



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



Institute of Particle Physics
粒子物理研究所

Energy-Energy Correlators as a Probe of the Vacuum-Medium Transition in Jet Showers

Lin Li (李林)

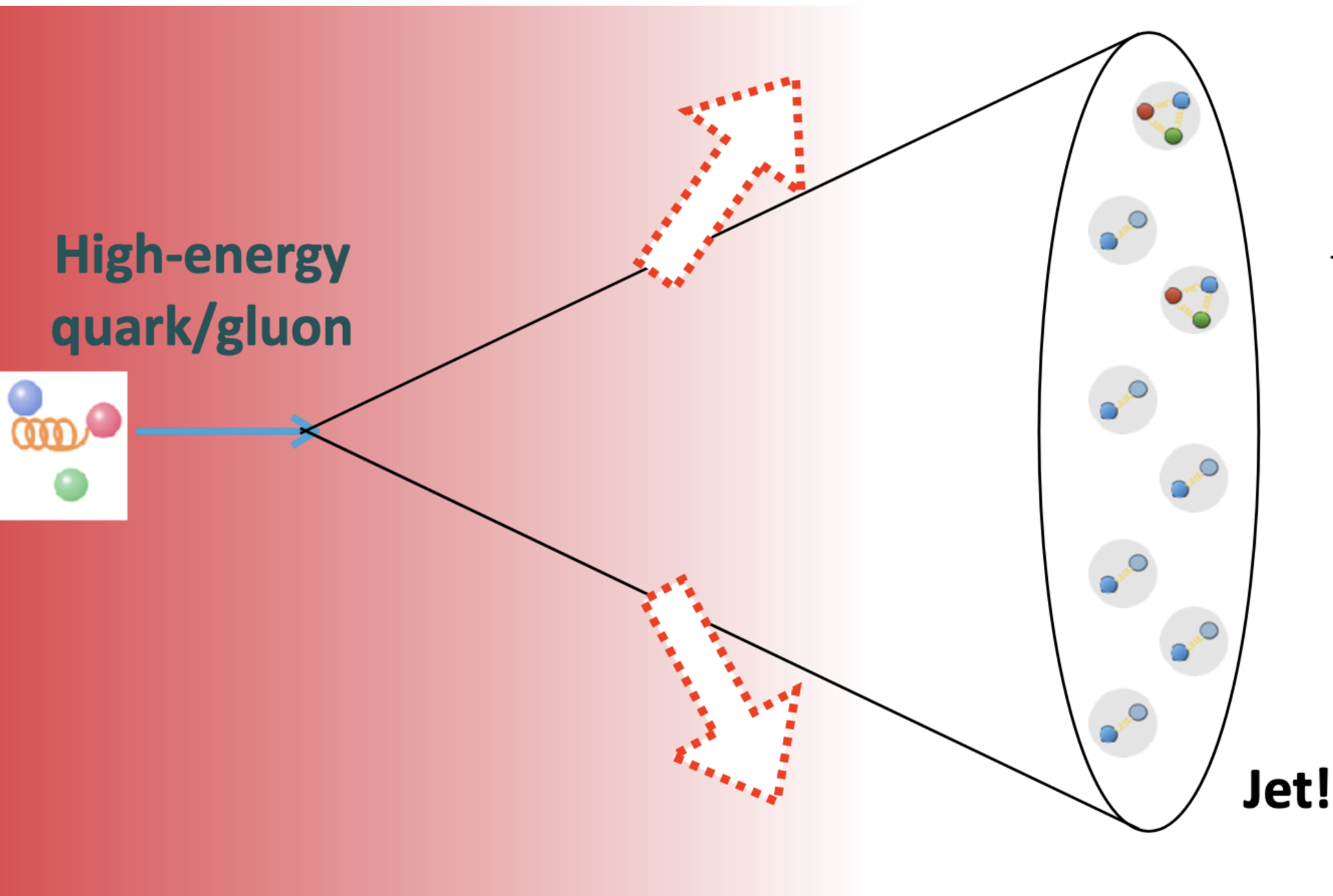
Central China Normal University

Collaborators: Yan-Ru Bao, Weiyao Ke, Guang-You Qin

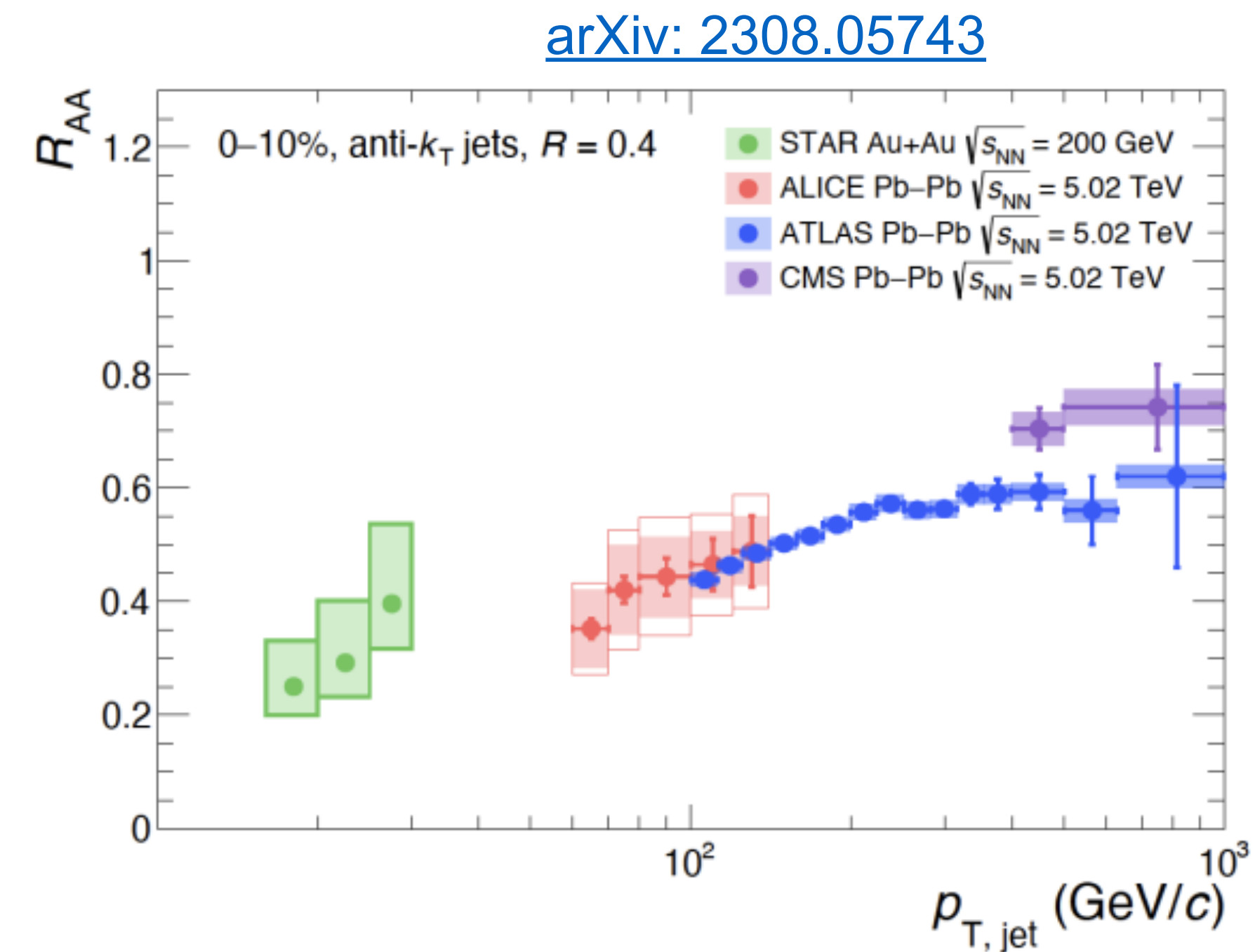
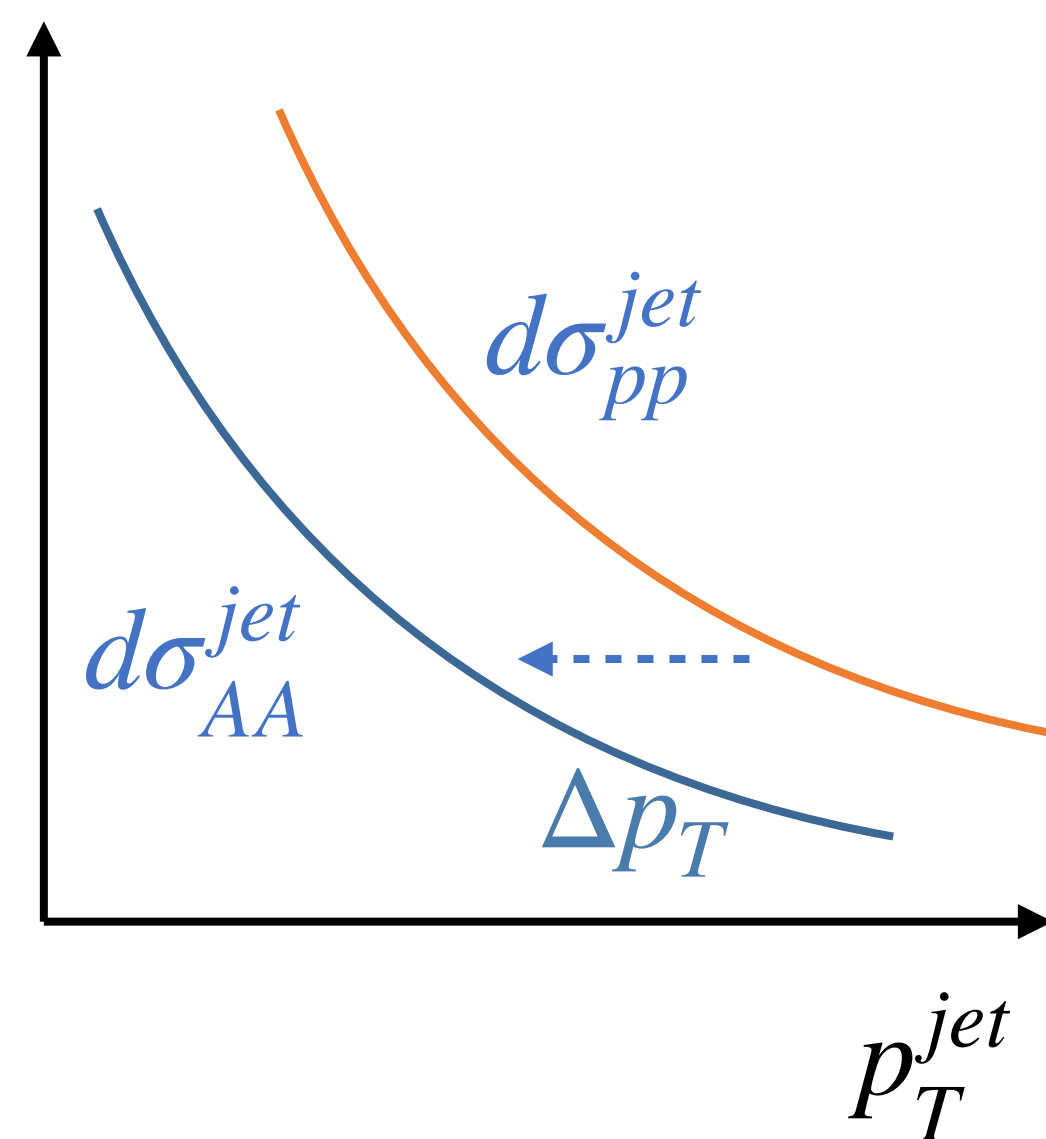
C3NT Workshop: Jet-soft dynamical medium interaction in high-energy heavy-ion collisions,
22/3/2026 - 4/4/2026, CCNU, WuHan

Why jets? Jet quenching is one of the key signatures of QGP

- ✿ Jets are produced early in the collision ($\tau \sim \frac{1}{p_T}$)
- ✿ Jets are extended in time and evolve simultaneously with the QGP.
- ✿ Jets carry imprints of medium interactions (energy loss, substructure modifications, medium response, etc).

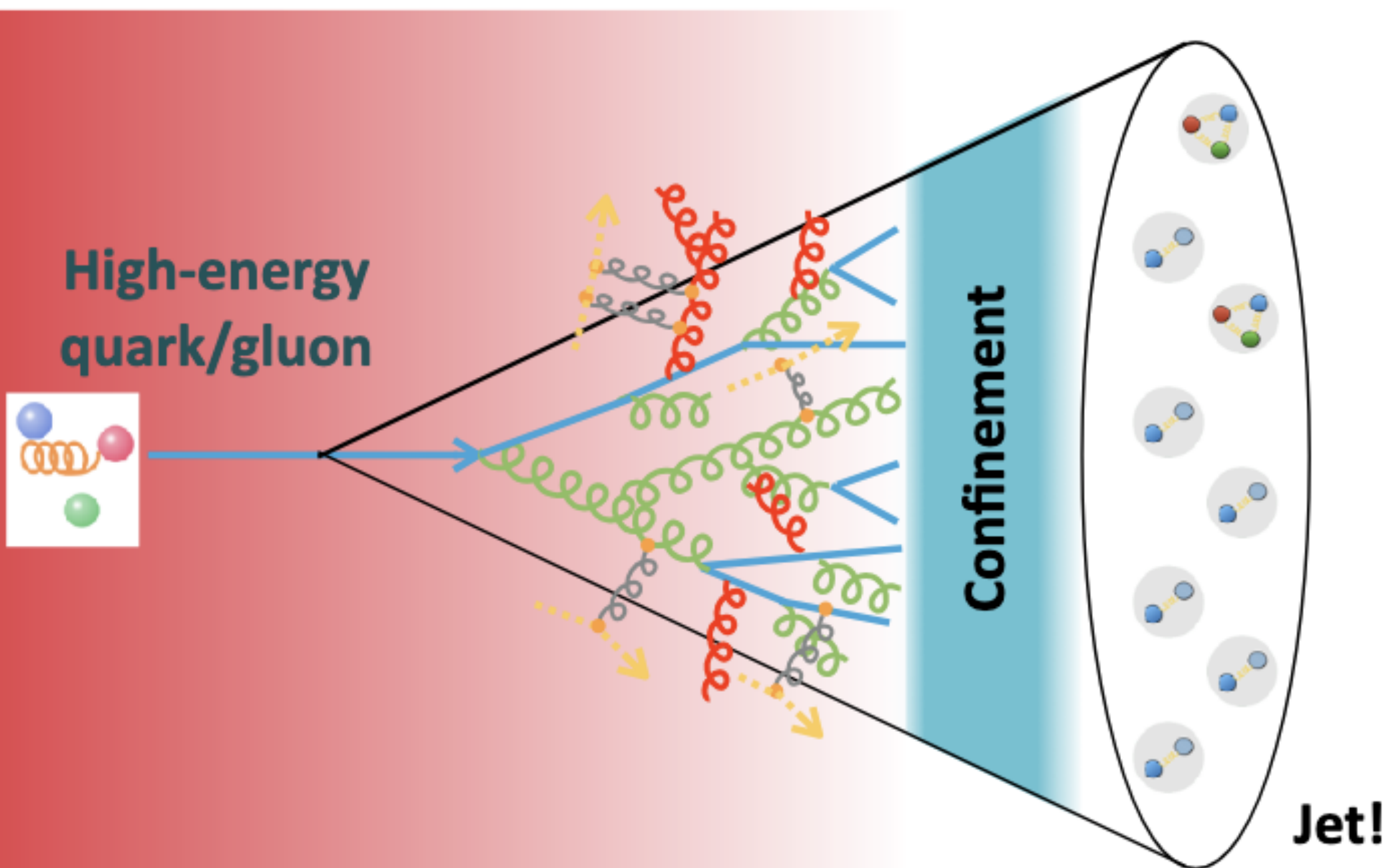


Jets “lose” (redistribute) energy when going through the QGP



Why jet substructure?

Treating jets as complex many-particle object with internal structure



▸ Interactions with QGP are imprinted in the jet structure via

- ❖ Medium-induced splittings
- ❖ Multiple collisions with the medium
- ❖ Medium response
- ❖ Hadronization in the medium

▸ Jet substructure: provides a controlled to access modifications from perturbative splittings to non-perturbative effects.

Jets “lose” (redistribute) energy when going through the QGP



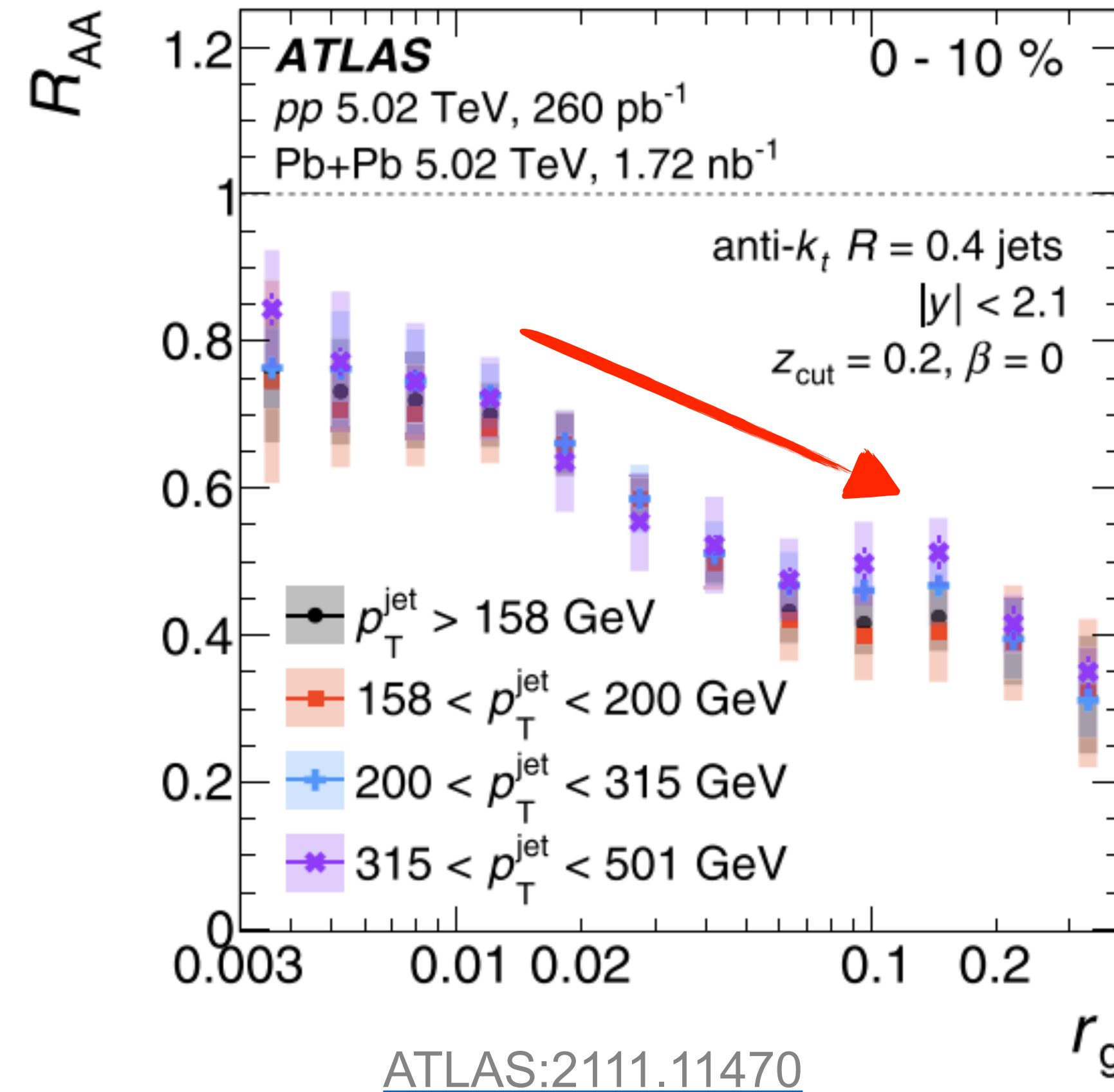
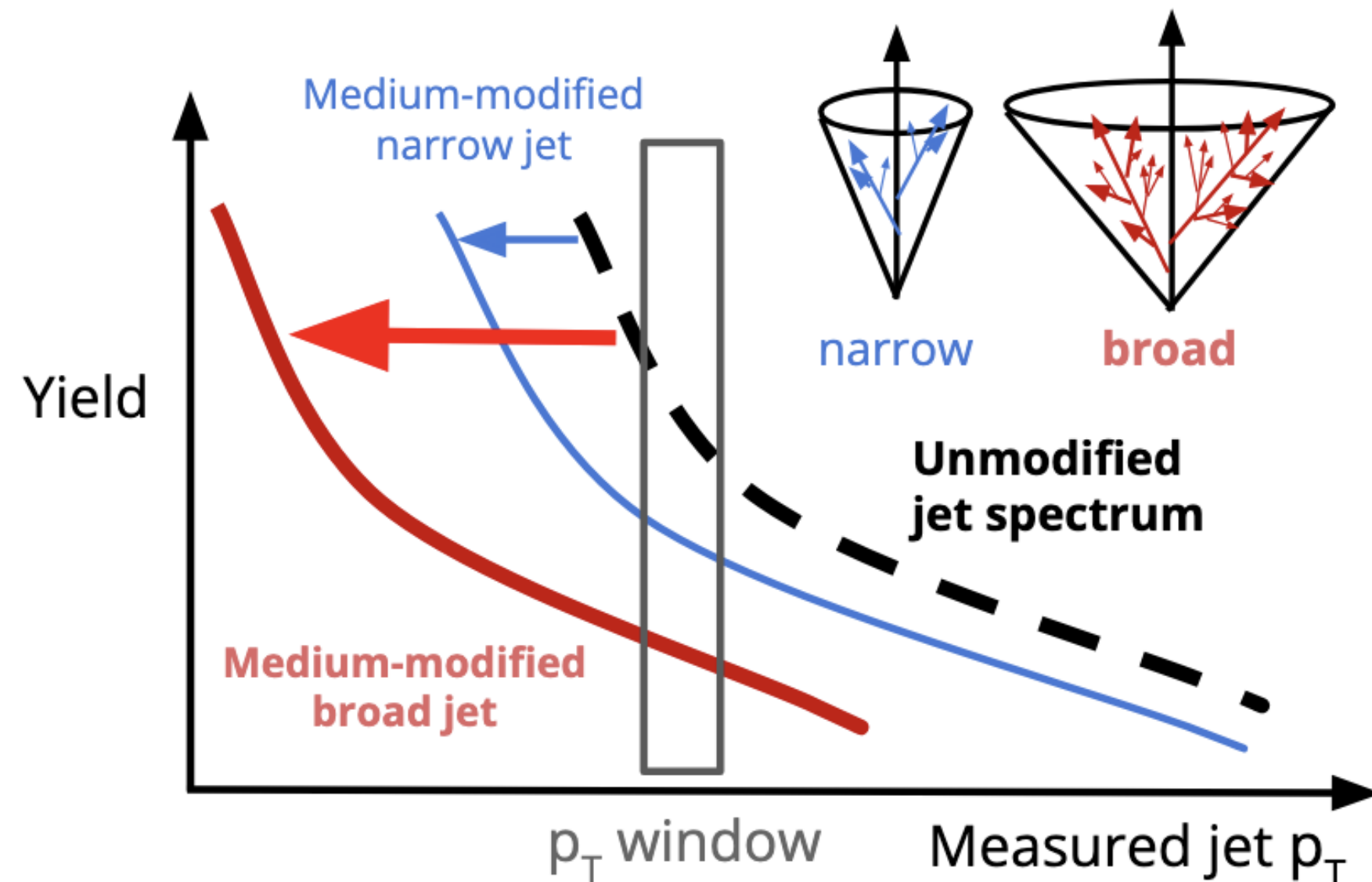
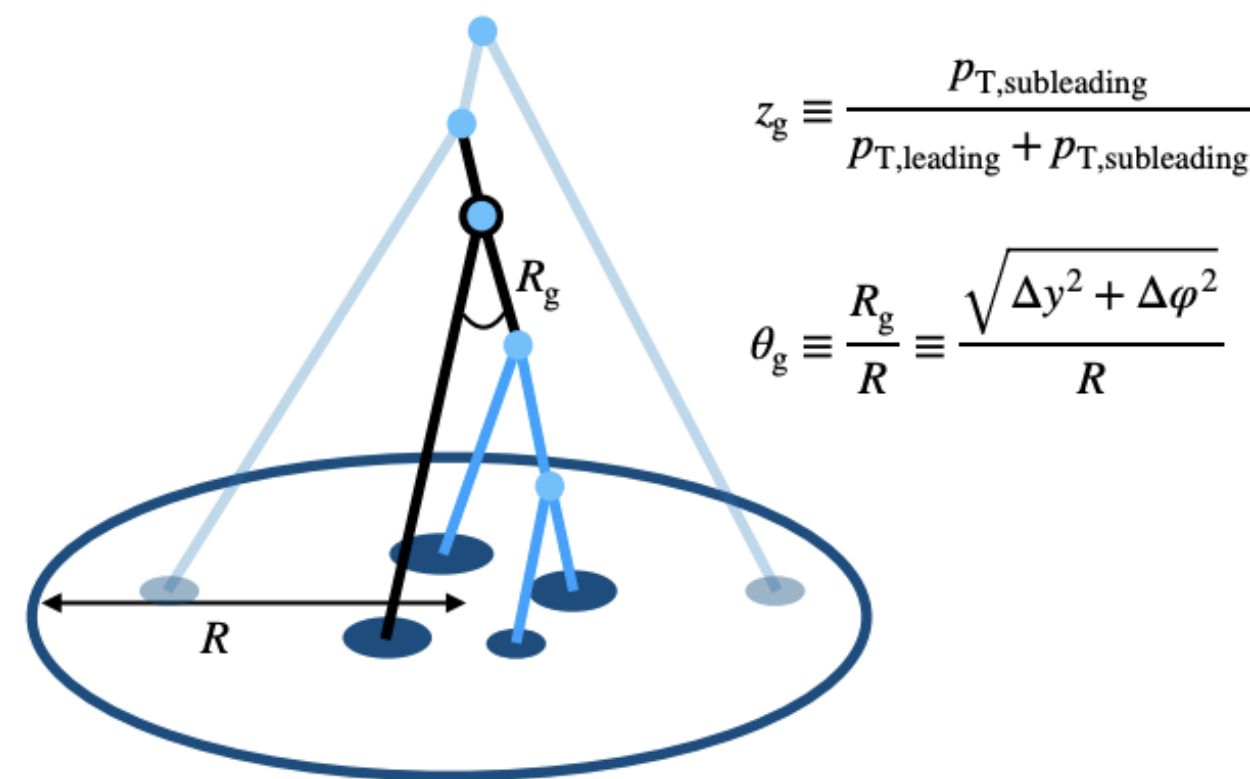
How jets redistribute energy when going through the QGP?



