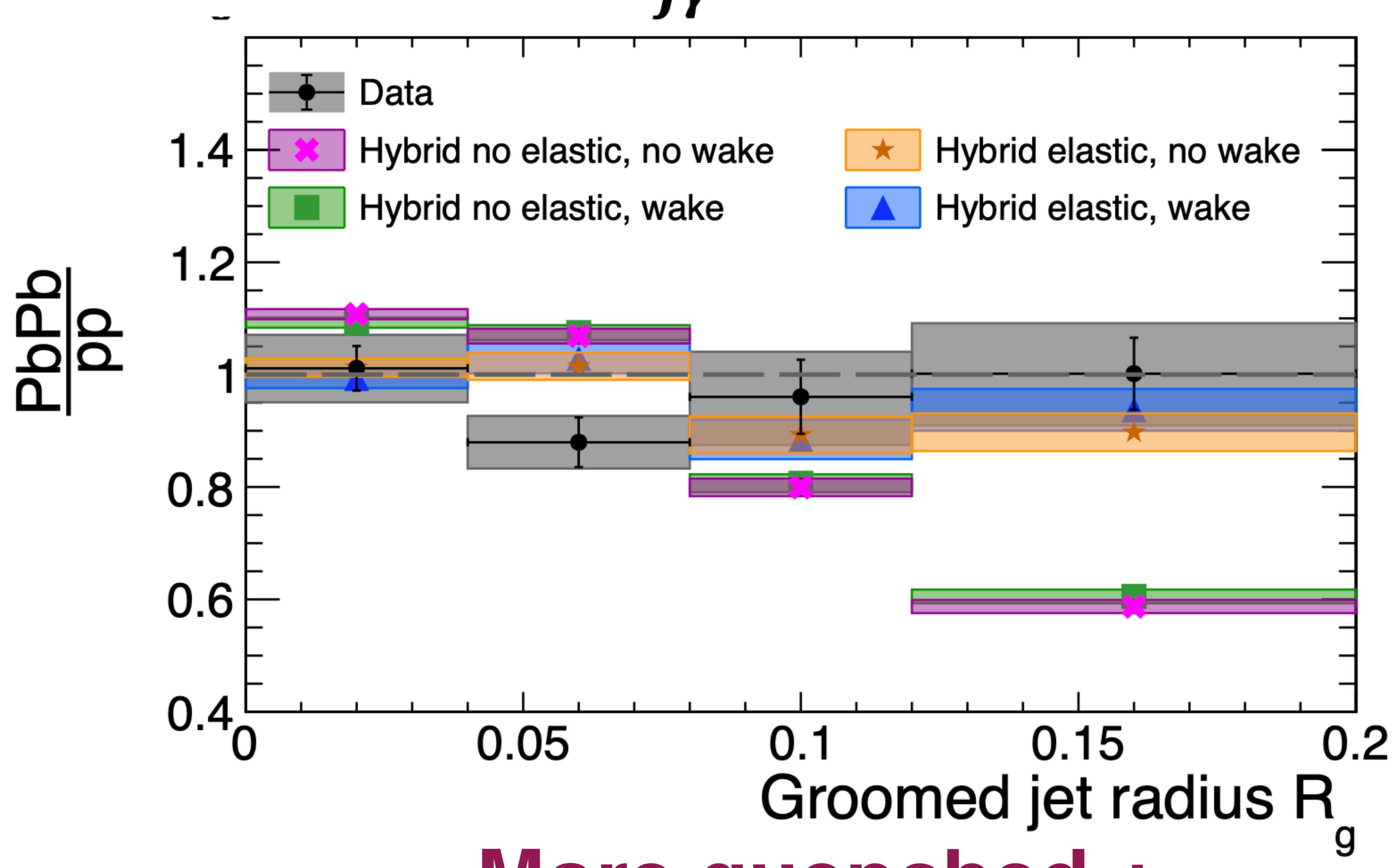
High x_j
Balanced dijet

$x_{j\gamma} > 0.8$



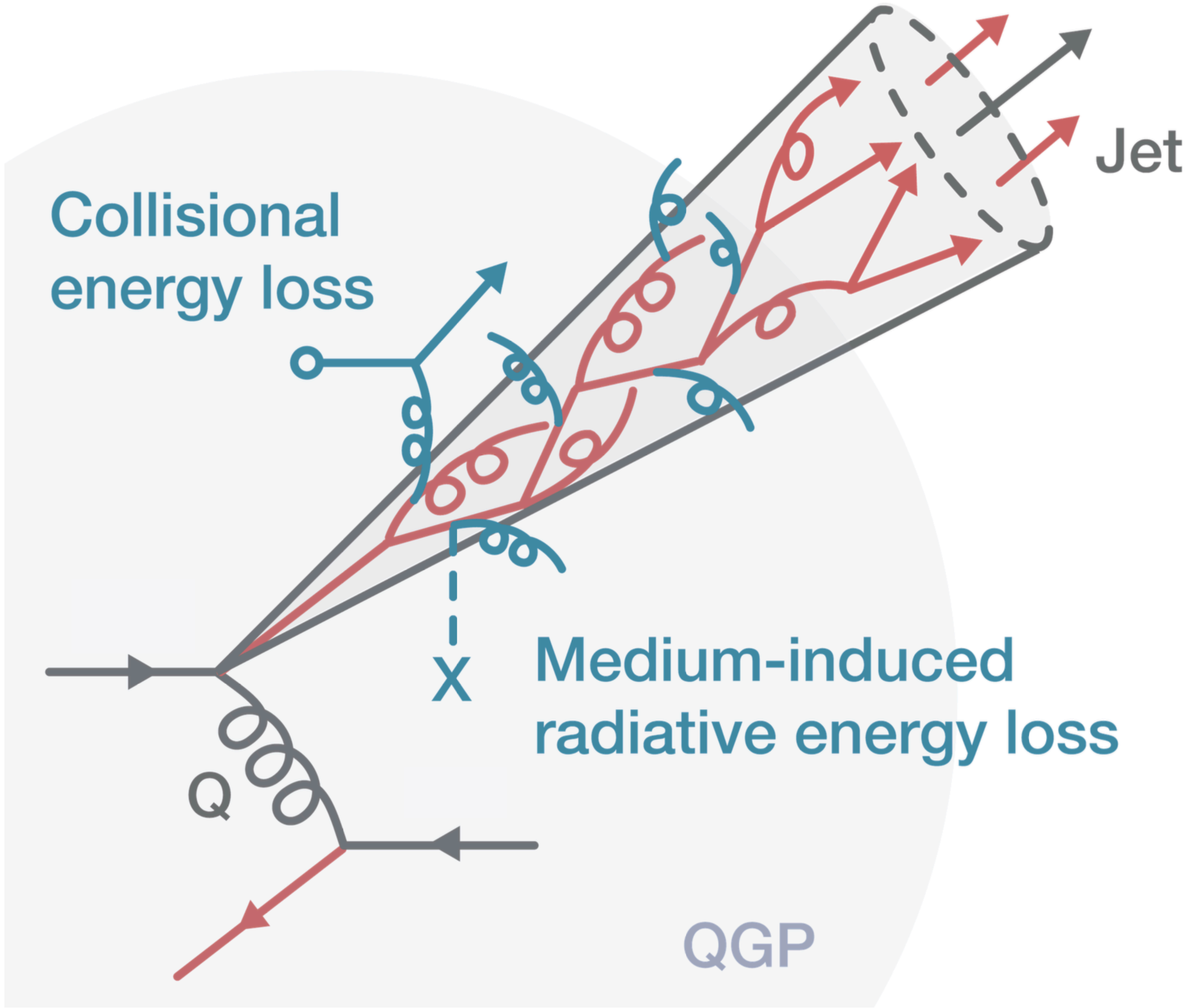
Less quenched jets:
narrowing still observed

$x_{j\gamma} > 0.4$



More quenched + unquenched jets:
no modification

Jets in heavy-ion collisions



Jet quenching
Jet yield suppression; jet acoplanarity; medium response

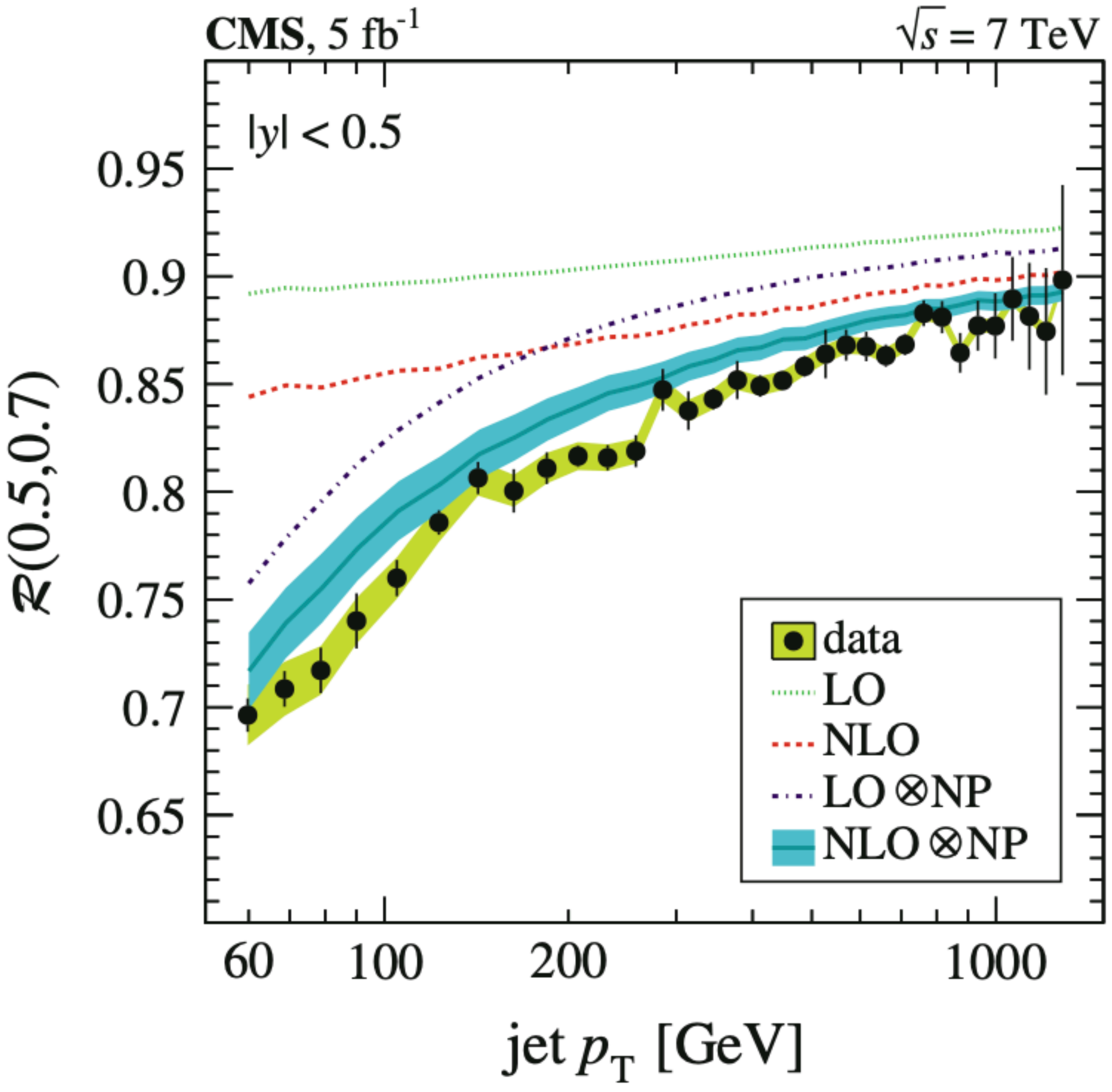
Jet substructure
Differential jet modification

