VANDERBILT UNIVERSITY

Central China Center for Nuclear Theory
华中核理论中心

Investigation of small-angle EEC in heavy-ion collisions

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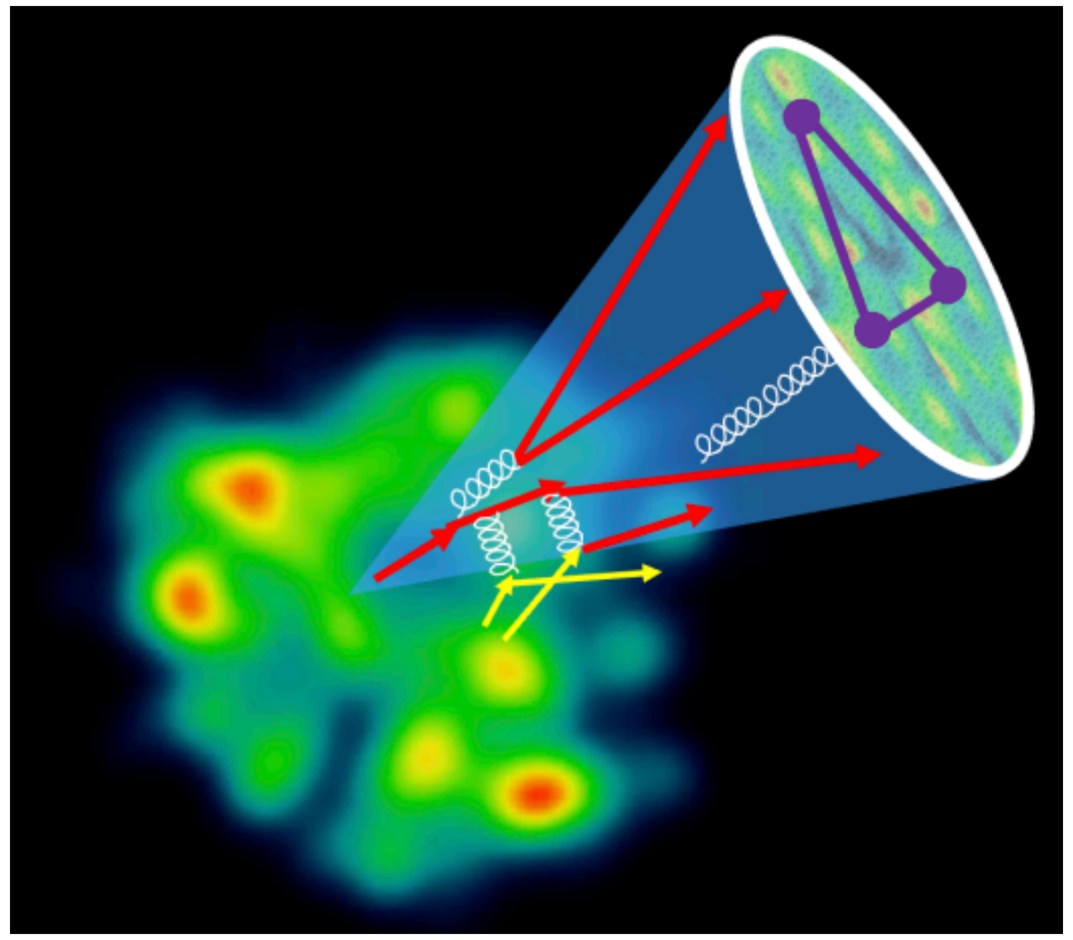
New Opportunities in Particle and Nuclear Physics with Energy Correlators

05/06/2025~05/16/2025

Energy-energy correlators

Energy-energy correlators(EEC) have recently emerged as excellent jet substructure observables for studying the space-time structure of the jet shower. [PRL 130 (2023) 5, 051901]

$$\langle \varepsilon^{(n)}(\overrightarrow{n_1}) \ldots \varepsilon^{(n)}(\overrightarrow{n_k}) \rangle$$



$\varepsilon^{(n)}(\overrightarrow{n_1})$ measures the asymptotic energy flux in the direction $\overrightarrow{n_1}$

$$\varepsilon^{(n)}(\overrightarrow{n_1}) = lim_{r\to\infty} \int dt r^2 n_1^i T_{0i}(t, r\overrightarrow{n_1})$$

The n-th weighted normalized two-point correlation:

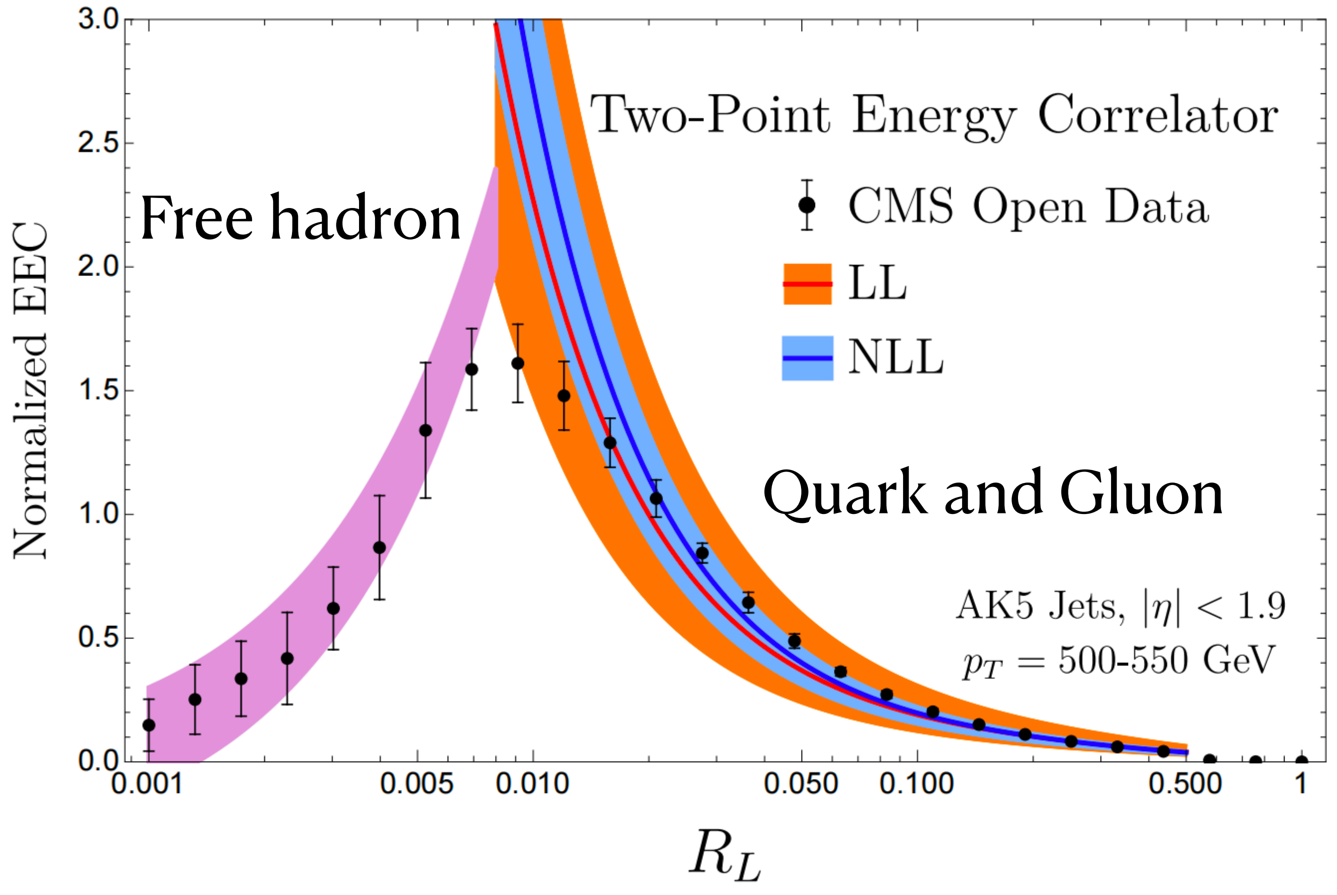
$$\frac{\langle \varepsilon^{(n)}(\overrightarrow{n_1})\varepsilon^{(n)}(\overrightarrow{n_2})\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\frac{d\sigma_{ij}}{d\overrightarrow{n_i}d\overrightarrow{n_j}}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\overrightarrow{n_i}-\overrightarrow{n_1})\delta^{(2)}(\overrightarrow{n_j}-\overrightarrow{n_2})$$

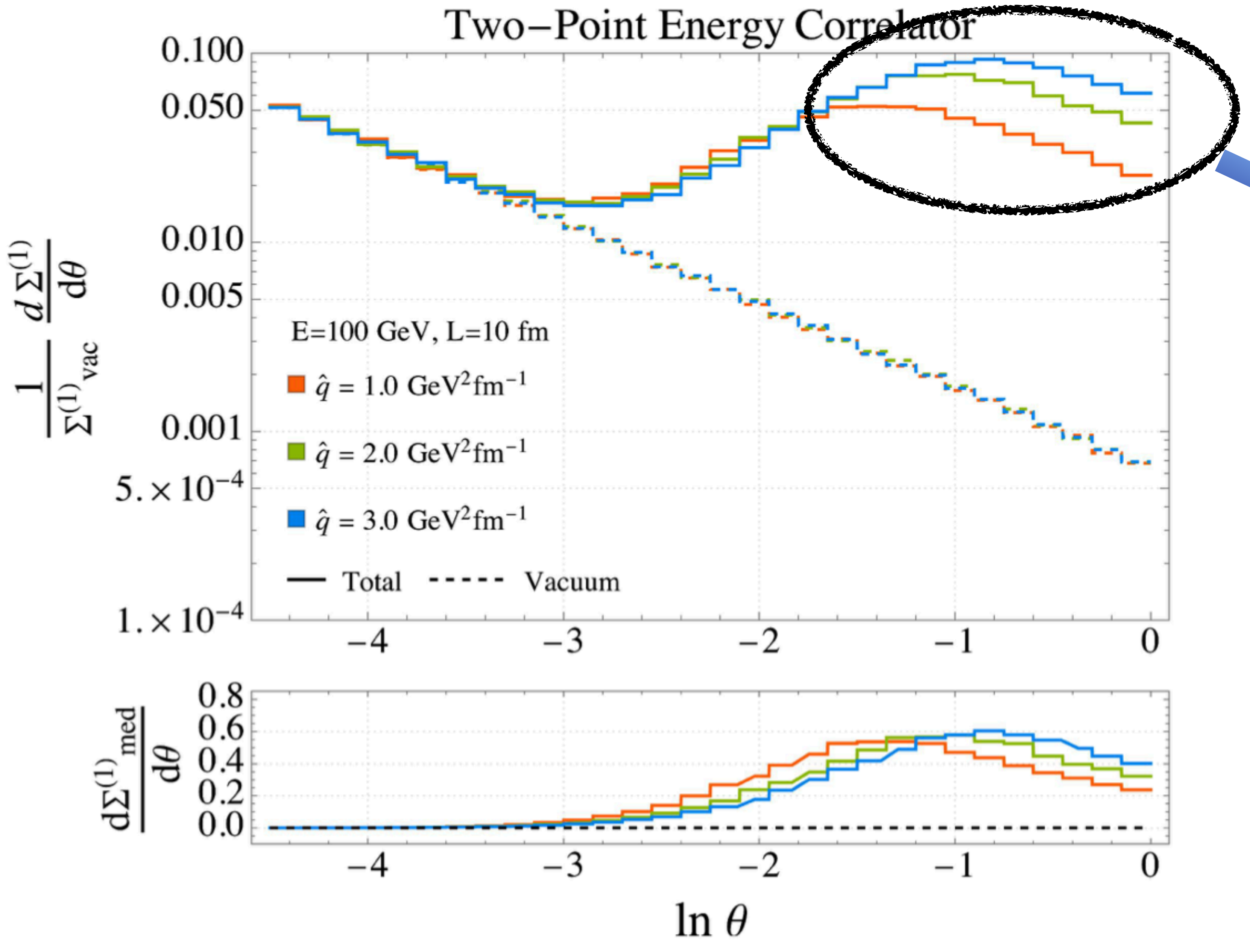
$$n = 1$$

$$\frac{d\Sigma^{(n)}}{d\theta} = \int d\vec{n}_{1,2}\frac{\langle \varepsilon^{(n)}(\vec{n_1})\varepsilon^{(n)}(\vec{n_2})\rangle}{Q^{2n}}\delta(\vec{n_1}\cdot\vec{n_2} - cos\theta)$$

$$cos\theta = \vec{n_1}\cdot\vec{n_2}$$

EEC in vacuum and medium





In vacuum, the EEC presents a clear separation between the perturbative and non-perturbative regions

$$R_L \sim \Lambda_{QCD}/p_T^{jet} \sim 10^{-2}$$

A smooth power law behavior in perturbative region

Medium-induced emissions lead to significant enhancement at large angle relative to vacuum splittings

Carlota A, et al. *Phys.Rev.Lett.* 130 (2023) 26, 262301
Patrick V, *et al. Phys.Rev.Lett.* 130 (2023) 5, 051901

LBT and CoLBT-hydro model

Linear Boltzmann Transport model (LBT):

$$p_1 \partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left|M_{12\to34}\right|^2 (2\pi)^4 \delta^4 (\sum_i p^i) + inelastic$$

LO pQCD High-Twist

Medium response: Recoil and Negative partons

CoLBT-hydro model:

Hard parton： LBT

Soft parton： CLVisc

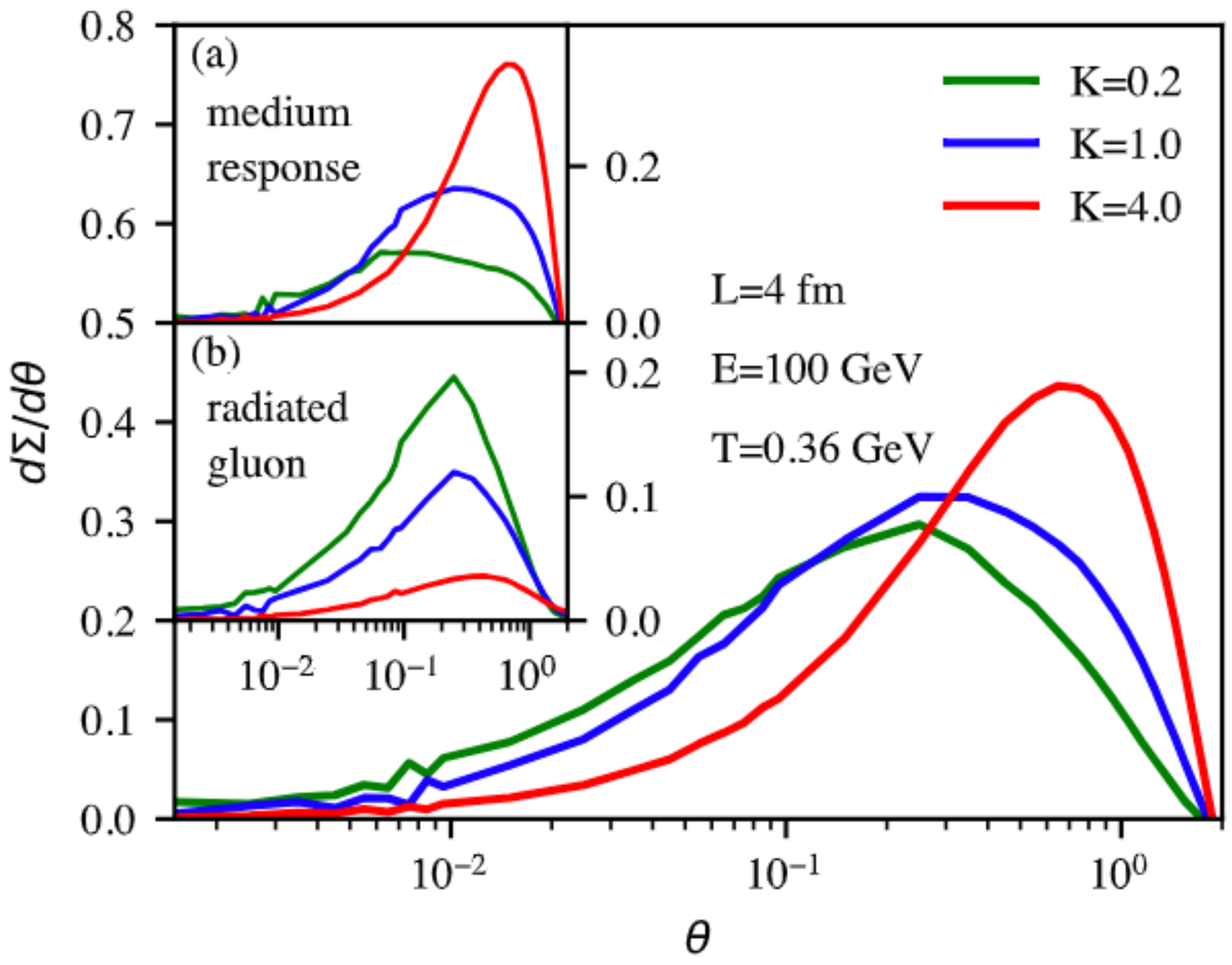
$$\partial_\mu T^{\mu\nu} = J^\nu$$

Parton hadronization + Hydro response

Effect of medium modification of EEC

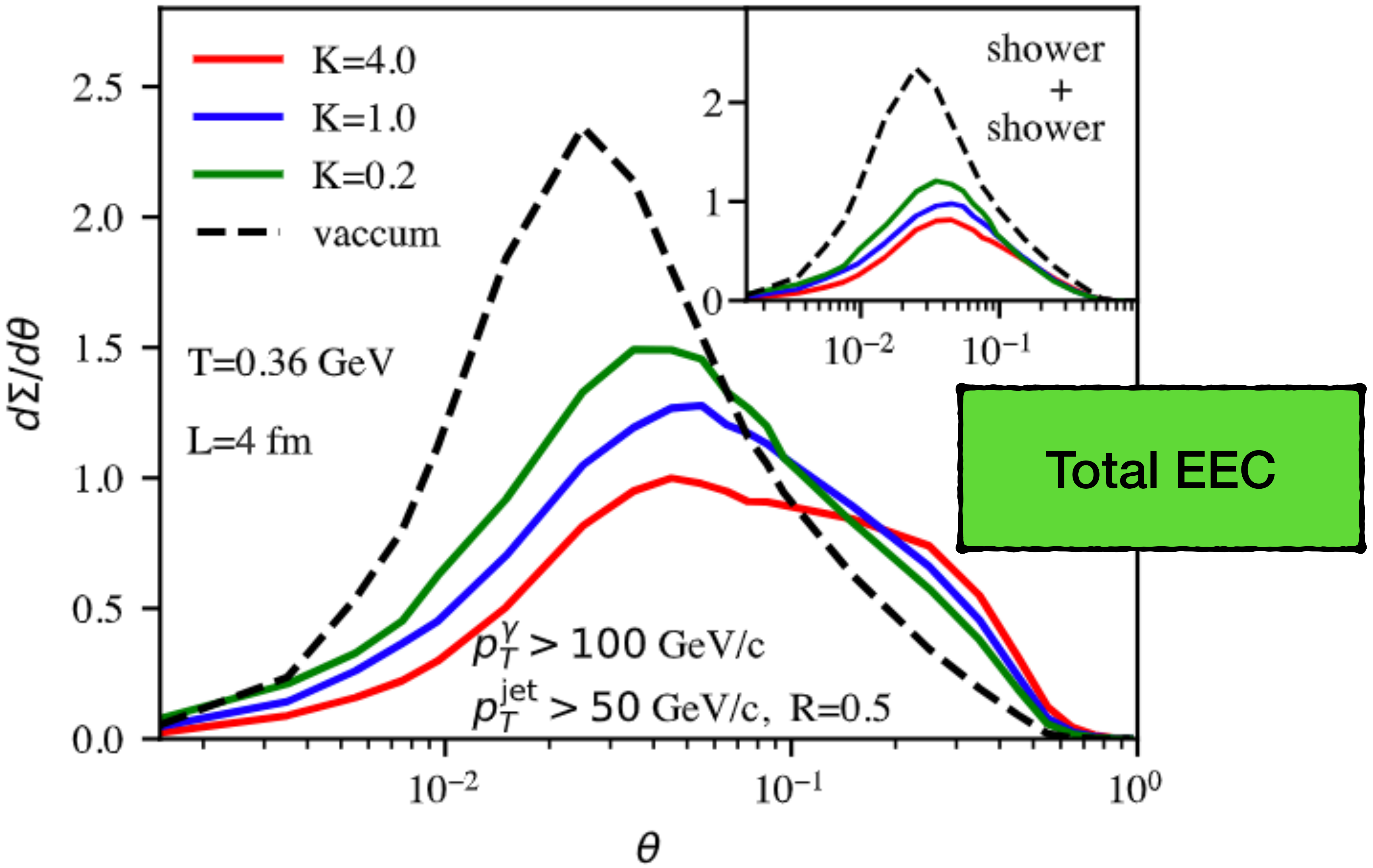
PRL 132 (2024) 1, 011901

Single parton



$$\mu_D^2 = \frac{3}{2} K g^2 T^2$$ (Collinear divergence)

Parton shower

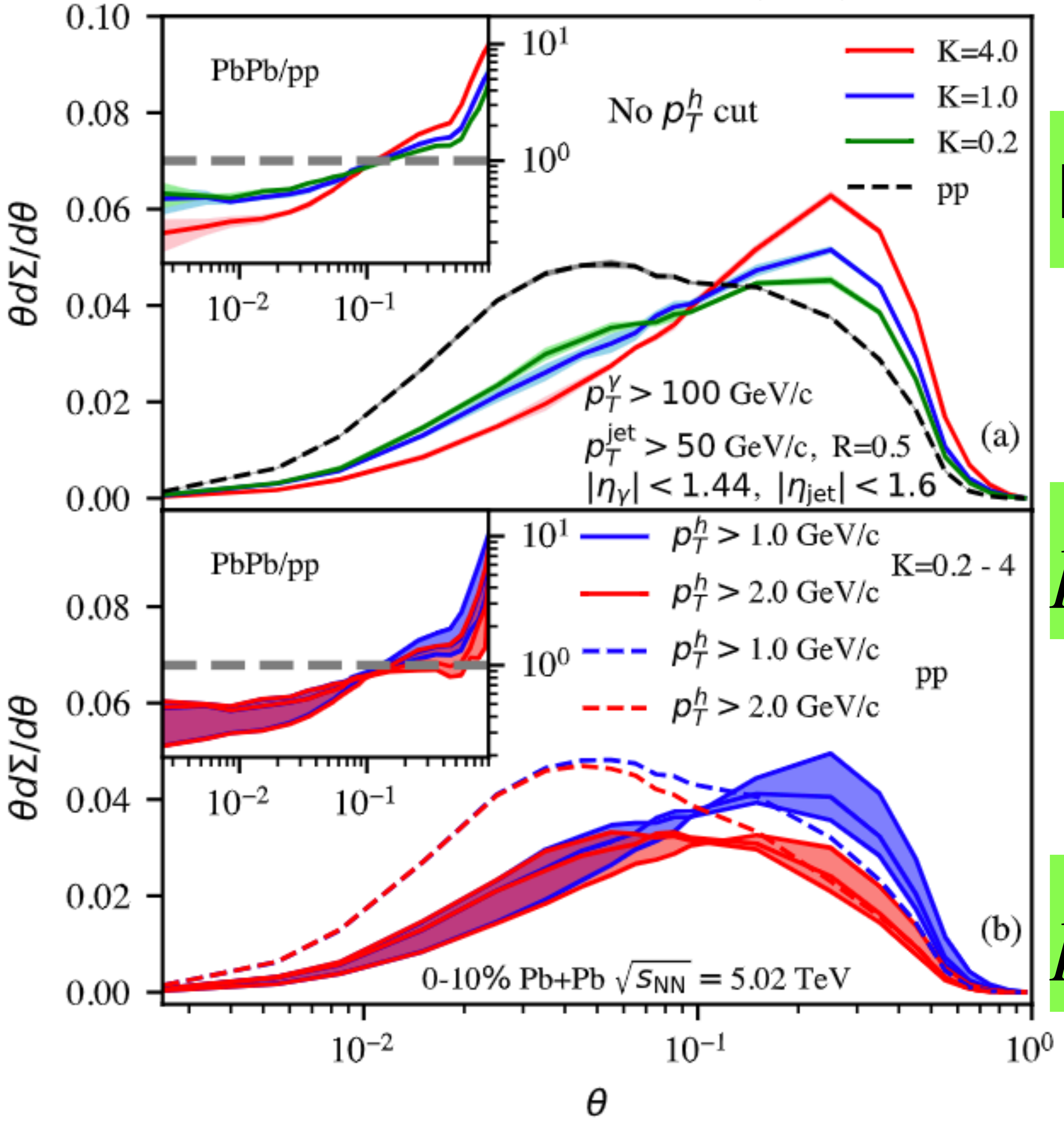


Transverse momentum transfer: $q_\perp \sim \mu_D$

Energy transfer to the medium: $\delta E \sim \mu_D^2/T$

EEC of γ-jet in Pb+Pb collisions

PRL 132 (2024) 1, 011901



No cut of p_T^h: { Enhancement at large angle; Suppression at small angle } → Sensitive to μ_D

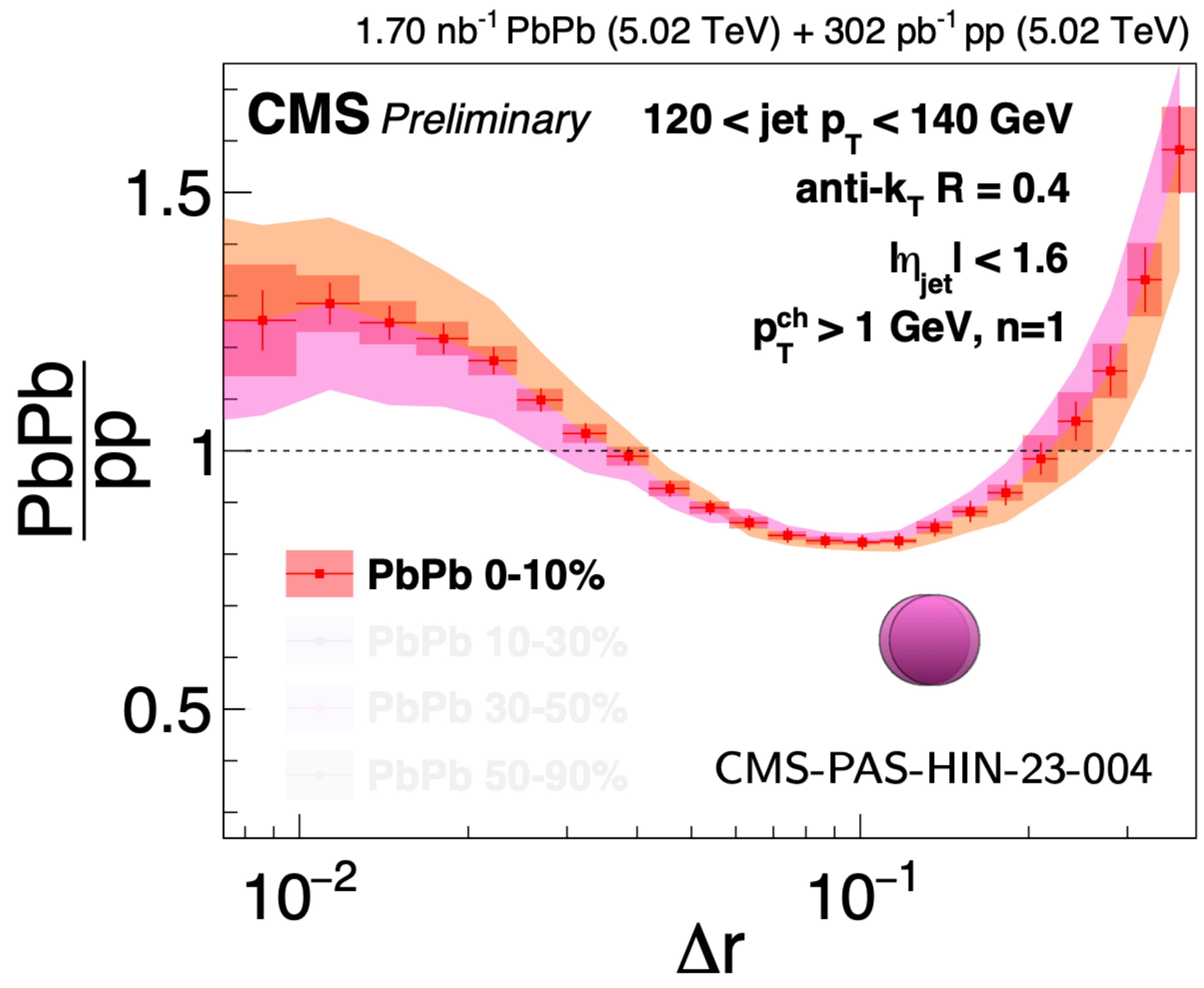
p_T^h >1GeV/c: Similar but enhancement reduced

p_T^h >2GeV/c: No enhancement expect K=4

EEC of single jet in Pb+Pb collisions at CMS

EECs of single inclusive jets in Heavy-Ion Collisions.