Probe the inner-working of QGP

Jet substructure: Angular scale r_g of the first hard splitting

broad angular structures are more suppressed in PbPb collisions



Energy loss bias (Selection bias): **Wider jets are more suppressed** → **Enriched narrower jets in a fixed p_T range in AA compared to pp**

Energy-Energy Correlators

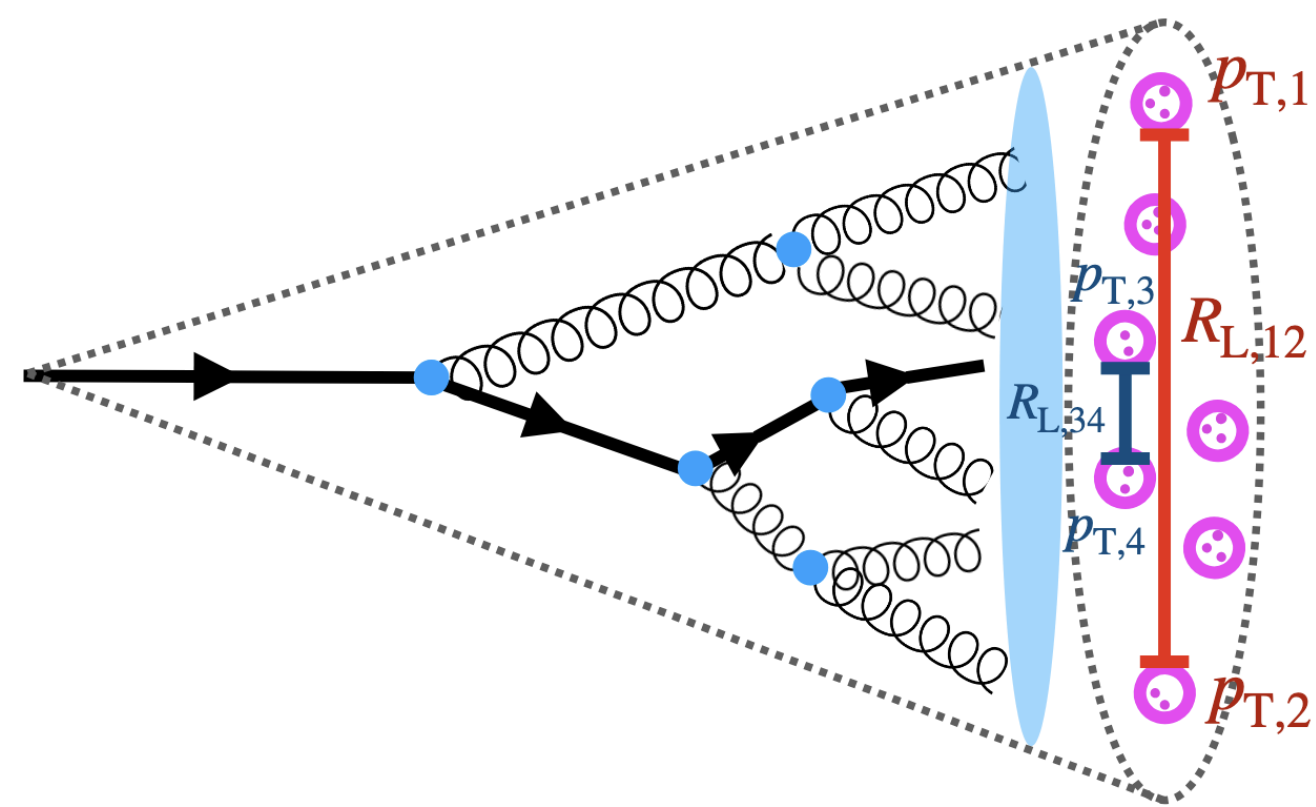


Figure from [Preeti Dhankher\(QNP 2024\)](#)

Energy-energy correlators (EEC) have recently emerged as excellent jet substructure observables for studying the jet shower.

$$EEC(R_L) = \frac{1}{N_{jet}} \sum_{i_1, i_2 \in jet} \int dR_L \frac{p_T^{i_1} p_T^{i_2}}{p_{T,jet}^2} (R_L - \Delta \hat{R}_L)$$

Energy weight

$$R_L = \sqrt{(\eta_{i1} - \eta_{i2})^2 + (\phi_{i1} - \phi_{i2})^2}$$

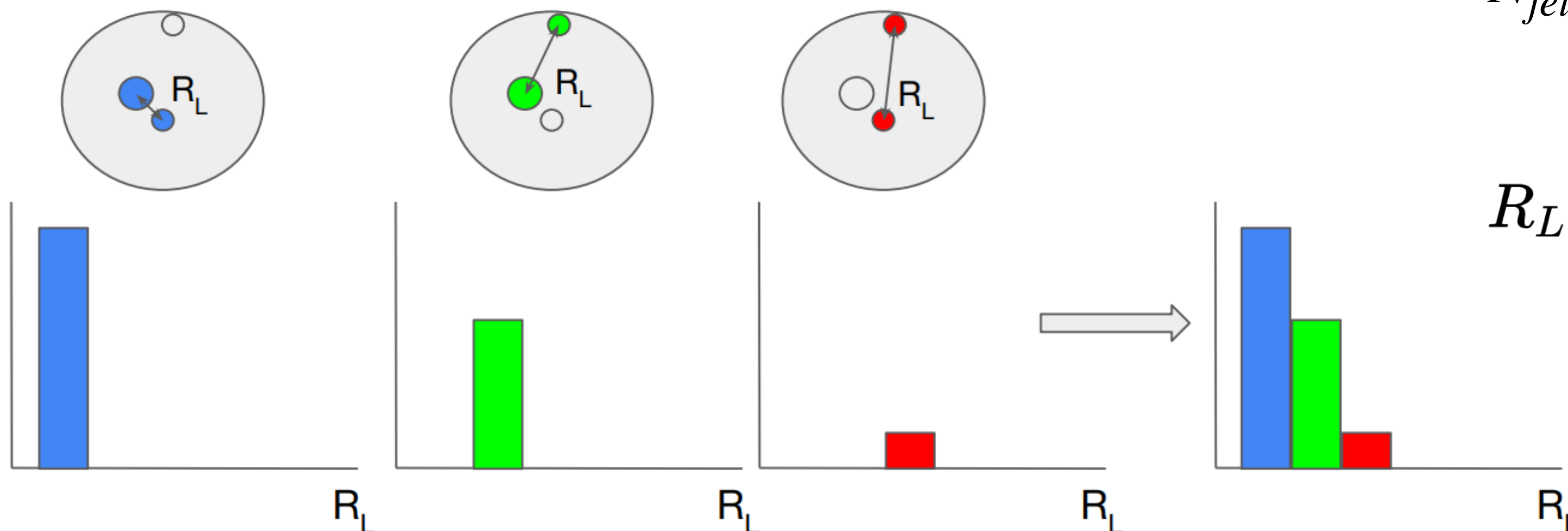
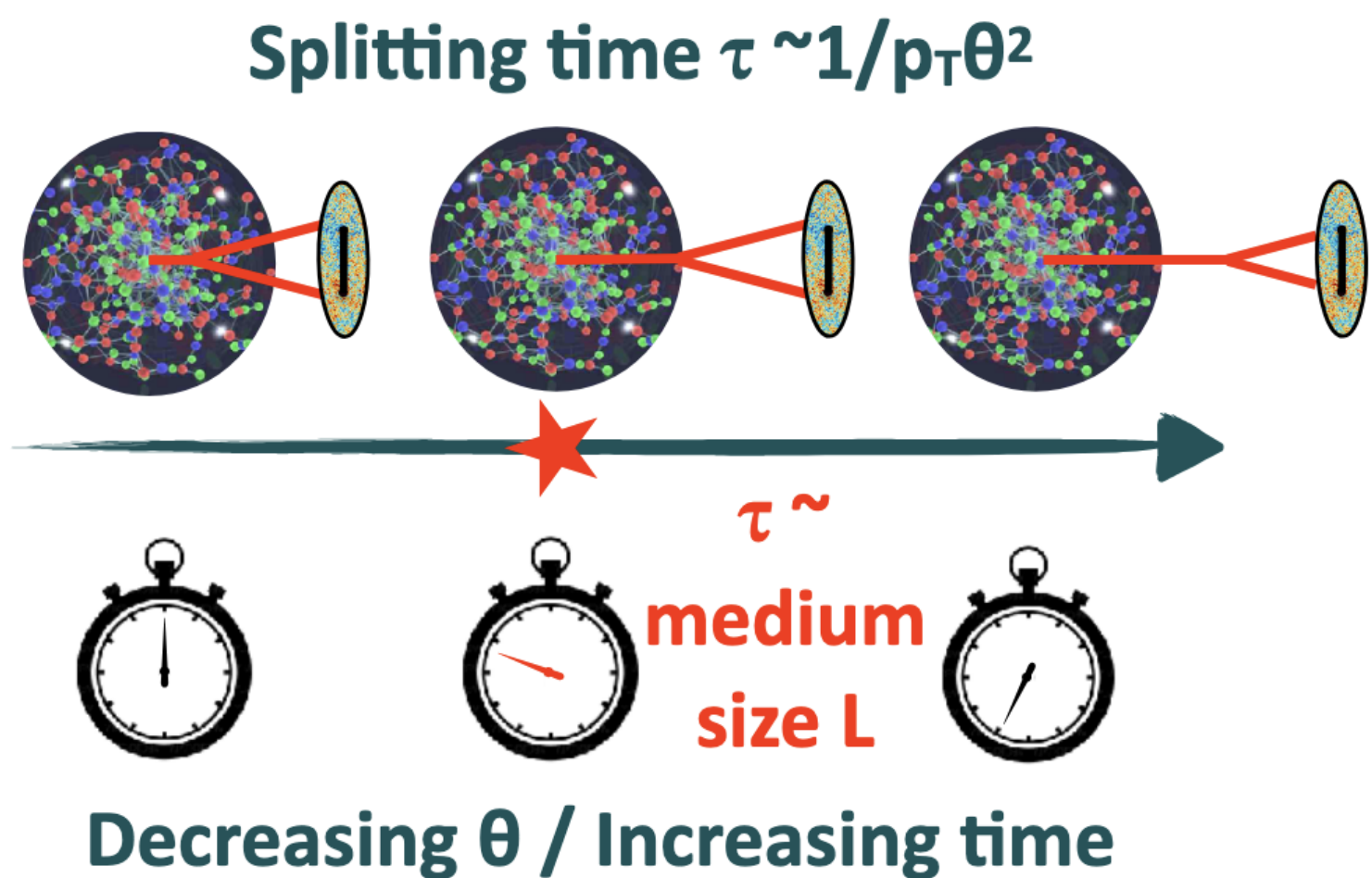


Figure from [Arjun Kudinoor \(quark matter 2025\)](#)

Why do we study energy-energy correlator?

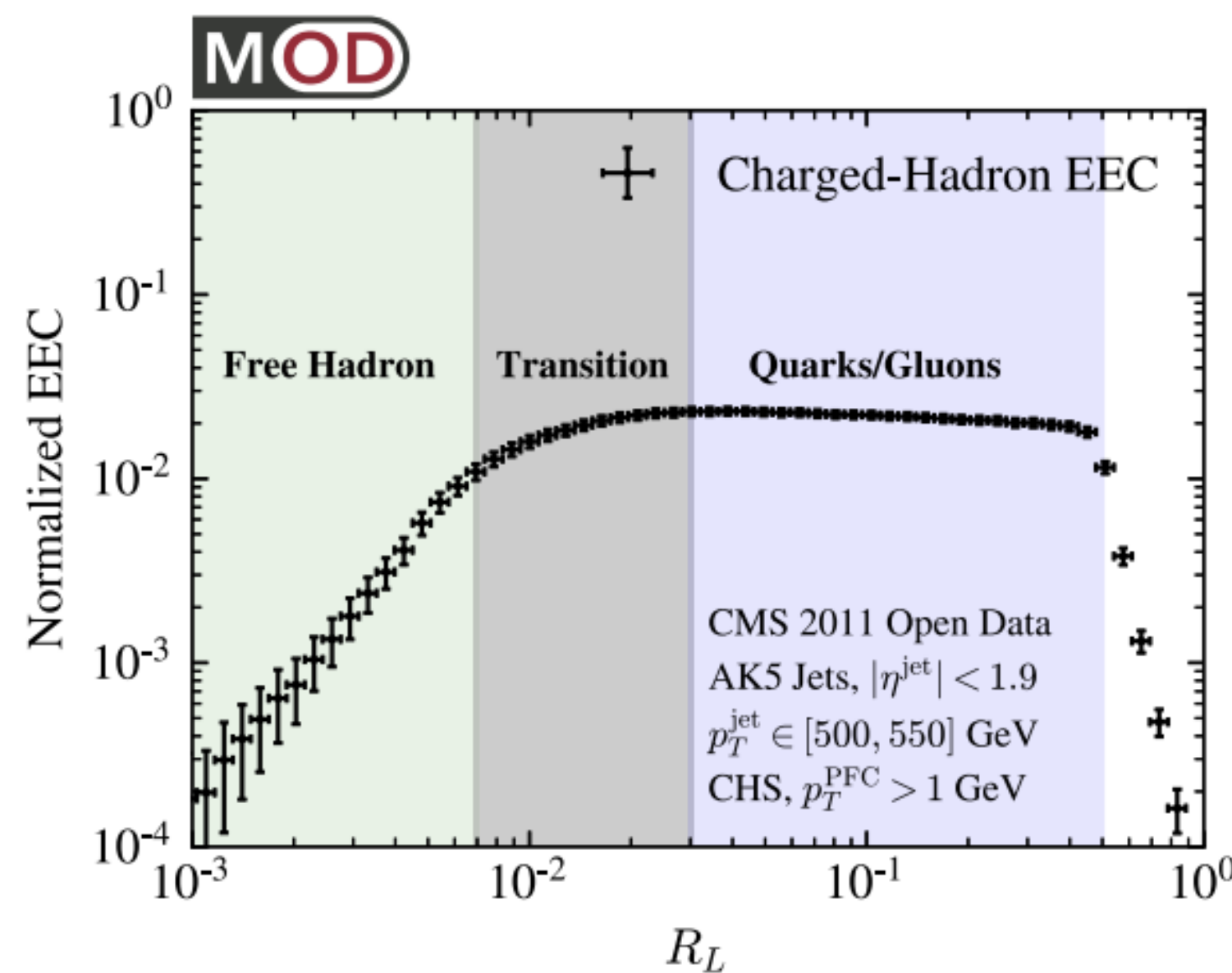


Wenqing Fan ([Quark Matter 2025](#))

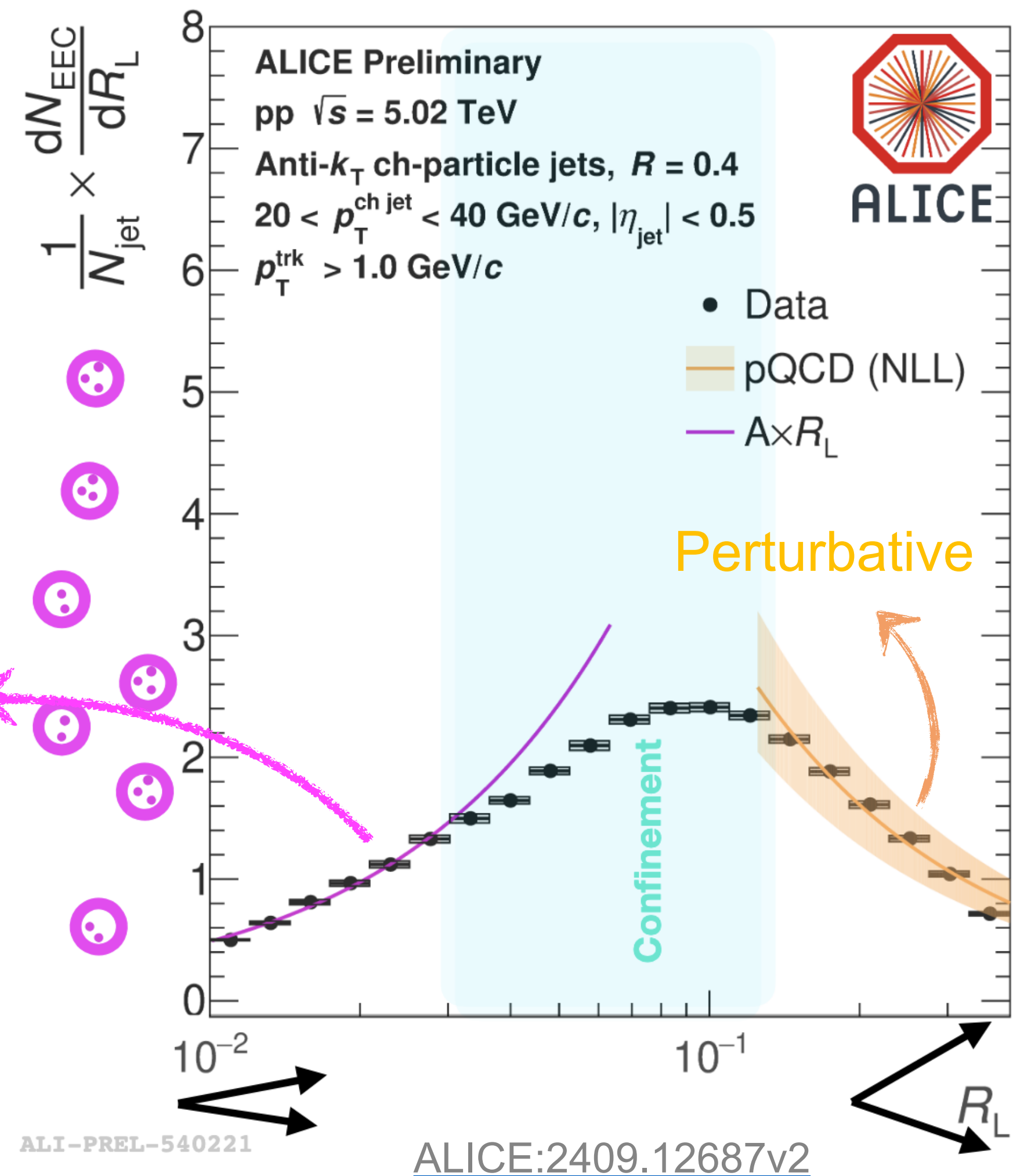
➤ Large angle scaling: $\frac{d \Sigma_{EEC}}{d\theta} \sim \frac{1}{\theta}$, perturbative, hard scattering