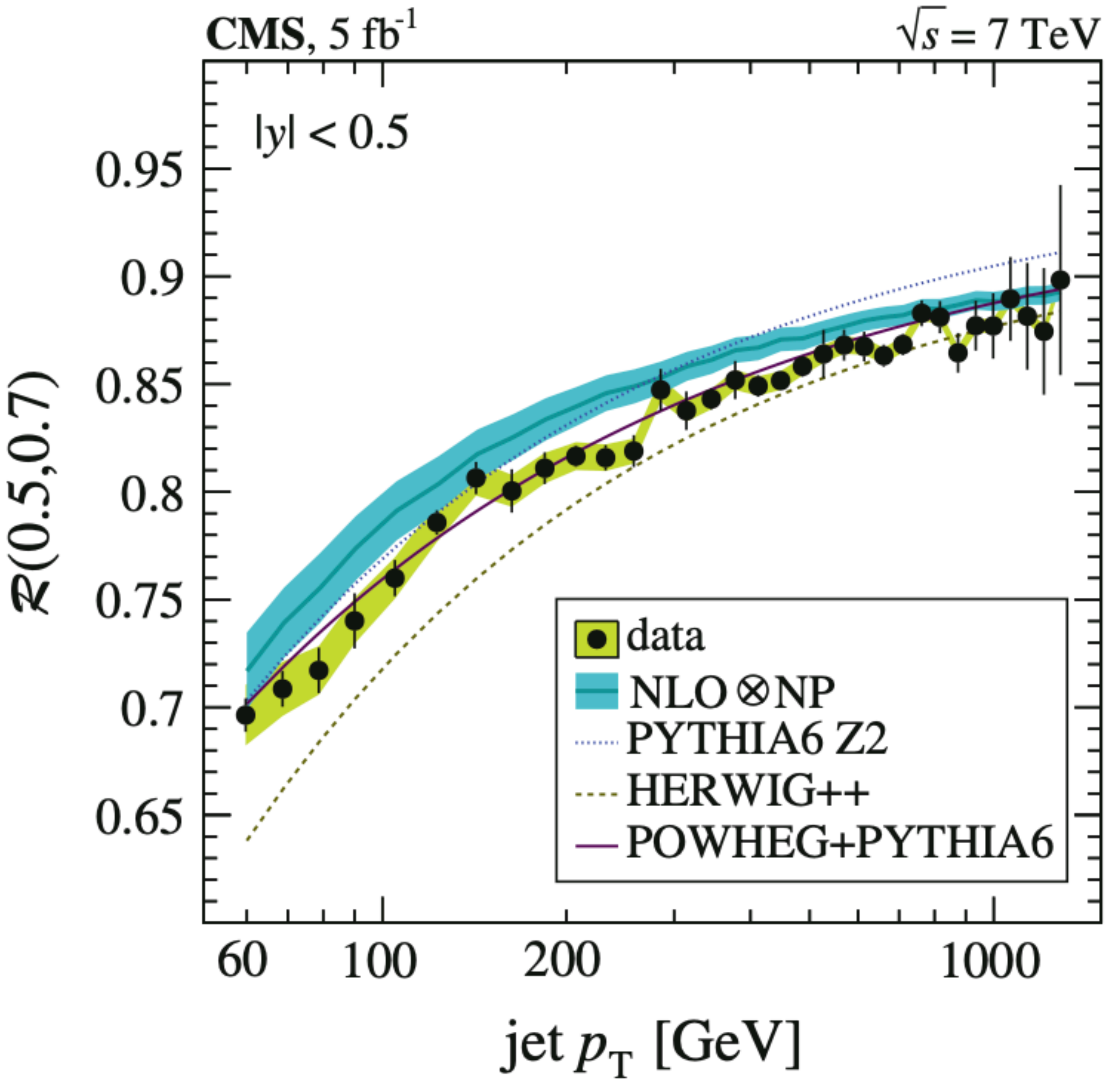
Non-perturbative & hadronization

Critical system size of jet quenching

Non-perturbative & hadronization in jet measurement

R. A. Fernandez et al., The Large Hadron Collider: Harvest of Run1

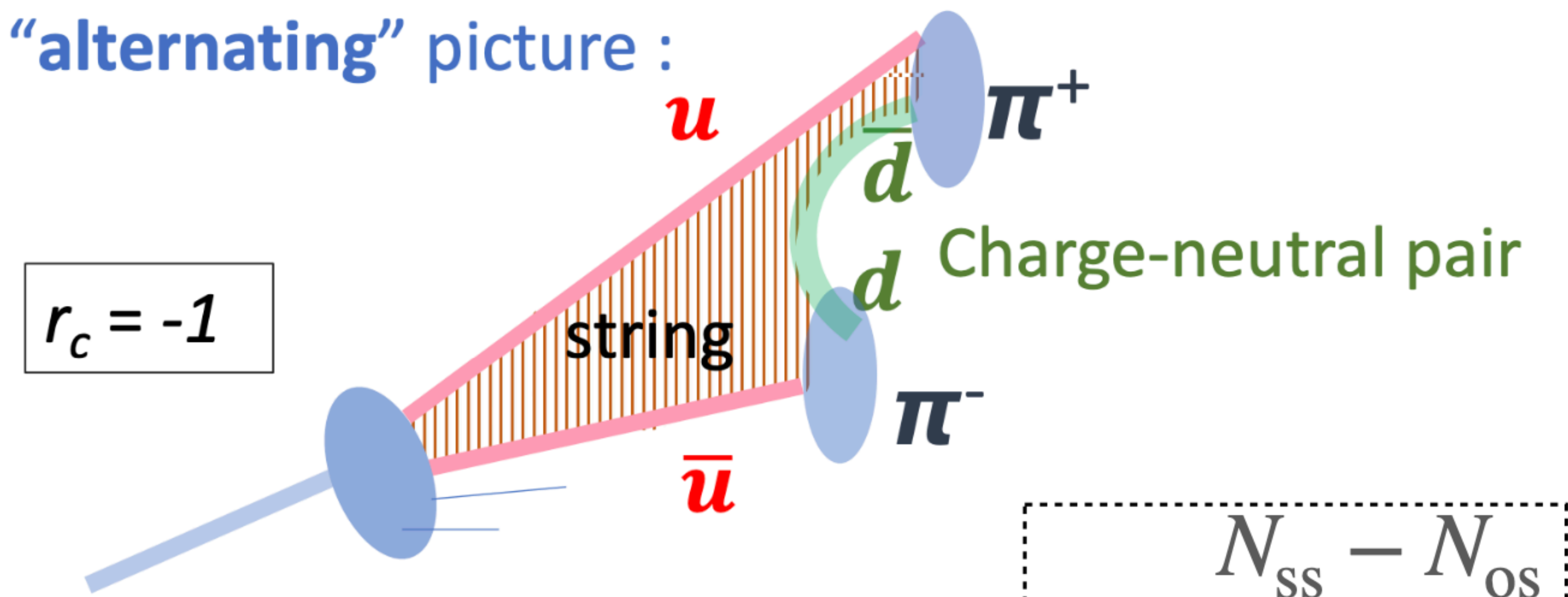




NLO+NP calculation still slightly overestimate the results.

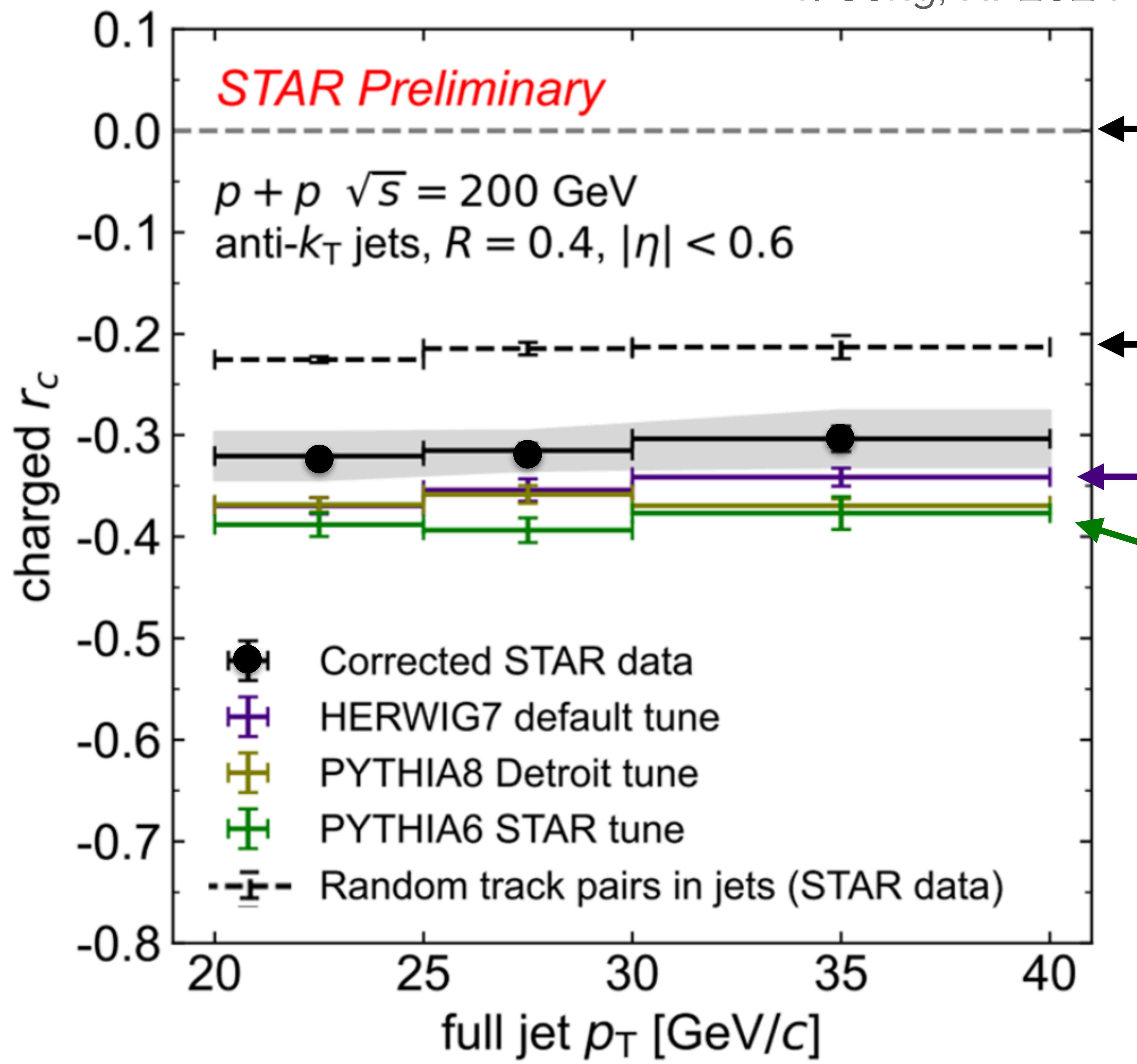
POWHEG+PYTHIA6: Non-perturbative & hadronization gives the best description.

Assessing fragmentation mechanism in jets

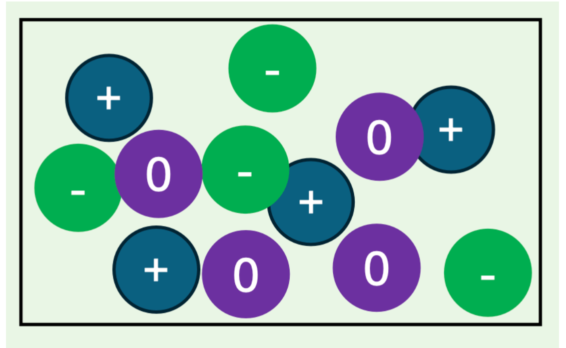


$$r_c = \frac{N_{ss} - N_{os}}{N_{ss} + N_{os}}$$

Y. Song, HP2024



(infinite) bath with no net charge, $r_c = 0$



pair of random tracks within a jet influenced by jet charge, $r_c = 0.2$

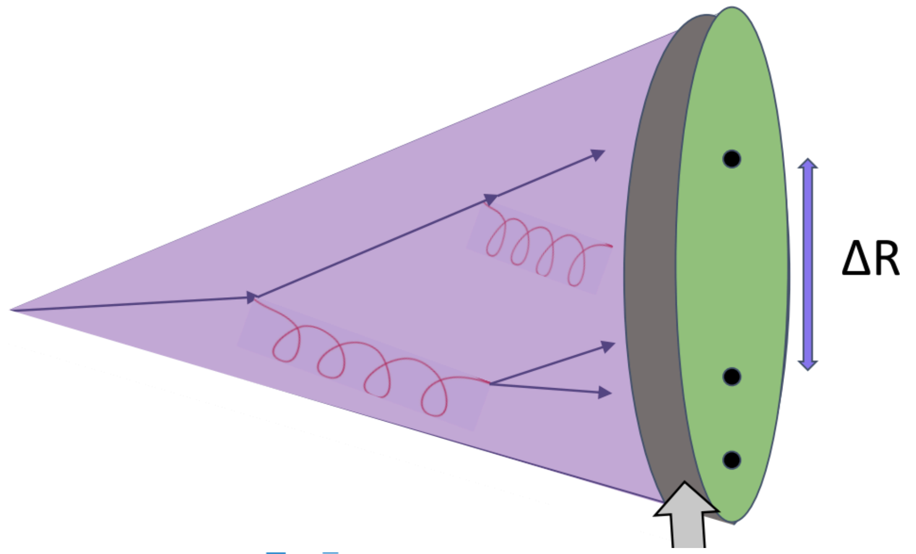
HERWIG (cluster hadronization)

PYTHIA (Lund string)

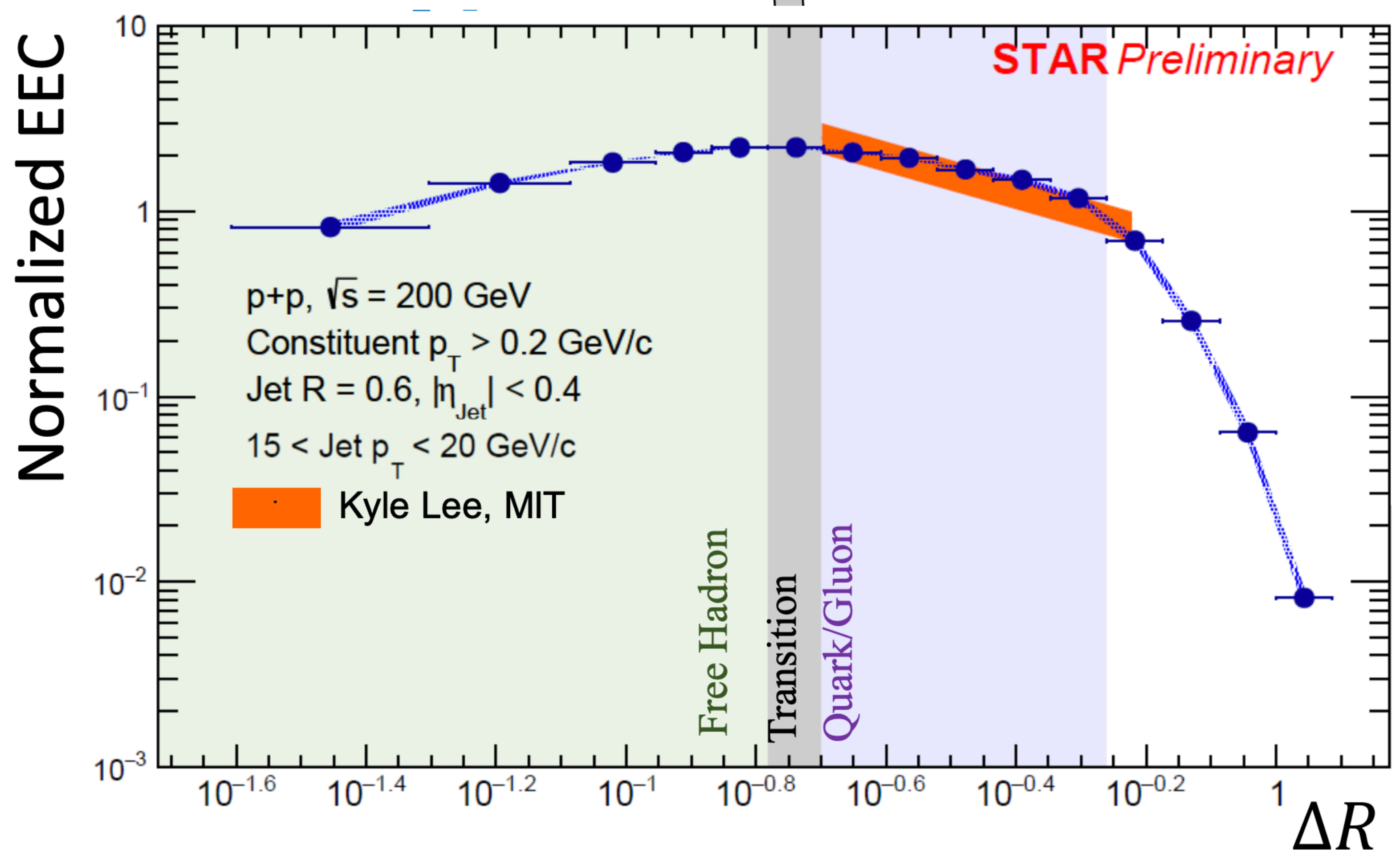
- **Both Lund string fragmentation and cluster hadronization models overestimate the charge correlation.**
- **Worth to pursuing the similar measurement in heavy-ion collisions.**

Modification to hadronization due to QGP?