CMS, arXiv:2503.19993



Large angle:

Medium response

Medium-induced emissions

Small angle: 10～40%

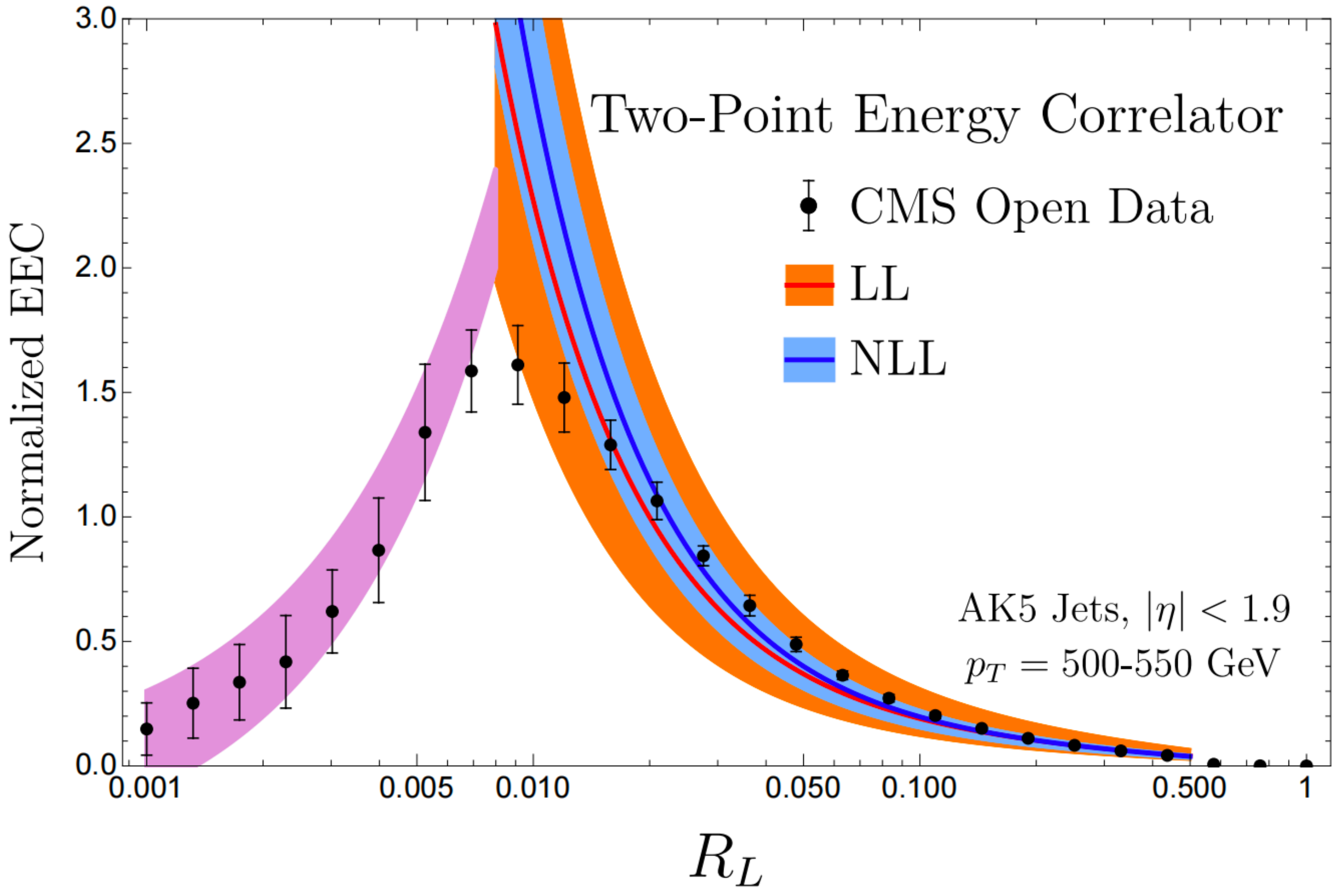
Where does the enhancement come from?

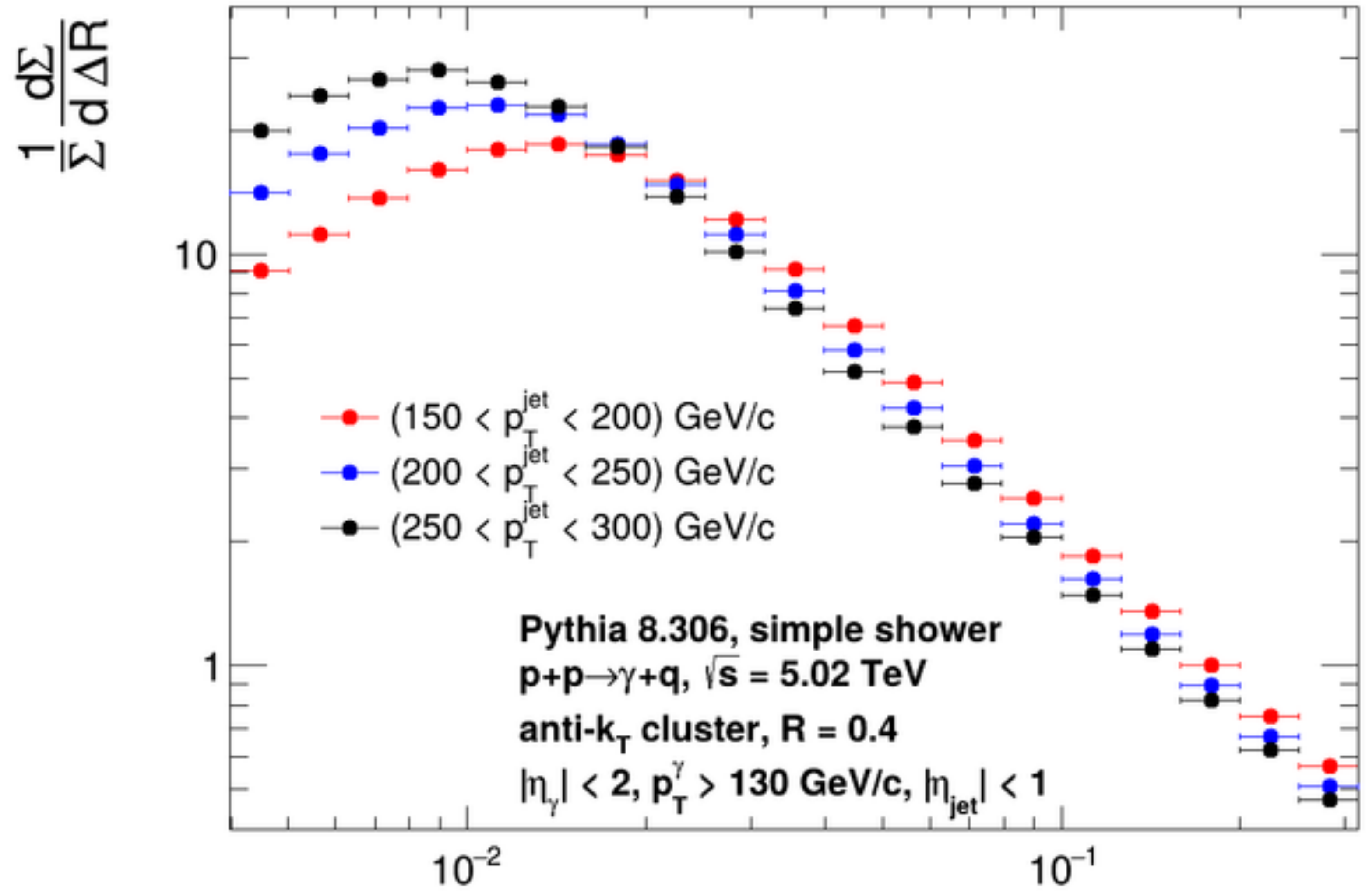
Energy loss or anything else …

CMS results shows significant enhancement at both small and large angle.

Jet p_T selection bias

In vacuum, the EEC presents a clear separation between the perturbative and non-perturbative region





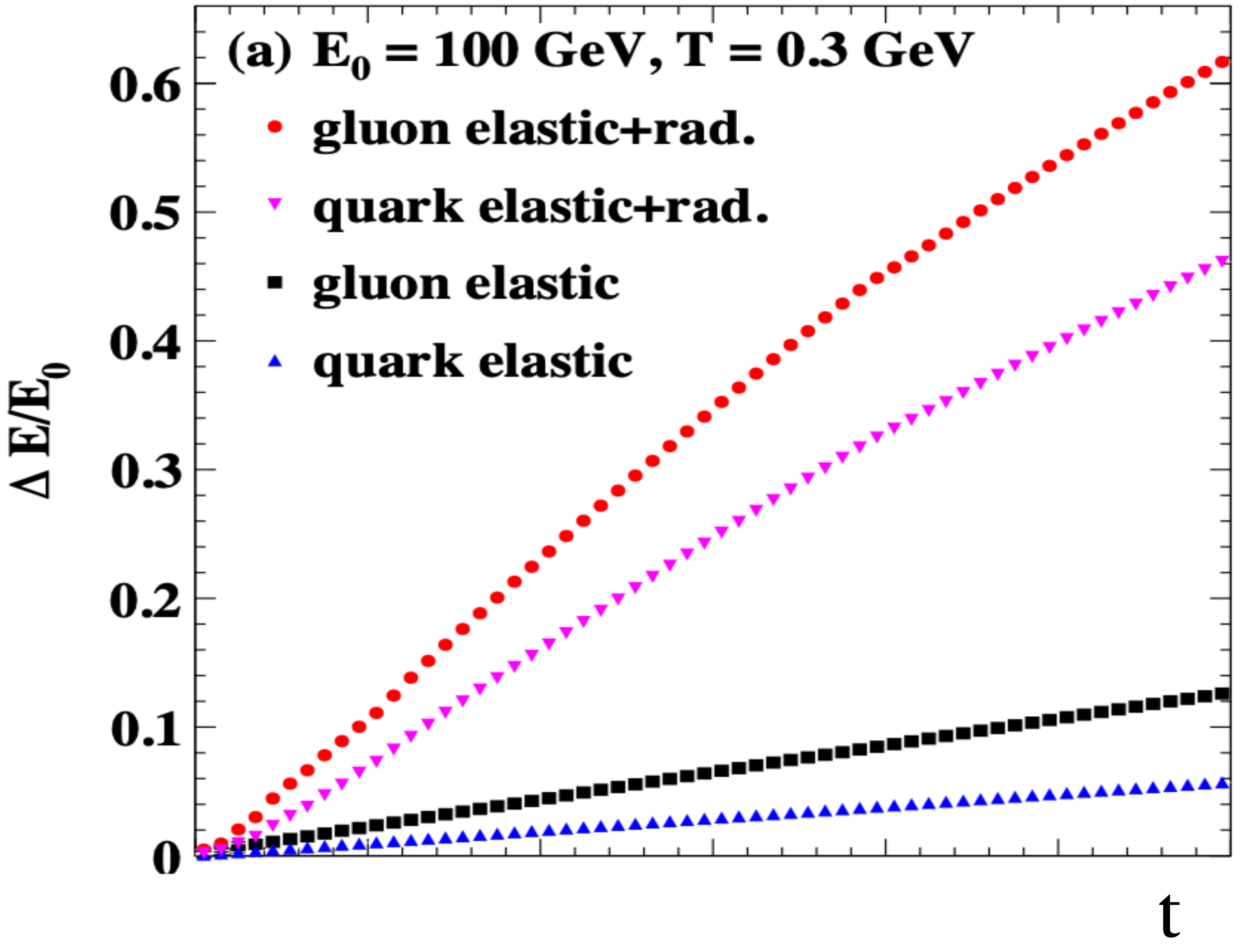
$$R_L \sim \Lambda_{QCD}/p_T^{jet} \sim 10^{-2}$$

Final		**Initial**
$p_{T,f}^{jet,AA}$	⟵ Energy loss	$p_{T,i}^{jet,AA}$
$\Vert$		$\vee$
$p_{T,f}^{jet,pp}$	⟵ No interaction	$p_{T,i}^{jet,pp}$