➤ Transition angle region: $\frac{d \Sigma_{EEC}}{d\theta}$, non-perturbative, transition

➤ Small angle: $\frac{d \Sigma_{EEC}}{d\theta} \sim \theta$, uncorrelated Paris, but sensitive to hadronization

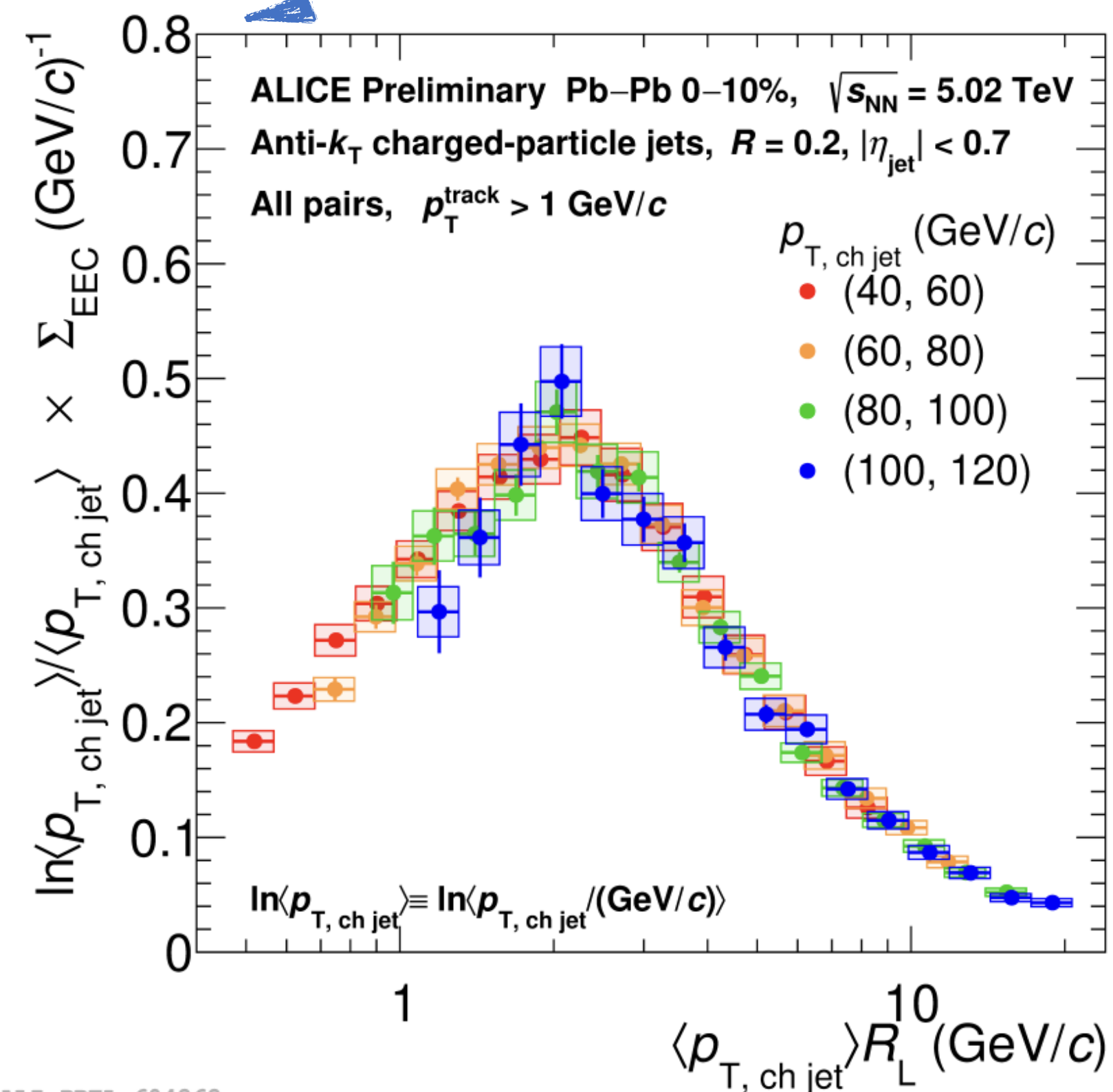
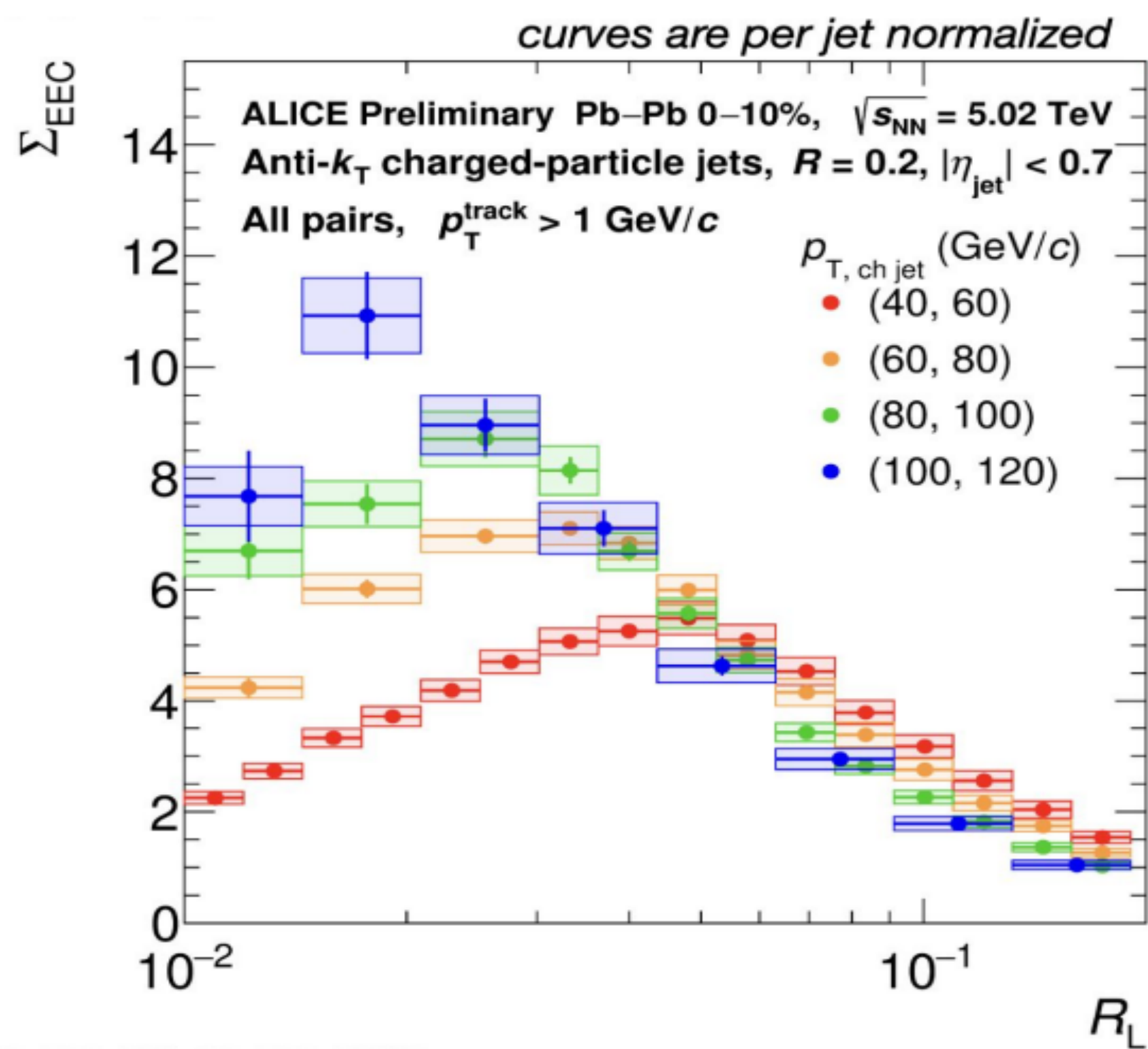


Hadron physics



Universal transition behavior

Scaling angle R_L by jet p_T and normalizing the y-scale.



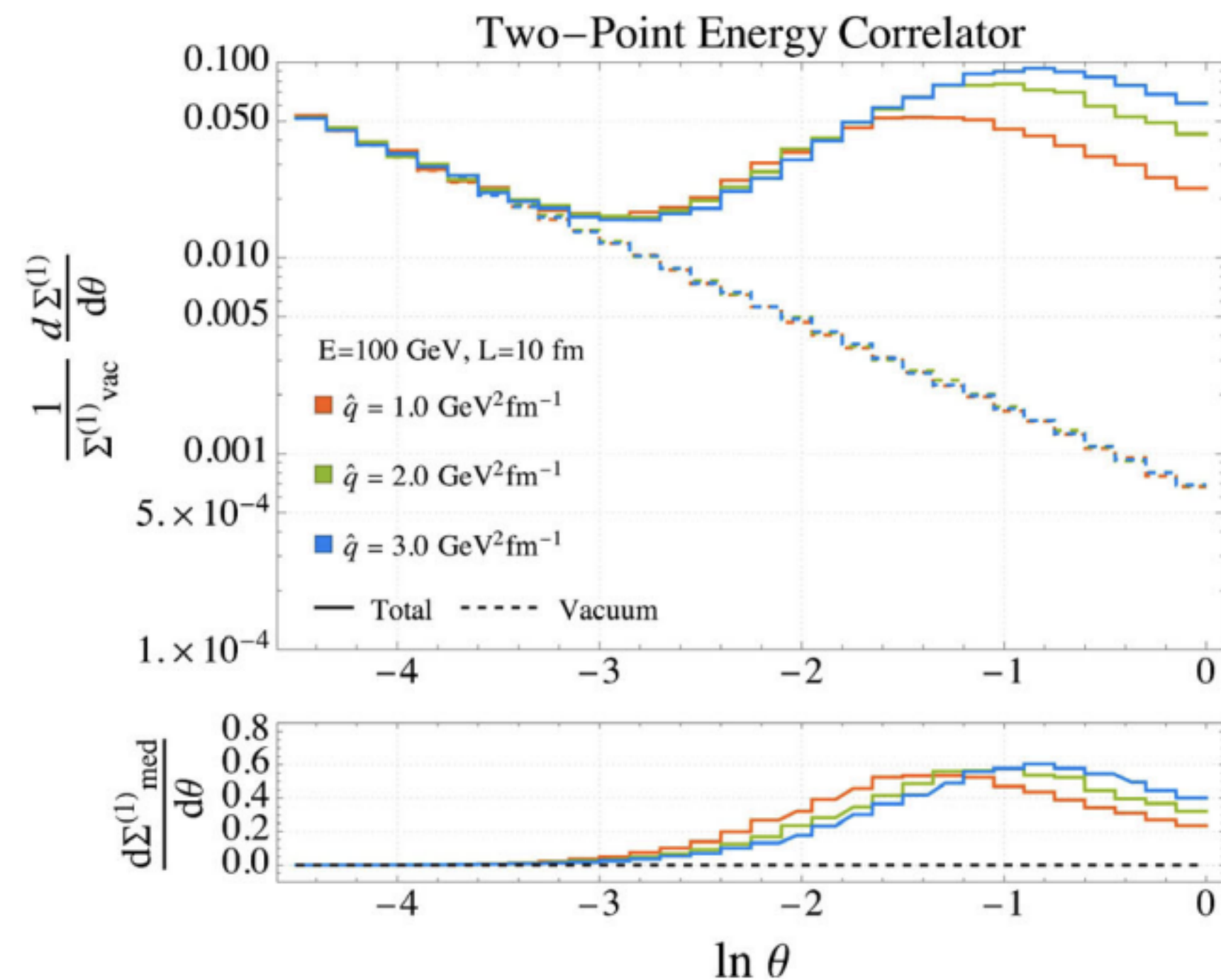
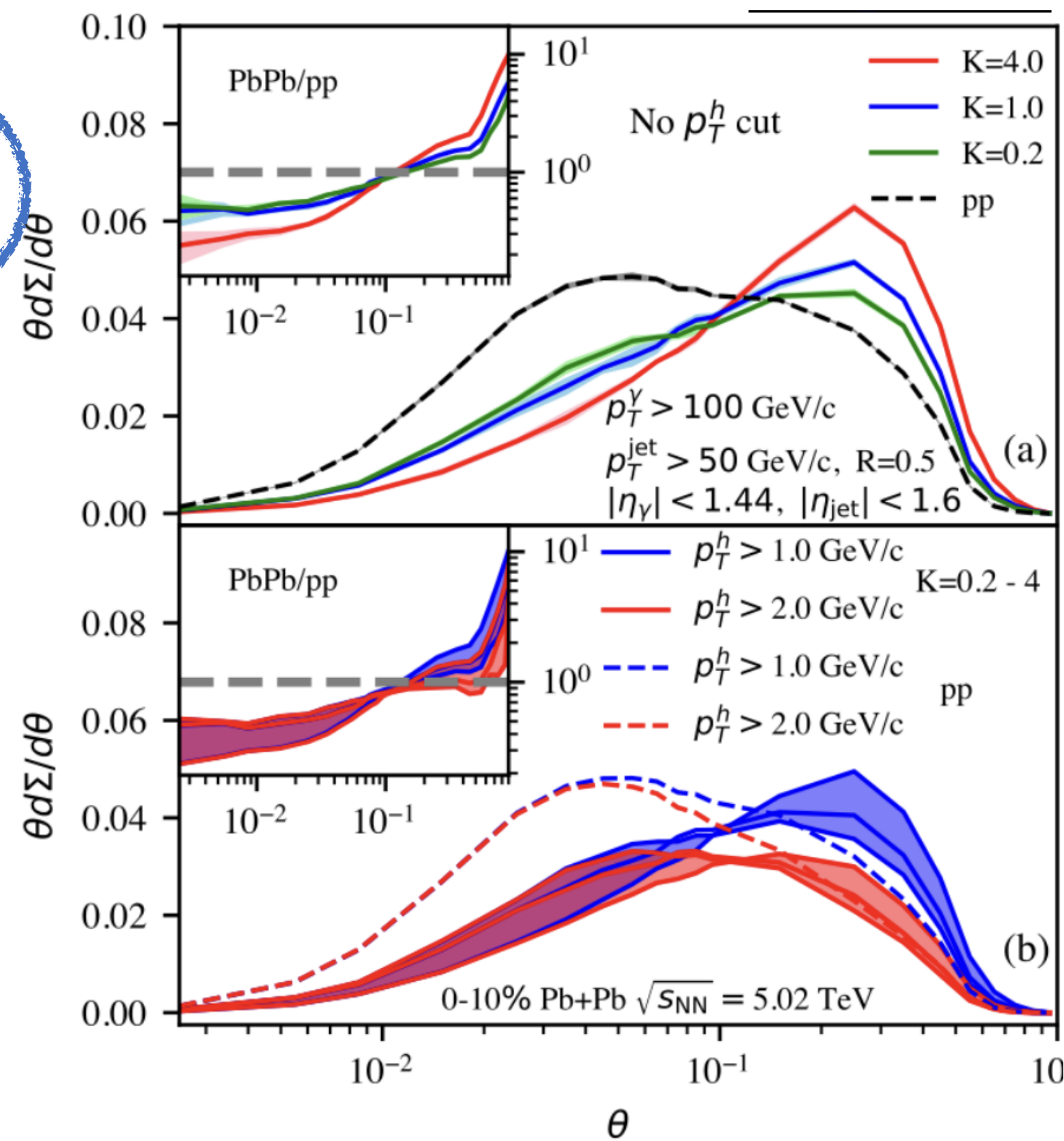
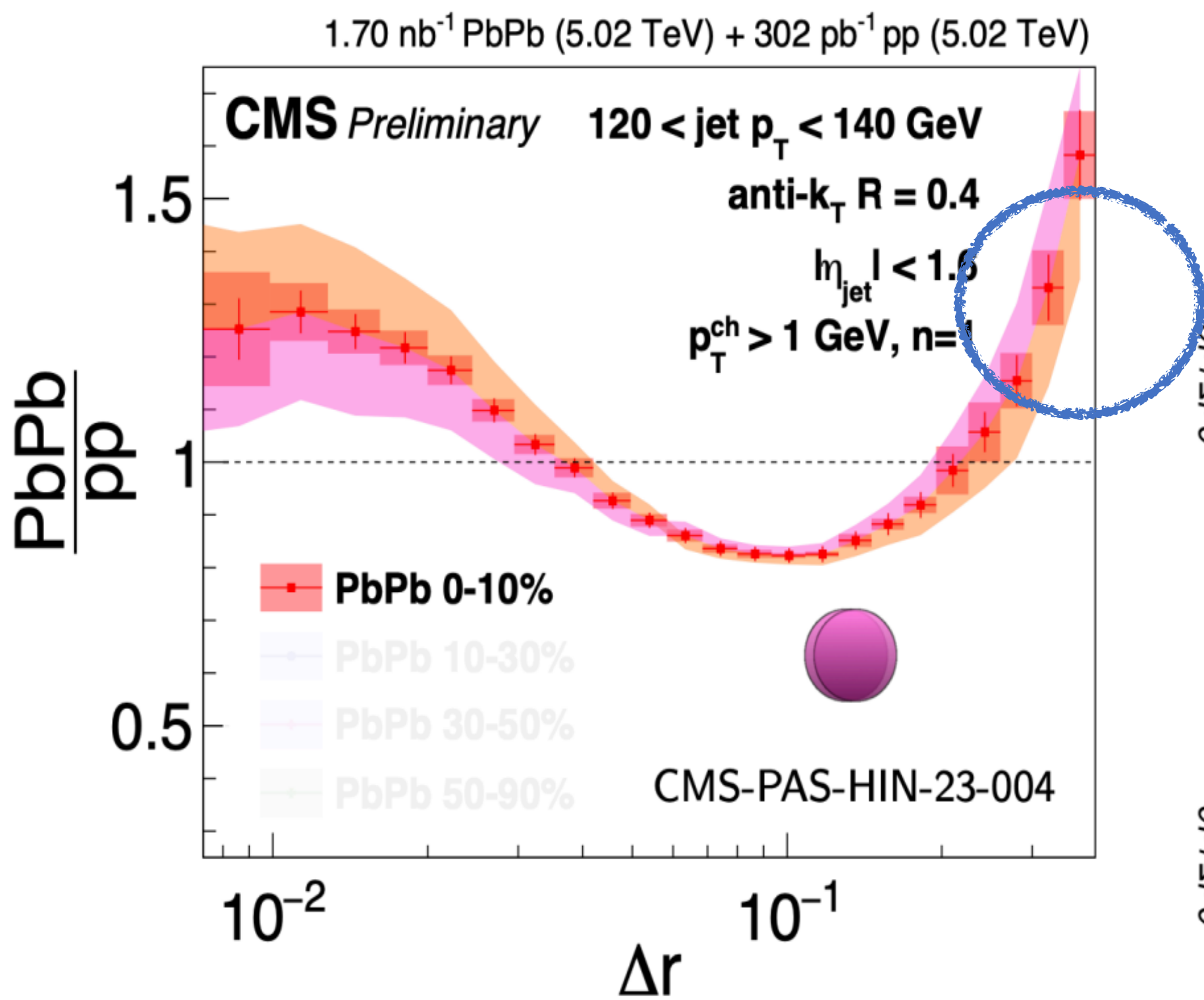
$$\Lambda_{QCD} \sim p_{T, jet} R_L$$

EECs distribution in different jet p_T aligns around 2.4 GeV/c
→ Universal scaling behavior !