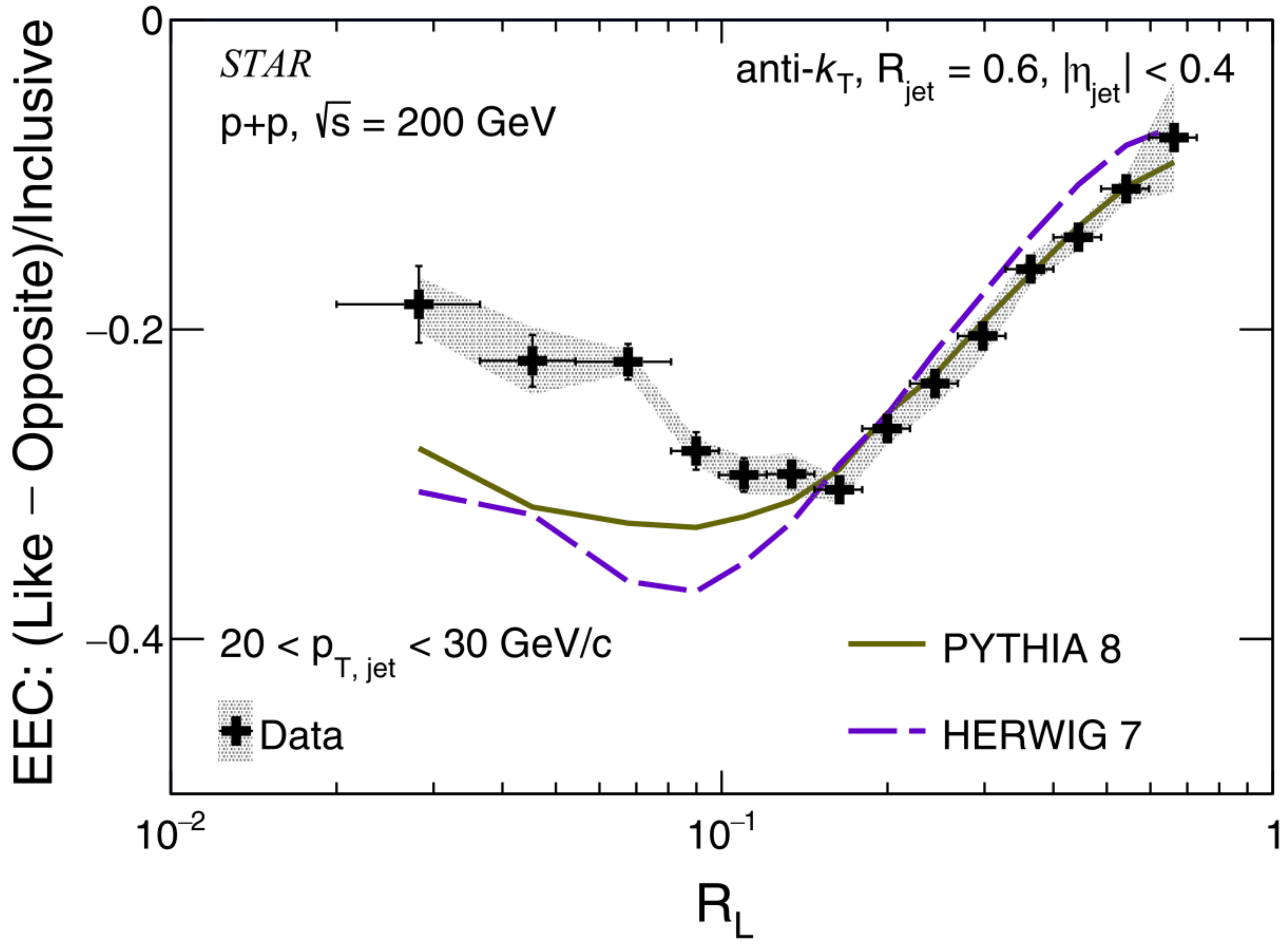
Put EEC into work

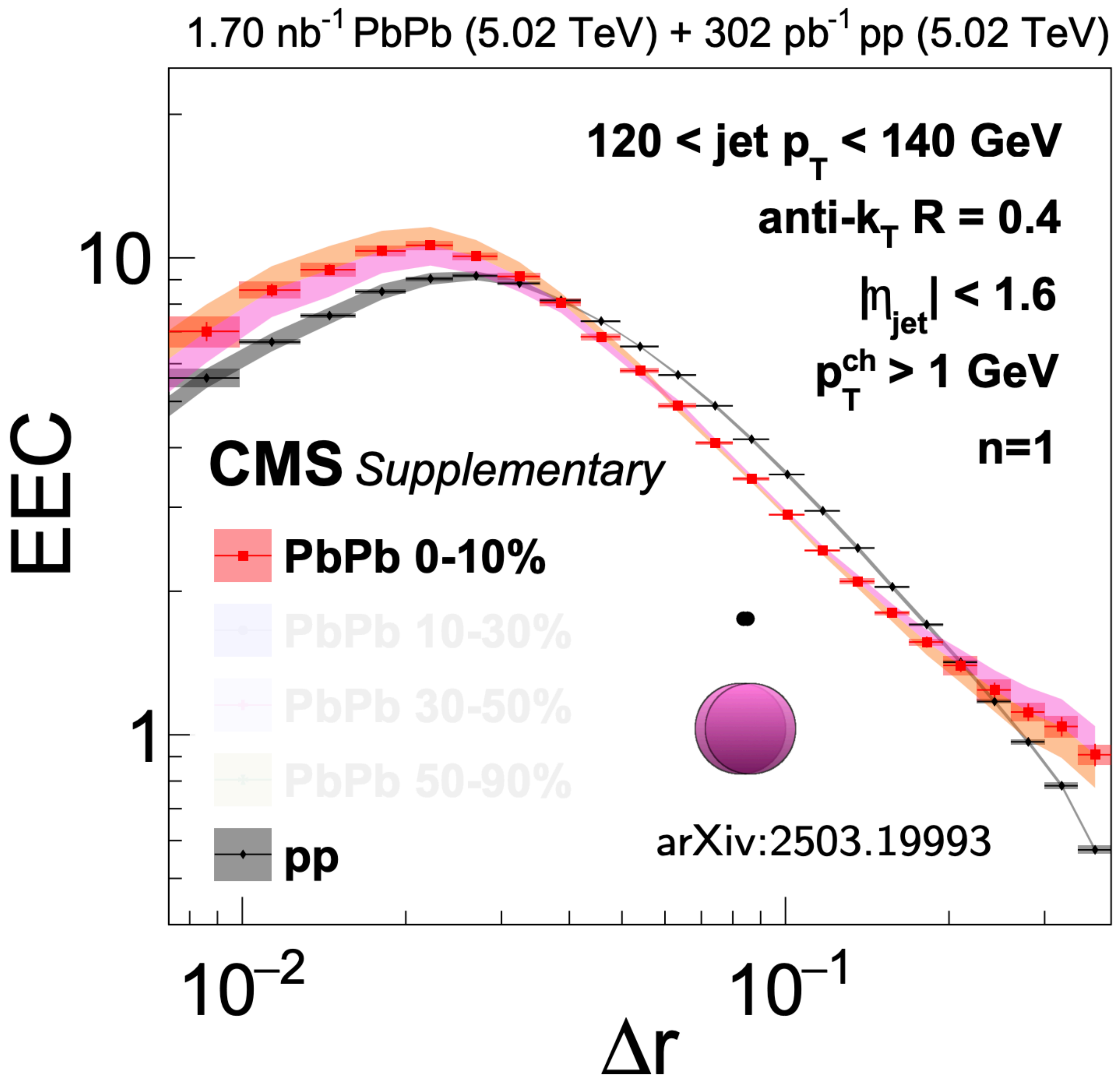


Transition region captures the time scale of hadronization



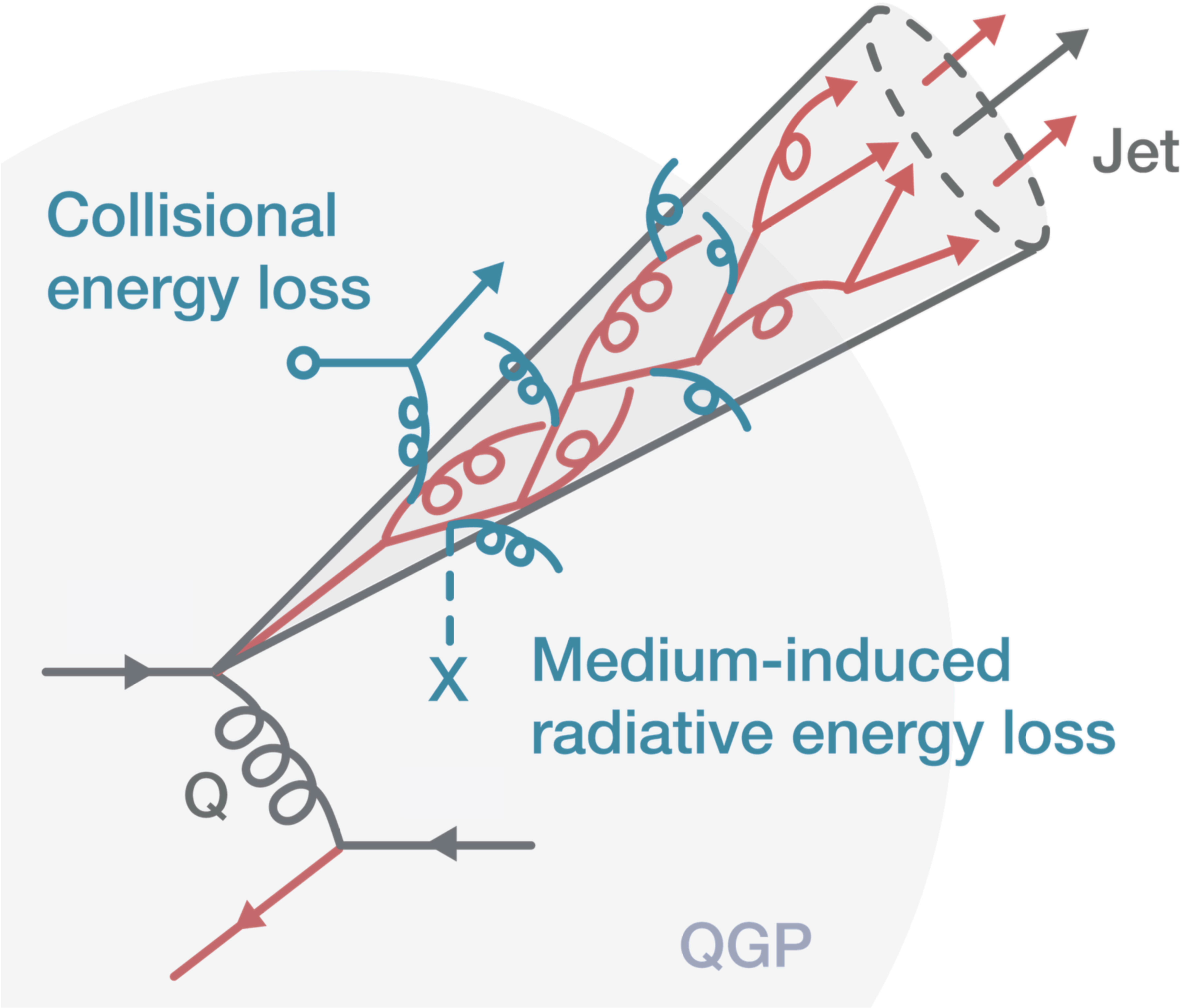
STAR, Phys. Rev. Lett. 135, 111901 (2025)





- **Transition between perturbative and non-perturbative regimes occurs within a specific angular region.**
- **Model calculations failed to describe the charge-dependent EEC at small angles.**
- **Energy loss moves the peak in Pb+Pb to smaller Δr.**

Jets in heavy-ion collisions



Jet quenching
Jet yield suppression; jet acoplanarity; medium response

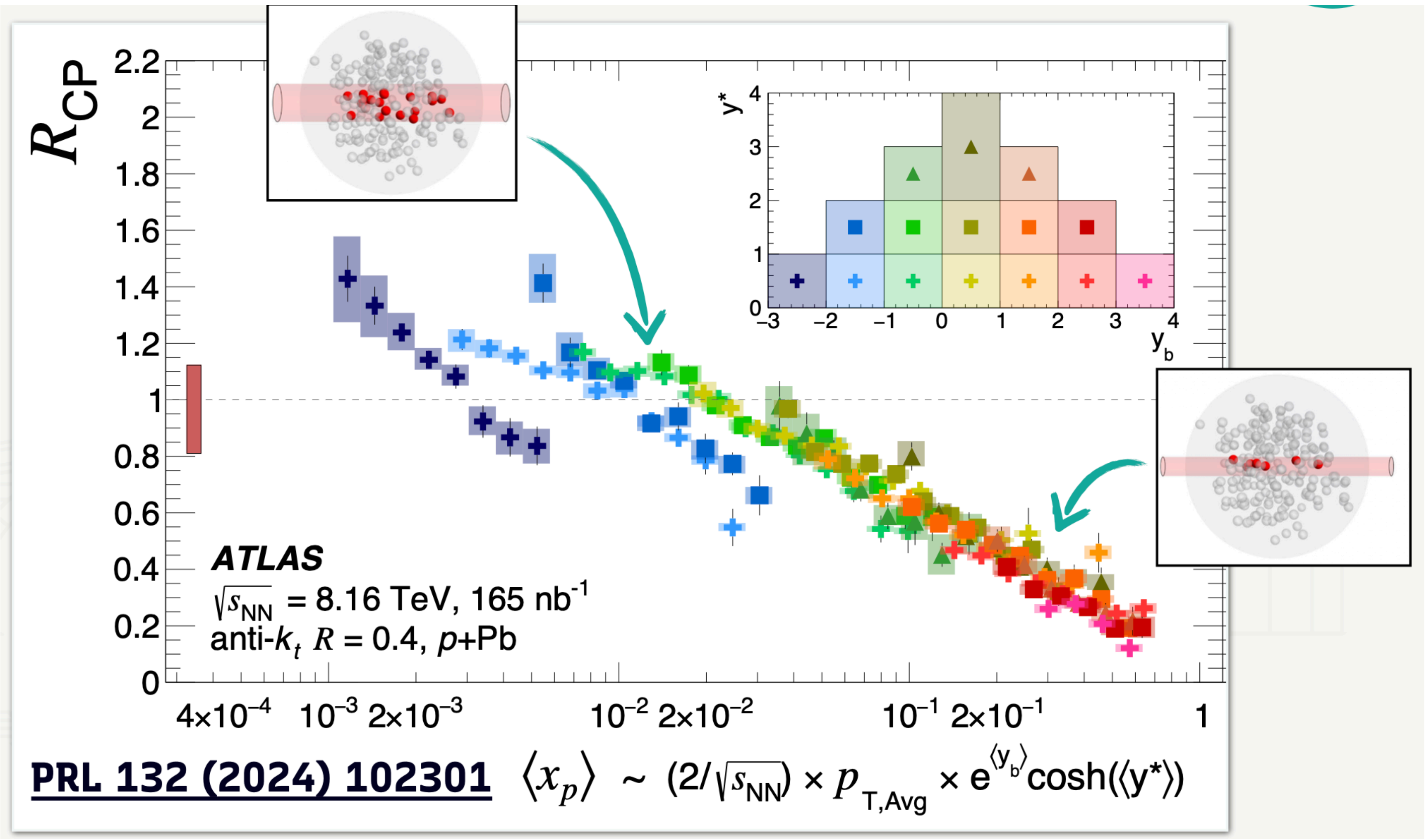
Jet substructure
Differential jet modification

Non-perturbative & hadronization
Charge correlator & EEC

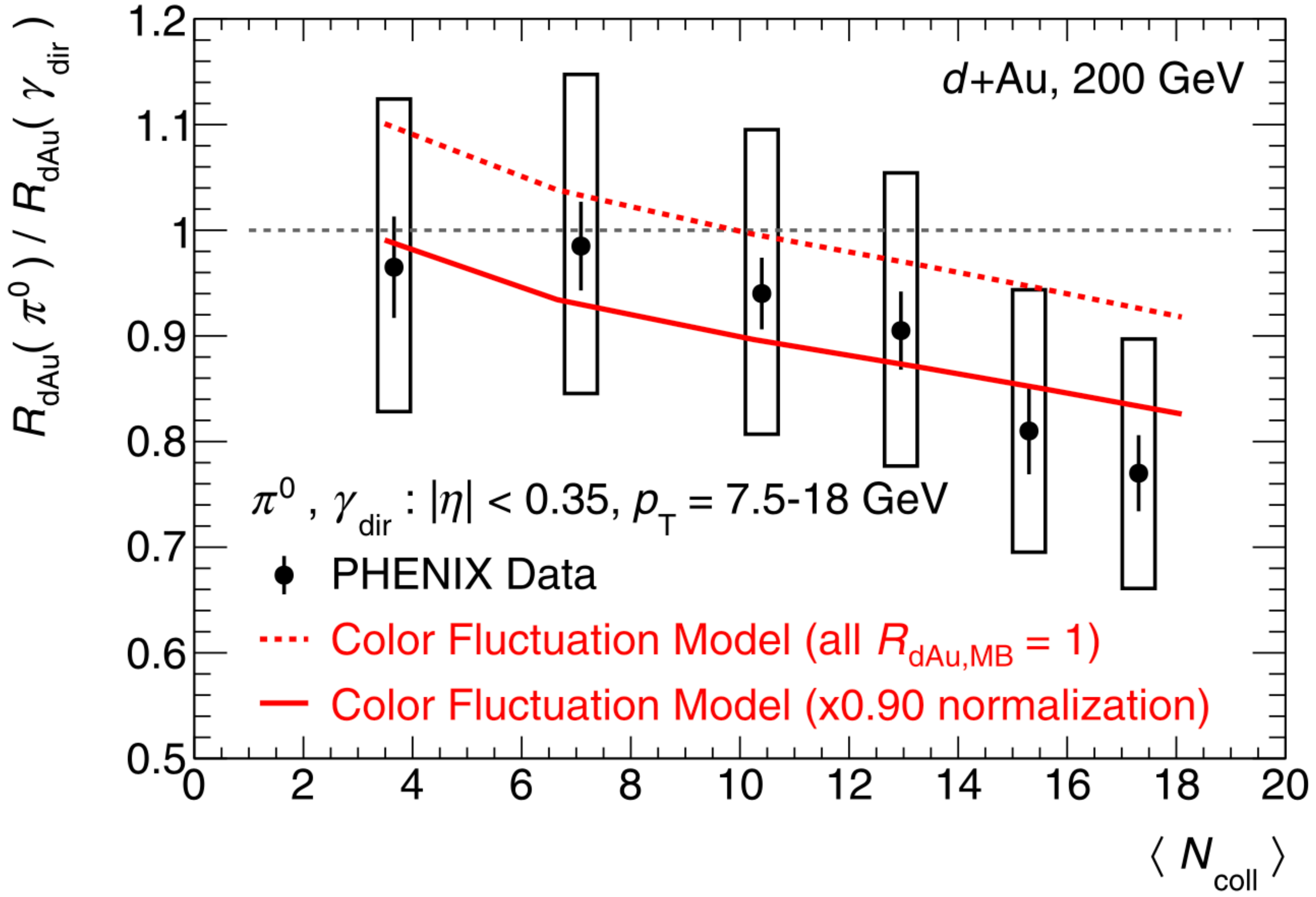
Critical system size of jet quenching

Evidence of jet quenching in small systems?