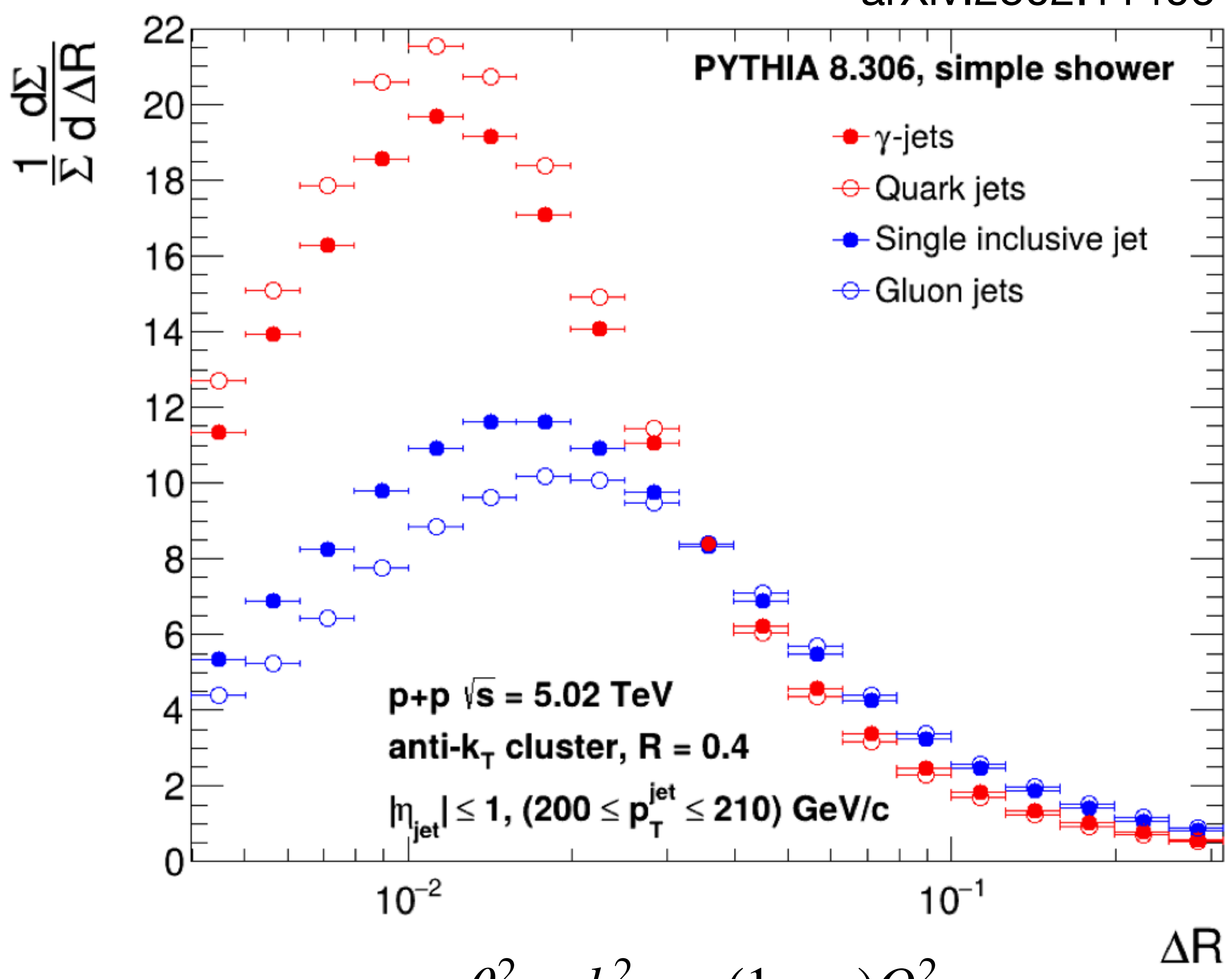
The peak of EEC from initial AA jet should shift to small angle,
Leading to enhancement of ratio AA to pp at small angle at beginning.

Quark and gluon jet EEC

The EEC inside the gluon jet always has a broad distribution and peak is shifted to large angle



arXiv:2502.11406



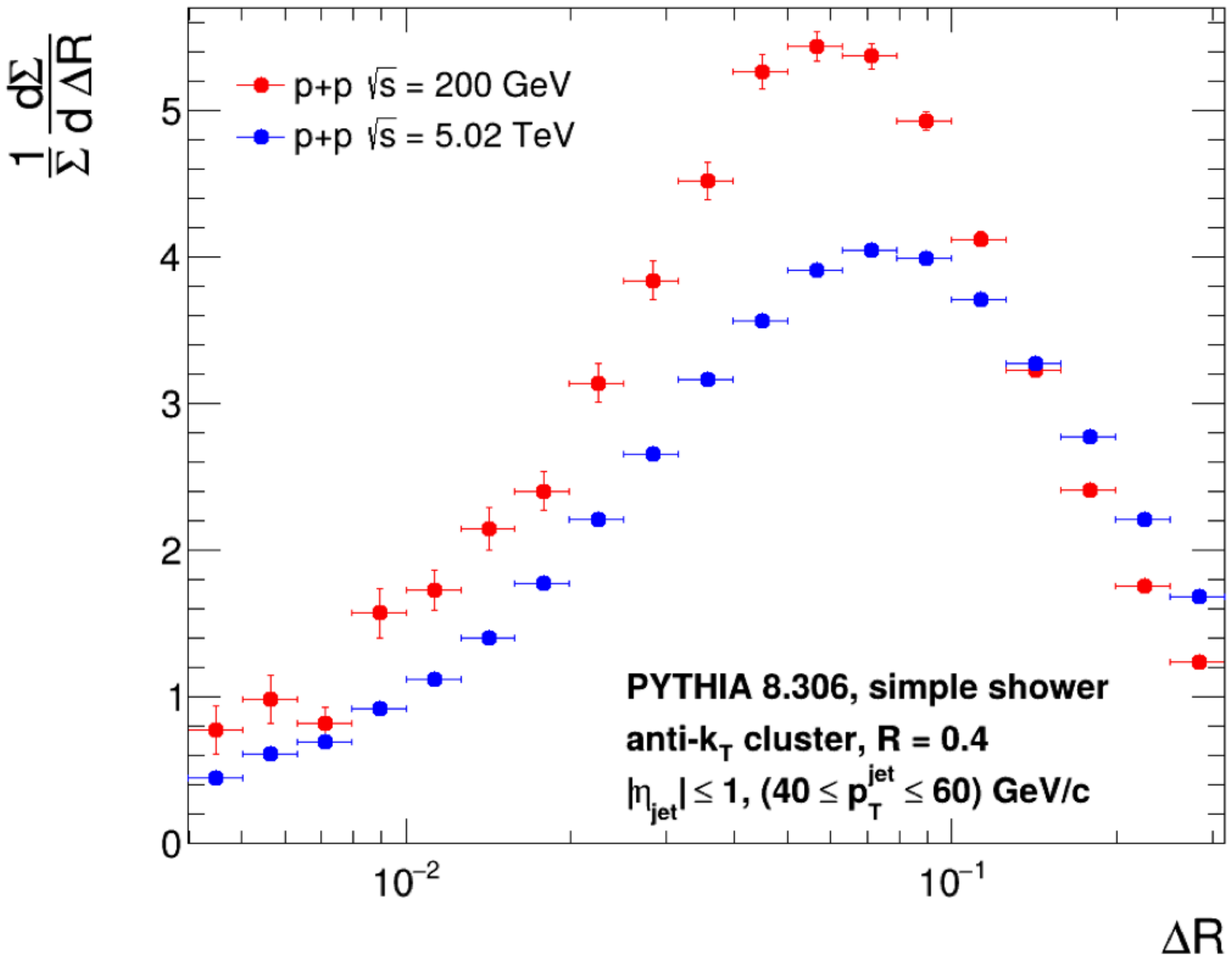
$\theta^2 \sim k_\perp^2 \sim z(1-z)Q^2$

Gluon has more color charge than quark, leading to more splitting.

Dependence of EEC on collision energy

Flavor dependence of jet EEC should lead to a colliding energy dependence of single inclusive jet EEC with same jet p_T.

arXiv:2502.11406



Initial parton momentum fraction: $x = 2p_T/\sqrt{s}$

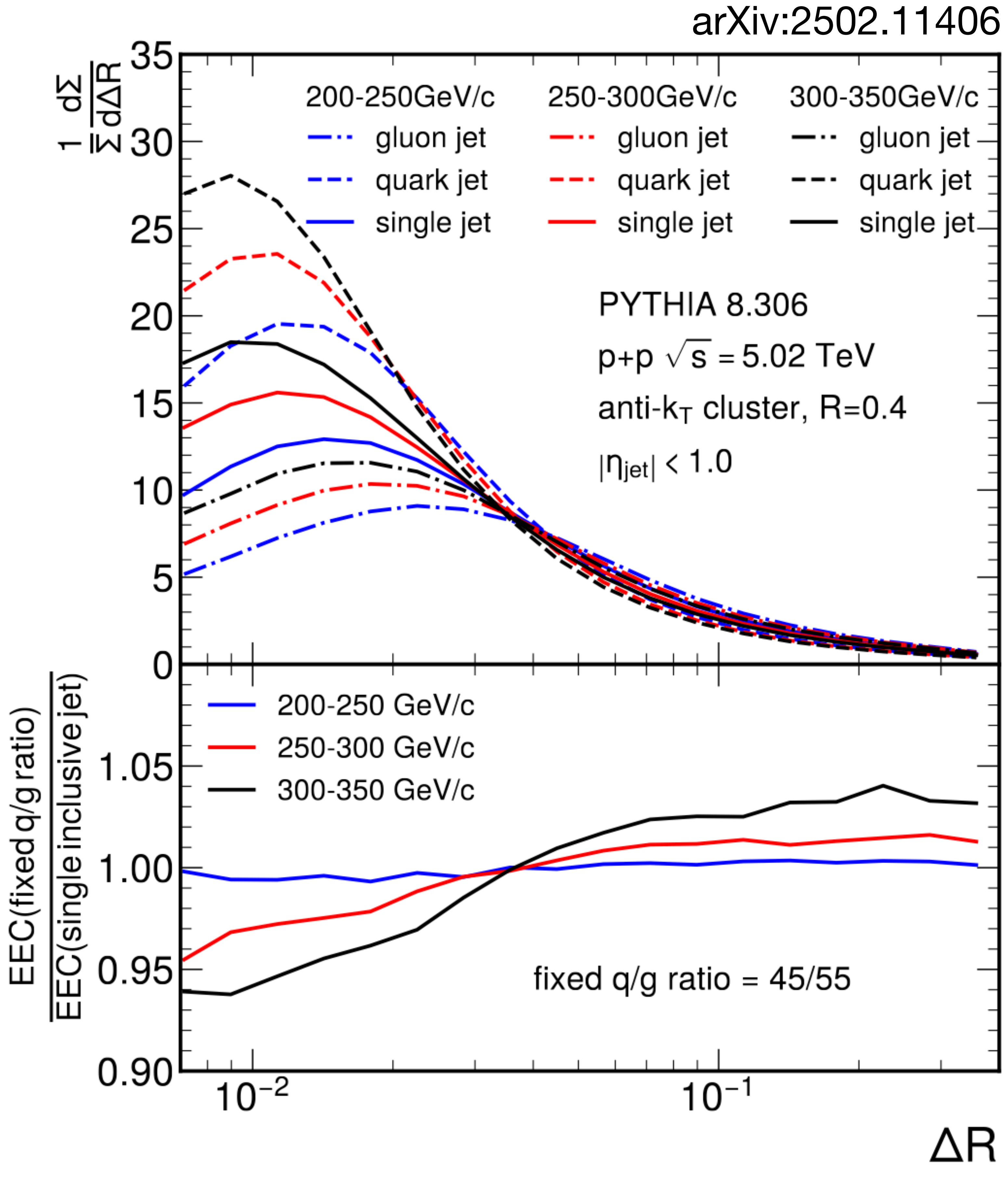
$$p_T^{jet} \in (40-60) GeV/c$$

SPHENIX, STAR

ALICE

Flavor dependence in jet p_T selection bias

When we consider the effect of jet p_T selection bias, we should also take account in the flavor dependence of EEC.

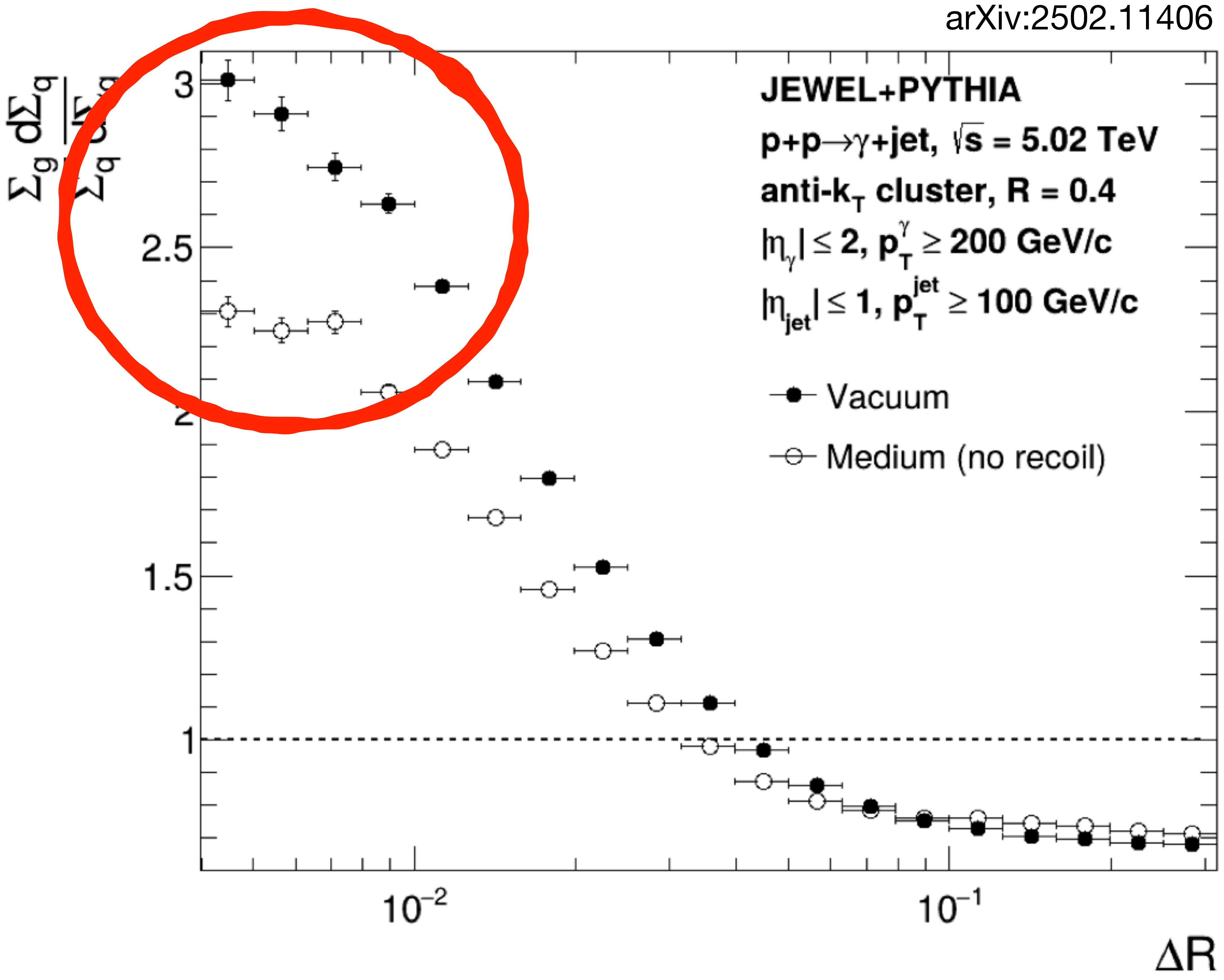


1. For $p_T^{jet} \in (200 - 250)$ GeV/c, we use quark and gluon jet to fit the single jet EEC. We find the ratio of quark to gluon is **45/55**.