EEC of single jet in Pb+Pb collisions at CMS

- Large angle:
- Medium response
- Medium-induced radiation

CMS, arXiv: [2503.19993](https://arxiv.org/abs/2503.19993)



Carlota Andres et al. [PRL 130, 262301](https://arxiv.org/abs/130.262301)

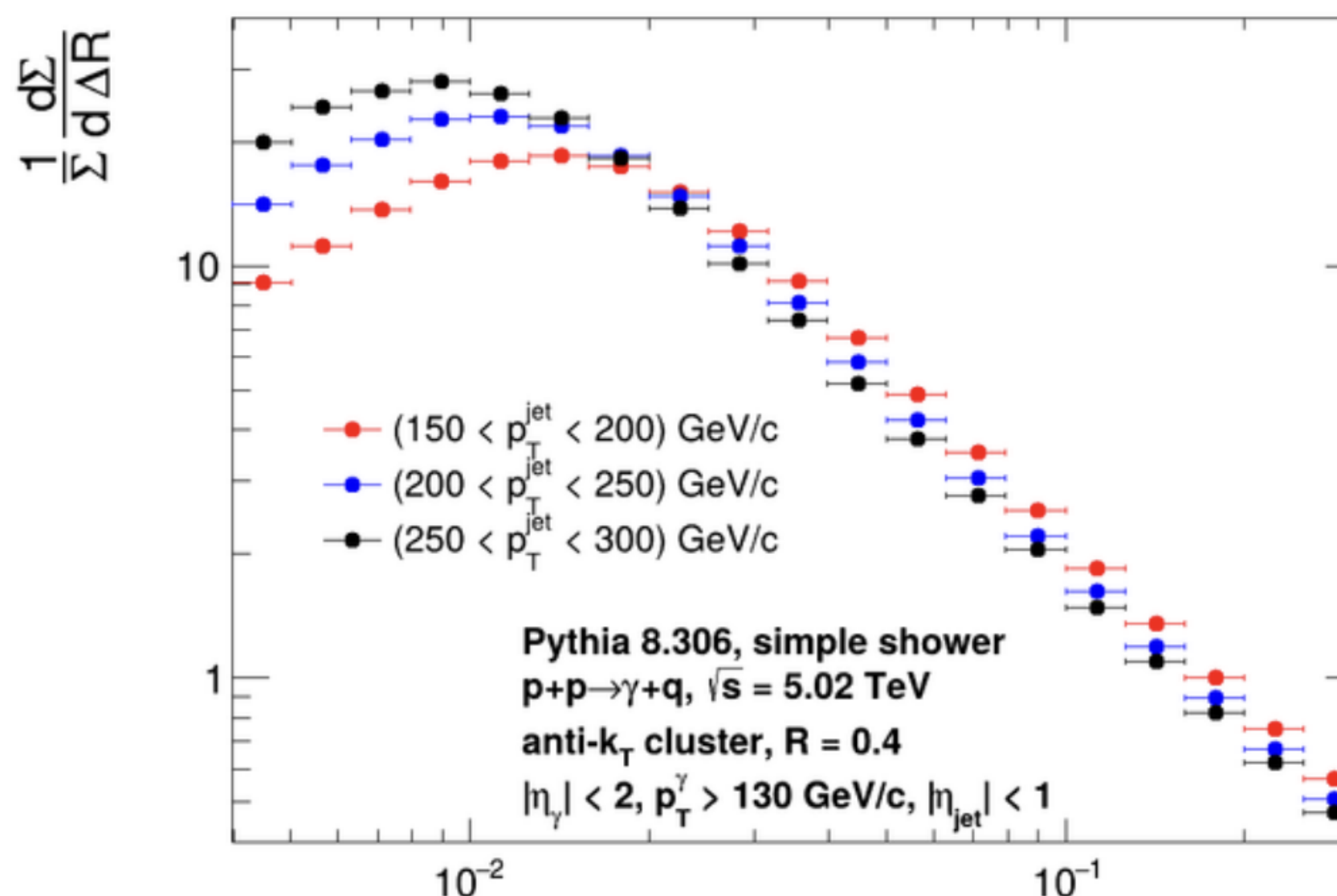
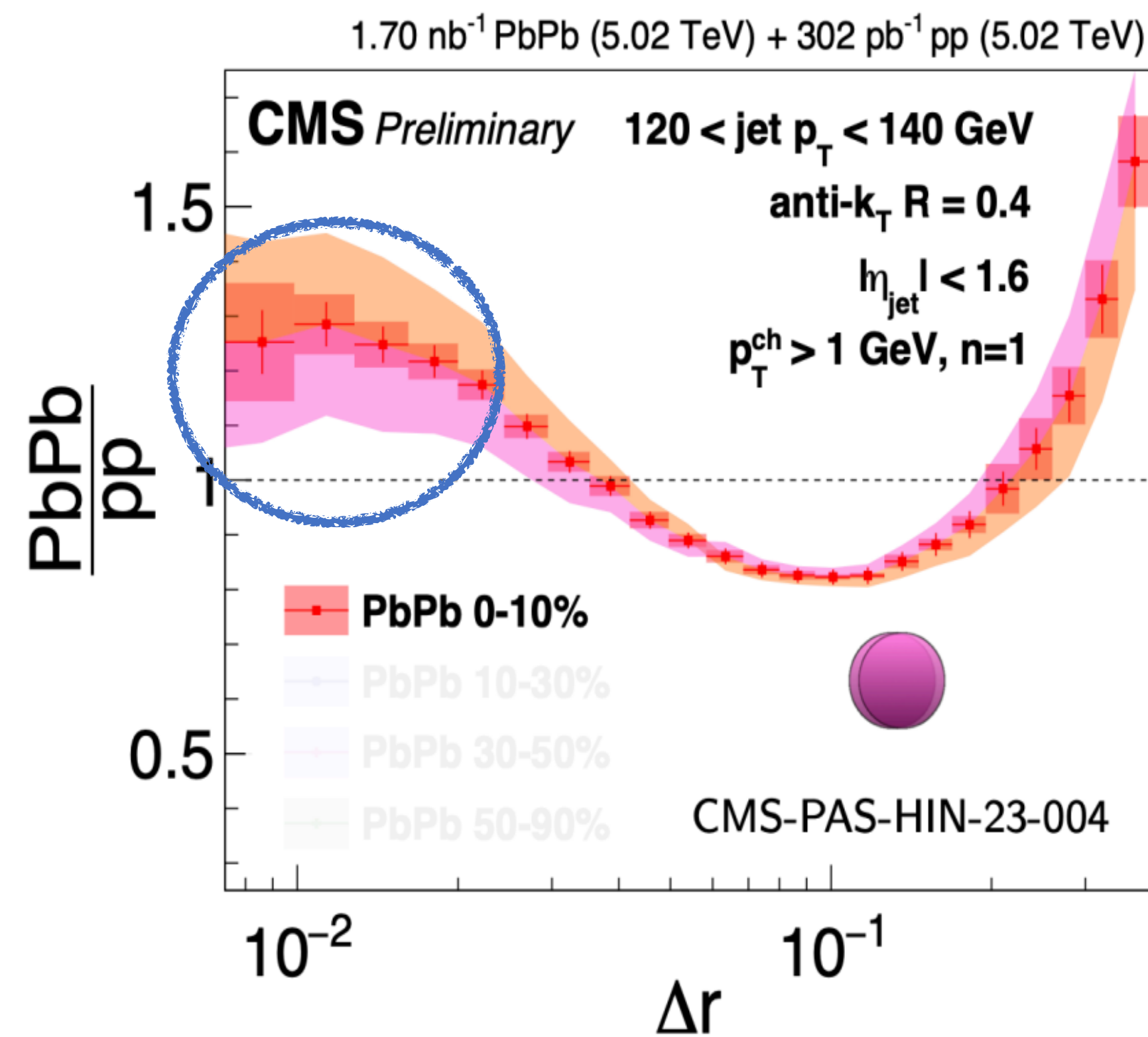
zhong.Y PRL 132 (2024) 1, 011901

EEC of single jet in Pb+Pb collisions at CMS

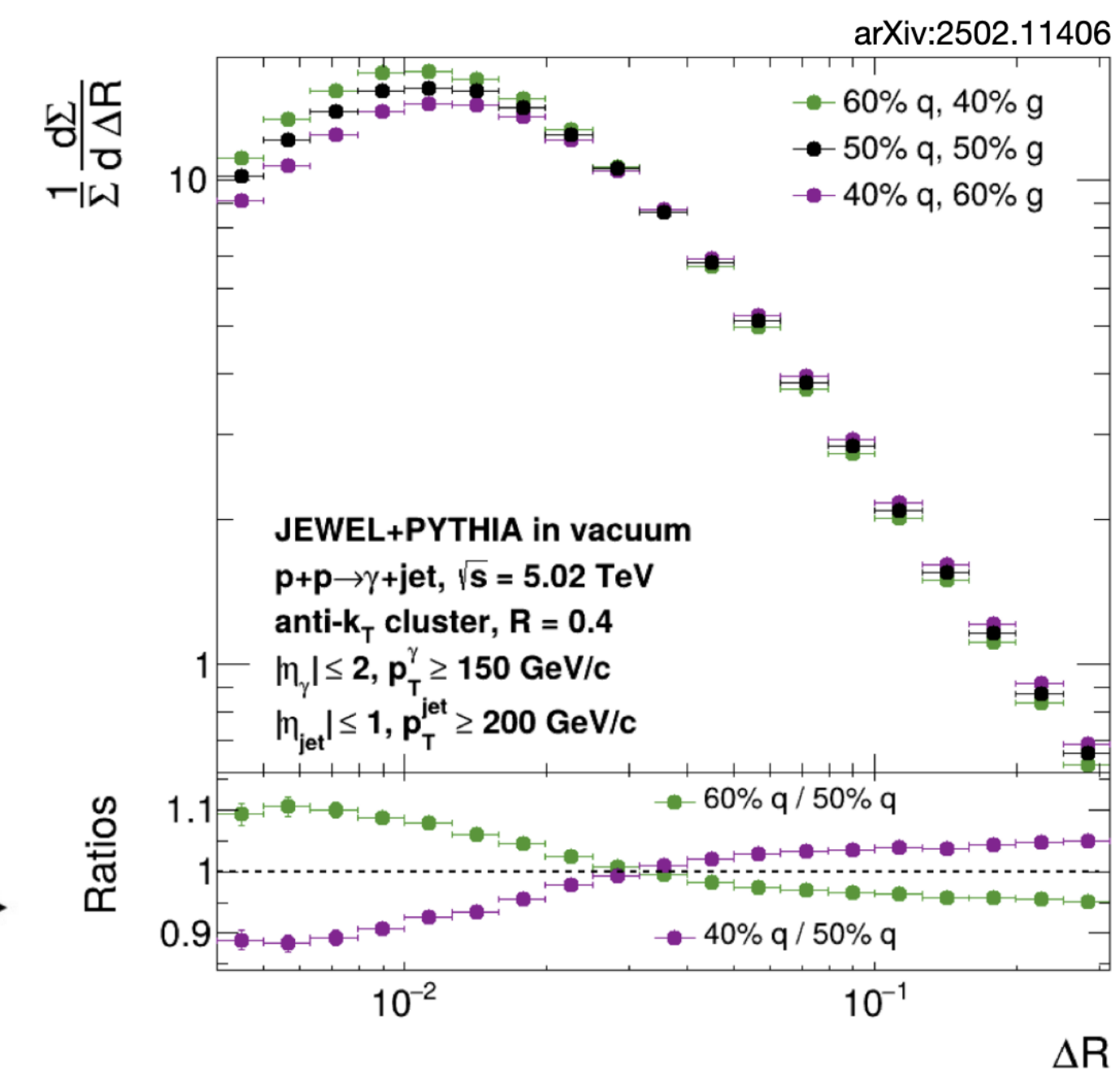
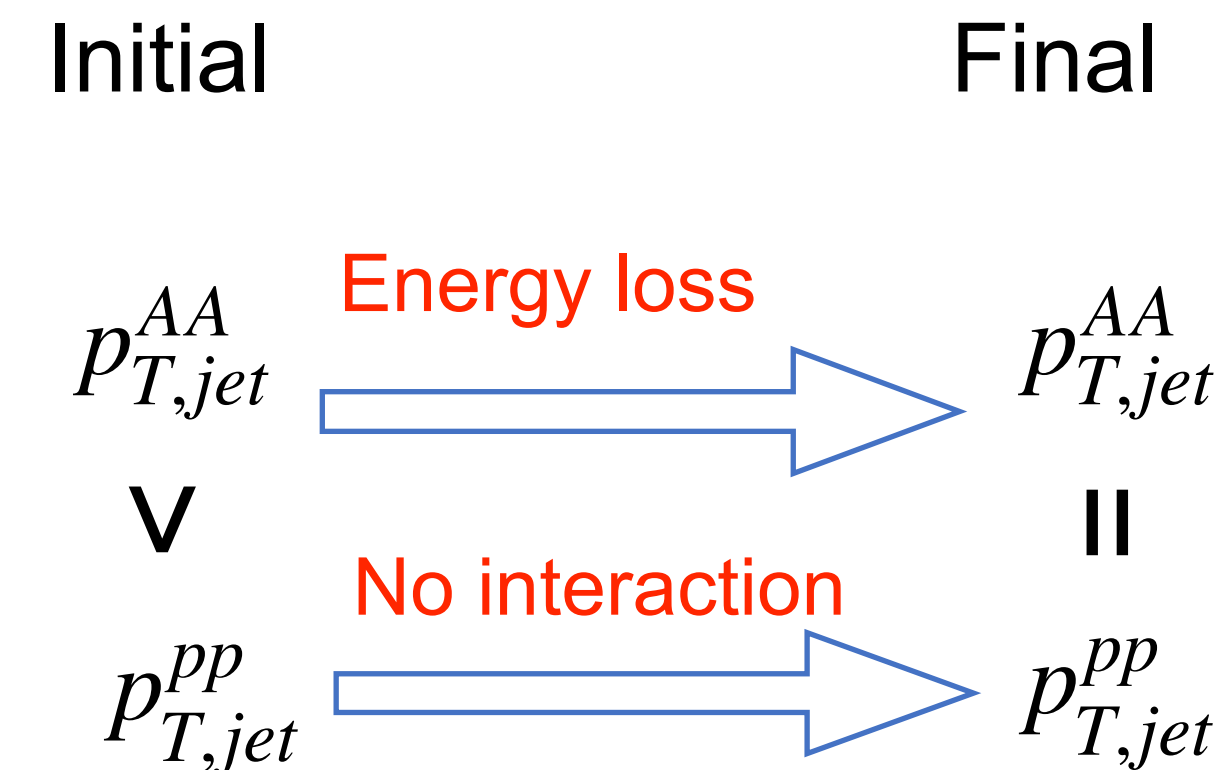
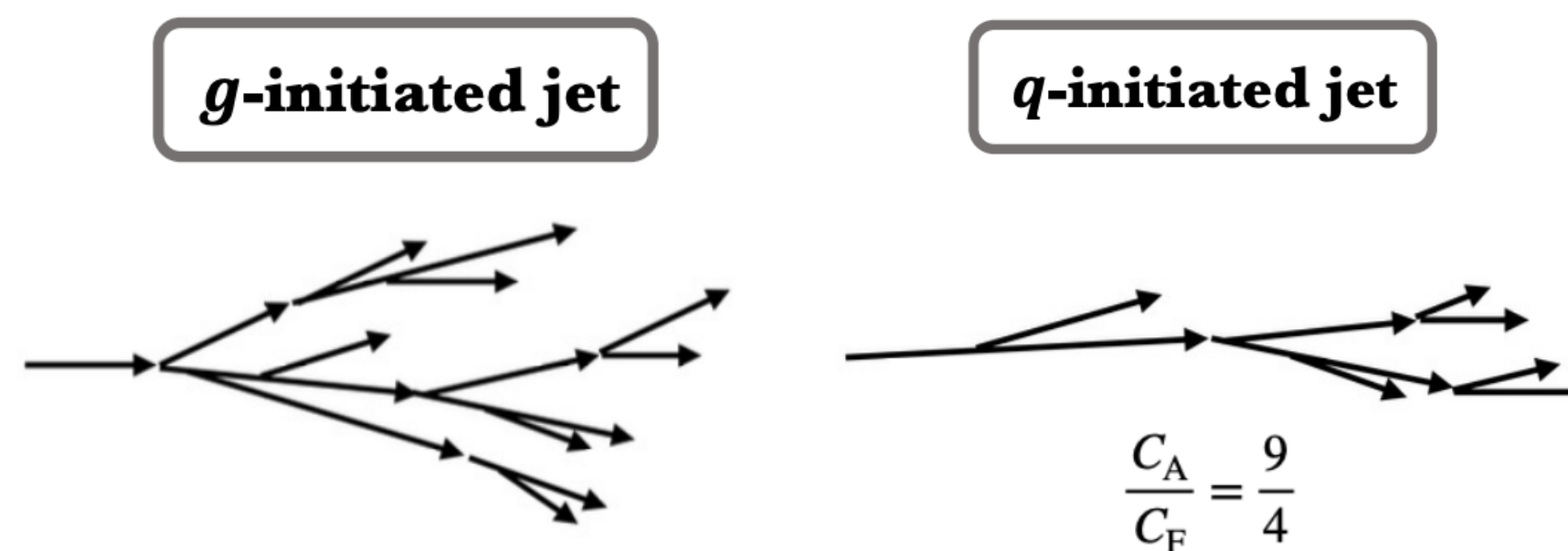
➤ Small angle:

● Jet pT selection bias

CMS, arXiv:2503.19993

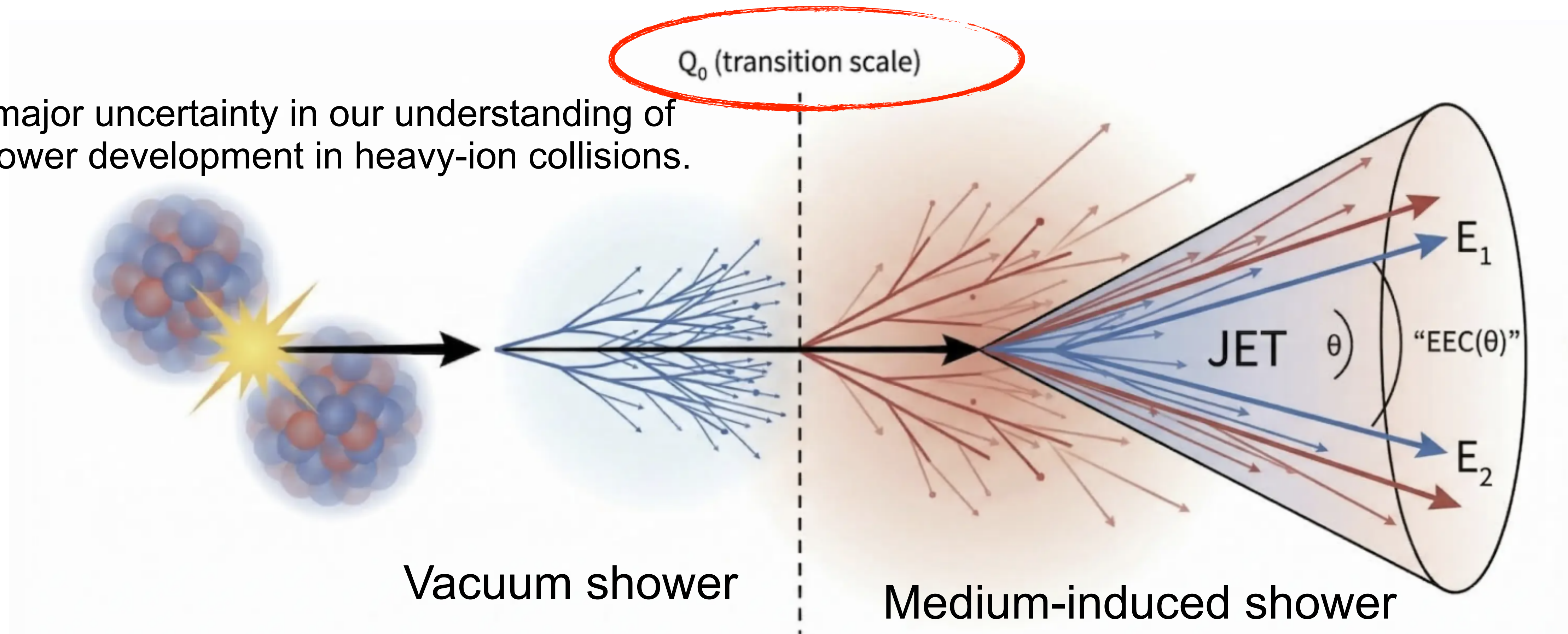


● Flavor dependence of jet



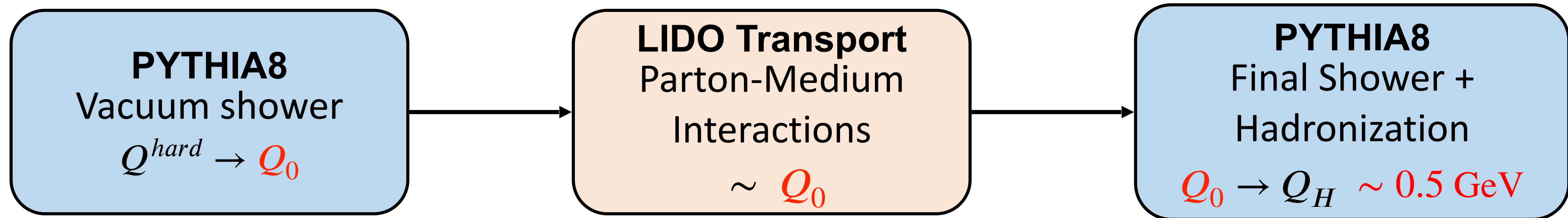
What else can EEC tell about parton shower in the medium?

A major uncertainty in our understanding of shower development in heavy-ion collisions.