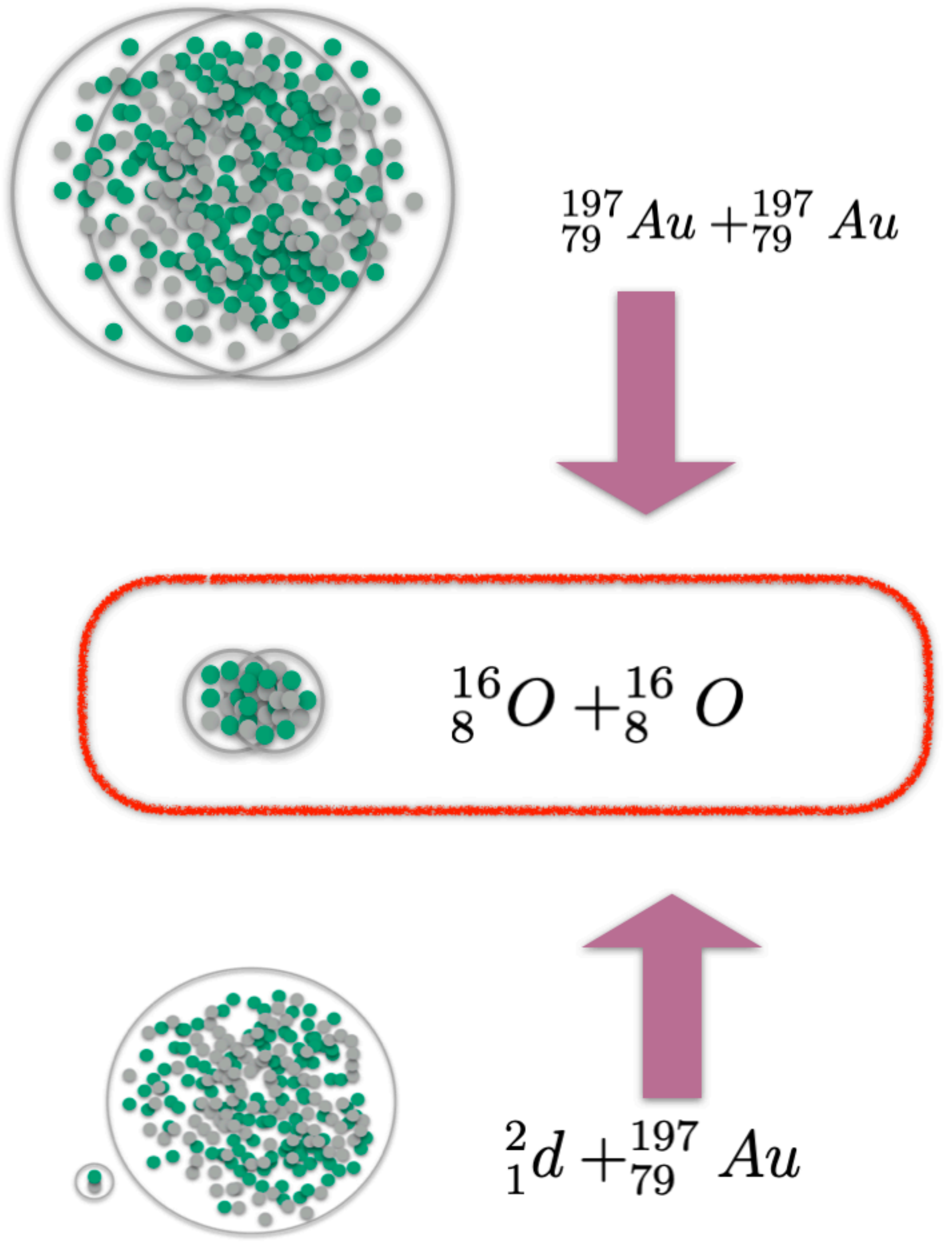
p/d +A collisions



ATLAS, Phys. Rev. Lett. 132, (2024) 102301



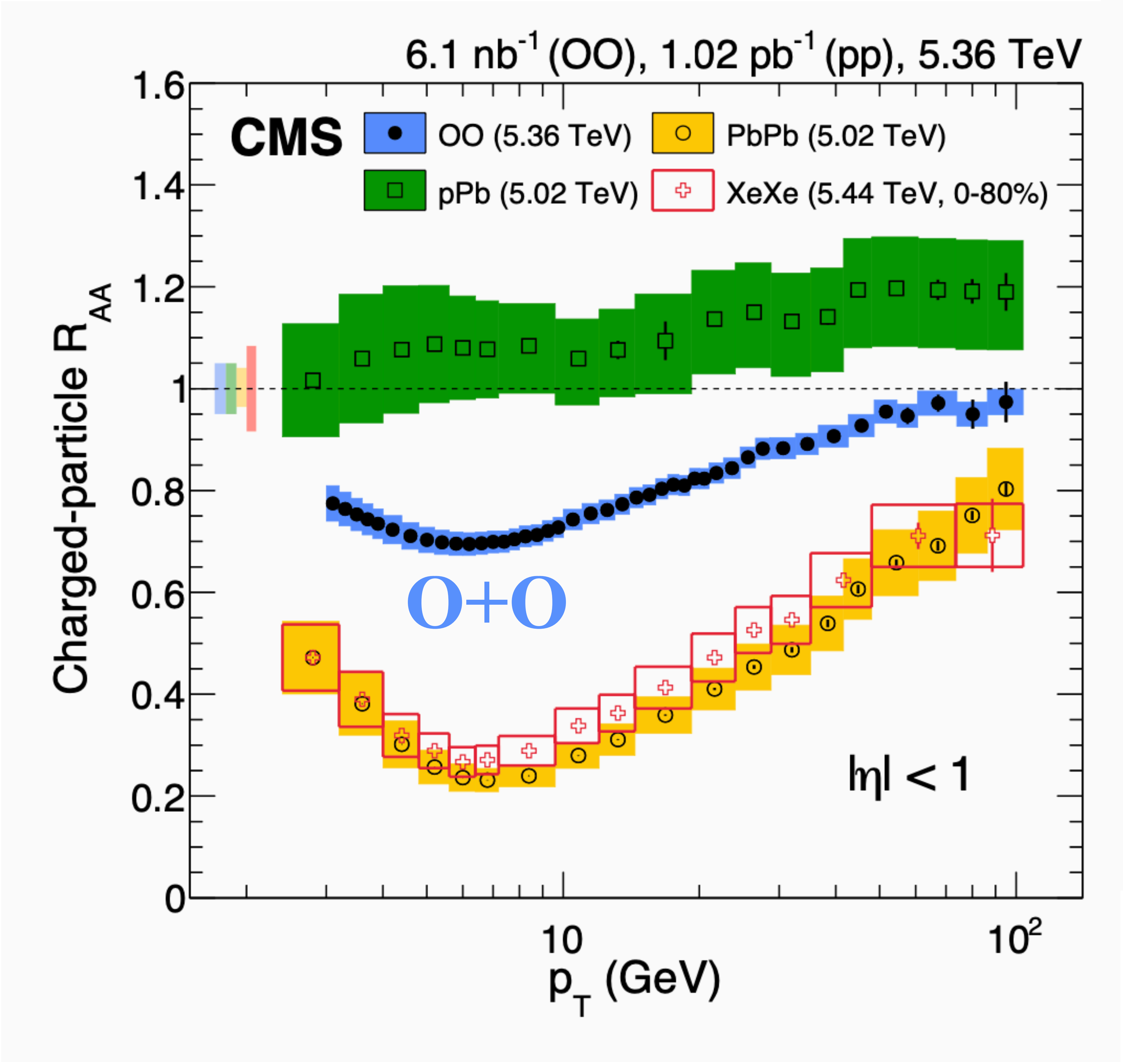
PHENIX, Phys. Rev. Lett. 134, 022302 (2025)

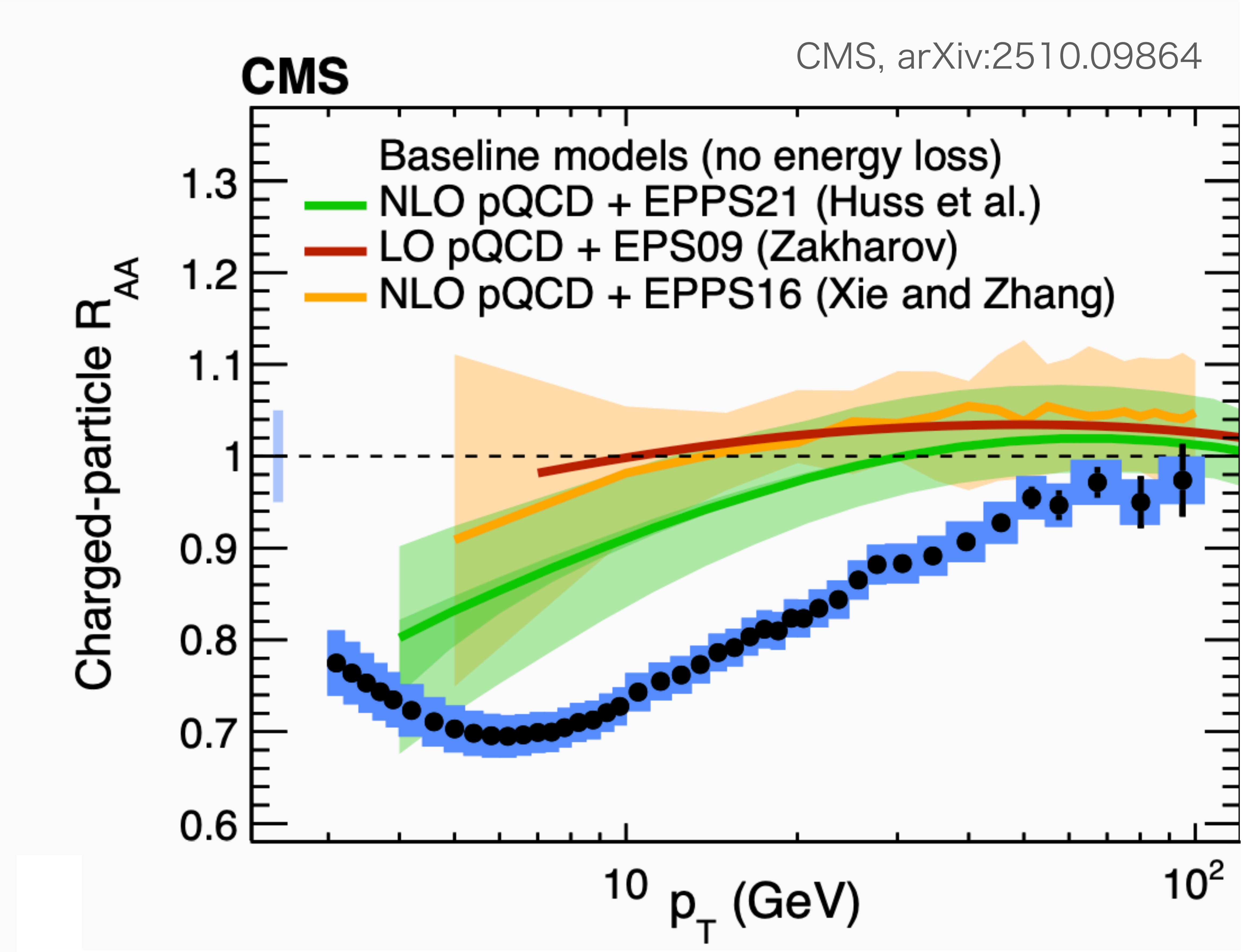


D. Perepelitsa, Phys. Rev. C 110, L011901 (2024)

- R_{CP} suppression fully driven by the “shrink” of proton configuration.
- PHENIX results can be explained with color fluctuation model.
- O+O collisions?