2. We assume this ratio is fixed for other p_T^{jet} ranges, and use q and g jet EECs to construct fake single jet EEC.

3. We calculate the ratio of EEC with fixed q/g fraction to EEC within single inclusive jet generated by PYTHIA8.

Medium effect on flavor dependence



Gluon jets

Larger energy loss

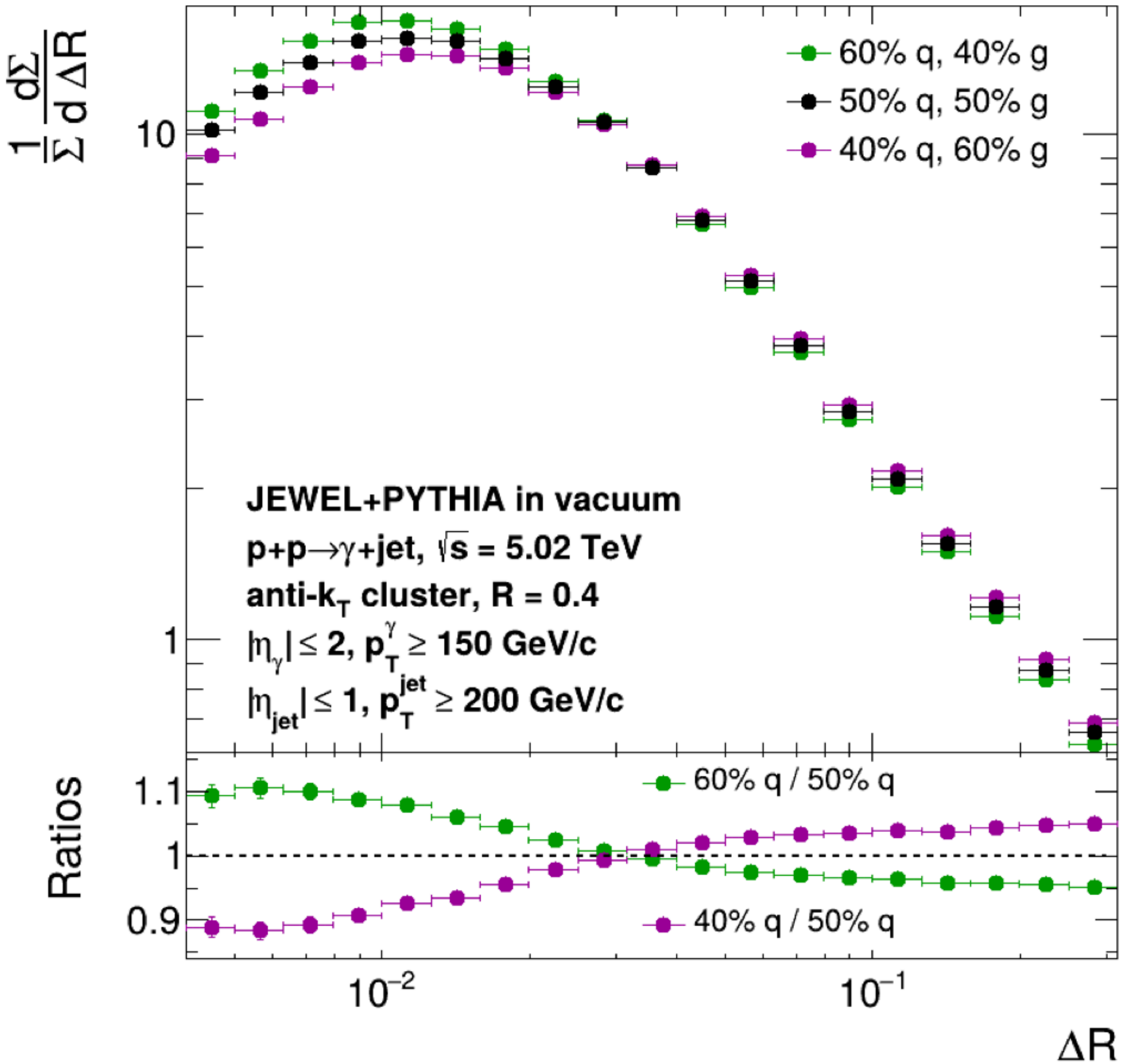
Strong selection bias

Reduce EEC differ.

Effect of gluon jet fraction on EEC

Greater energy loss experienced by gluon jets compared to quark jets also reduces the fraction of gluon jets in the final state in A+A collisions relative to p+p collisions.

arXiv:2502.11406



As the fraction of gluon jets decreases, the overall distribution shifts toward smaller angles.

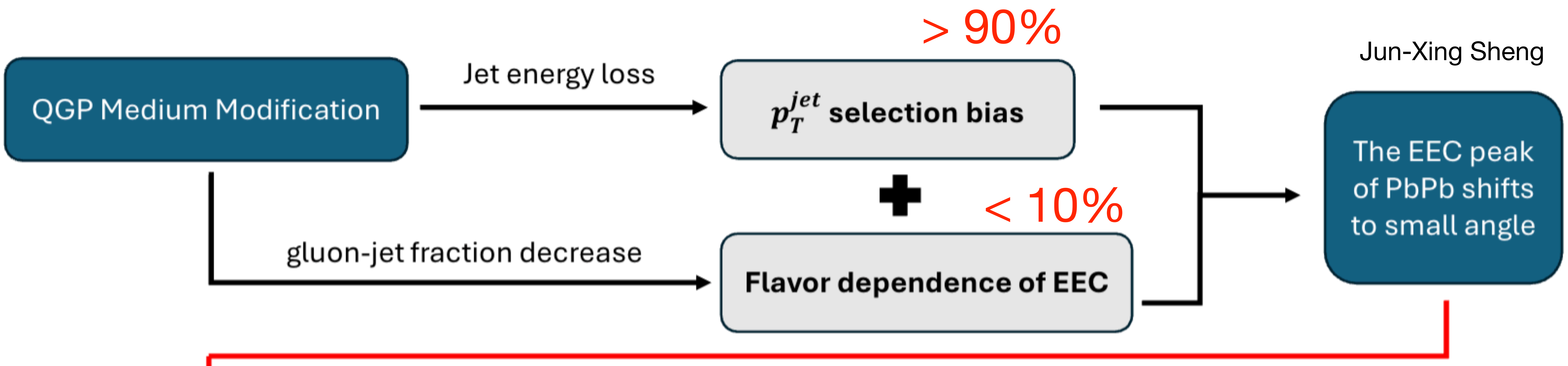
10% change in the gluon jet fraction almost leads to a 10% variation in the EEC distribution at small angles.

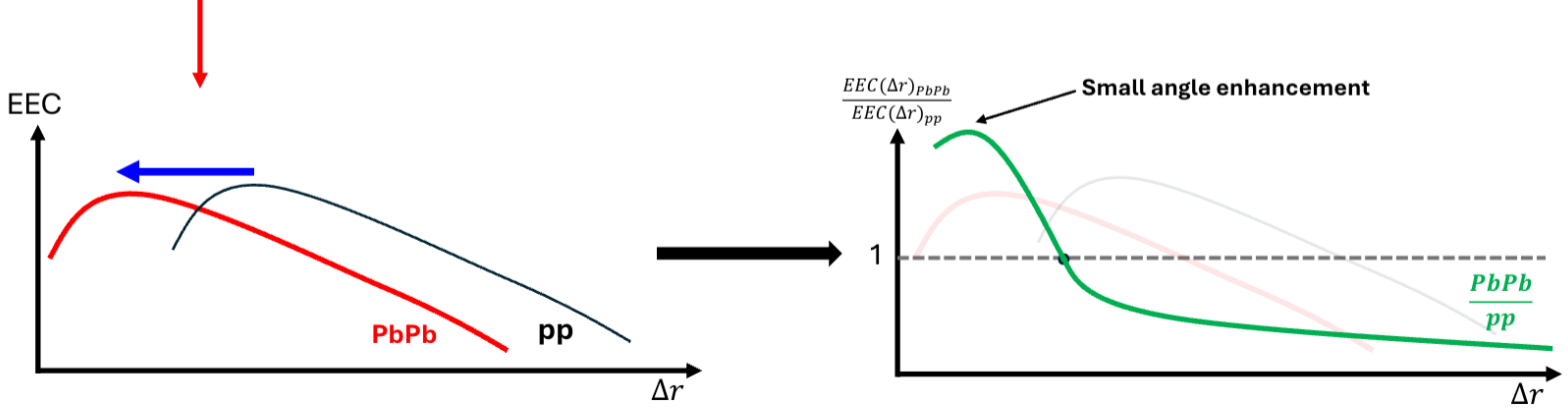
With JEWEL: $p_T^{\text{jet}} \in (120 - 140)GeV/c$

Gluon jet fraction: 66%(pp) -> 64.5%(AA)

Only contribute to 6% of the enhancement

Medium effects on EEC

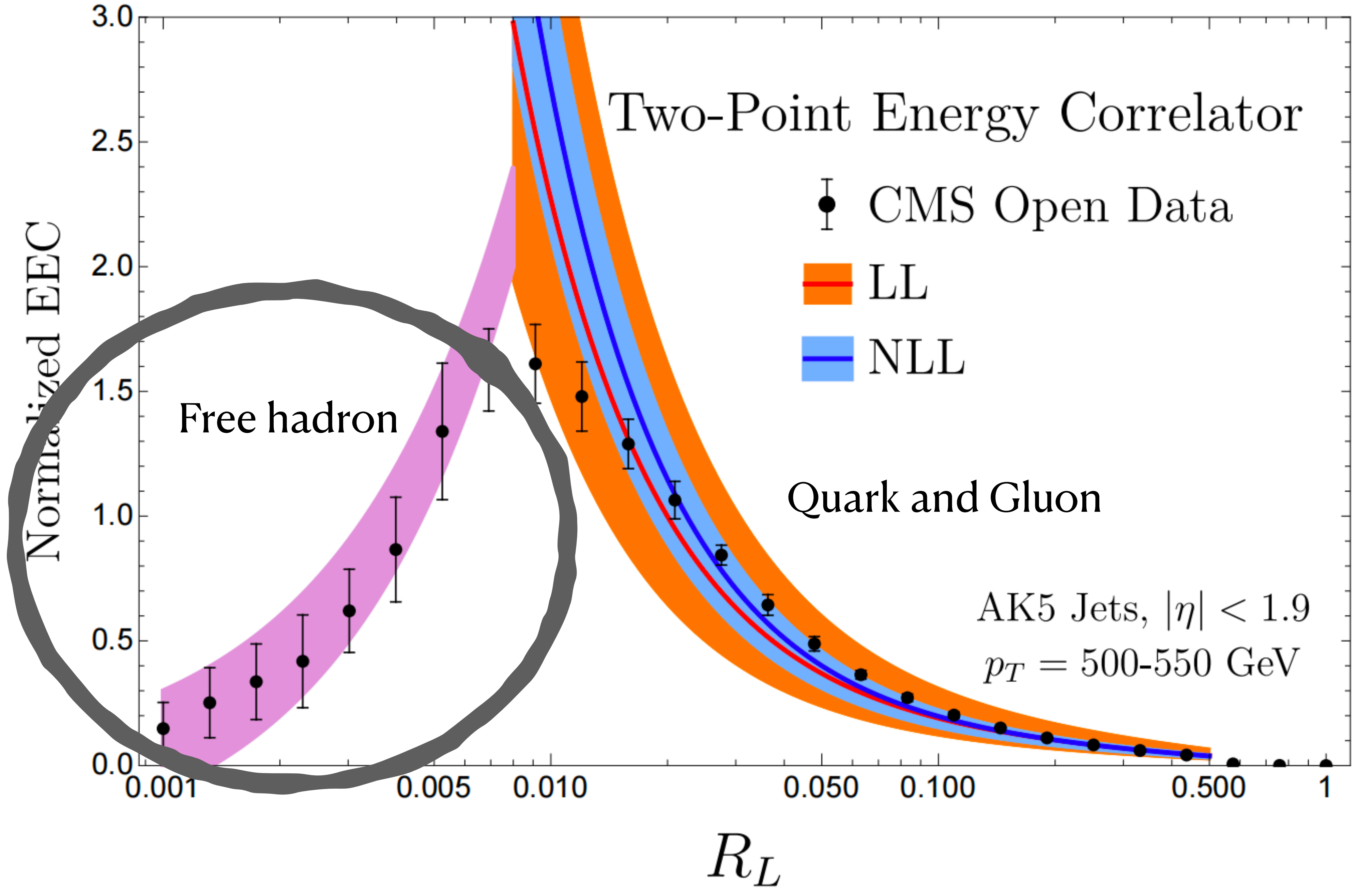




Effect of hadronization on EEC

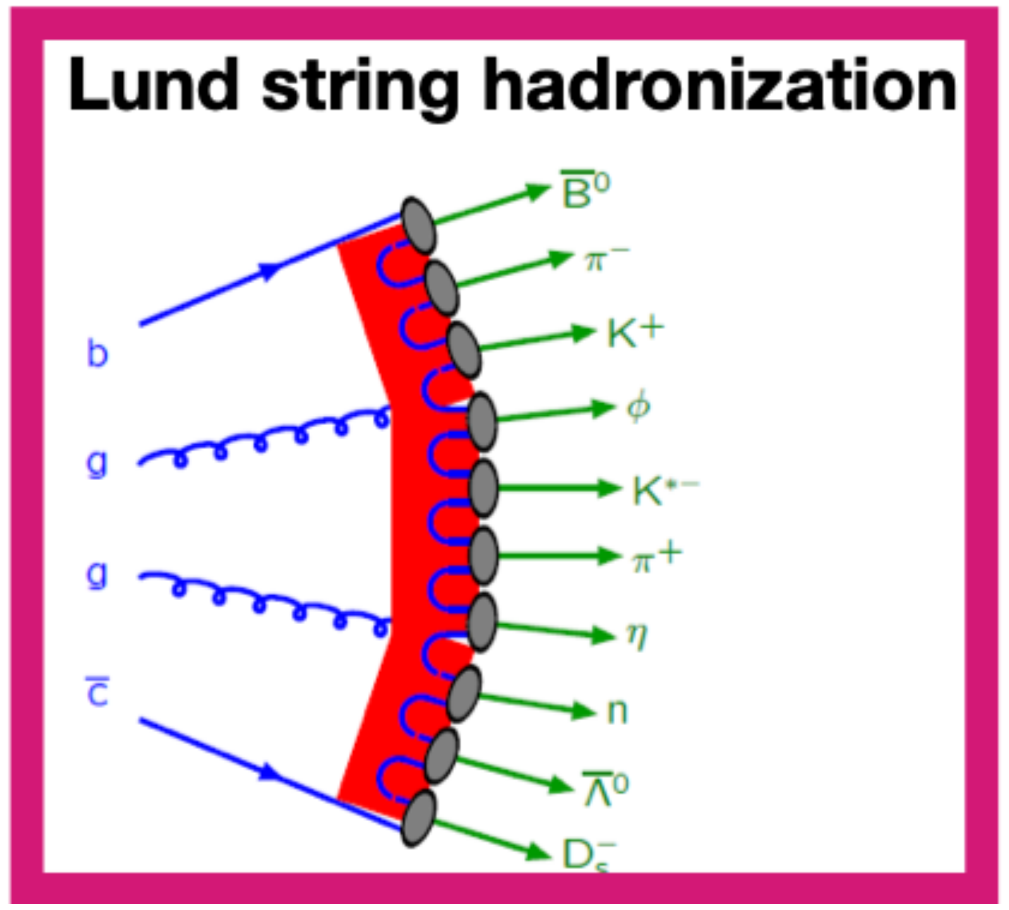
The small angle corresponds to free hadron.