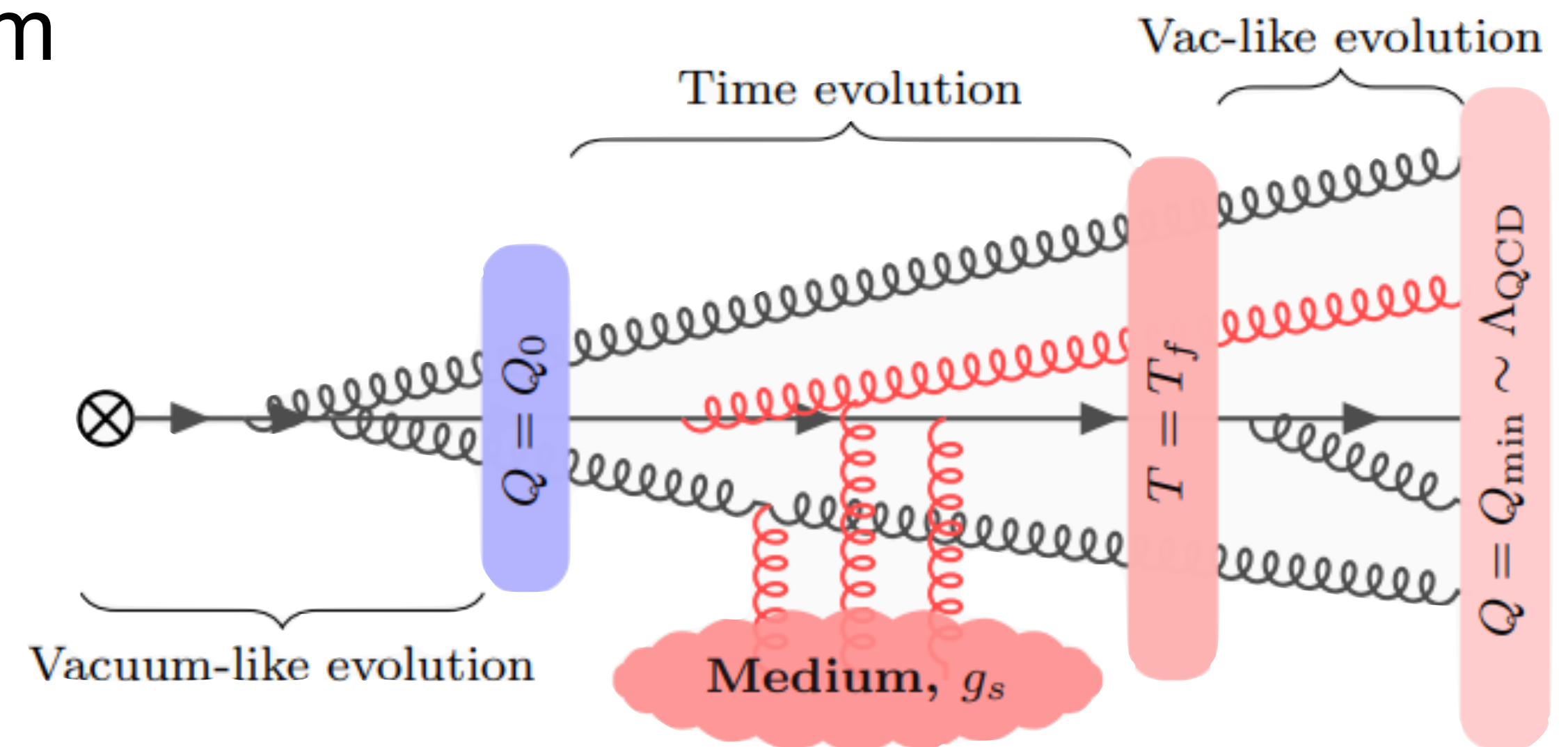
Use EEC to probe the impact of the transition scale Q_0 between vacuum and medium-induced showers.

Our tool to study jet in medium: the LIDO Model



Framework Components

- **PYTHIA8**: Initial jet production and Vacuum shower evolution
- **LIDO**: In-medium transport (Partons decouple below $T < T_f$)
- **PYTHIA8**: Vacuum shower + fragmentation.
- **2+1D Hydrodynamics**: QGP background evolution



[PRC 100\(2019\)064911](#)

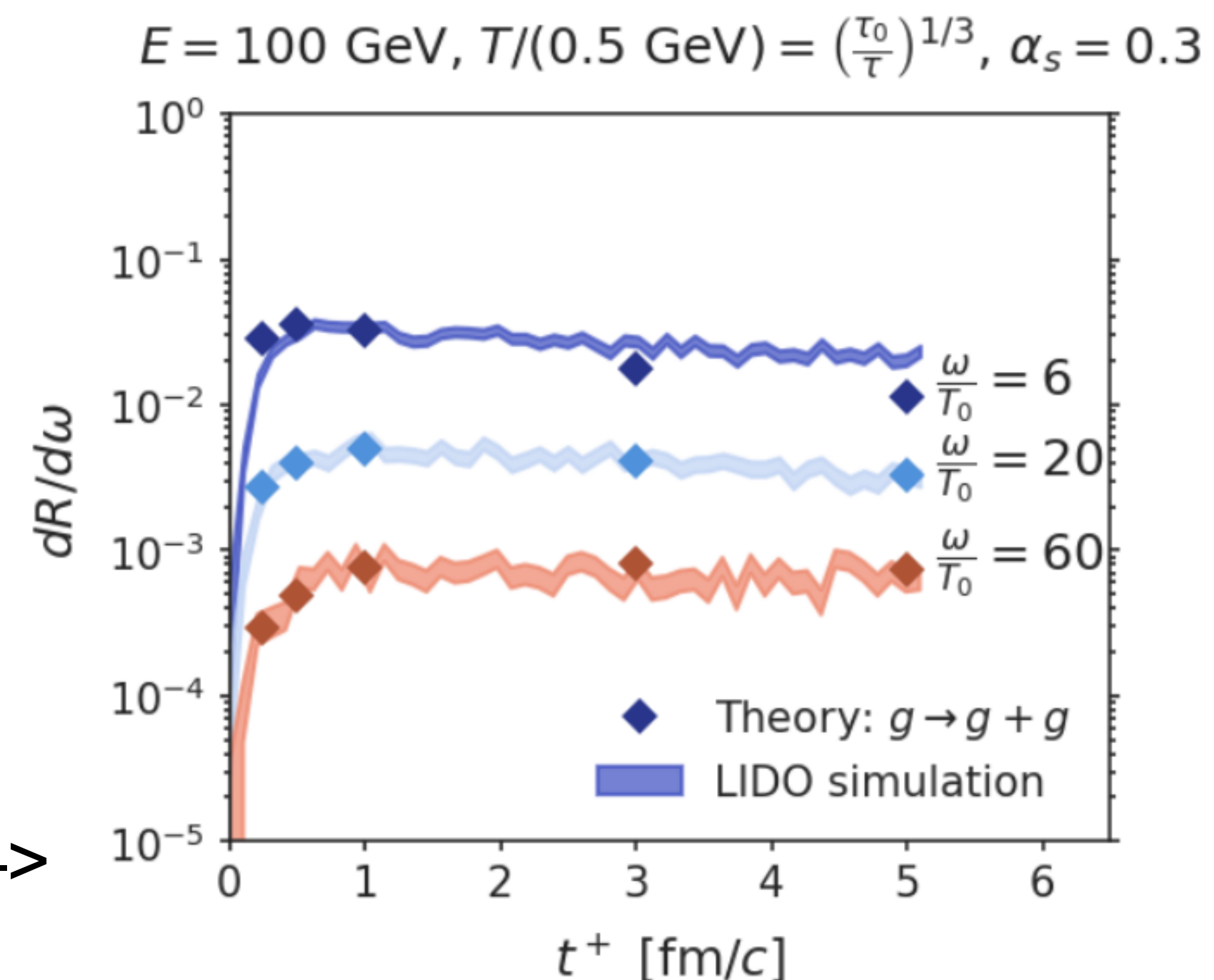
LIDO modeling: 1. hard parton transport

The semiclassical transport equation for hard partons ($p \cdot u > E_{min}$) in the incoherent limit is:

$$p \cdot \partial [f \Theta(p \cdot u - E_{min})] = (p \cdot u) \Theta(p \cdot u - E_{min}) \{ D + C_{1 \leftrightarrow 2} + C_{2 \leftrightarrow 2} + C_{2 \leftrightarrow 3} \}$$

- Diffusion term: $D[f]$
- Large-momenta-transfer elastic collisions: $C_{2 \rightarrow 2}[f]$
- Diffusion-induced parton splitting/merging: $C_{1 \rightarrow 2}[f]$
- Large-momenta-transfer inelastic collisions: $C_{2 \rightarrow 3}[f]$
- $E_{min} = \theta T$, θ is a parameter

LPM coherence is implemented in real-time simulation →



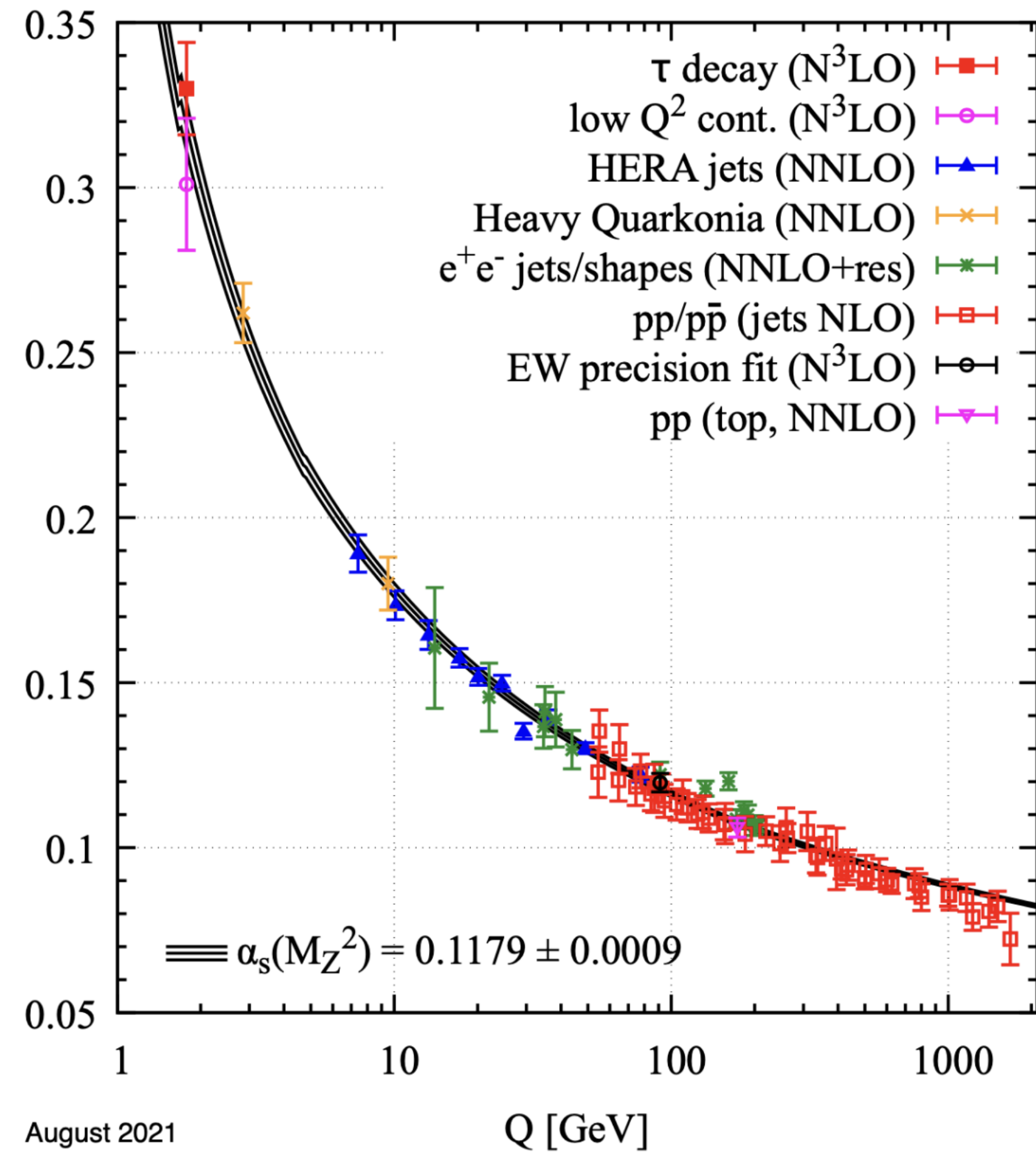
[PRC 82 \(2010\) 064902](#)
[PRC 58 \(1998\) 1706](#)

LIDO modeling: 2. temperature-dependent running coupling

☺ The strong coupling $\alpha_s(Q, T)$ ceases to run for momentum transfers below the thermal scale:

$$\alpha_s(Q, T) = \frac{4\pi}{9} \cdot \frac{1}{\ln\left(\frac{\max\{Q^2, \mu_{\min}^2\}}{\Lambda_{\text{QCD}}^2}\right)}$$

$$\mu_{\min} = C_M \times \pi T$$



LIDO modeling: 3. a simplified medium linear response model

- Energy-momentum deposition to soft sector:

$$\frac{d\delta p^\mu}{dt}(t, \mathbf{x}) = \int_p \Theta(p \cdot u < E_{\min}) p^\mu \frac{d}{dt} f_H(t, \mathbf{x}, p)$$

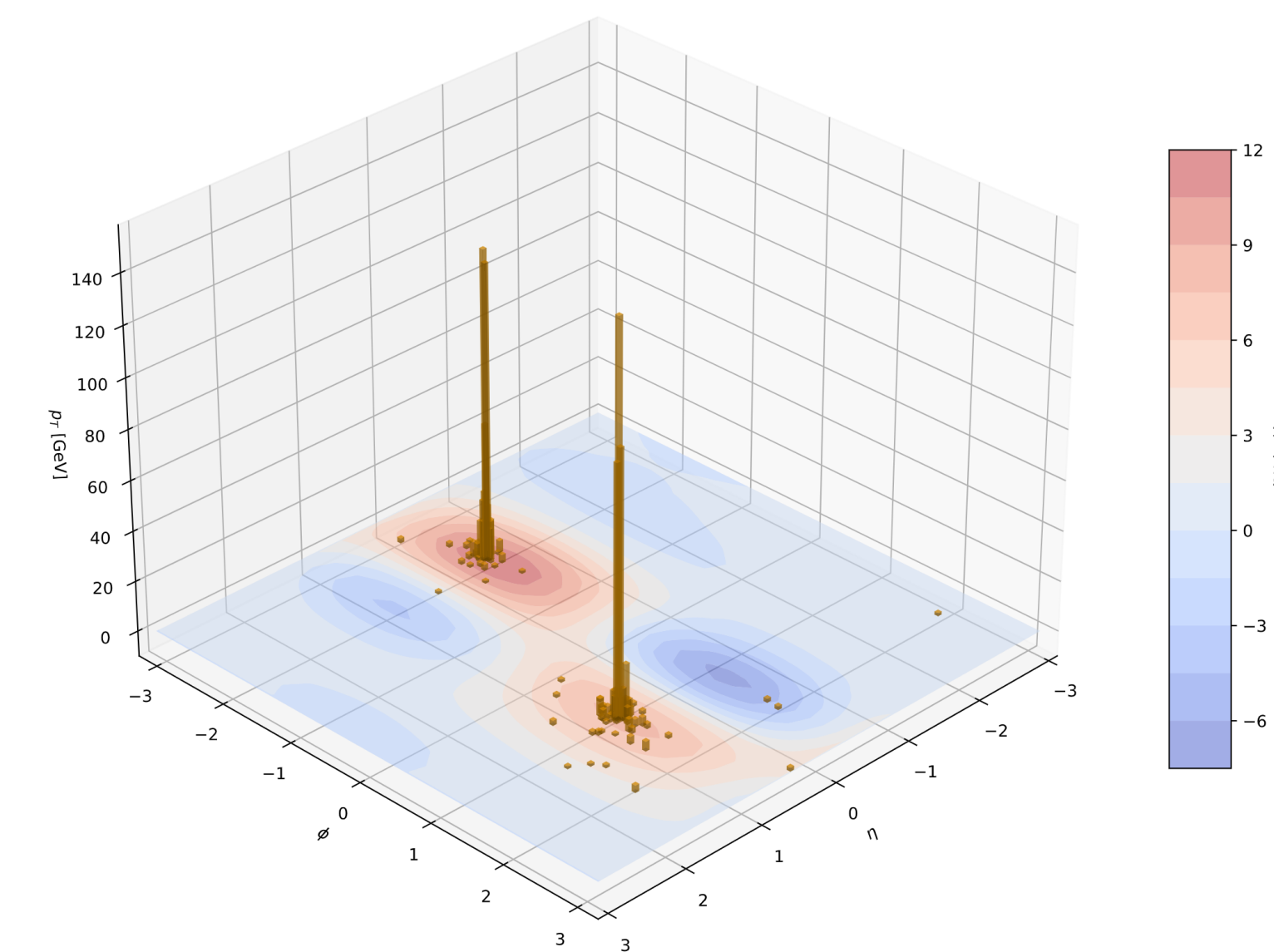
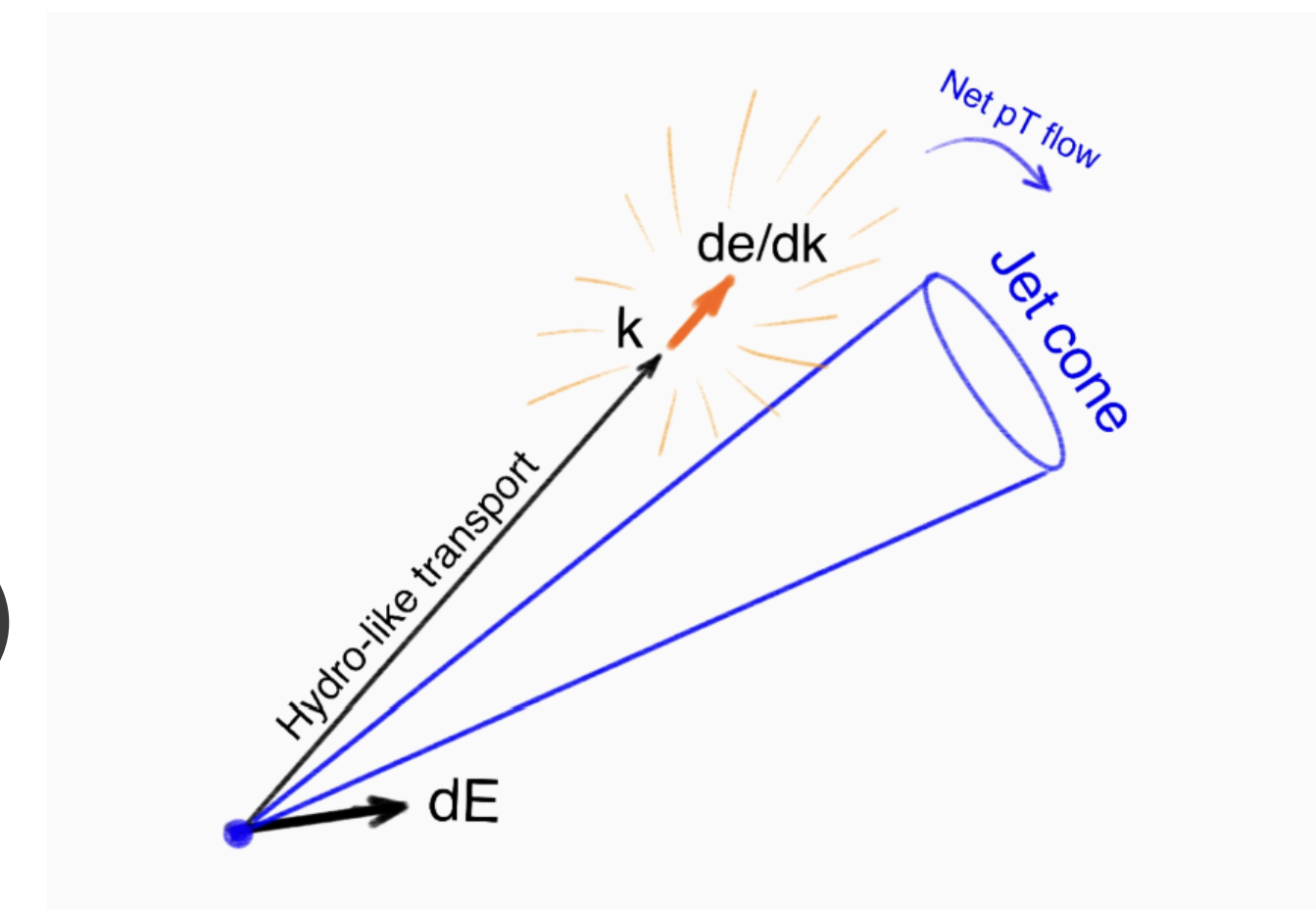
- Ideal-hydro response in real space (no transverse flow)

$$\frac{de}{d\Omega'_k} = \frac{\delta p^0 + \hat{k}' \cdot \delta \vec{p} / c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega'_k} = \frac{3(c_s \delta p^0 + \hat{k}' \cdot \delta \vec{p}) \hat{k}'}{4\pi}$$

- Freeze-out to massless particles under a radial transverse flow $v_\perp \Rightarrow$ corrects the momentum density in $\eta - \phi$ plane.

$$\frac{d\Delta p_T}{d\phi d\eta} = \int \frac{3}{4\pi} \frac{\frac{4}{3} \sigma u_\mu - \hat{p}_\mu}{\sigma^4} \delta p^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}$$

$$\sigma = \gamma_\perp [\cosh(\eta - \eta_s - \eta_{\hat{k}}) - v_\perp \cos(\phi - \phi_{\hat{k}})]$$