Jet quenching in O+O at LHC

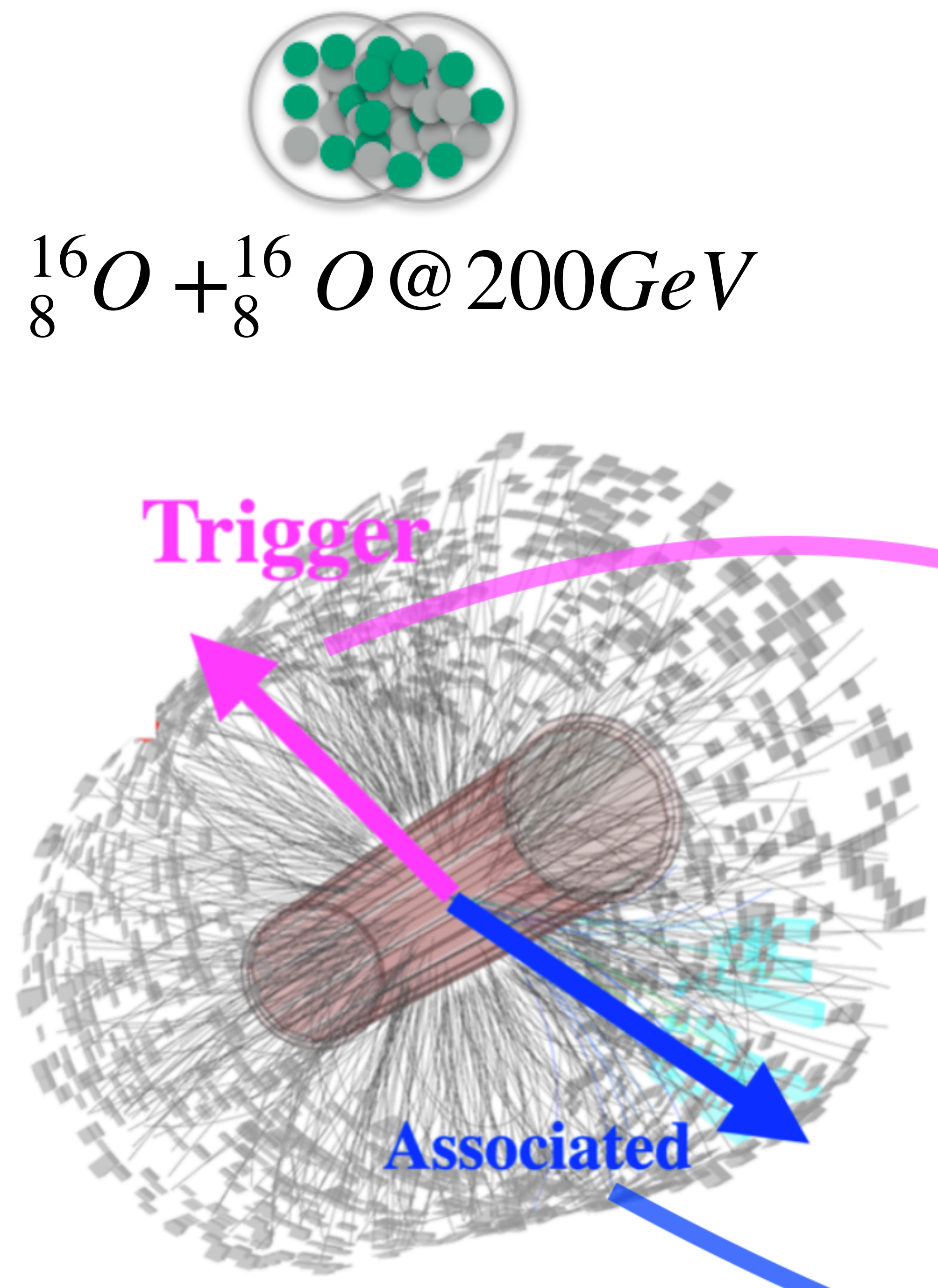


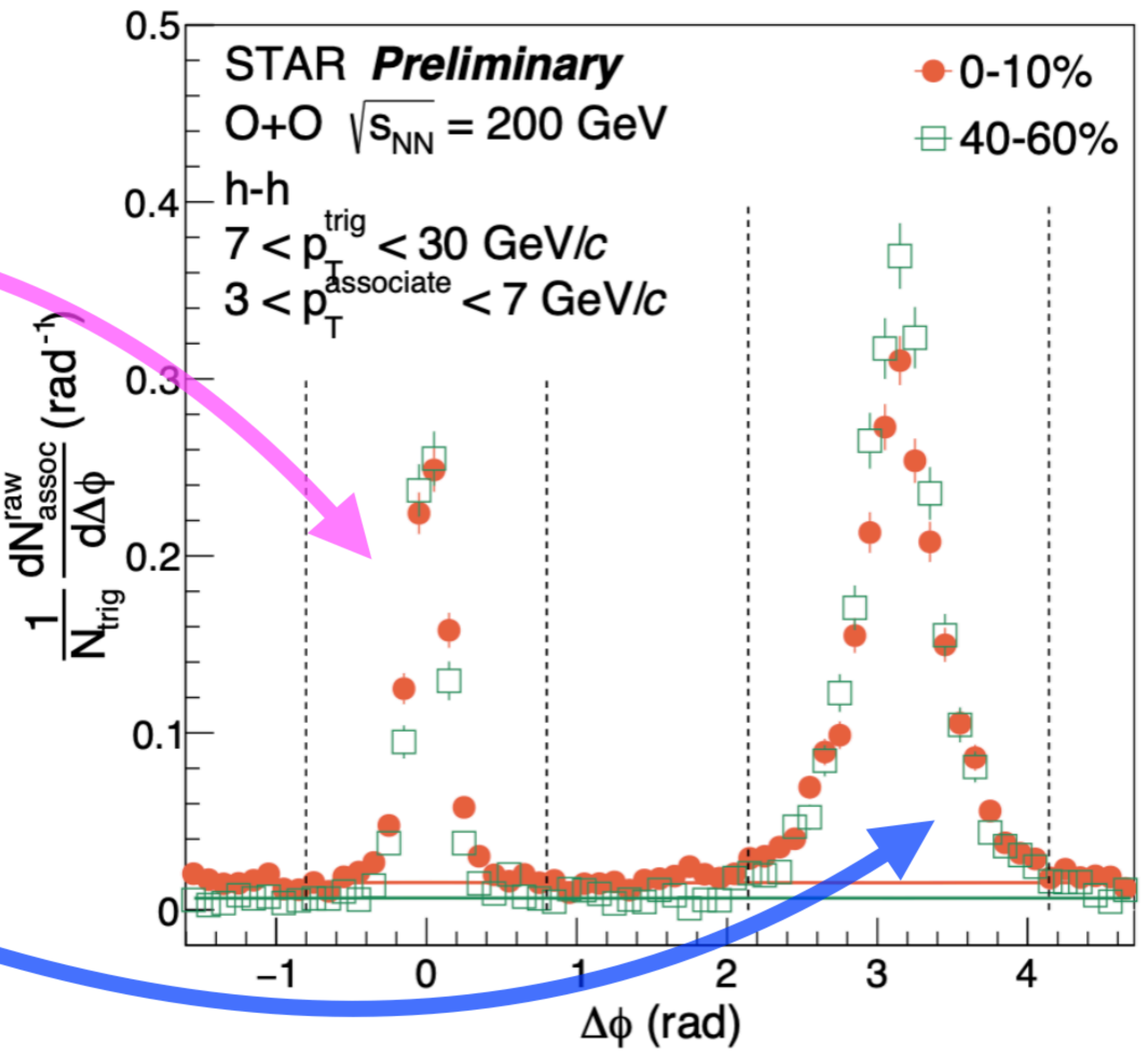


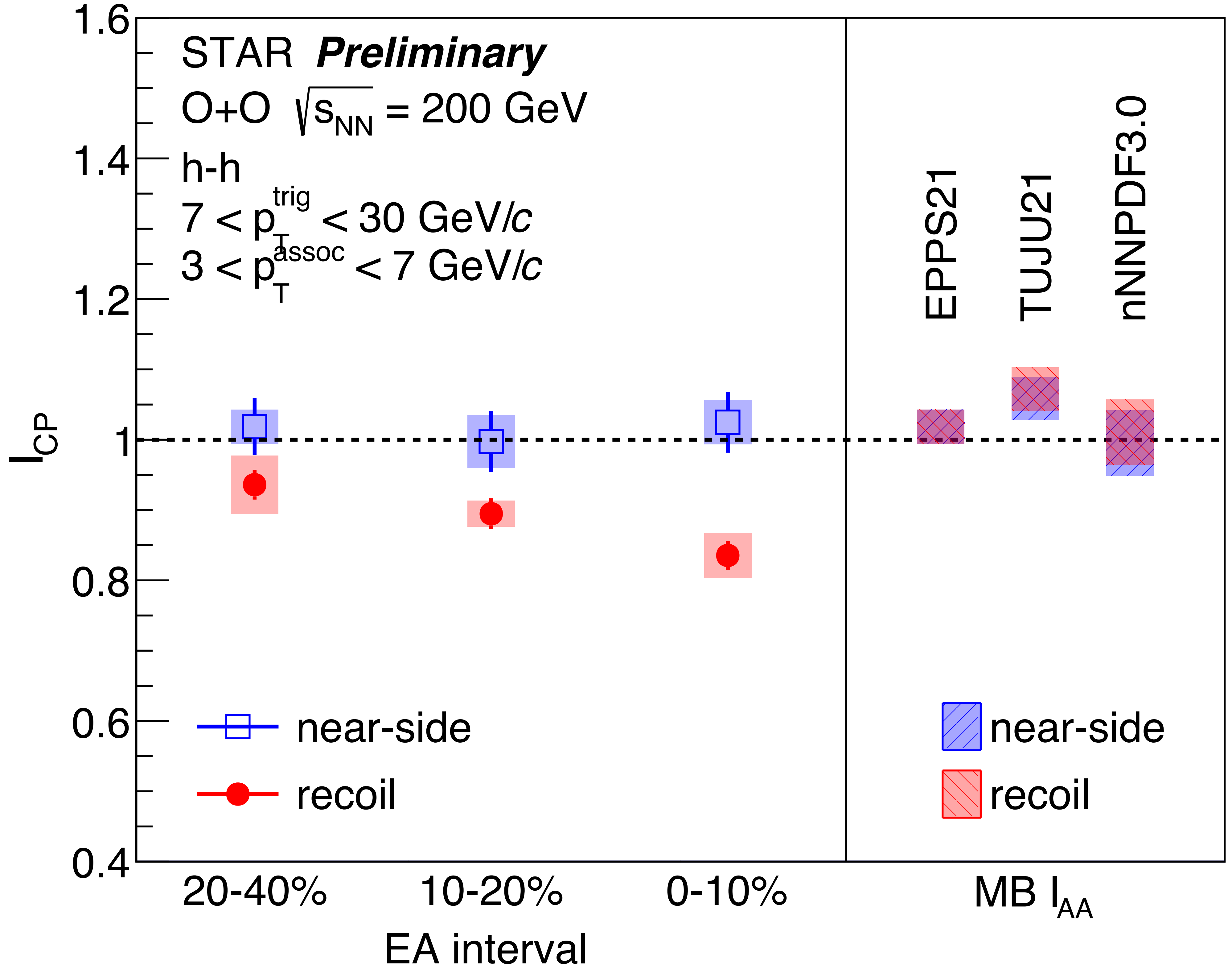
- **Significant suppression in O+O, R_{AA} smaller than 1.**
- **Energy loss model predicts O+O data well.**

Dihadron correlation in O+O collisions

SiJie Zhang Light Ion Workshop 2025



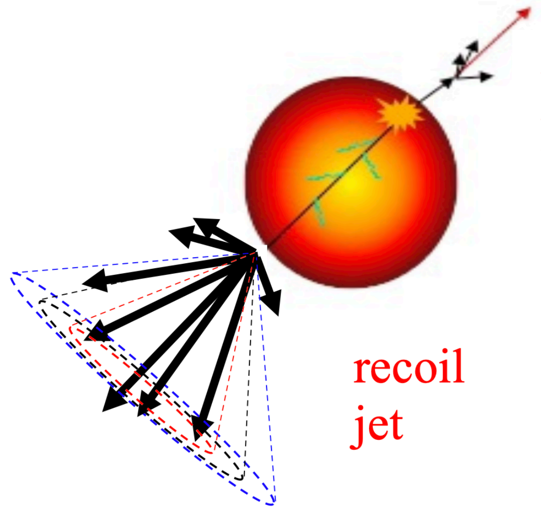




- Associated side: High-EA events show significant suppression compared to low- EA.
- I_{CP}: Trigger side ~ 1; Associated side deviates significantly.
- Theoretical calculations (without jet quenching) match the Trigger side only.

Icp vs. p_T in O+O collisions

$^{16}_{8}O + ^{16}_{8}O @ 200GeV$



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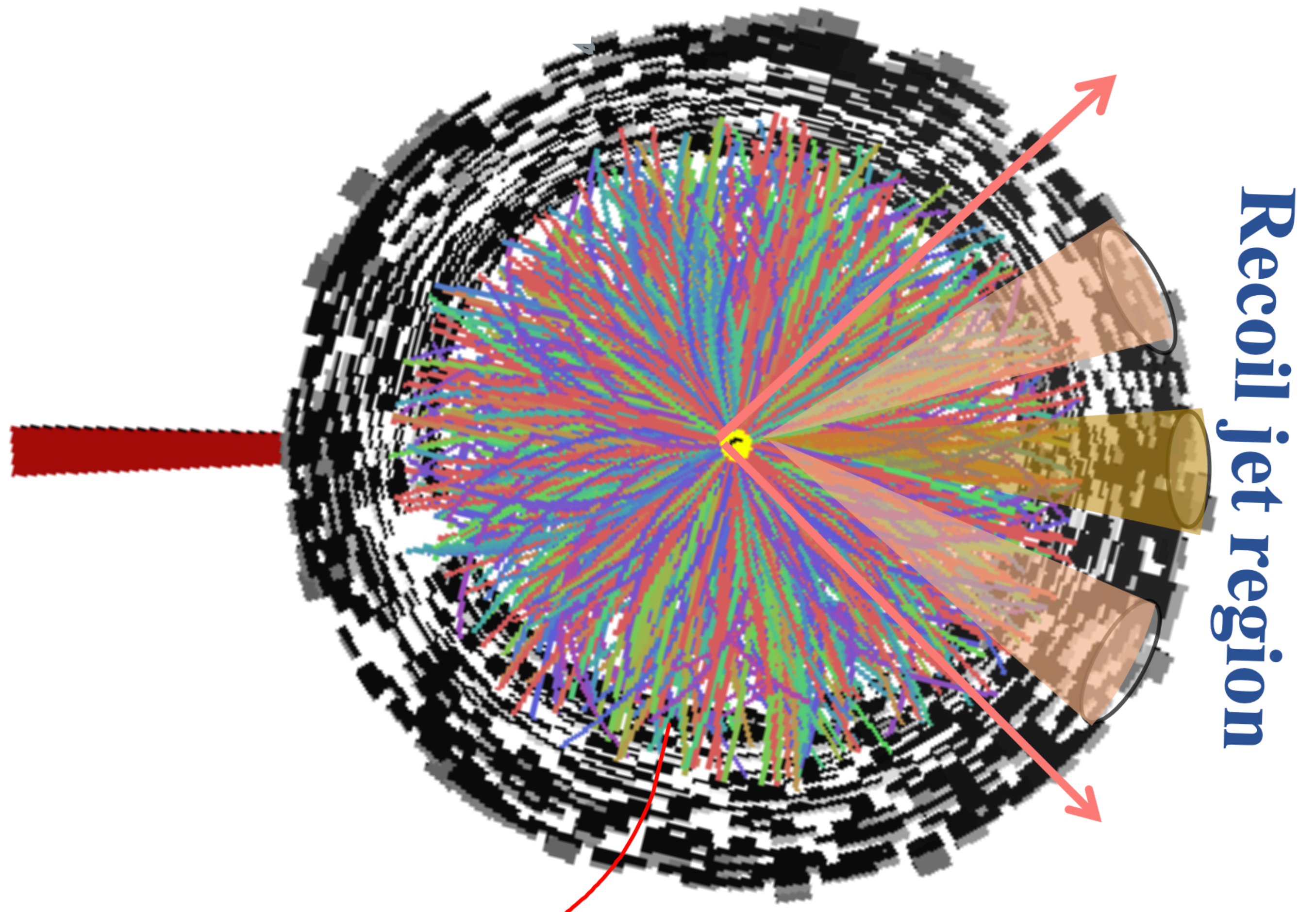
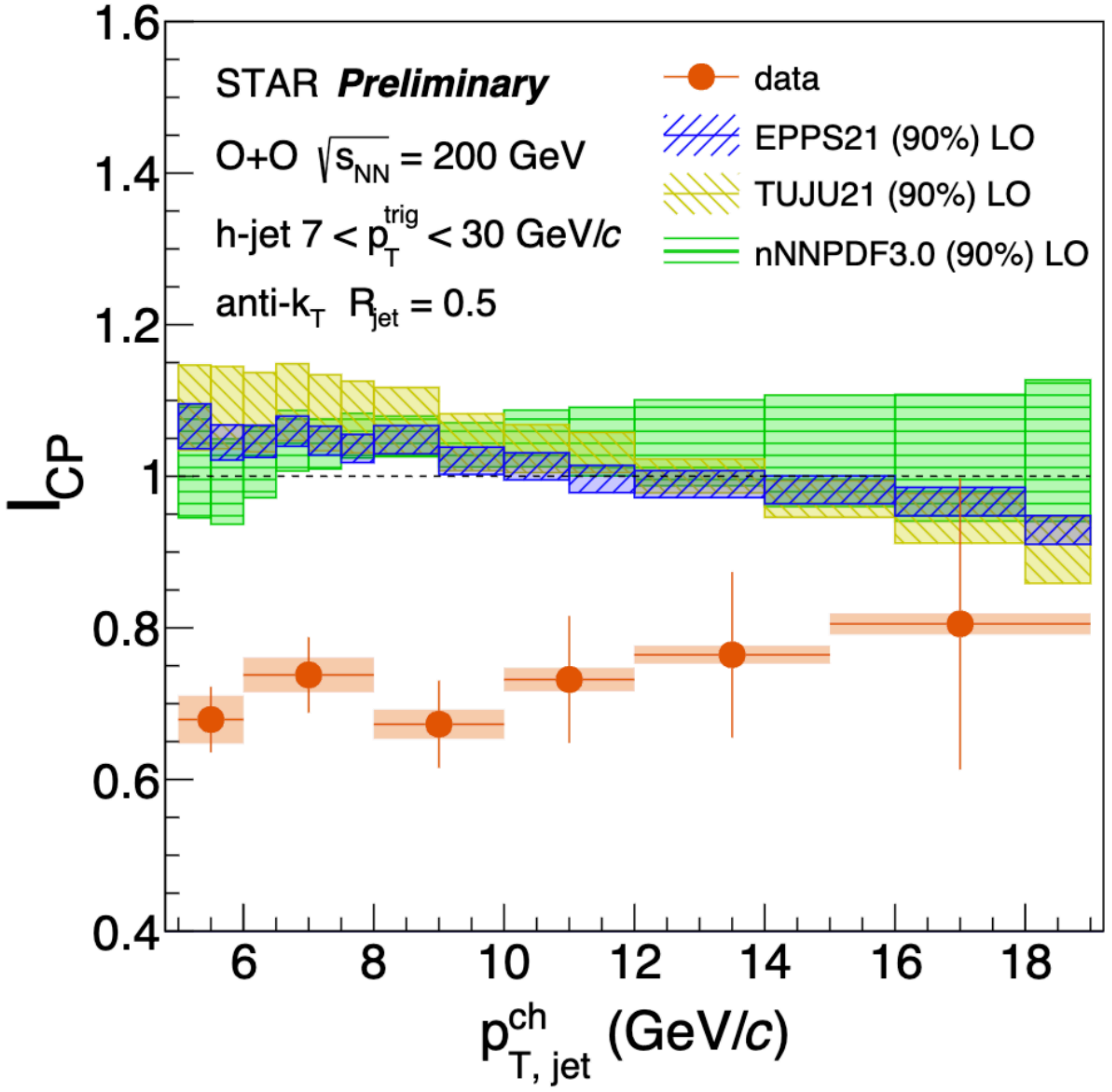




jet quenching!