Should small-angle EEC help us distinguish different hadronization model?

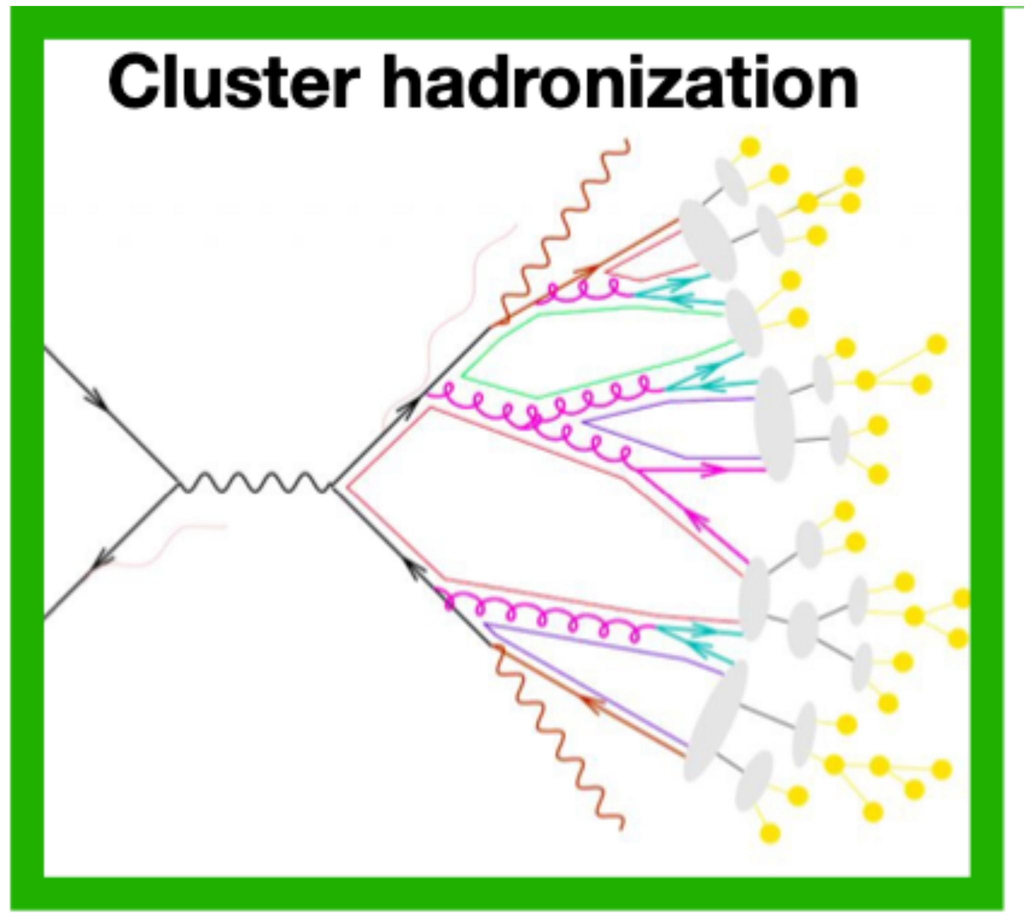


Lund string and cluster model

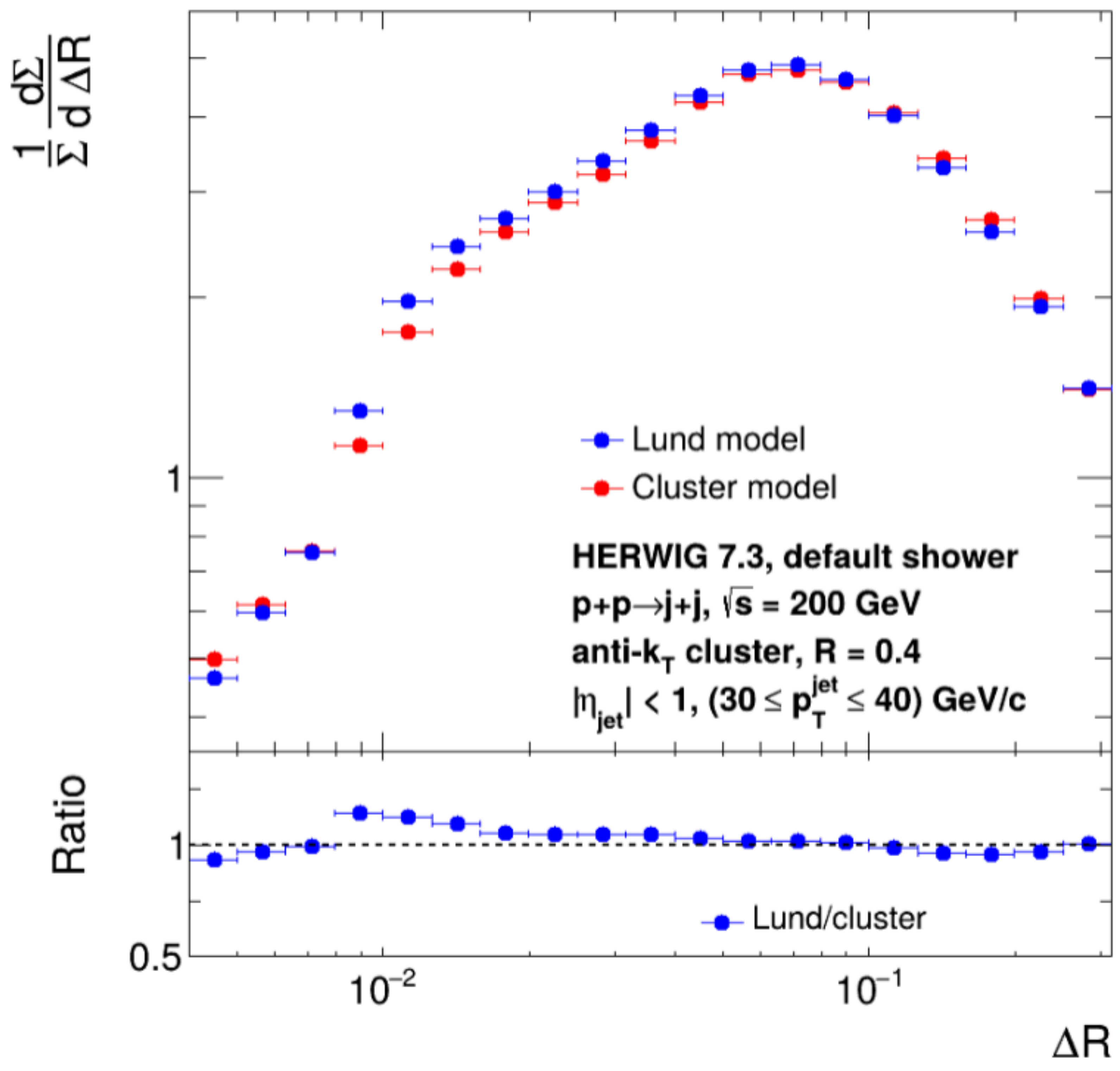
Nuno Madureira

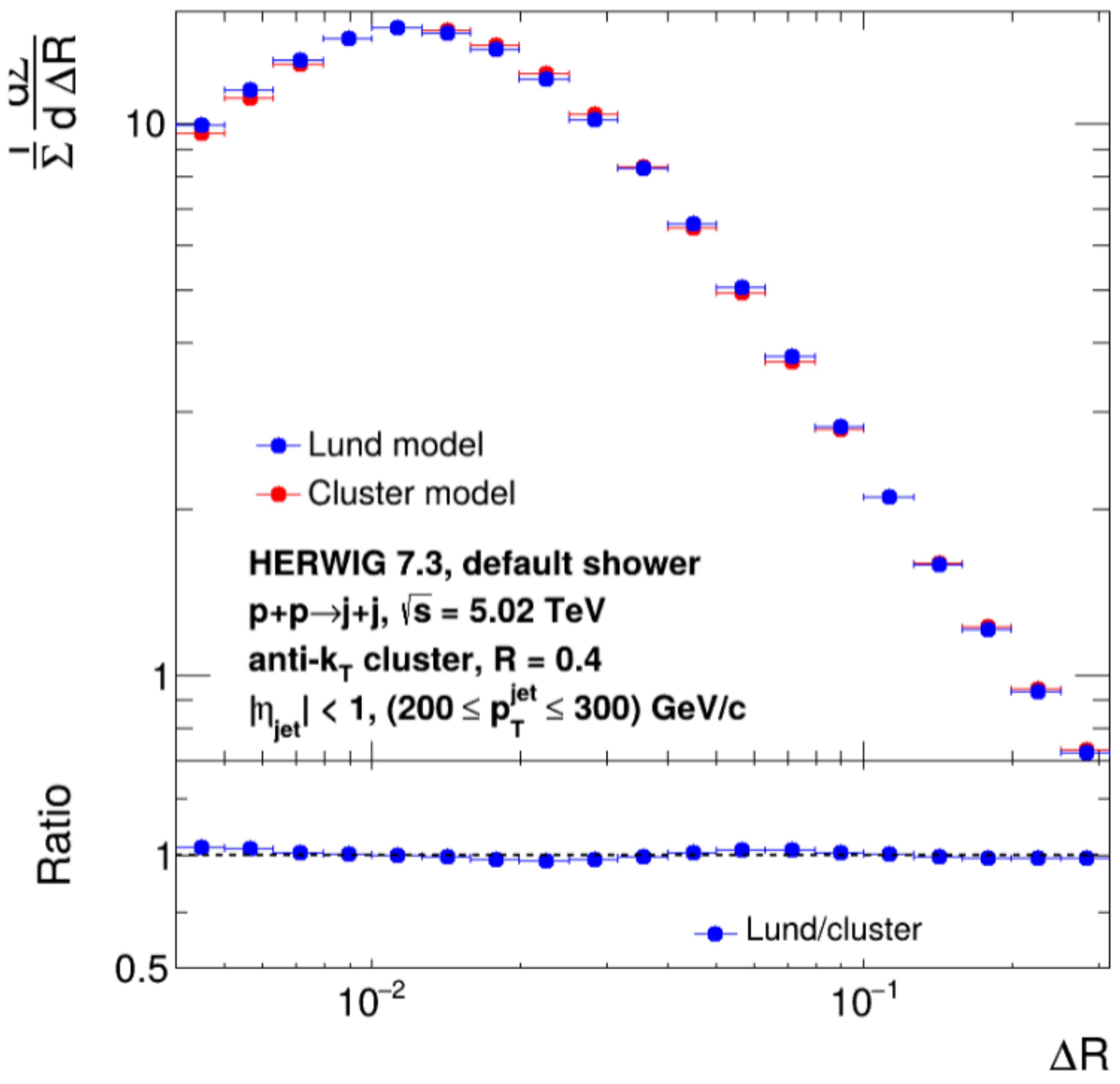


PYTHIA



HERWIG

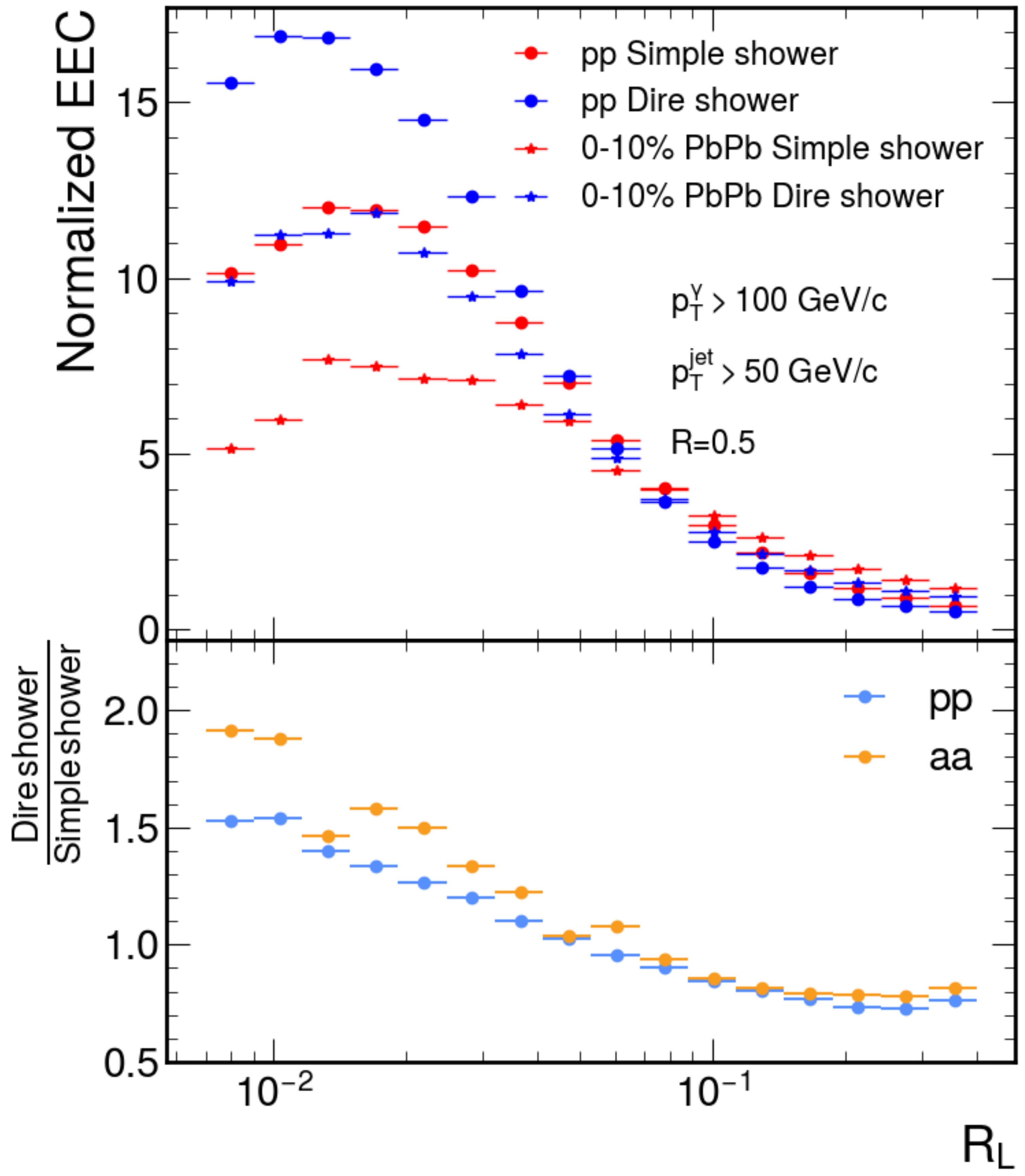


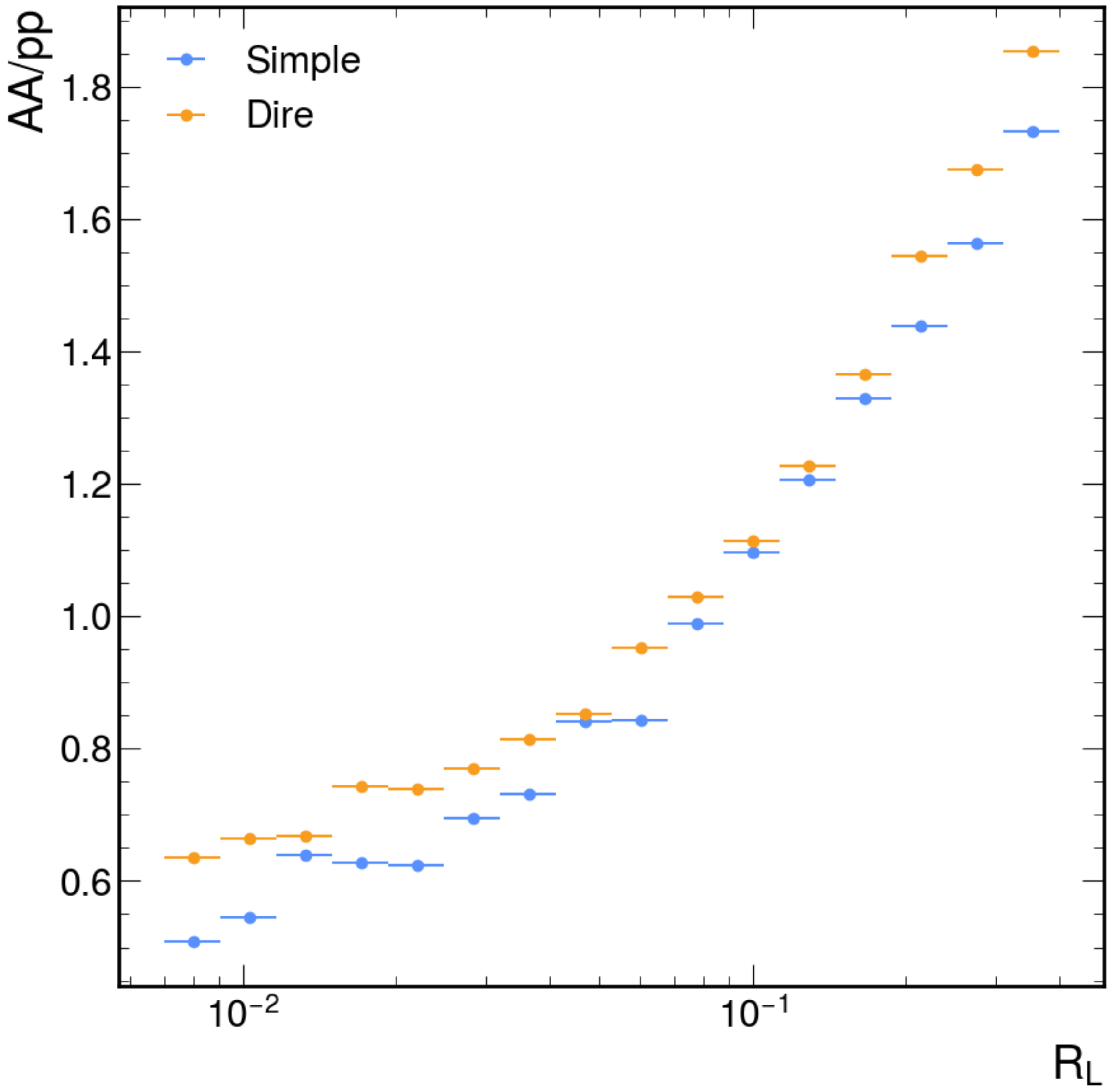