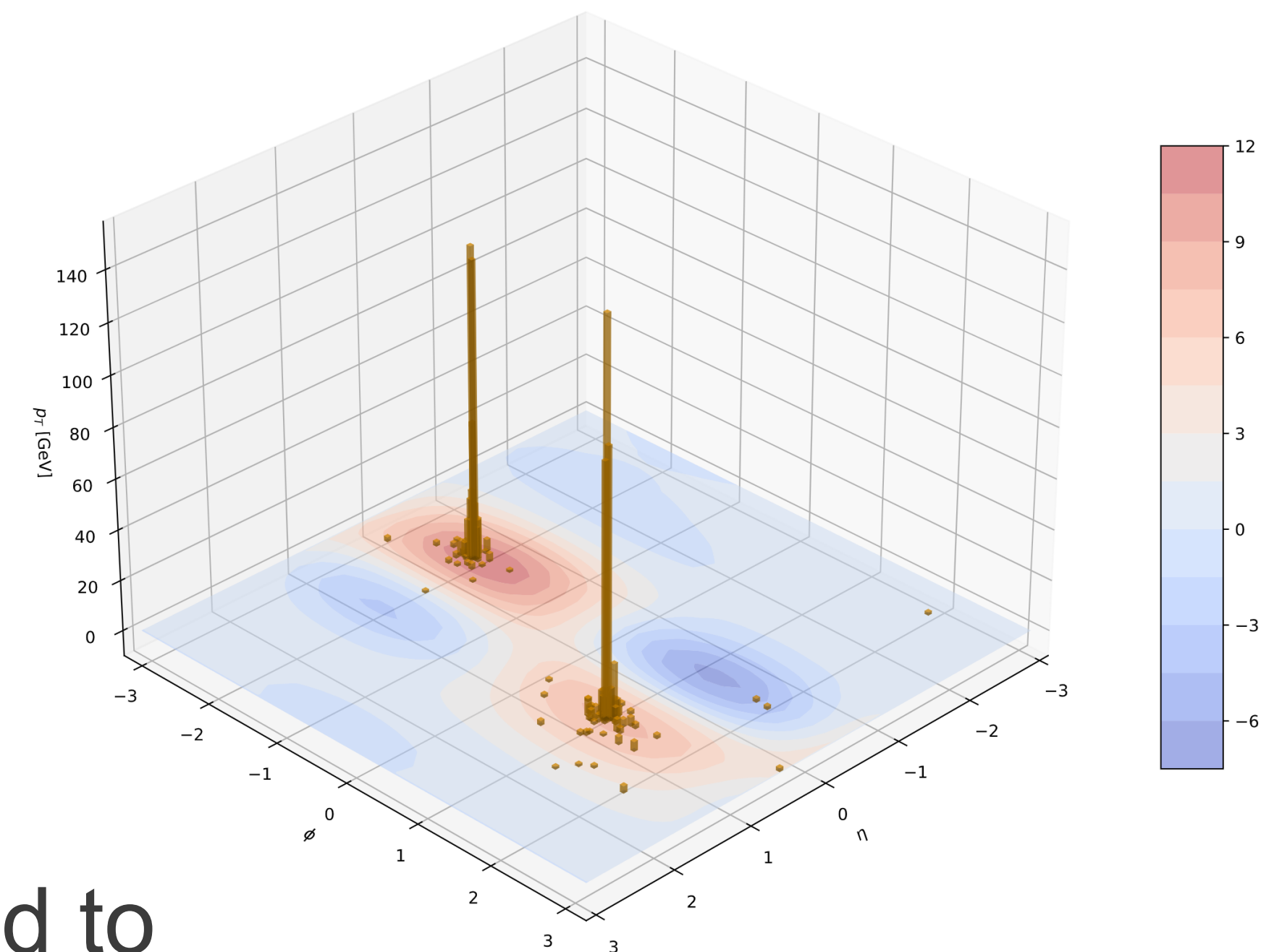


Jet definition in LIDO with medium response

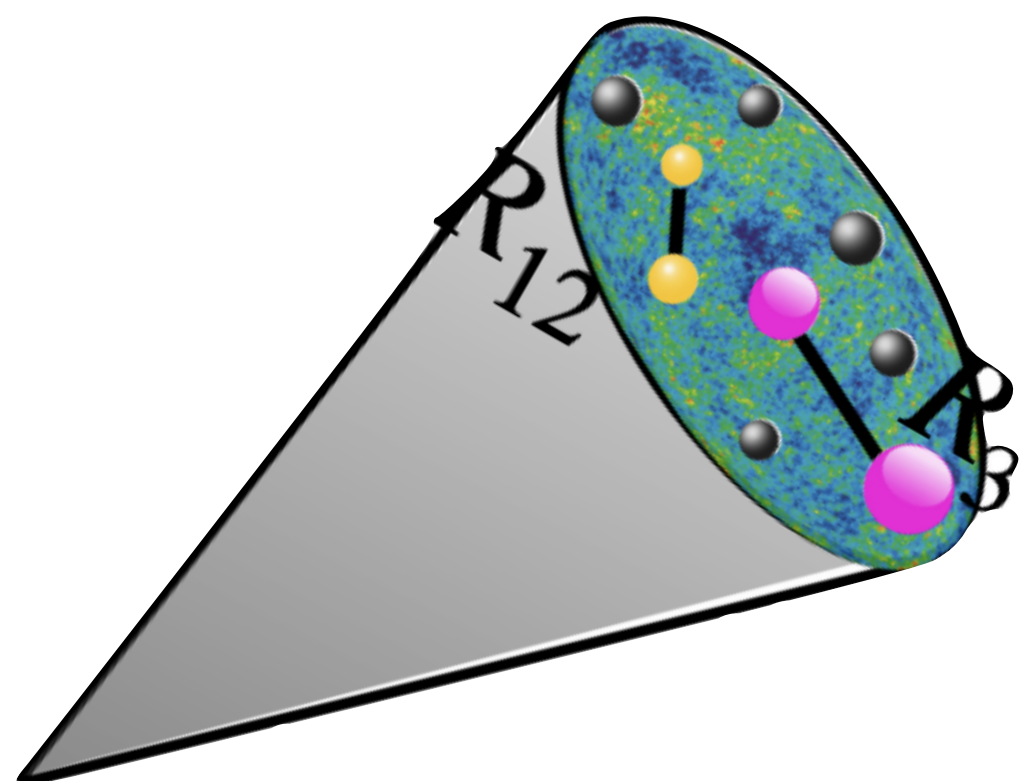
- Jets (anti- K_T) are reconstructed from energy bins $E_{T,ij}$, defined by

$$E_{T,ij} = \underbrace{\frac{d\Delta p_T}{d\phi d\eta}(\eta_i, \phi_j) \Delta\eta \Delta\phi}_{\text{from medium response}} + \underbrace{\sum_{\substack{|\eta_k - \eta_i| < \Delta\eta/2 \\ |\phi_k - \phi_j| < \Delta\phi/2}} p_{T,k}}_{\text{from parton fragmentations}}$$

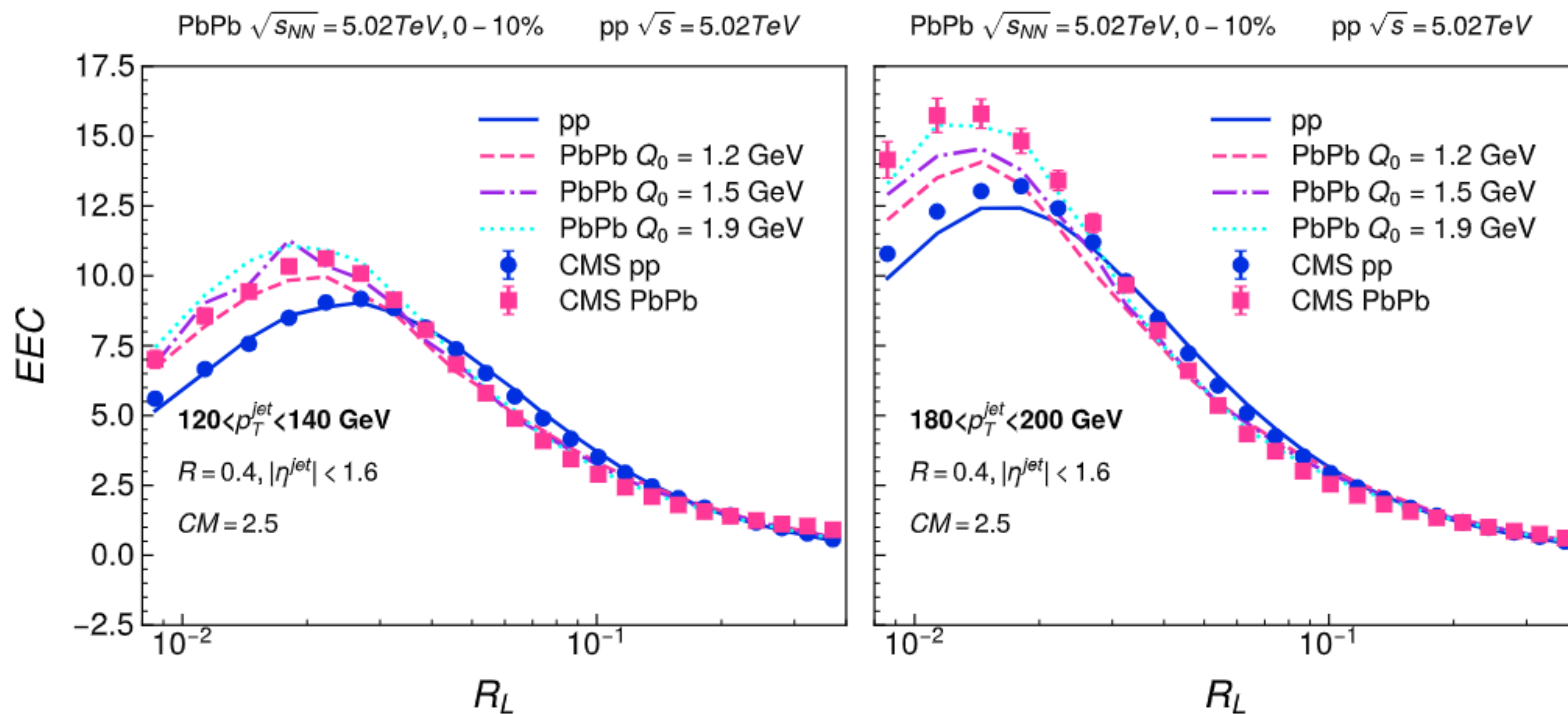
- Uncorrelated medium background are assumed to be perfectly subtracted.



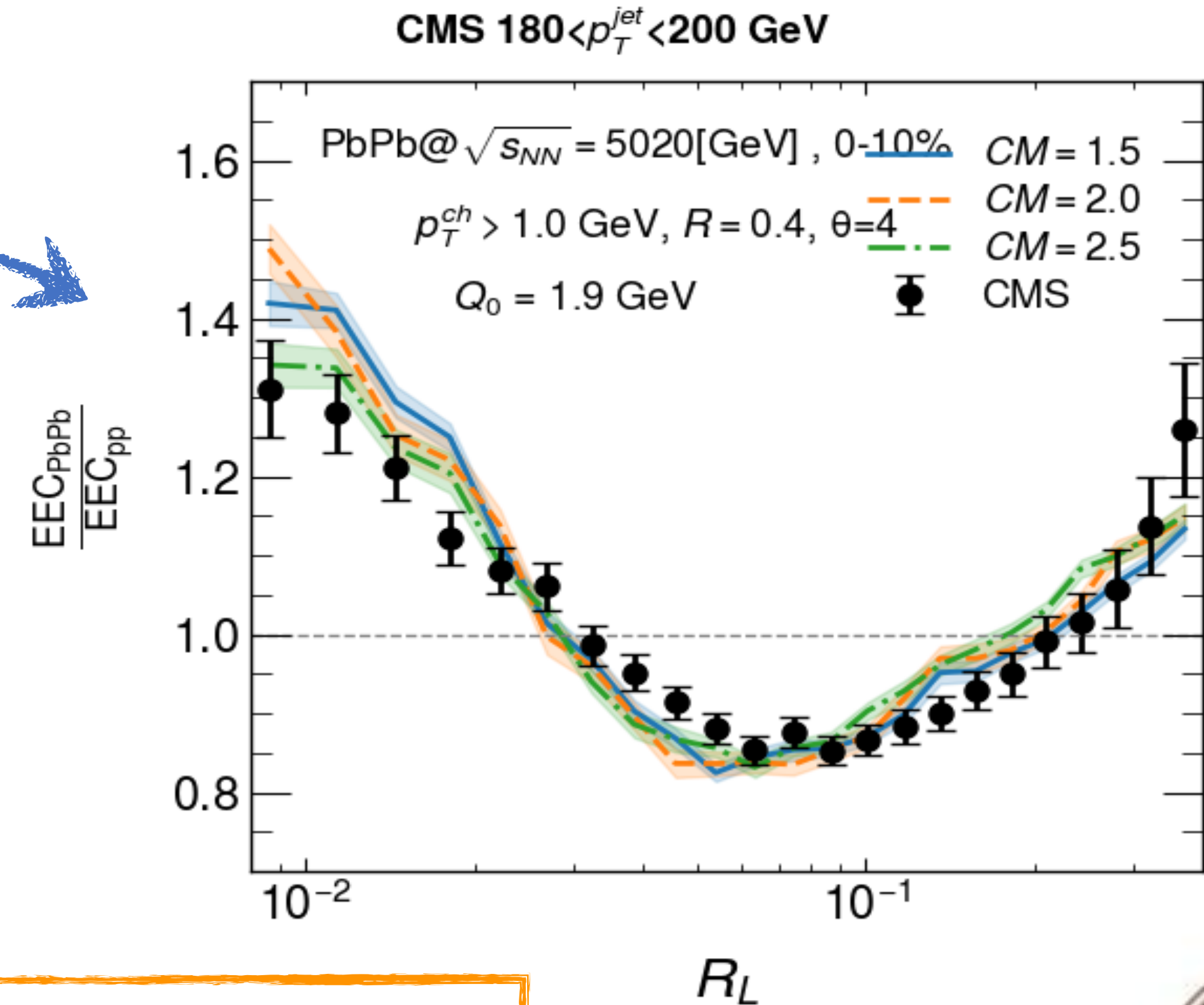
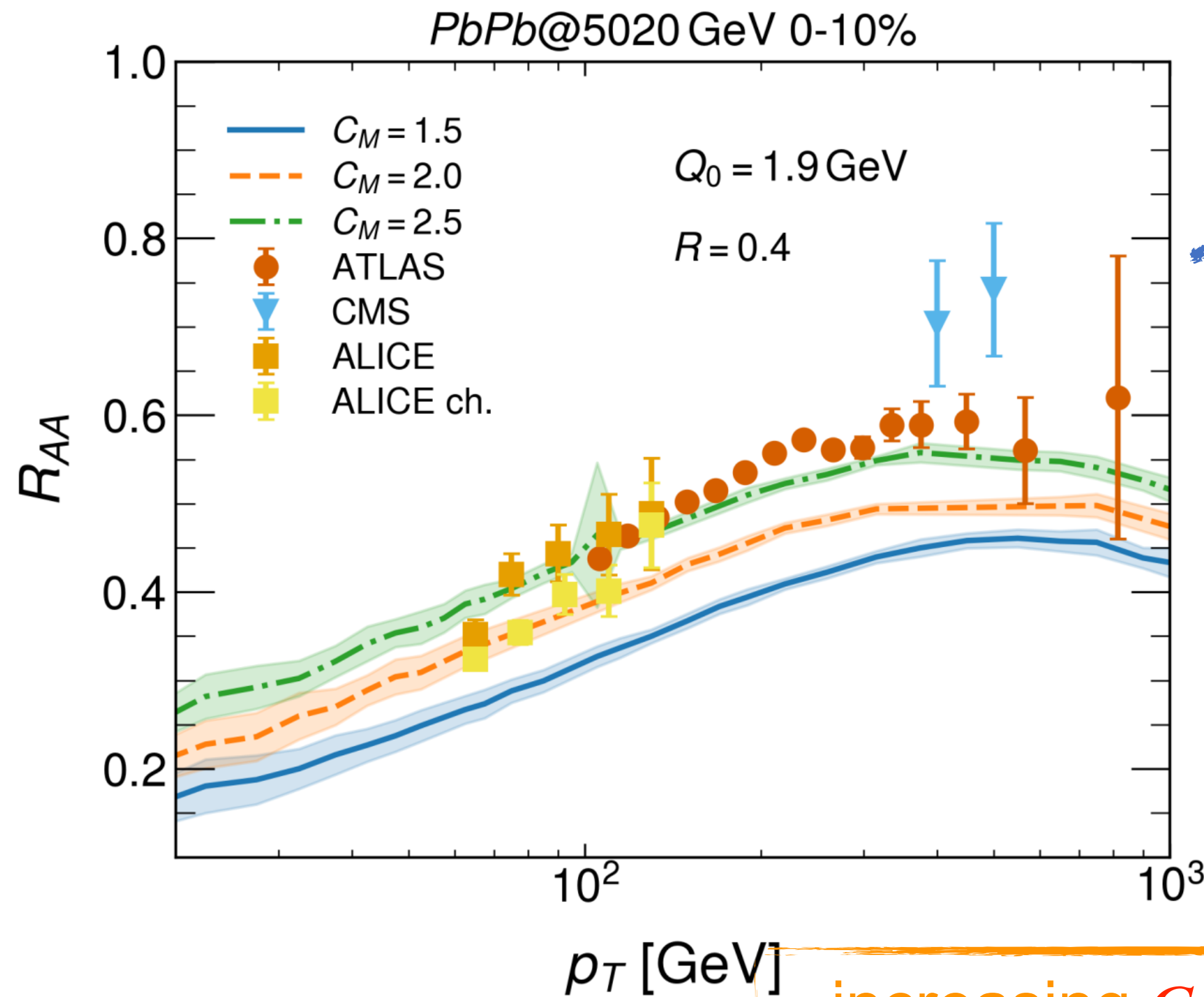
0. EEC in pp baseline: Theory vs. CMS Data



$$EEC(\Delta r) = \frac{1}{W_{\text{pairs}}} \frac{1}{\delta r} \sum_{\text{jets} \in [p_{T,1}, p_{T,2}]} \sum_{\text{pairs} \in [\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})^n$$



1. Sensitivity of EEC and Jet R_{AA} to the Jet-Medium Coupling cutoff C_M



increasing $C_M \Rightarrow$ decreasing jet-medium coupling at $T \Rightarrow$ less suppression

R_{AA} is more sensitive to α_s than EEC

$$\alpha_s(Q, T) = \frac{4\pi}{9} \cdot \frac{1}{\ln\left(\frac{\max\{Q^2, \mu_{\min}^2\}}{\Lambda_{\text{QCD}}^2}\right)} \quad \mu_{\min} = C_M \times \pi T$$



1. Sensitivity of EEC and Jet R_{AA} to the Jet-Medium Coupling cutoff C_M

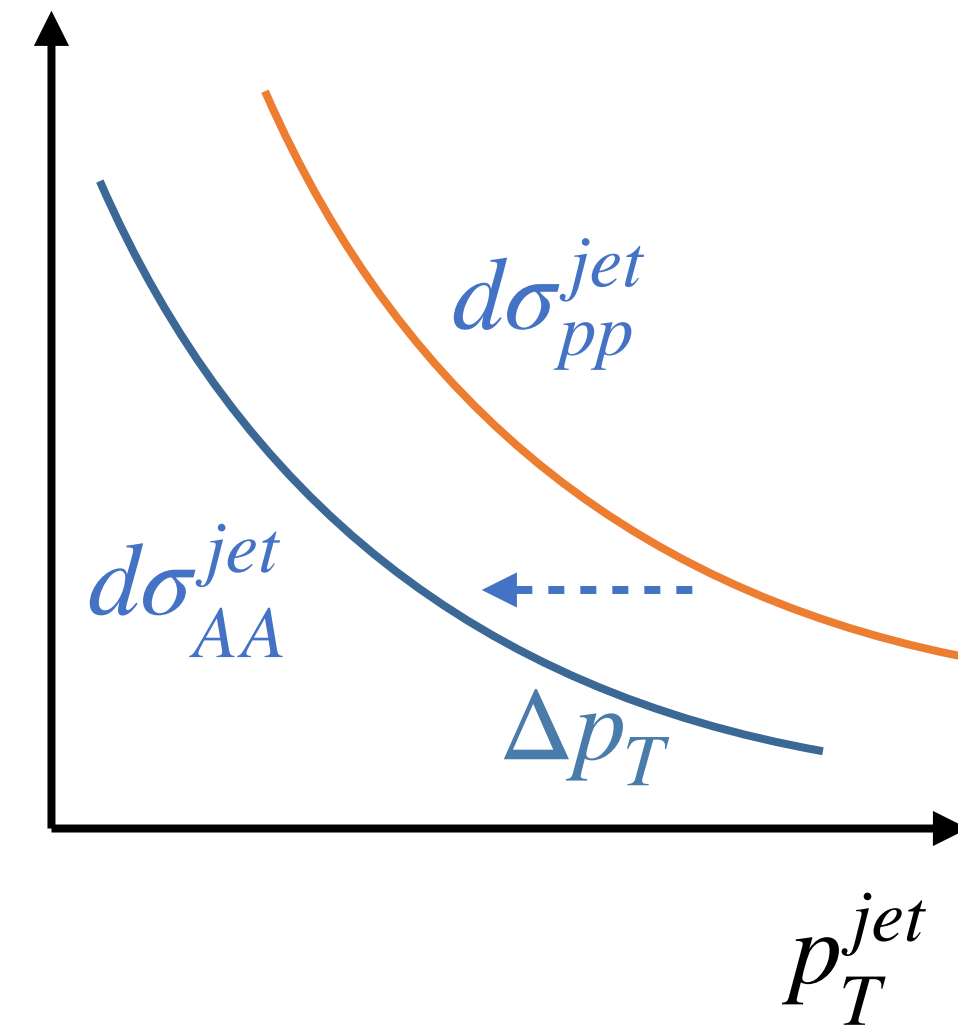
Jet nuclear modification factor:

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

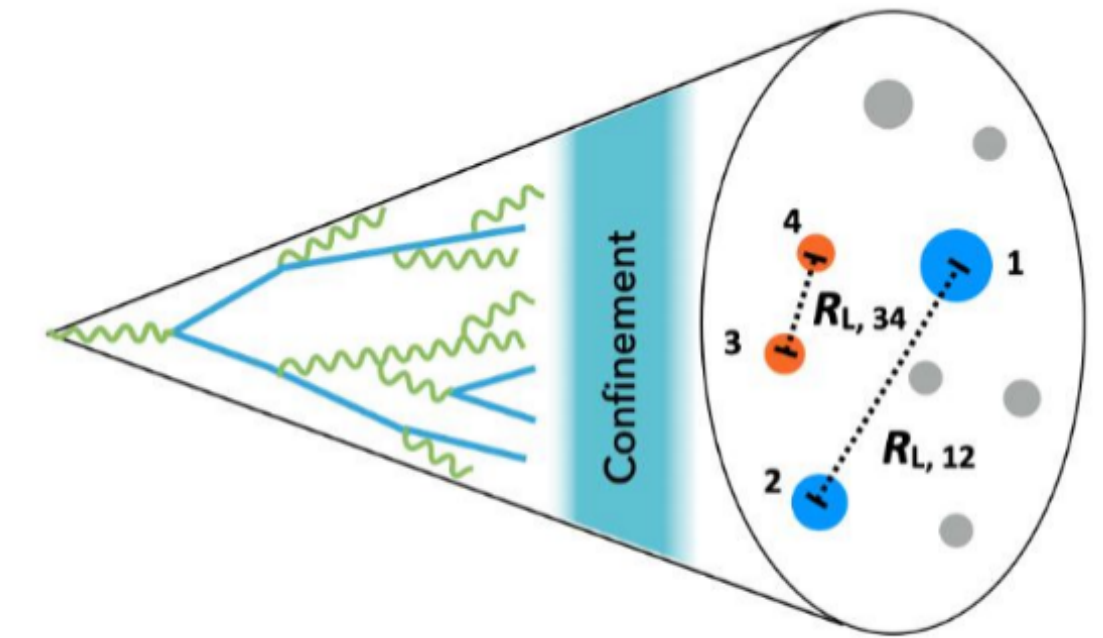
Energy-energy correlator:

$$EEC(R_L) = \frac{1}{N_{jet}} \sum_{i_1, i_2 \in jet} \int dR_L \frac{p_T^{i_1} p_T^{i_2}}{p_{T,jet}^2} (R_L - \Delta \hat{R}_L)$$