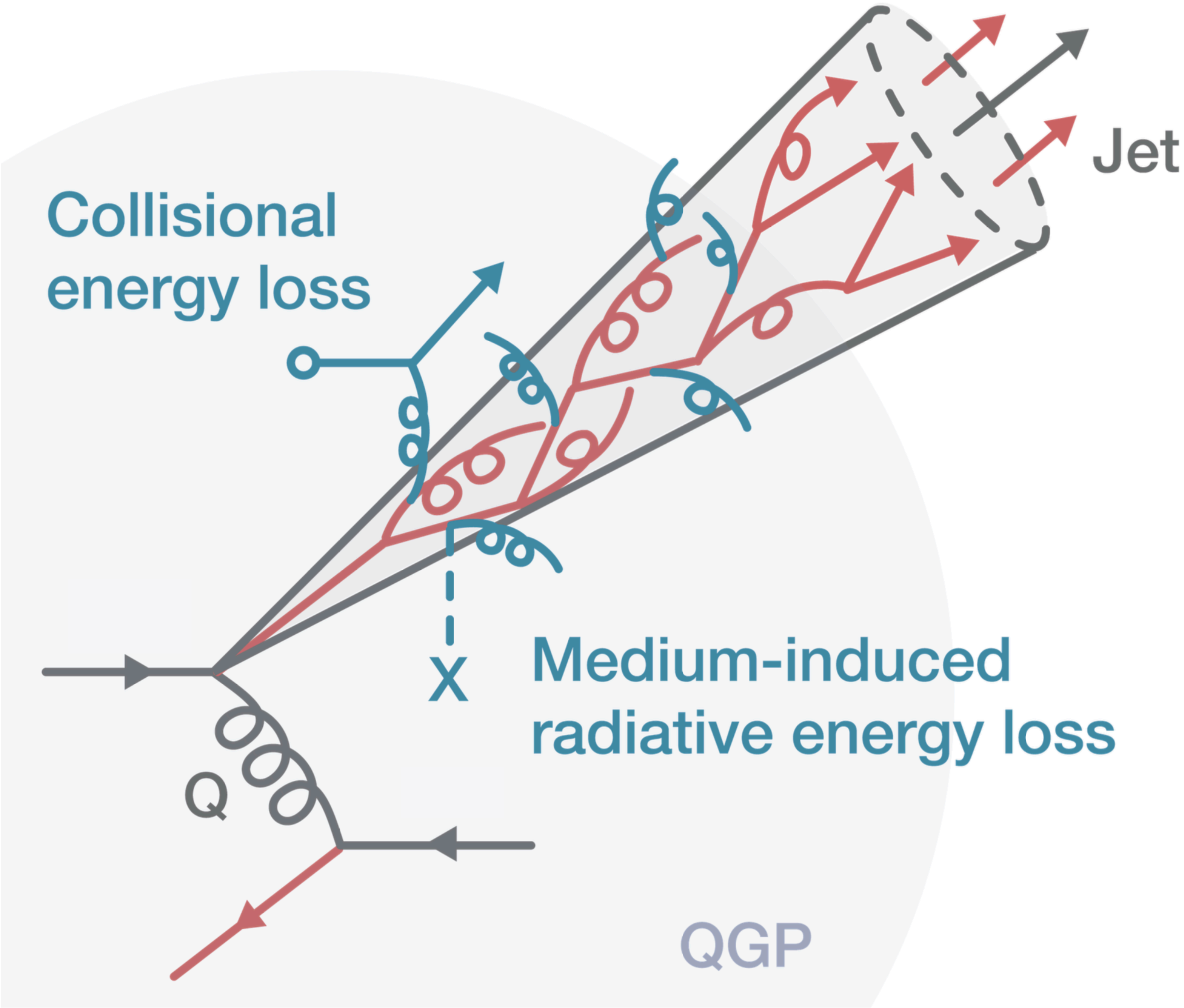
Coincidence measurement

$$\frac{d\sigma_{h+jet}}{\sigma_h}$$

Ratio of absolutely normalized hard cross sections

- $I_{CP} < 1$ indicates a significant suppression of away-side jet yield.
- Theoretical calculations (without jet quenching) fail to describe the experimental data.

Jets in heavy-ion collisions



Jet quenching
Jet yield suppression; jet acoplanarity; medium response

Jet substructure
Differential jet modification

Non-perturbative & hadronization
Charge correlator & EEC

Critical system size of jet quenching
Jet quenching observed in O+O

Summary & Outlook

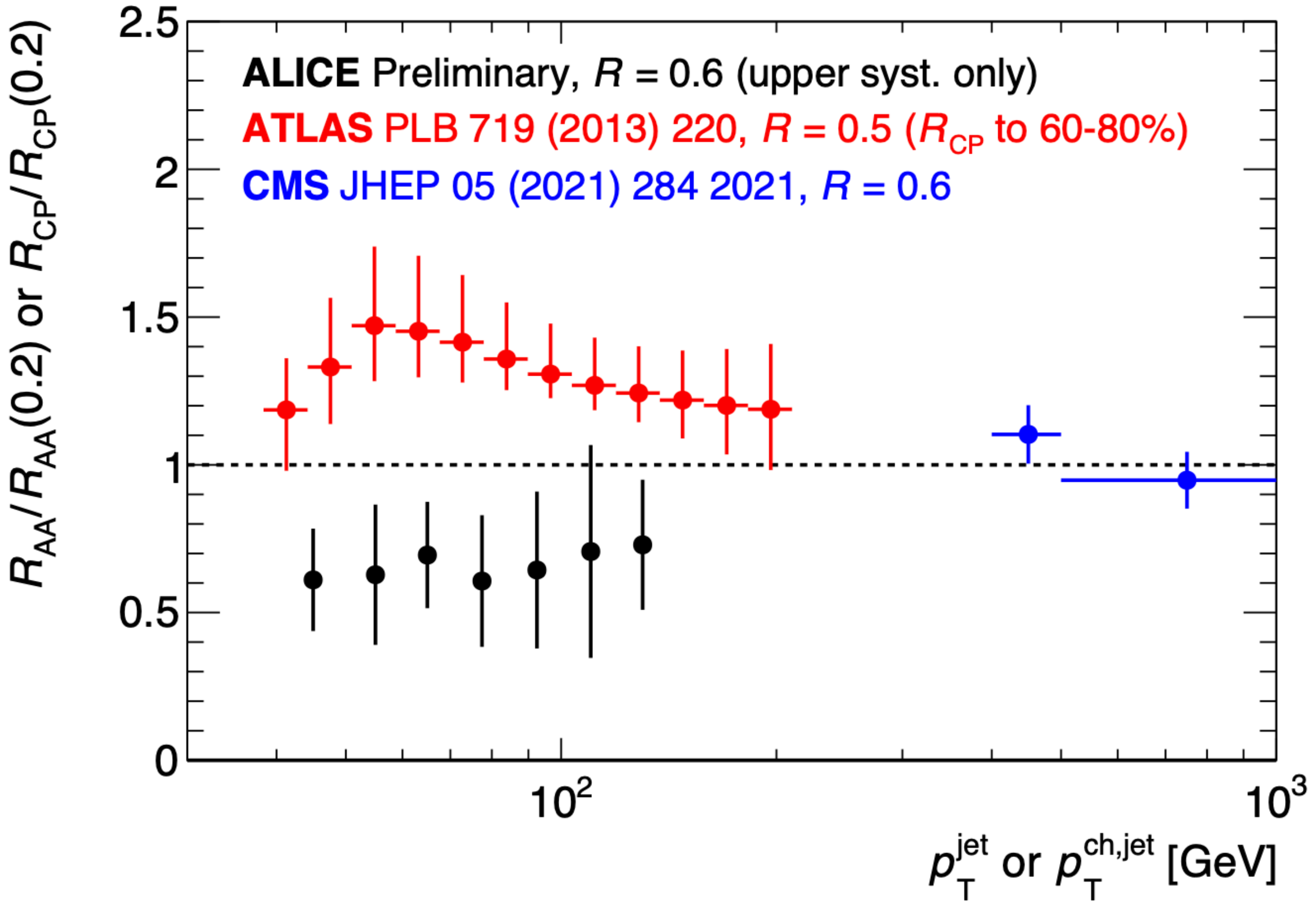
- ◉ Jet measurements have evolved into precise tomographic probes.
- ◉ Microscopic picture of energy loss ➜ quantify intrinsic properties and inner structure of QGP.
  - ▸ Extending measurements to low-p_T jets and large jet radii is a critical frontier
  - ▸ Medium response: connecting to QGP properties.
  - ▸ EEC: locate hadronization transition, separate perturbative/ non-perturbative regimes.
- ◉ Light-ion collisions ➜ key to comprehensively mapping transport properties and path-length effects.

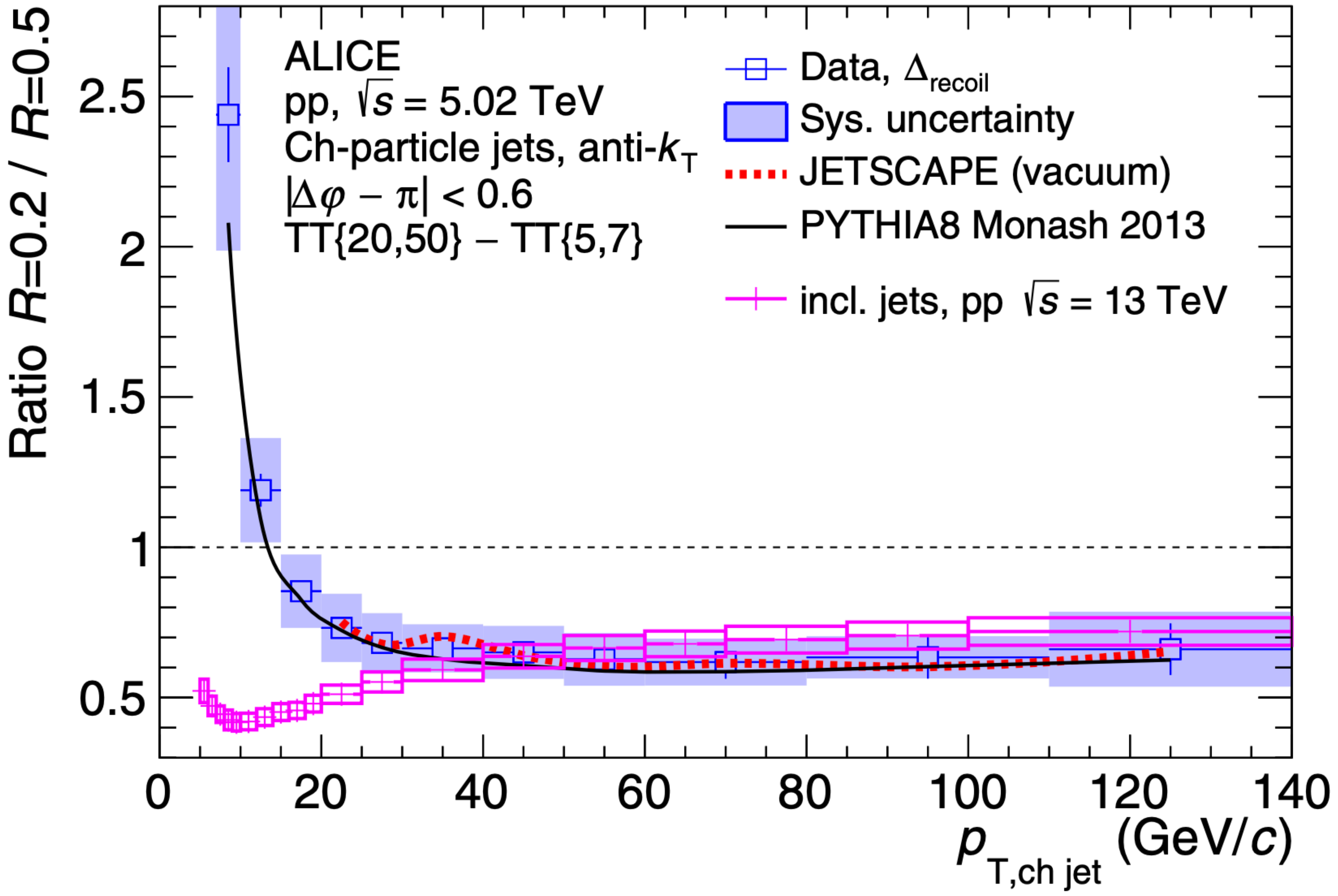
Stay tuned for more exciting measurements!