In pp collisions, we can't see the clear dependence of EEC on hadronization model (**Lund** and **Cluster**)

Effect of parton shower algorithm on EEC

Njet





PYTHIA:

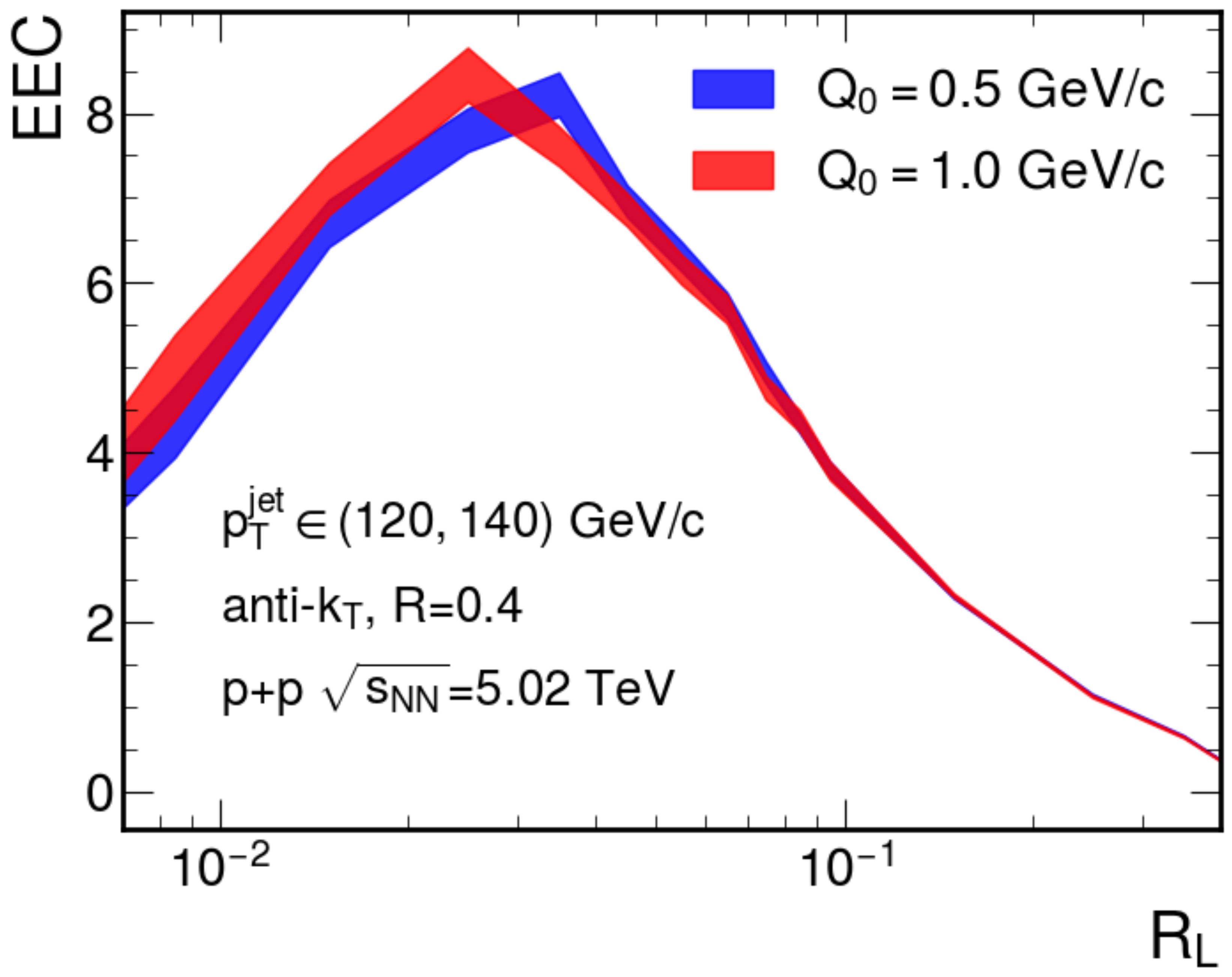
1. Simple shower(default)
2. Dire shower(dipole)

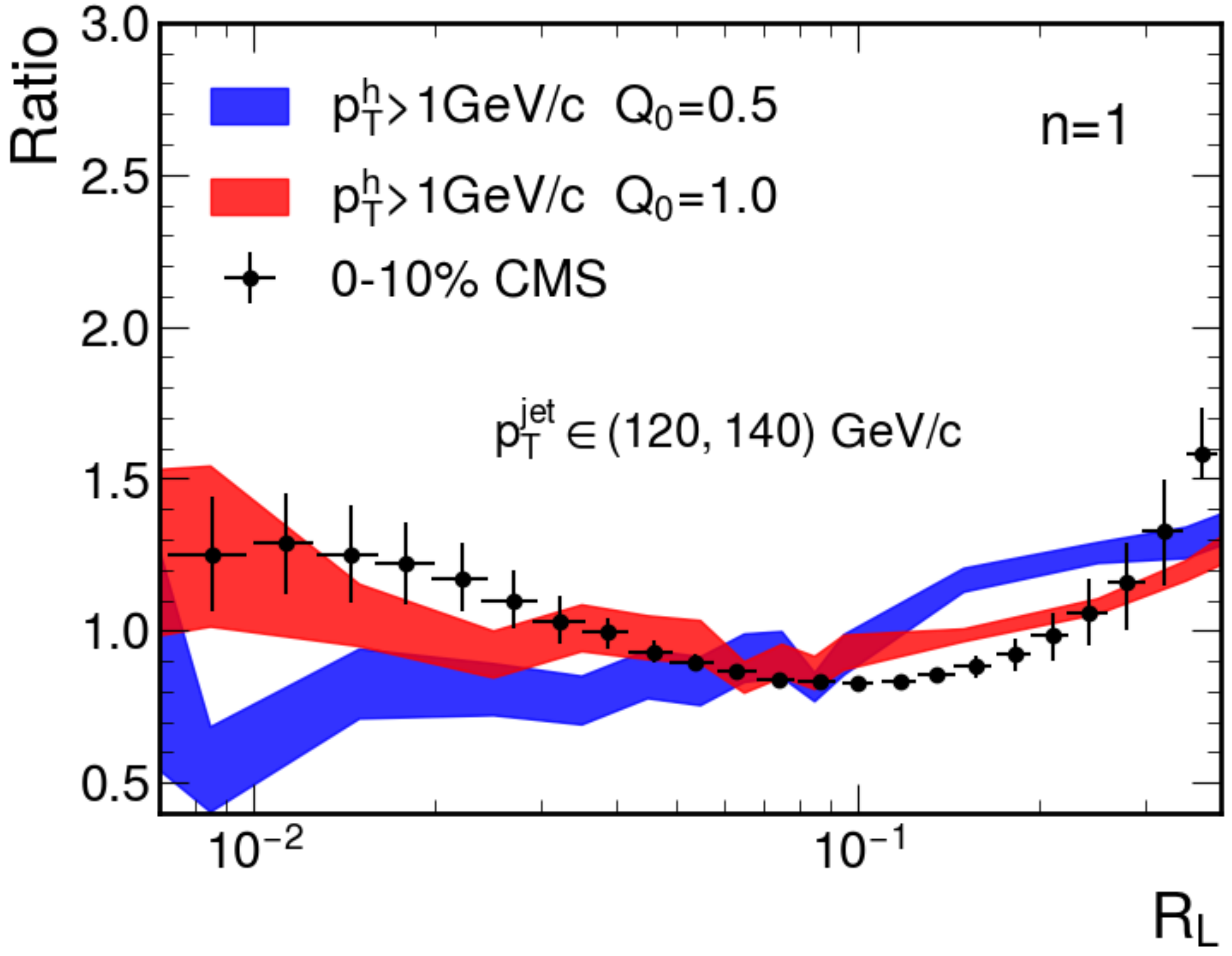
The selected parton shower model has a significant impact on the EEC distribution, and this effect remains present in AA collisions.