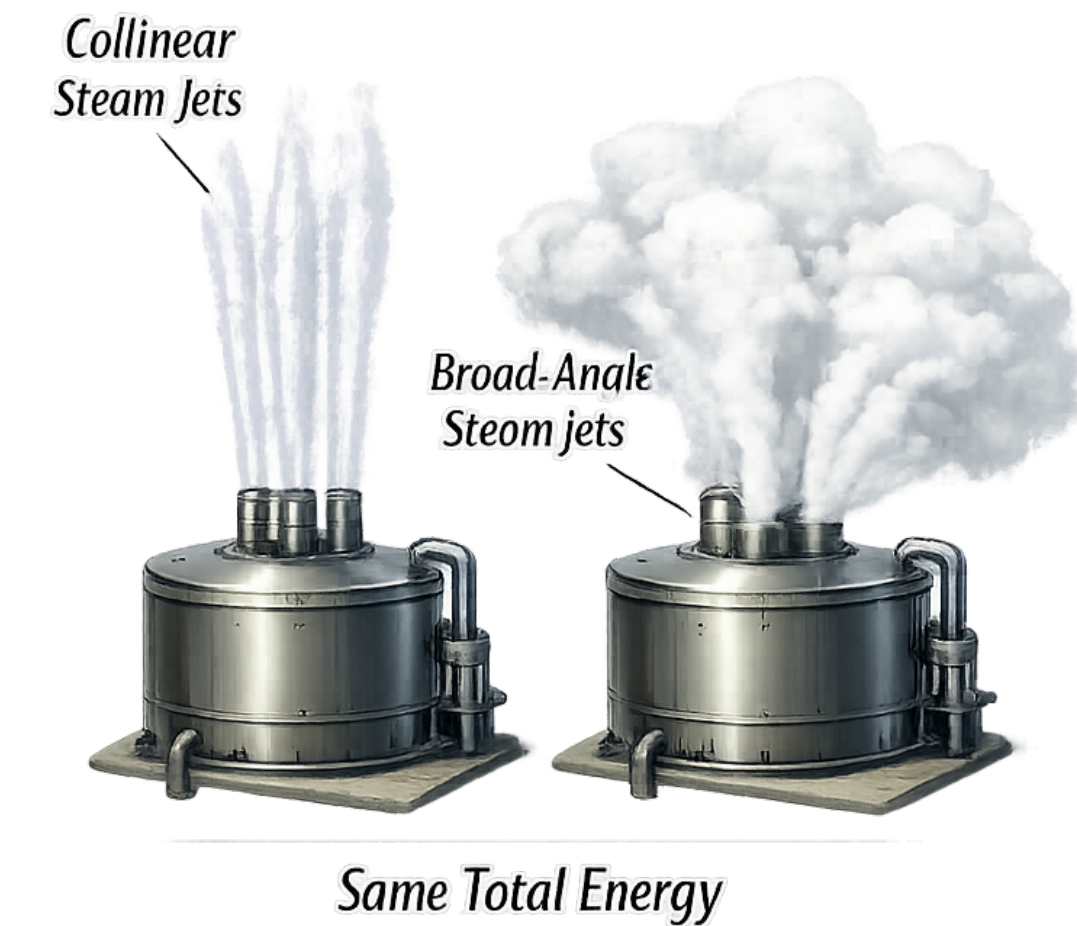
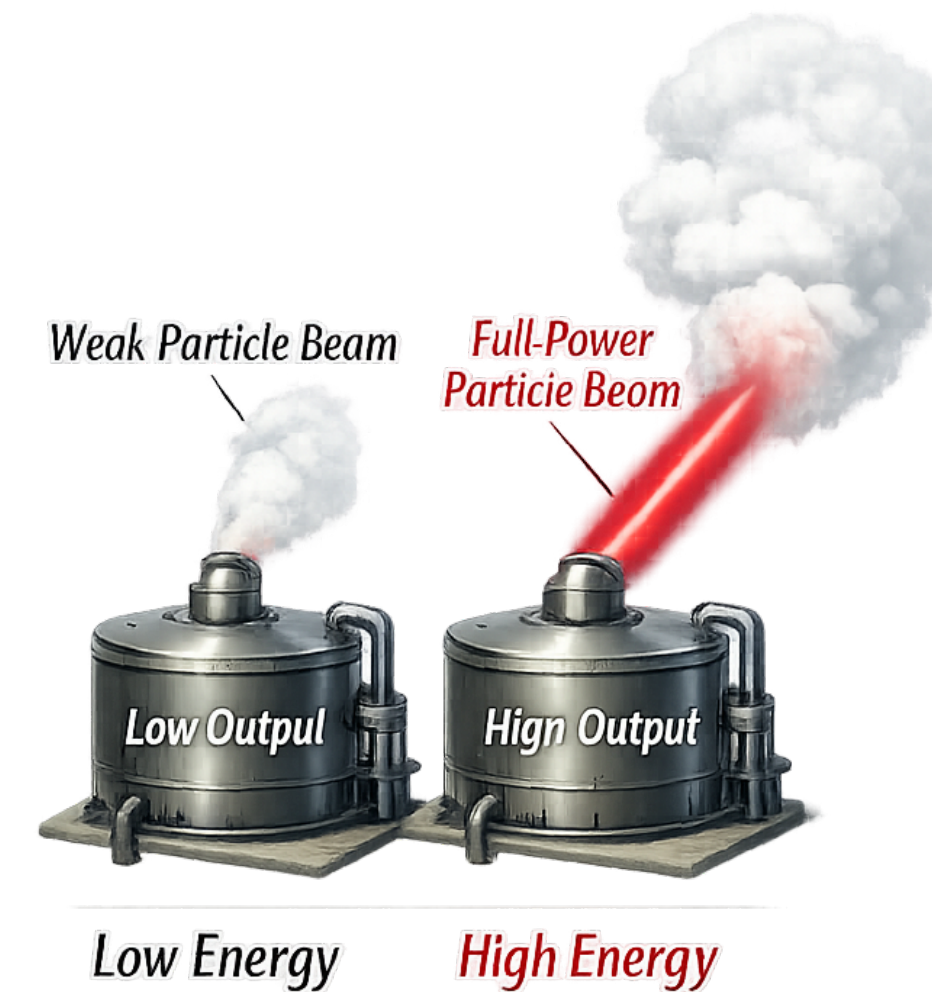
- R_{AA} : Governed by total energy loss → Strongly affected by soft interactions → **Stronger sensitivity**
- EEC : Probes relative angular structure in jets → Normalized & energy-weighted → **weak sensitivity**



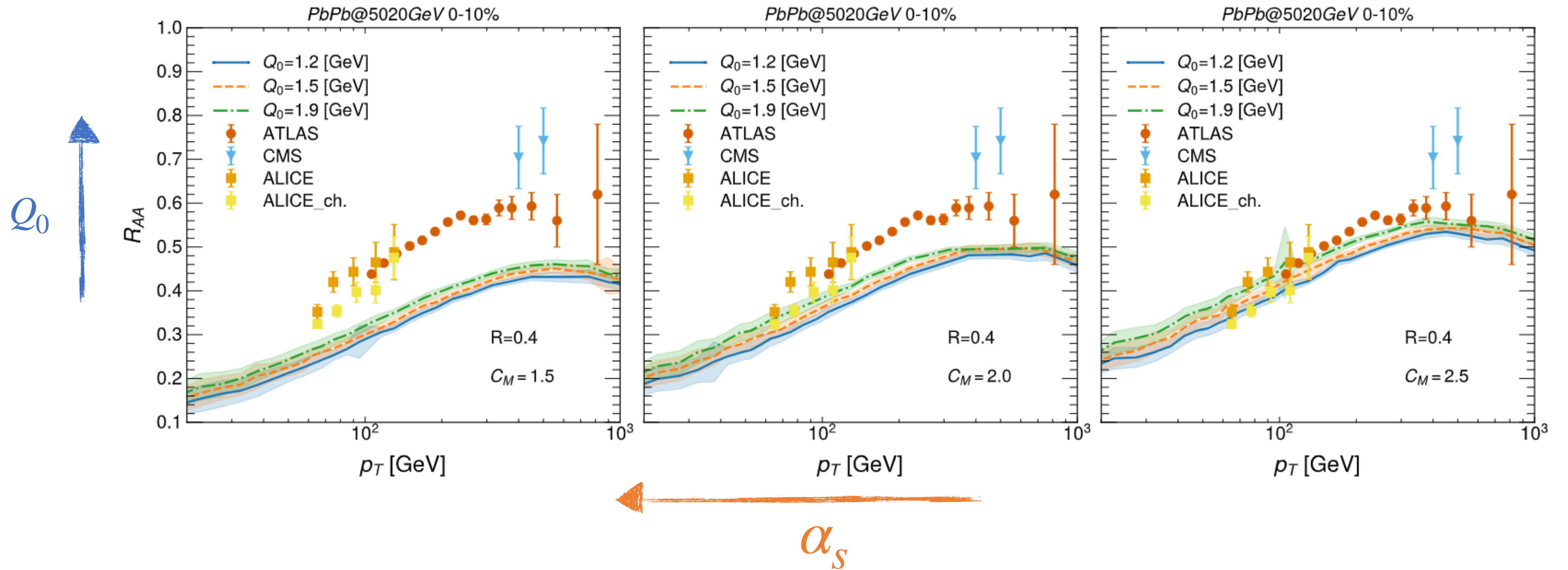
R_{AA} – Sensitive to Energy Loss



EEC – Sensitive to Angular Structure



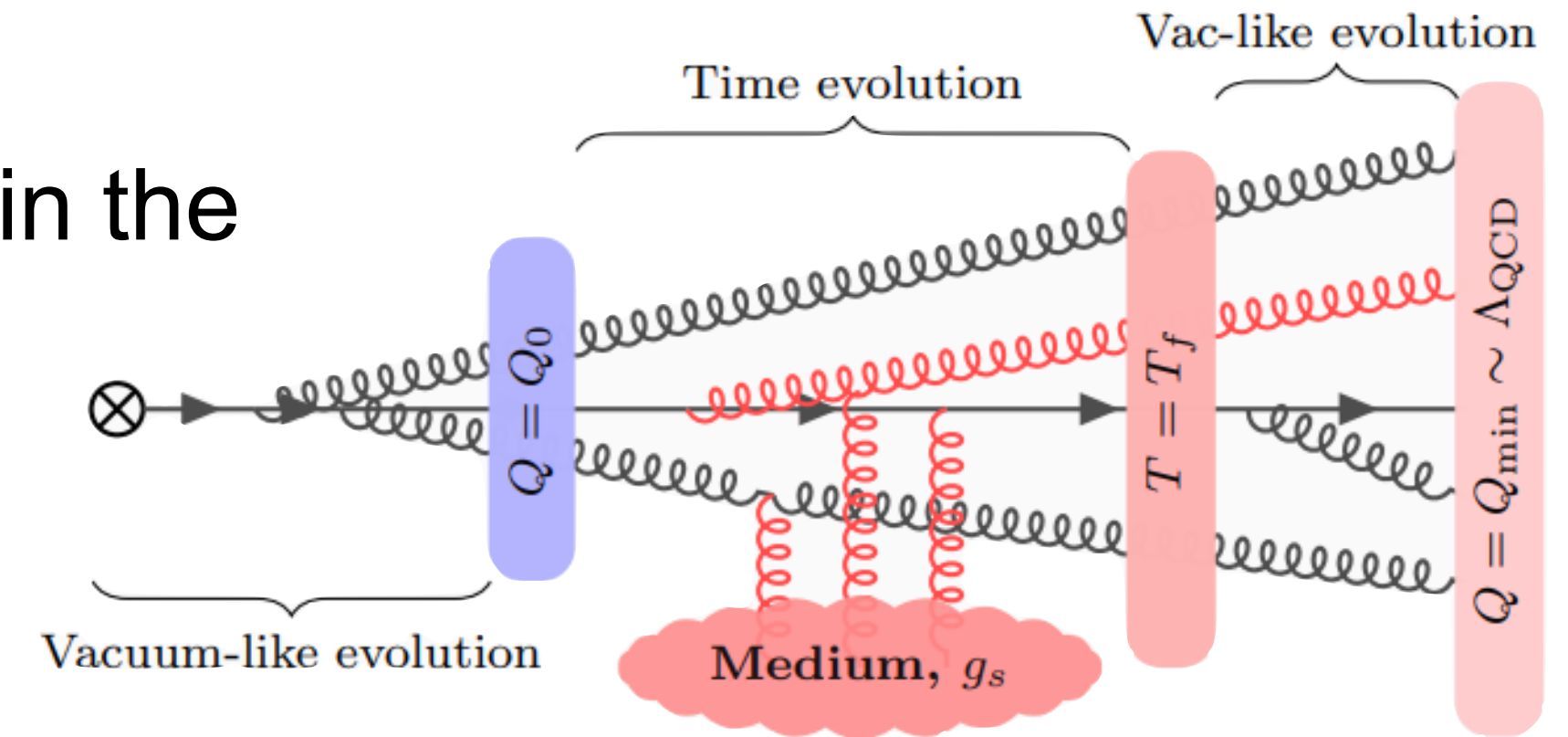
2. Parameter sensitivity: transition scale Q_0



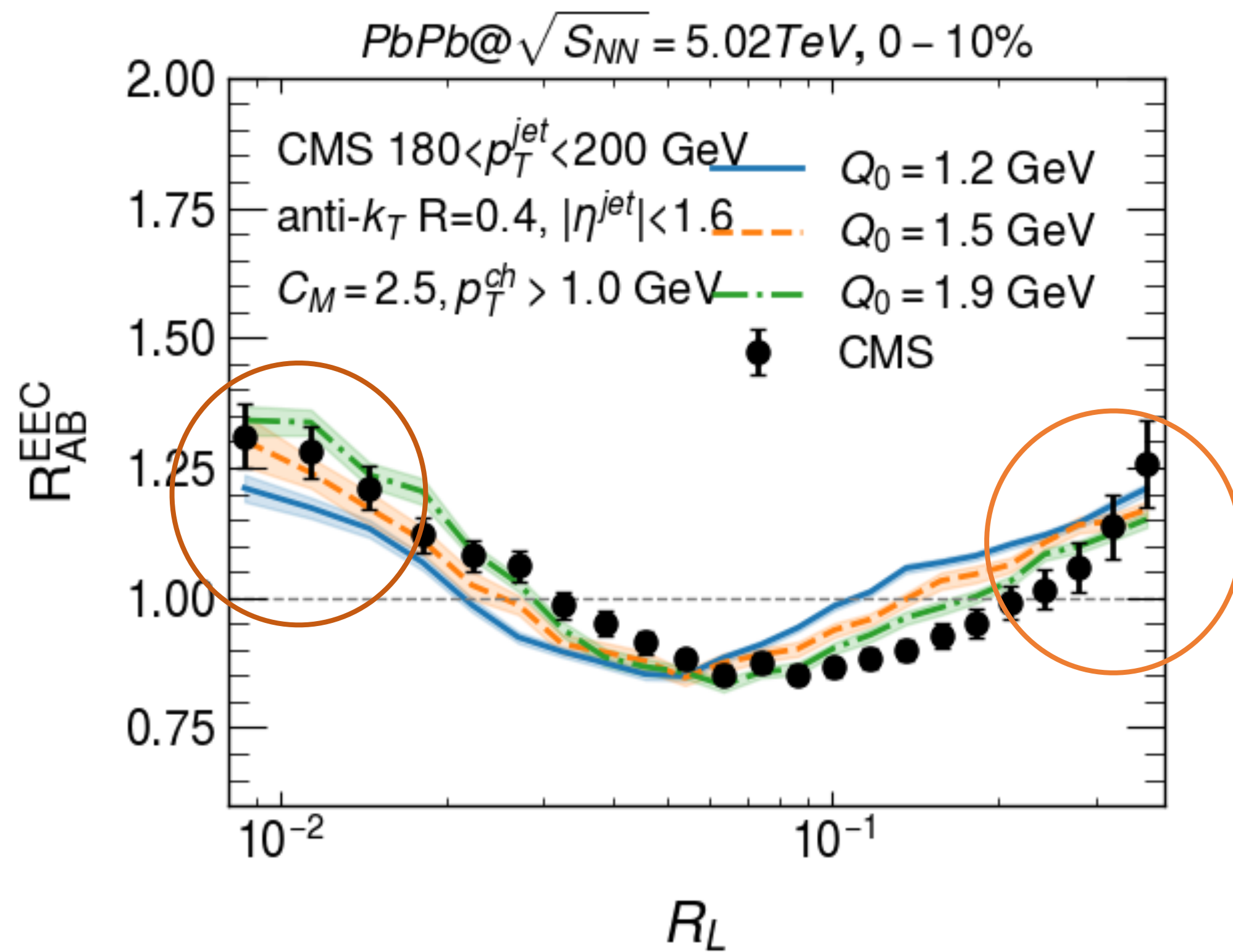
Q_0 modulates jet quenching magnitude with a weaker dependence

2. Sensitivity of EEC to the Vacuum–Medium Transition Scale Q_0

Q_0 (Scale separating vacuum & medium shower) \uparrow : fewer partons in the shower, interacting earlier with the medium.

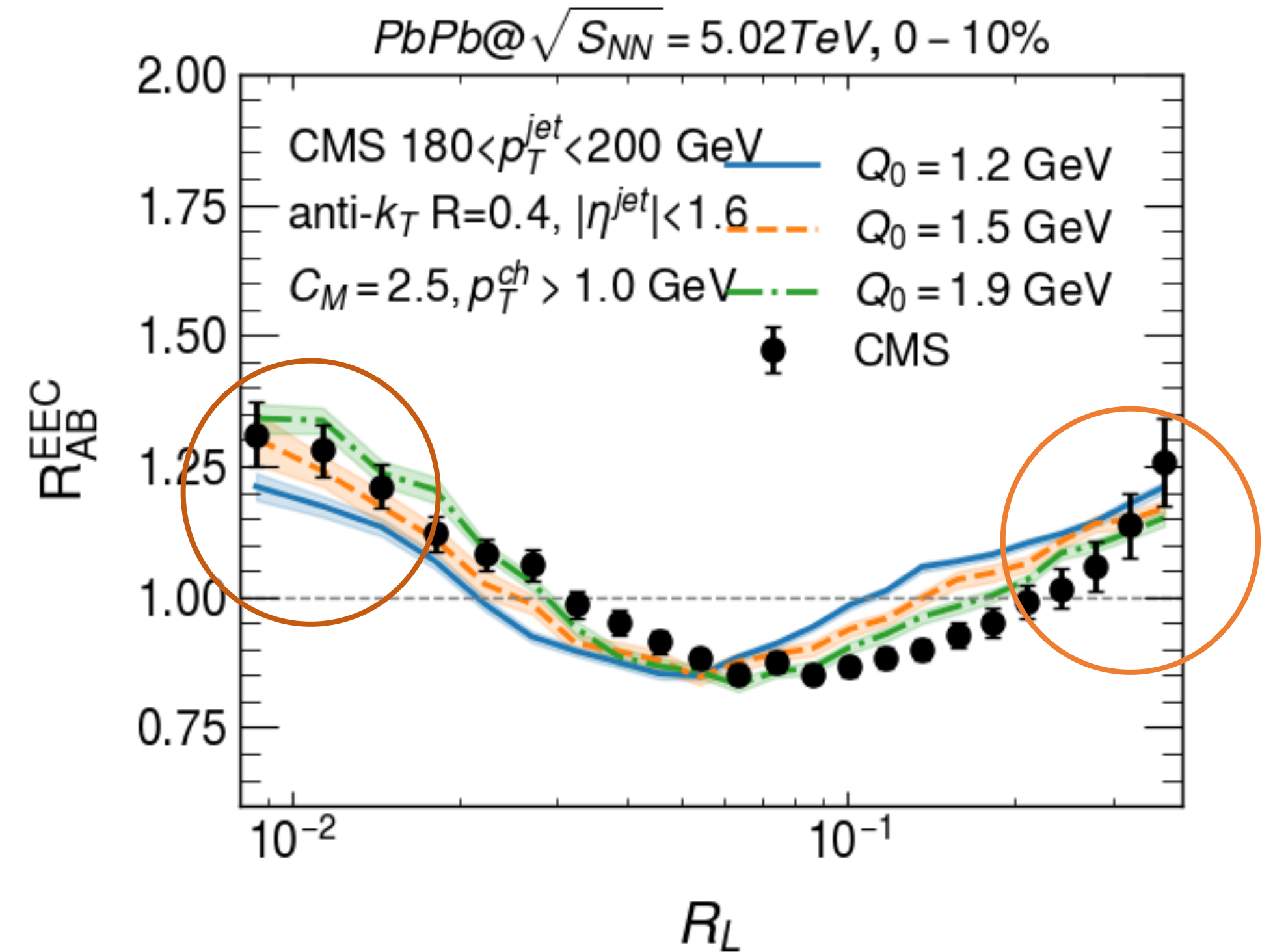
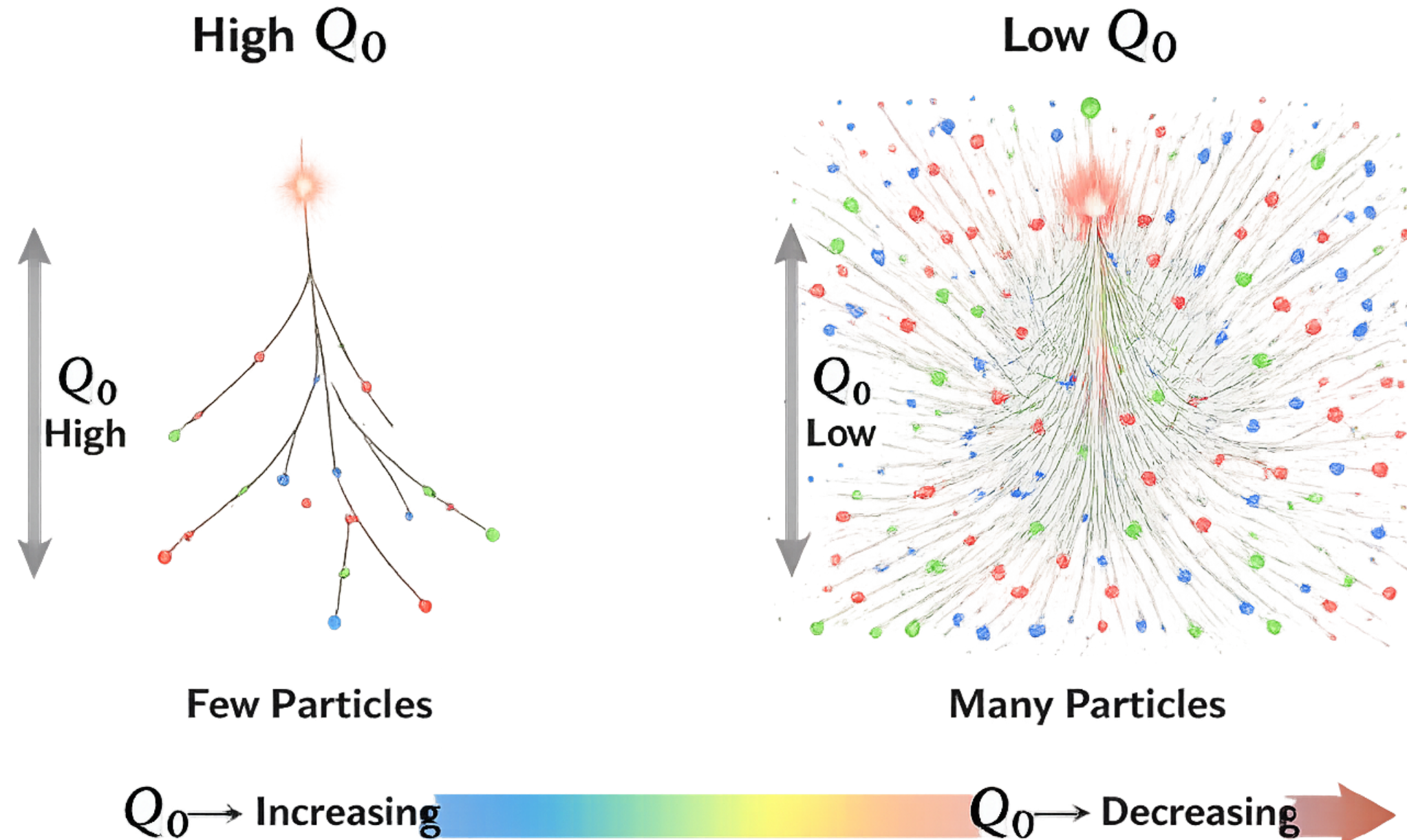