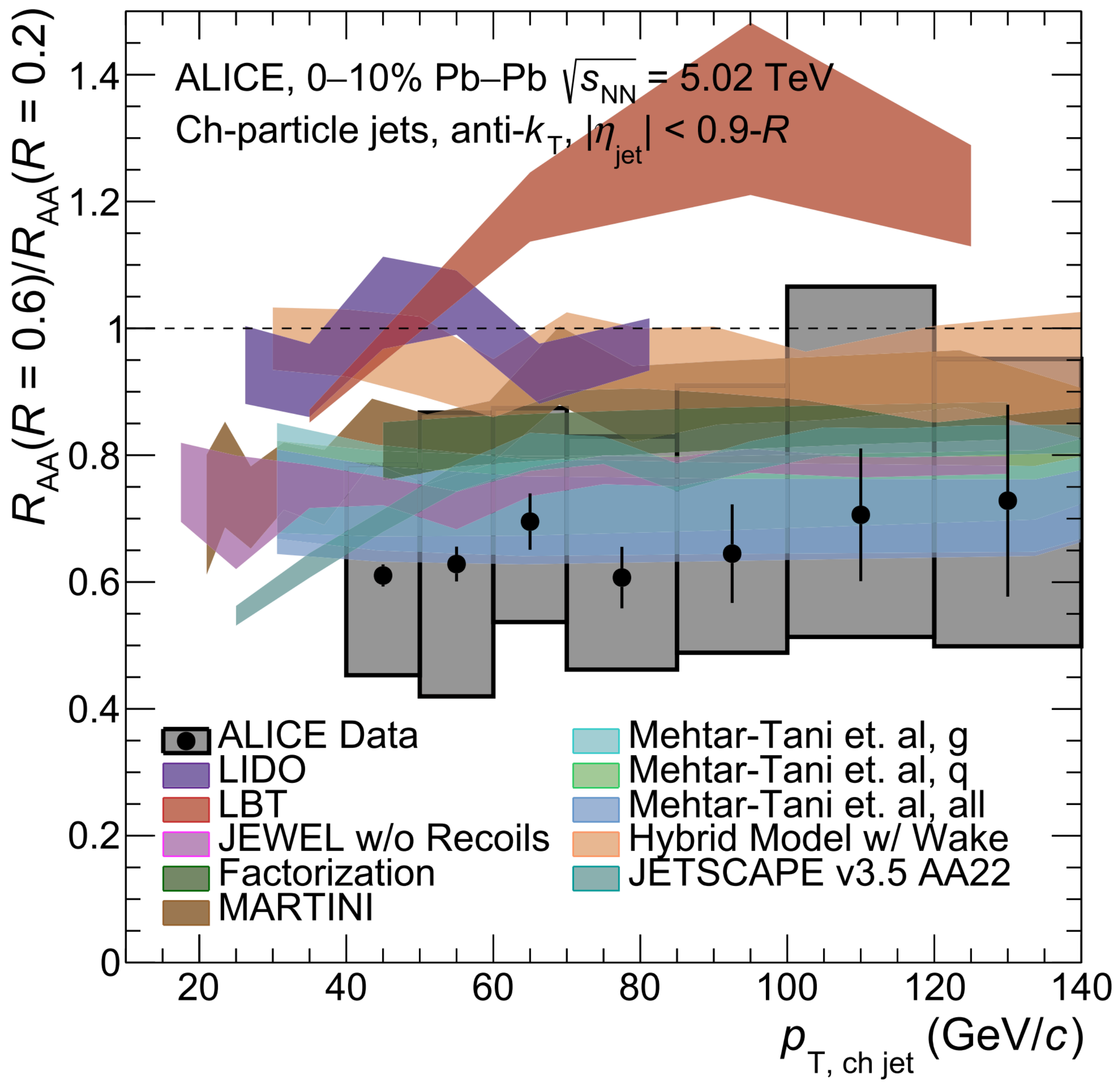
Backup

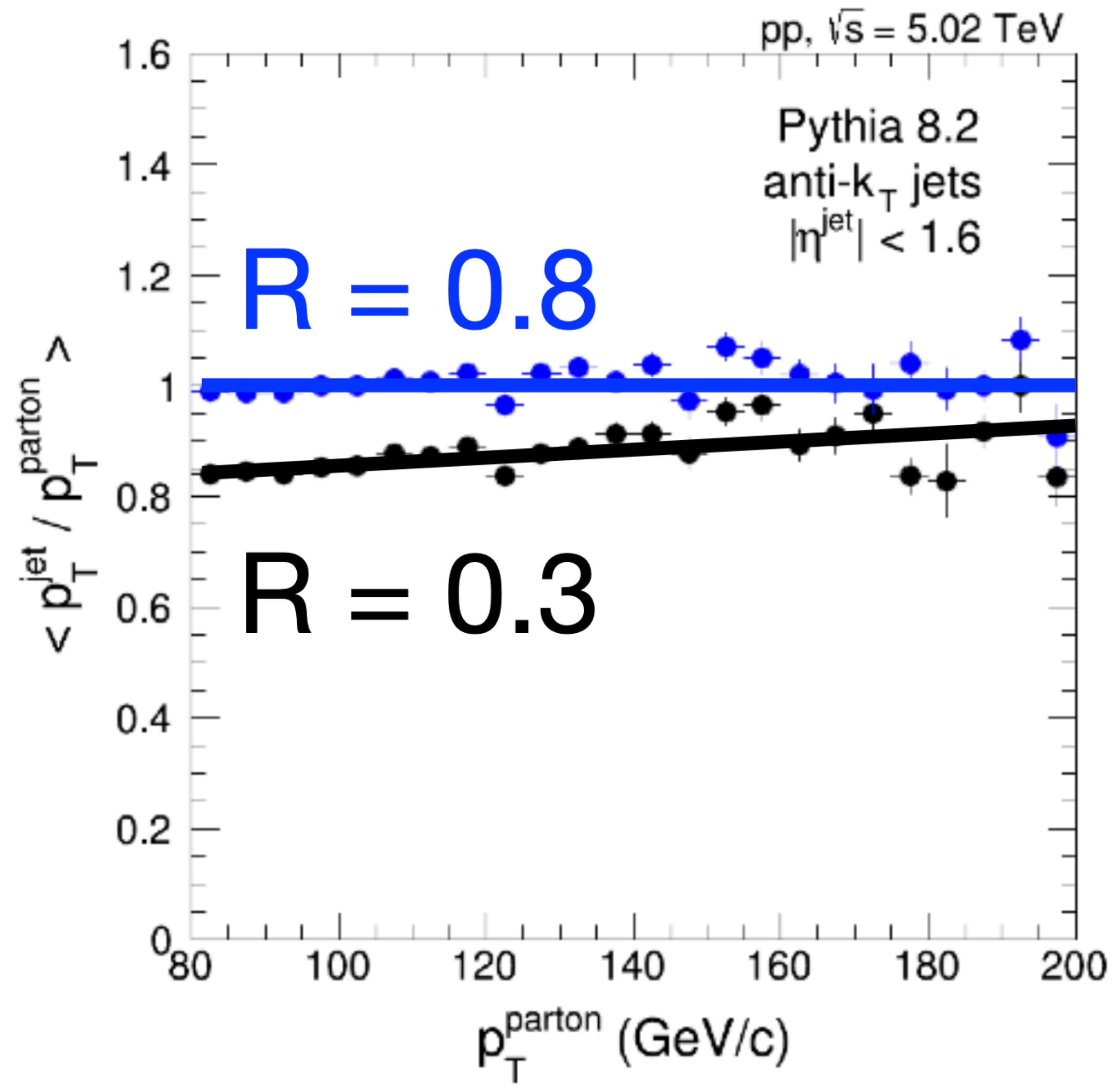
R-dependence

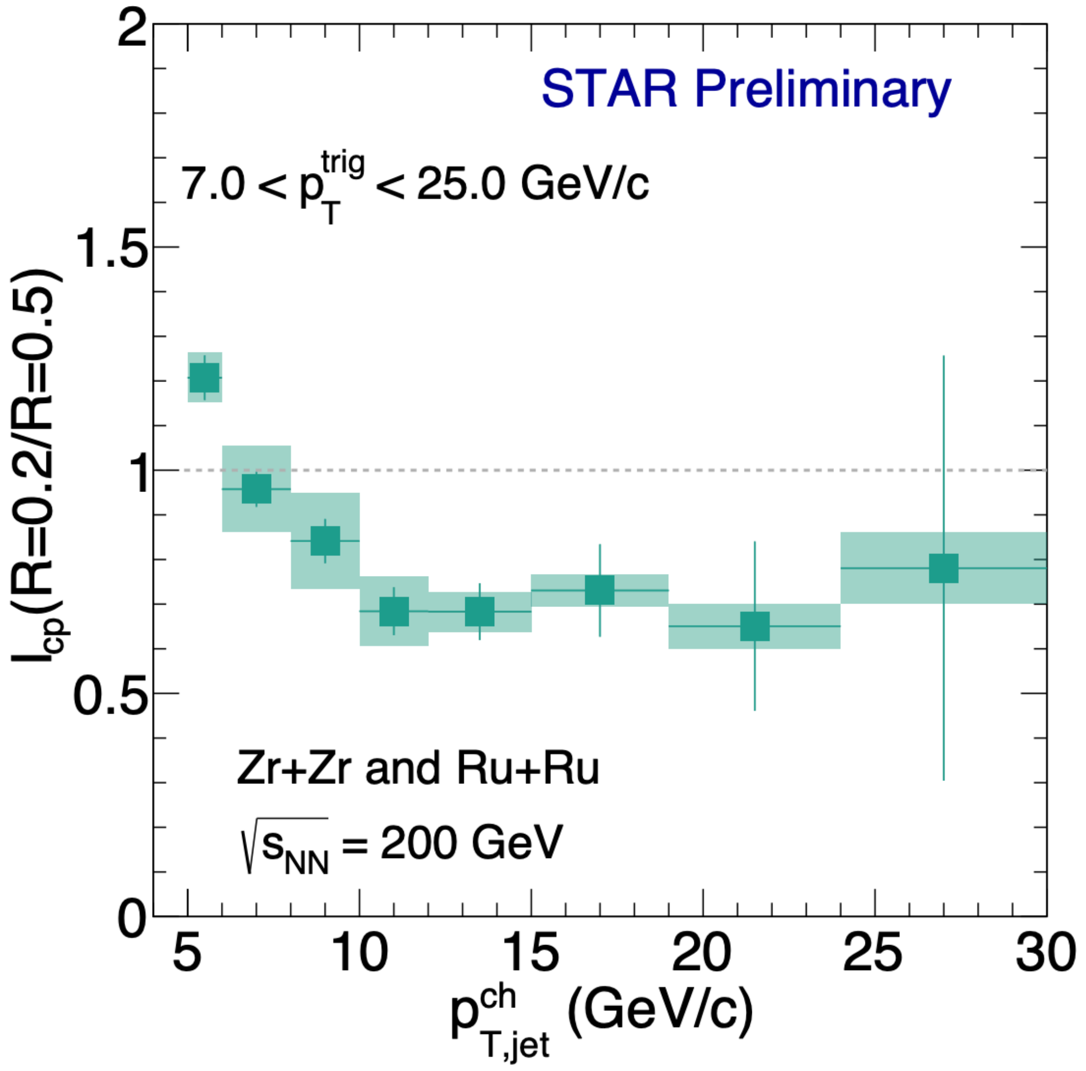
By Dennis Perepelitsa

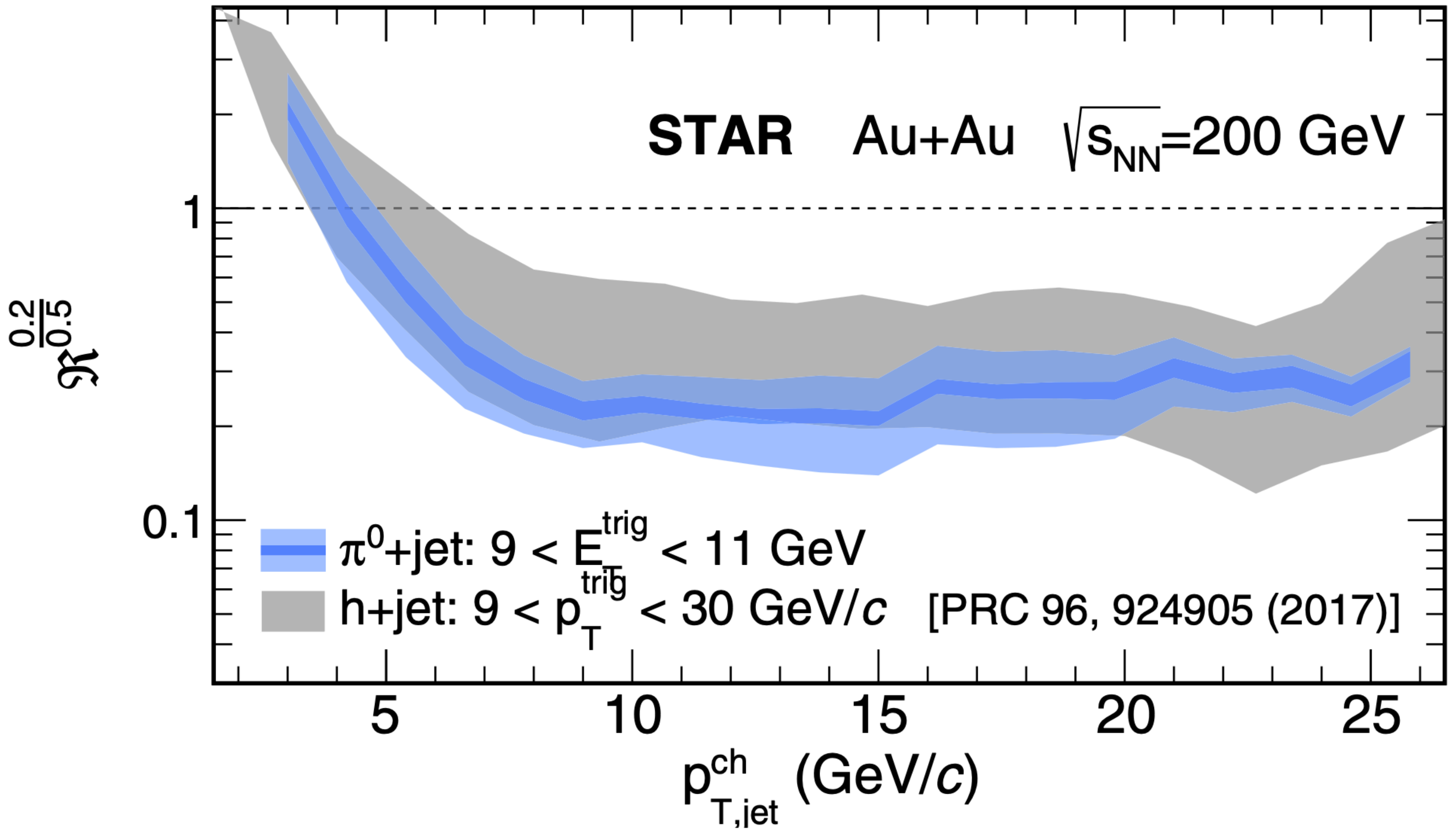










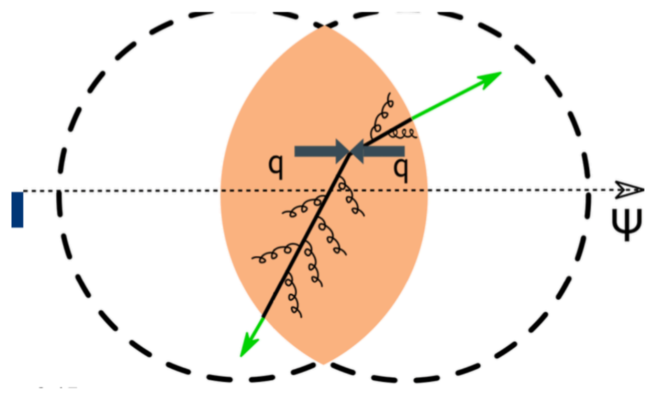


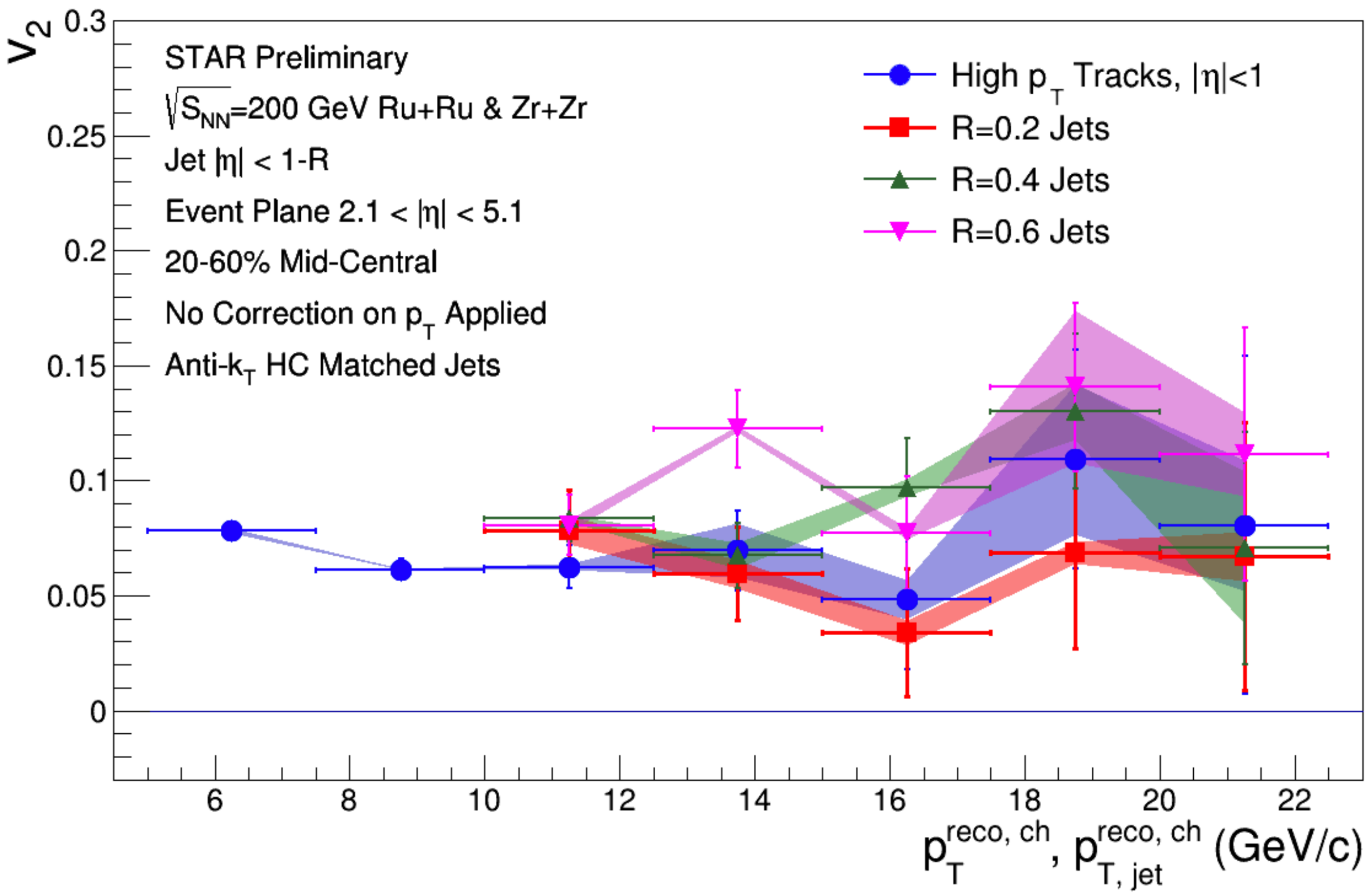
Path length dependence: jet anisotropy

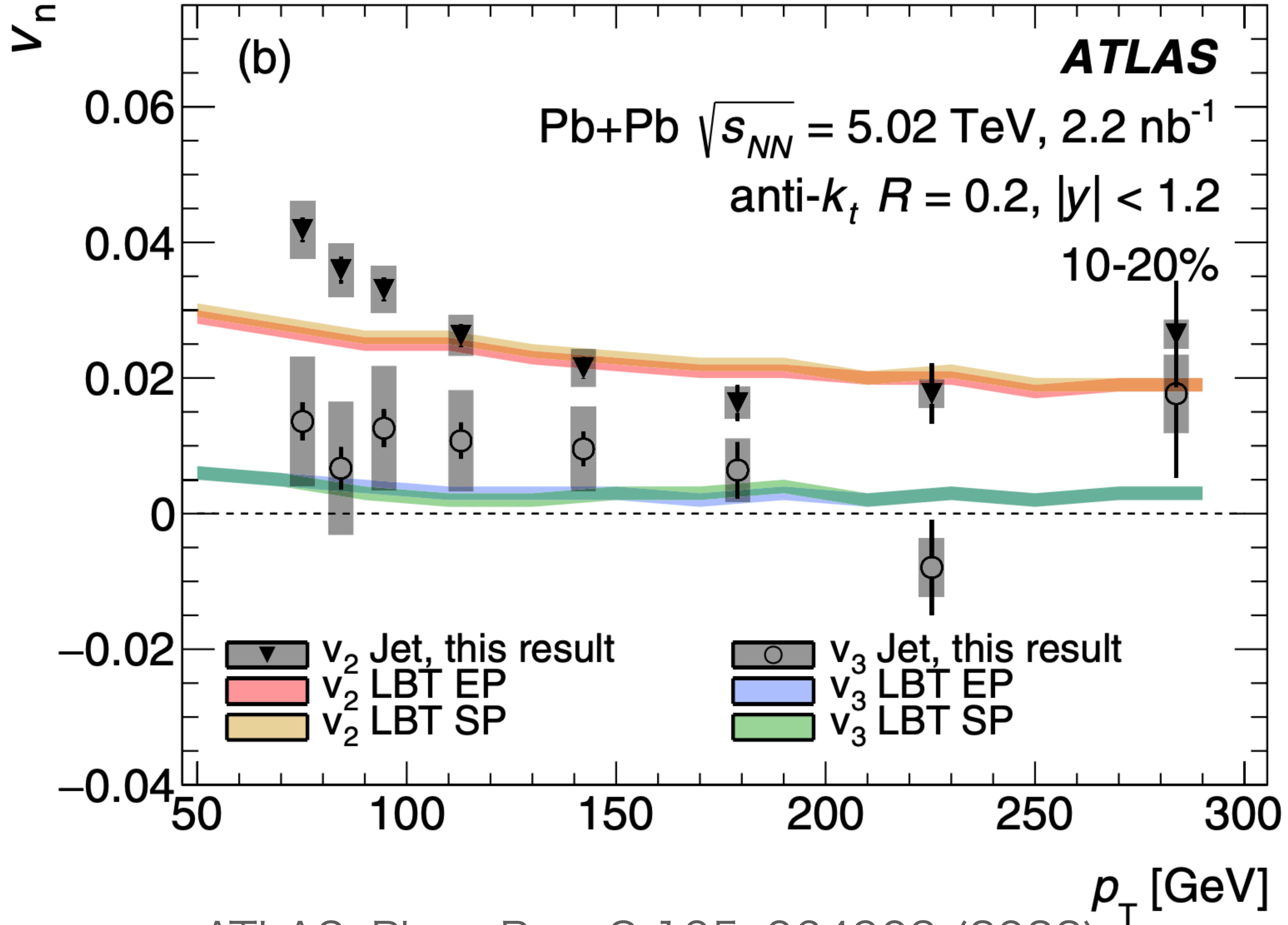
Knowing all the building blocks of a Swiss watch doesn't explain how it works.

building blocks: yield

how it works: dynamics







ATLAS, Phys. Rev. C 105, 064903 (2022)

- Weak pT dependent jet v_2 in isobar collisions, almost independent with R.
- LBT can qualitatively capture the sizable jet v_2 and v_3, underestimate v_2 below 100GeV.

Jet Hadrochemistry

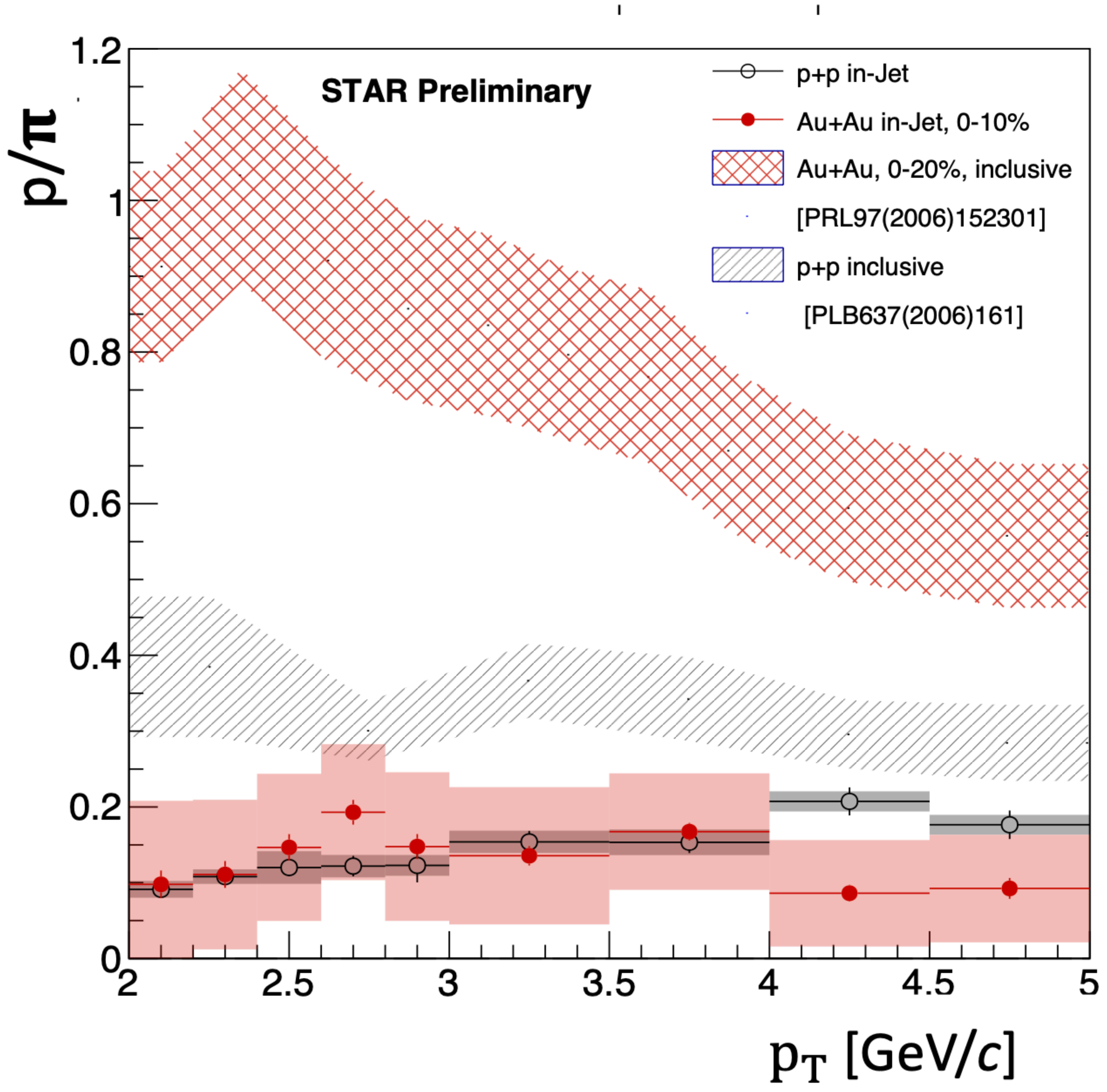
Particle Identification in jets