EEC can probe different parton shower in both AA and pp collisions

Effect of parton shower algorithm on EEC

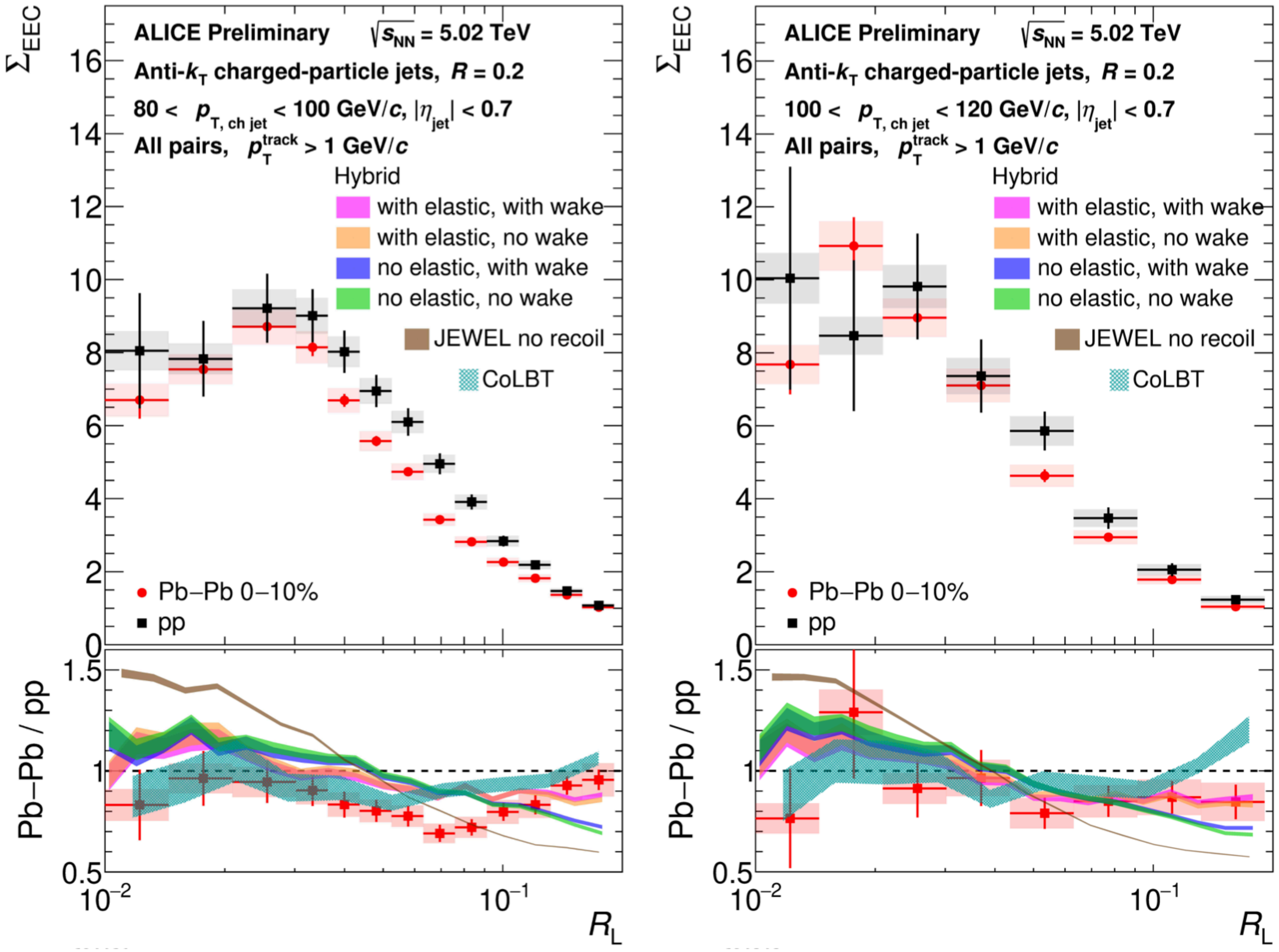
Q_0 is the minimum value for high-virtuality parton undergoes vacuum splittings. It controls the scale at which partons begin to hadronize.





Q_0 affects EEC distribution in both pp and AA collisions. It significantly affects the ratio distribution, leading to an enhancement at small angles.

Prediction of jet's EEC for ALICE



CoLBT results with Q_0=1.0 GeV also give a **nice description** of single jet EEC for ALICE group.

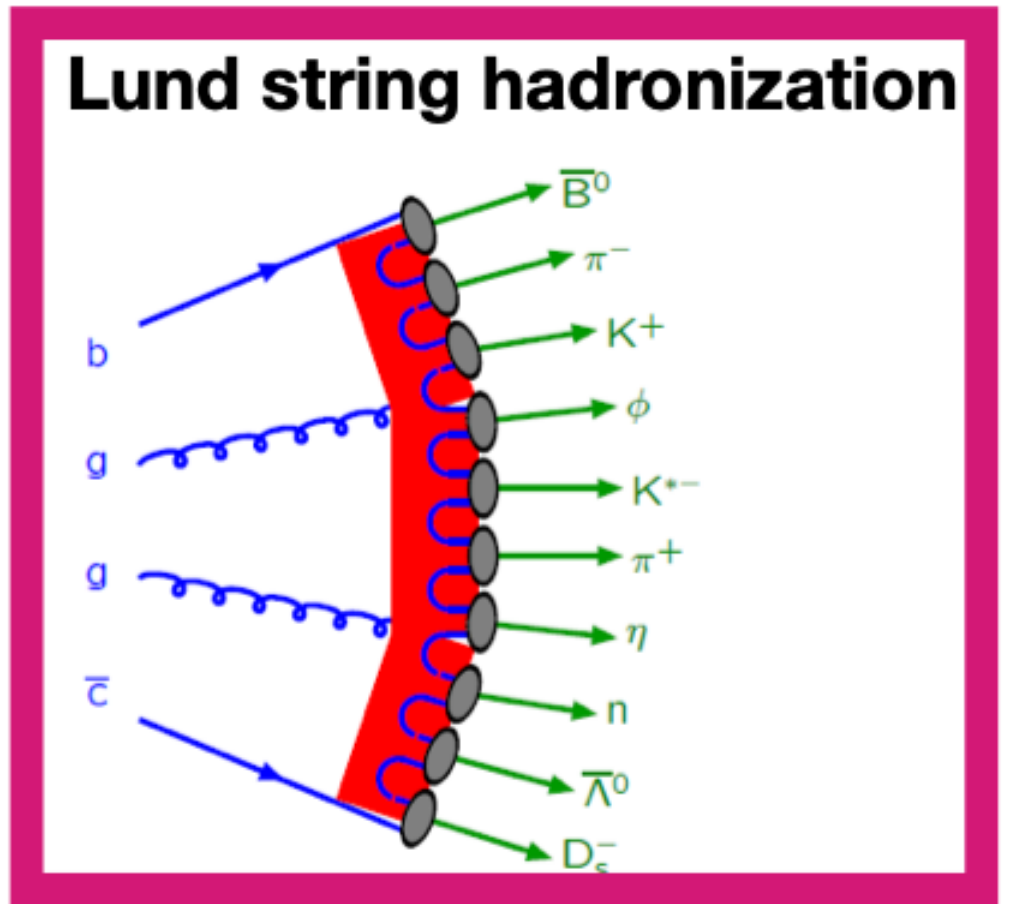
Ananya Rai, QM2025

Summary

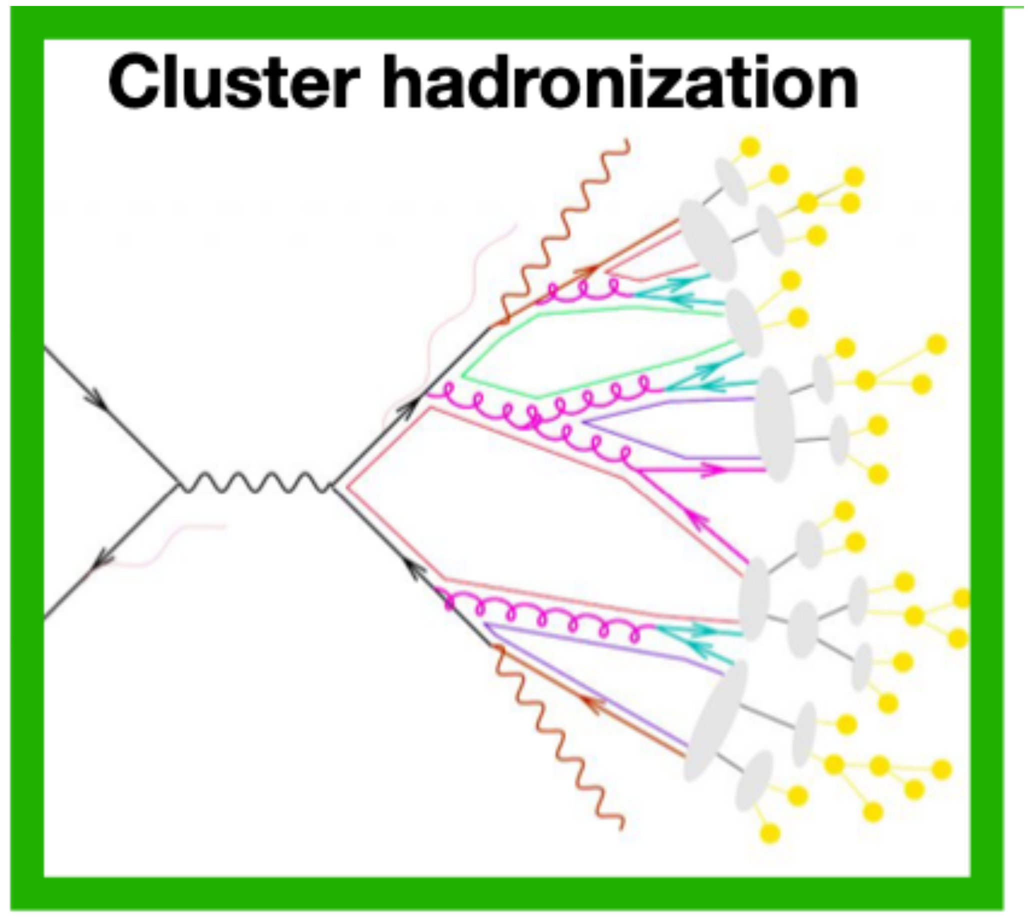
- Medium effects contribute significantly to the EEC, which can help probe the short-distance structure of the QGP medium. (Jet quenching, medium response, and medium-induced emissions)
- Jet’s EEC exhibits a clear dependence on the initial parton flavor, providing insights into the EEC ratio differences between AA and pp collisions.
- The EEC shows potential for distinguishing between different hadronization models, though further validation is needed.
- EEC can help us examine different parton shower mechanisms and is useful for determining parameters in parton shower algorithms.

THANK YOU

Lund string and cluster model



PYTHIA



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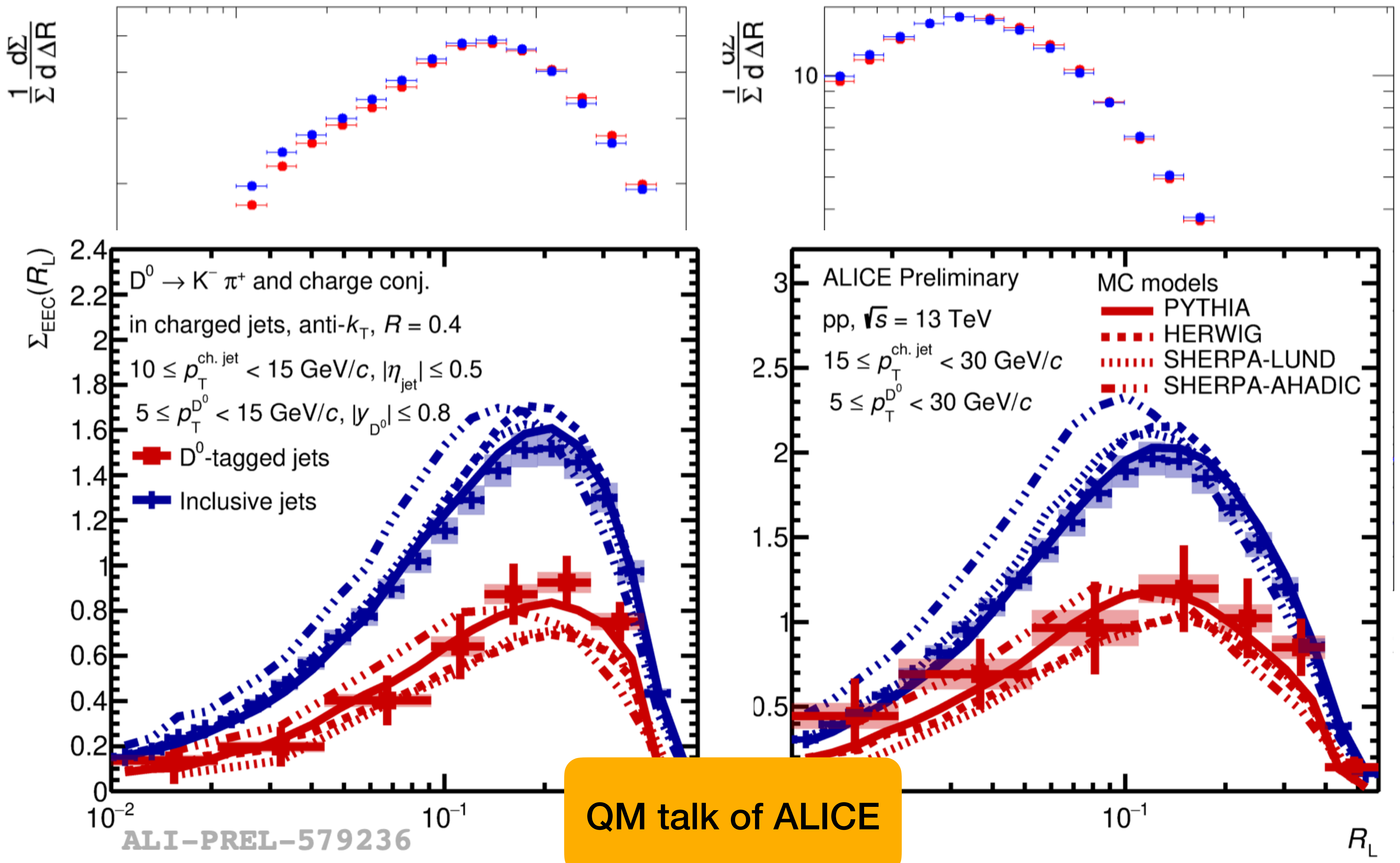

QM talk of ALICE