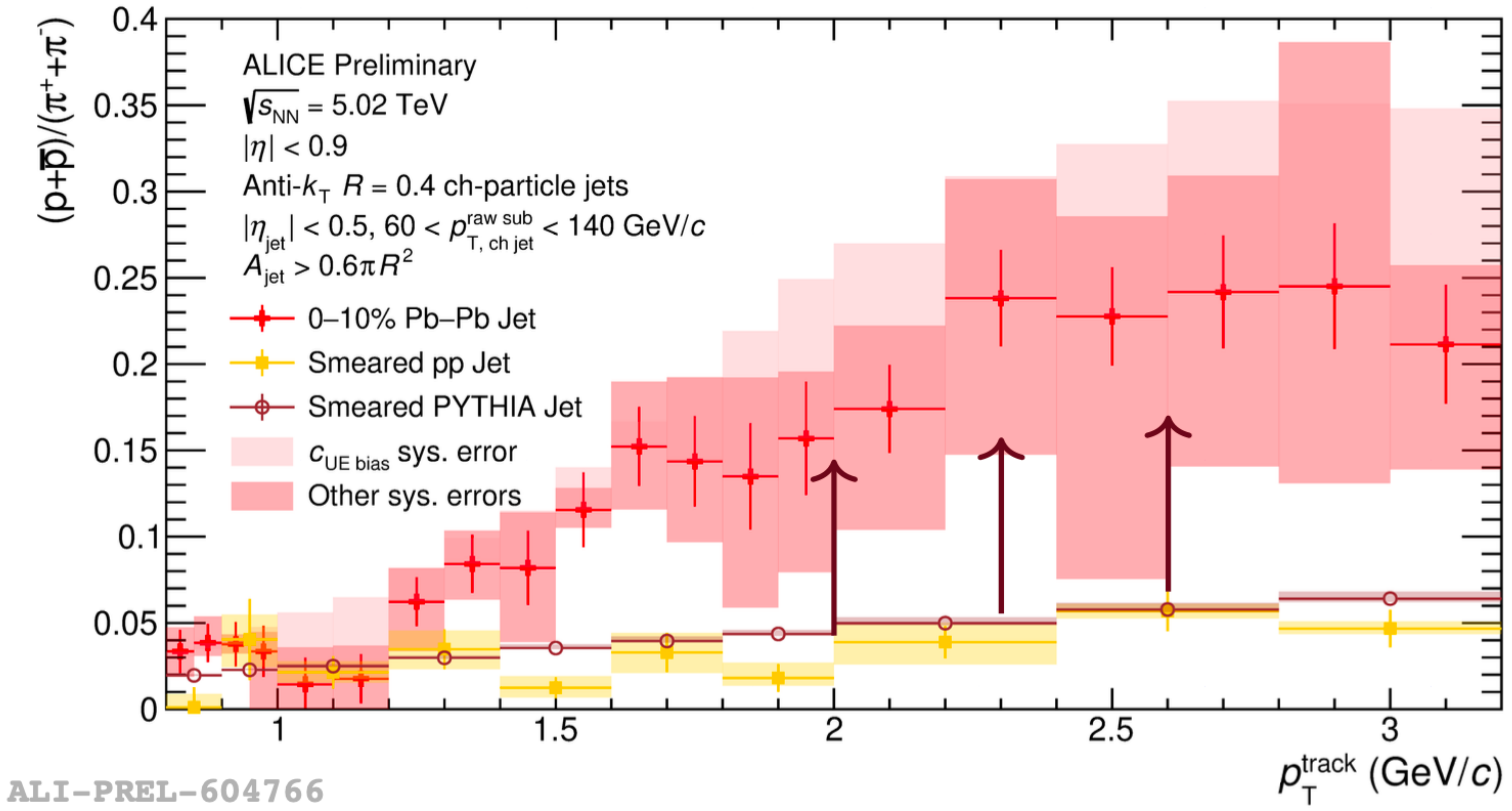
Jet-medium interactions modify baryon-to-meson ratios?

Gabriel Dale-Gau, QM2025

Sierra Cantway, QM2025

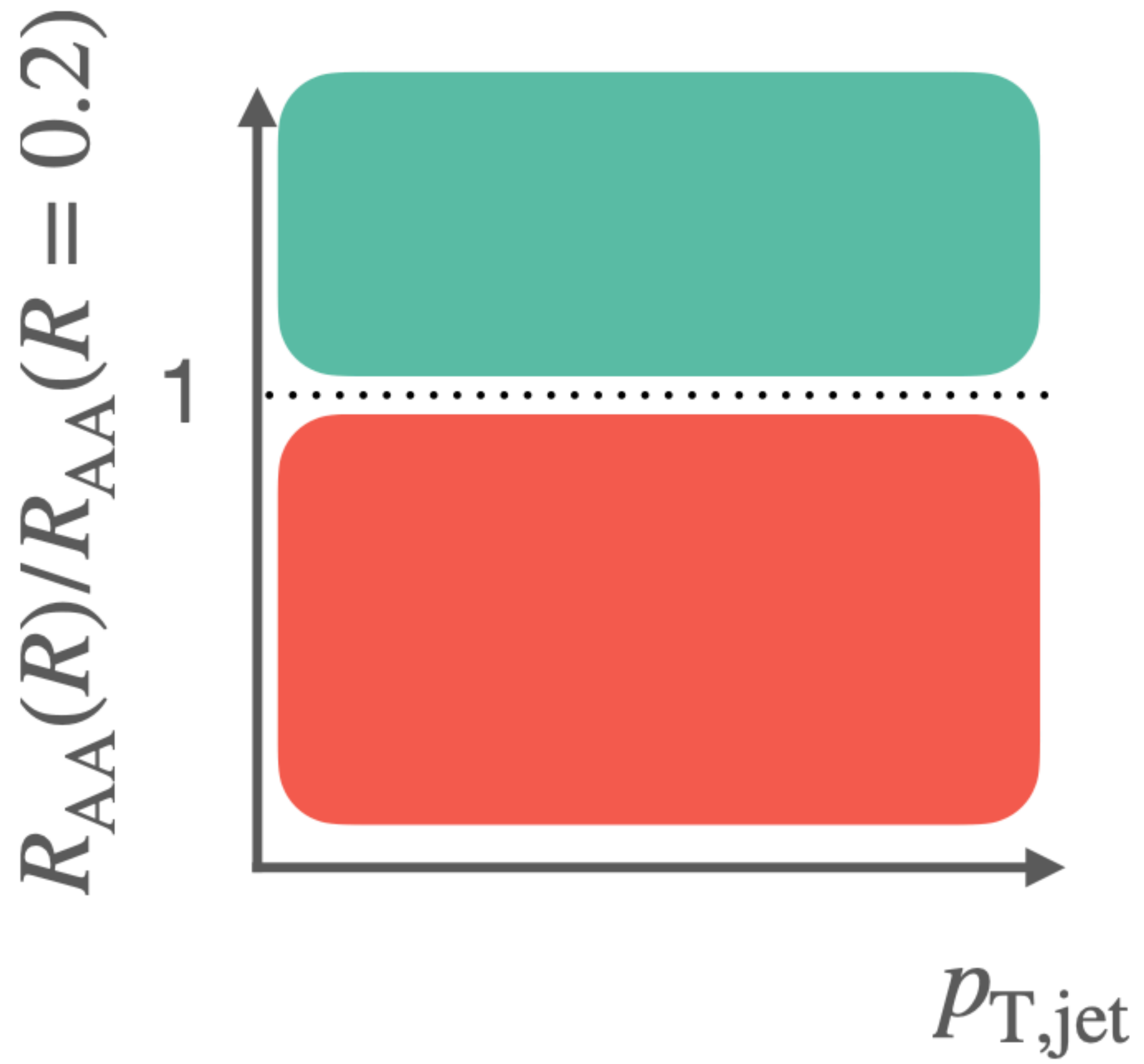
R = 0.3, Jet p_T^{raw} > 9 GeV/c , p_T^{cons} > 2 GeV/c





- **STAR: p/π measured in central Au+Au are consistent with p+p results.**
- **ALICE: Hint of excess for Pb+Pb results for p/π in jets.**
- **Different p_T jet and hadron, quark/gluon fraction?**

R-dependence of the R_{AA}



→ Recovery of wide angle radiation R_{AA} ↗

→ Medium response adds energy to the jet cone R_{AA} ↗

→ Large *R* jets have more effective energy loss sources, therefore could experience more quenching. R_{AA} ↘

→ Increase gluon to quark ratio at fixed p_{T}, gluons lose more energy R_{AA} ↘

New view: use differential R_{AA} to determine relative strength of effects!