- **Small angles:** Larger $Q_0 \rightarrow$ stronger enhancement.
- **Large angles:** Smaller $Q_0 \rightarrow$ steeper slope.
- **Intermediate angles:** Curves for different Q_0 intersect near a common point.



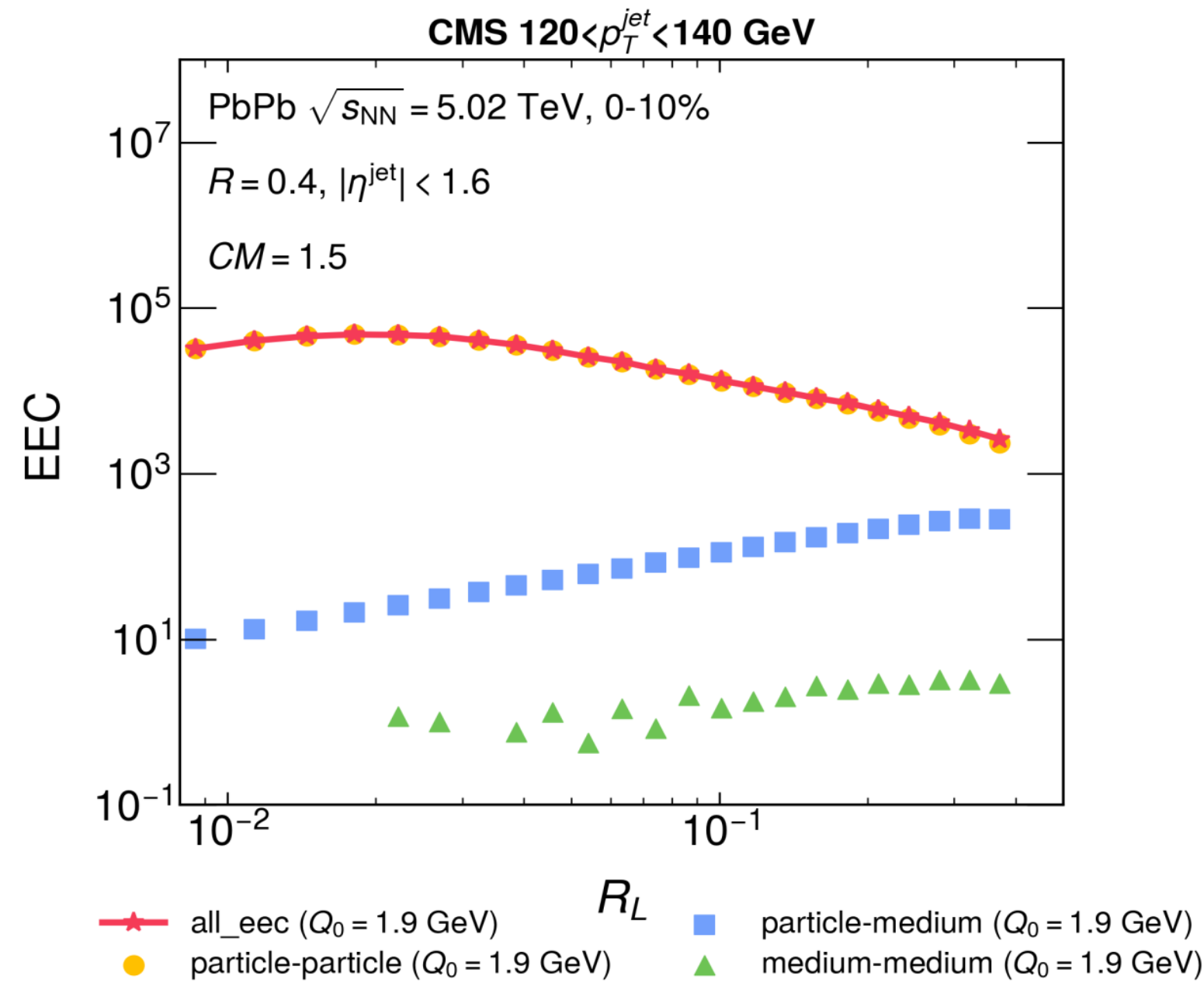
2. Sensitivity of EEC to the Vacuum–Medium Transition Scale Q_0

Evolution of Vacuum Showers with Q_0



- ❖ At large angles, a smaller Q_0 leads to more shower particles, resulting in stronger medium-induced radiation.
- ❖ At small angles, a smaller Q_0 leads to a richer vacuum shower reduces the quark-gluon energy-loss difference thereby suppressing their selection bias.

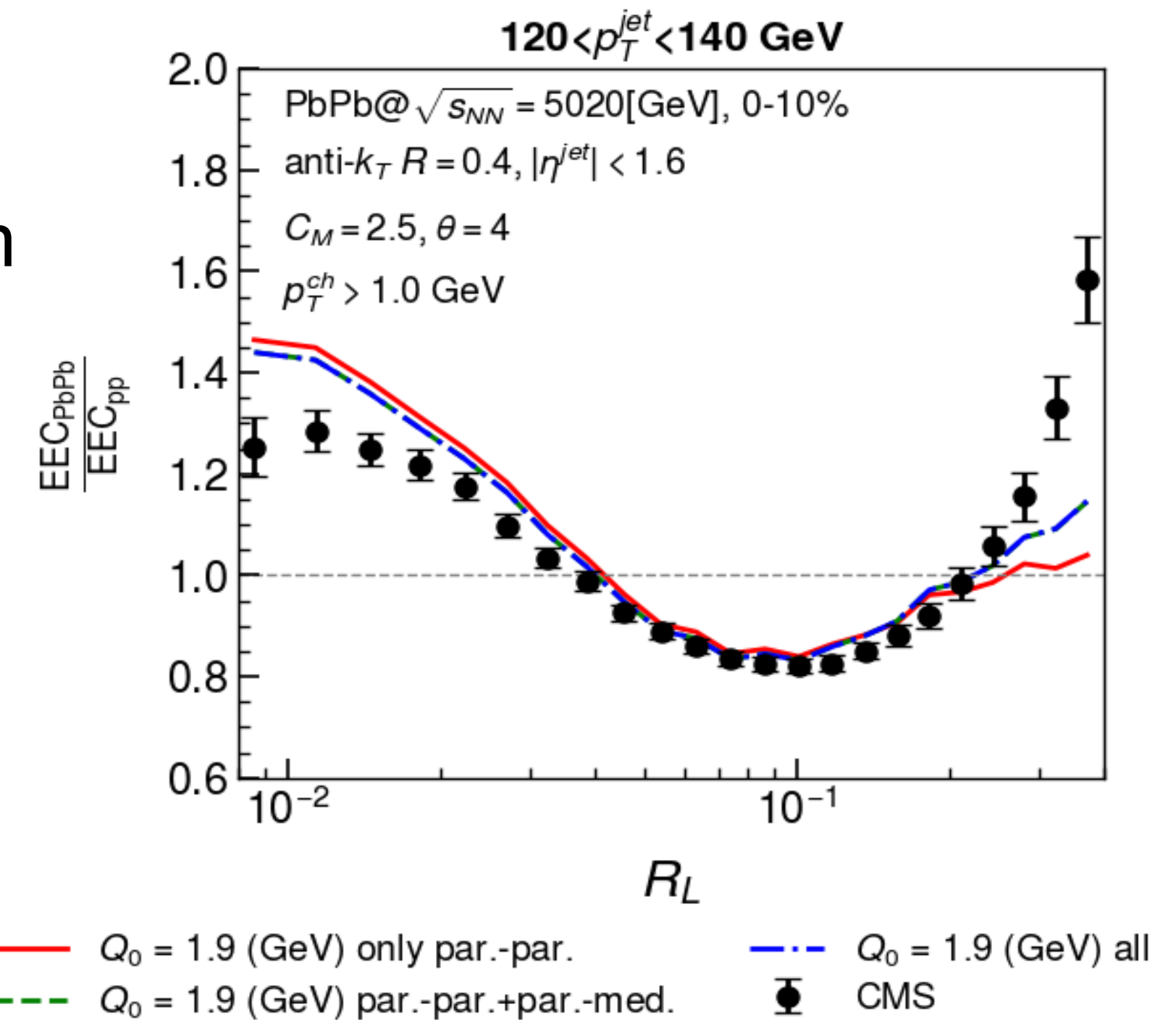
3. Effect of medium response in EEC



- Medium particles generated from transverse momentum density:

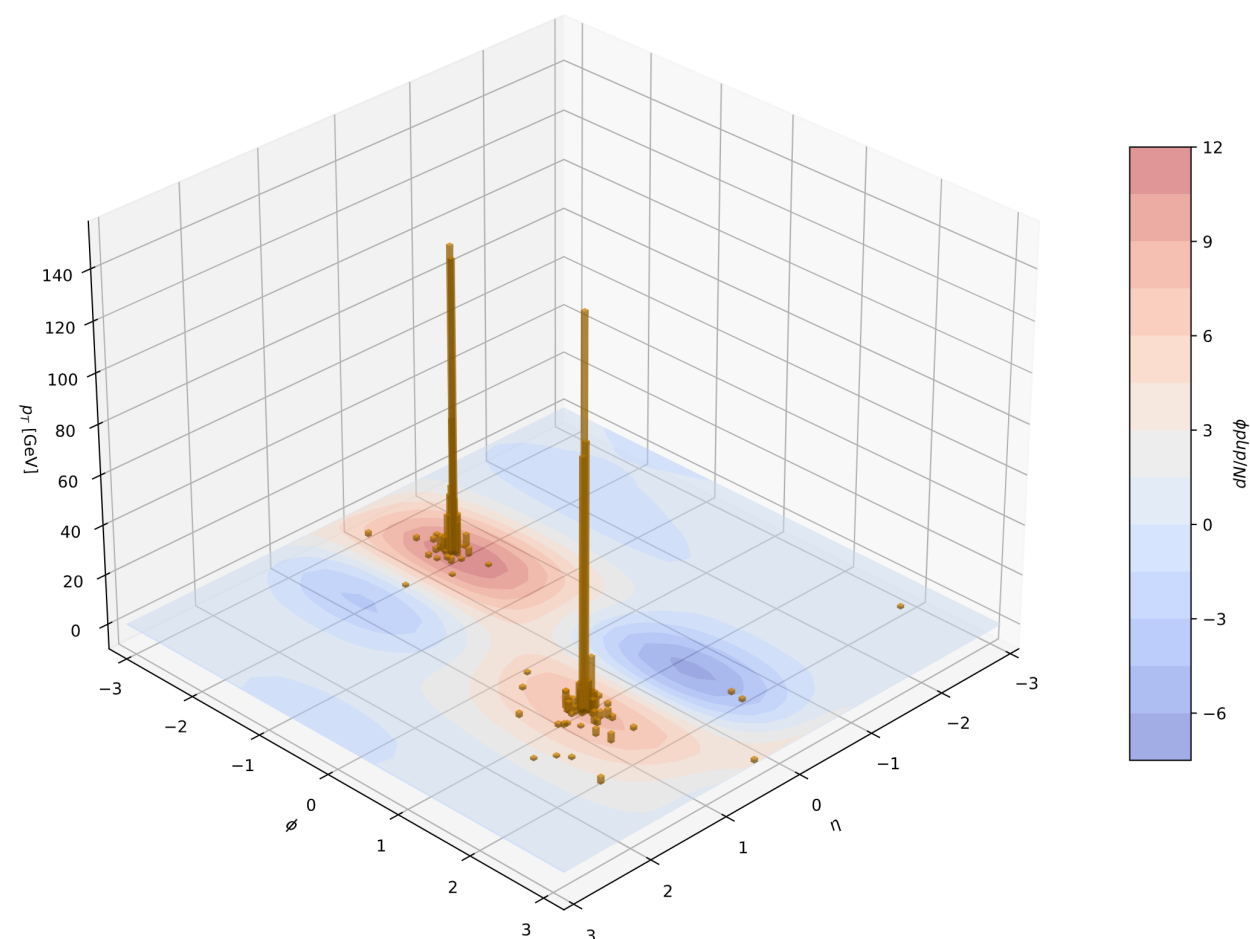
$$\frac{dp_T}{d\eta d\phi} \Delta\eta \Delta\phi$$

via energy-tower method

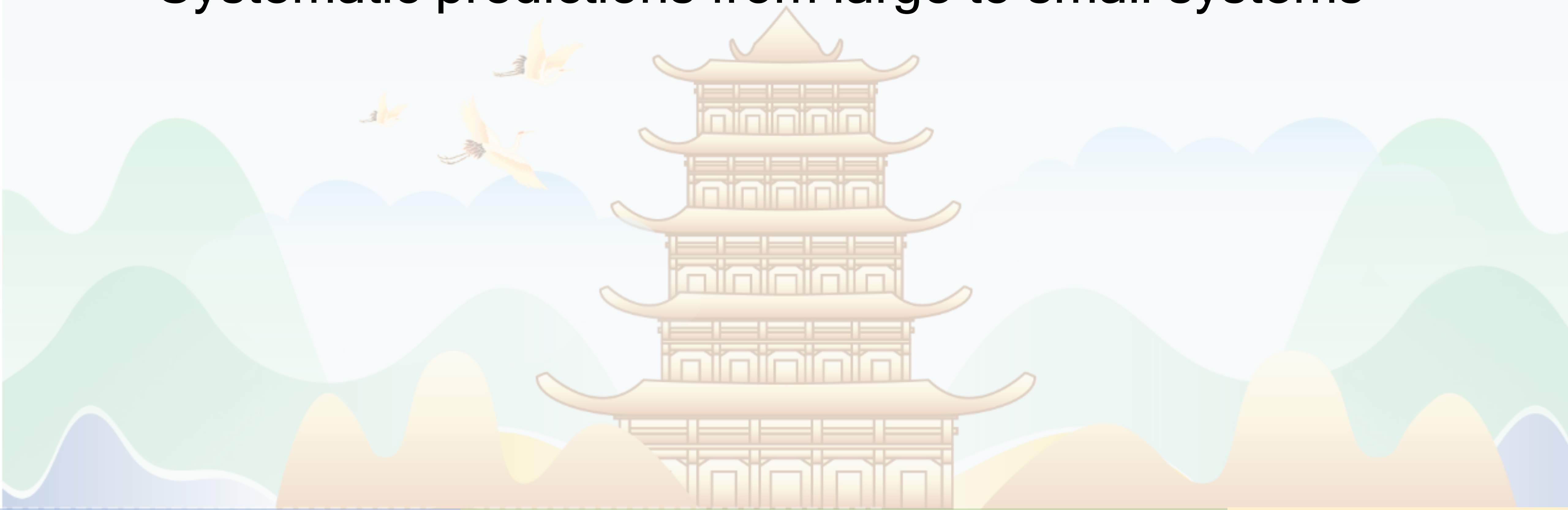


- EEC include:

- ① Hard particle – Hard particle correlations
- ② Medium response – Hard particle correlations
- ③ Medium response – Medium response correlations.



Systematic predictions from large to small systems

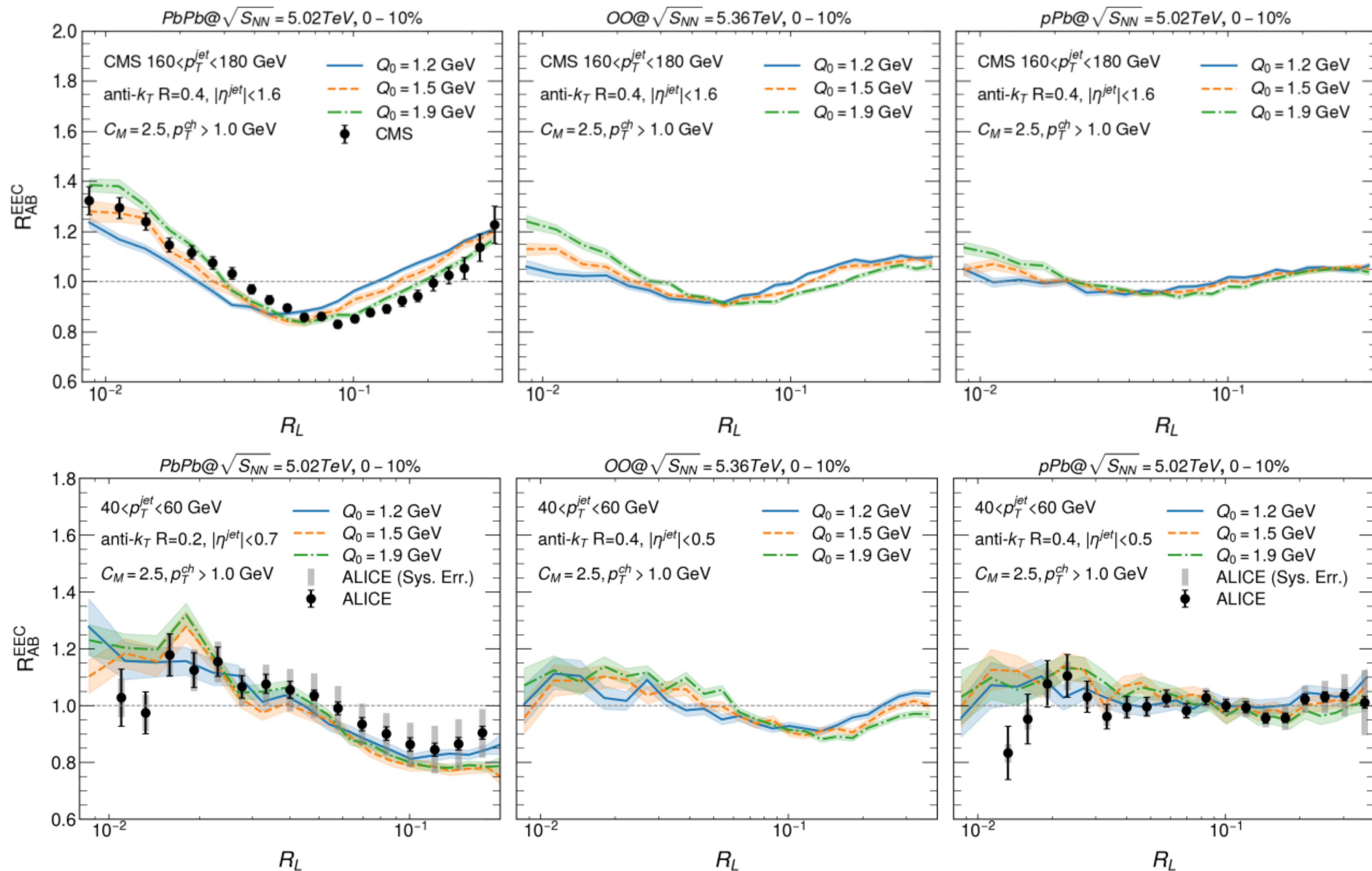


EEC from large to small systems: Pb-Pb, O-O and p-Pb

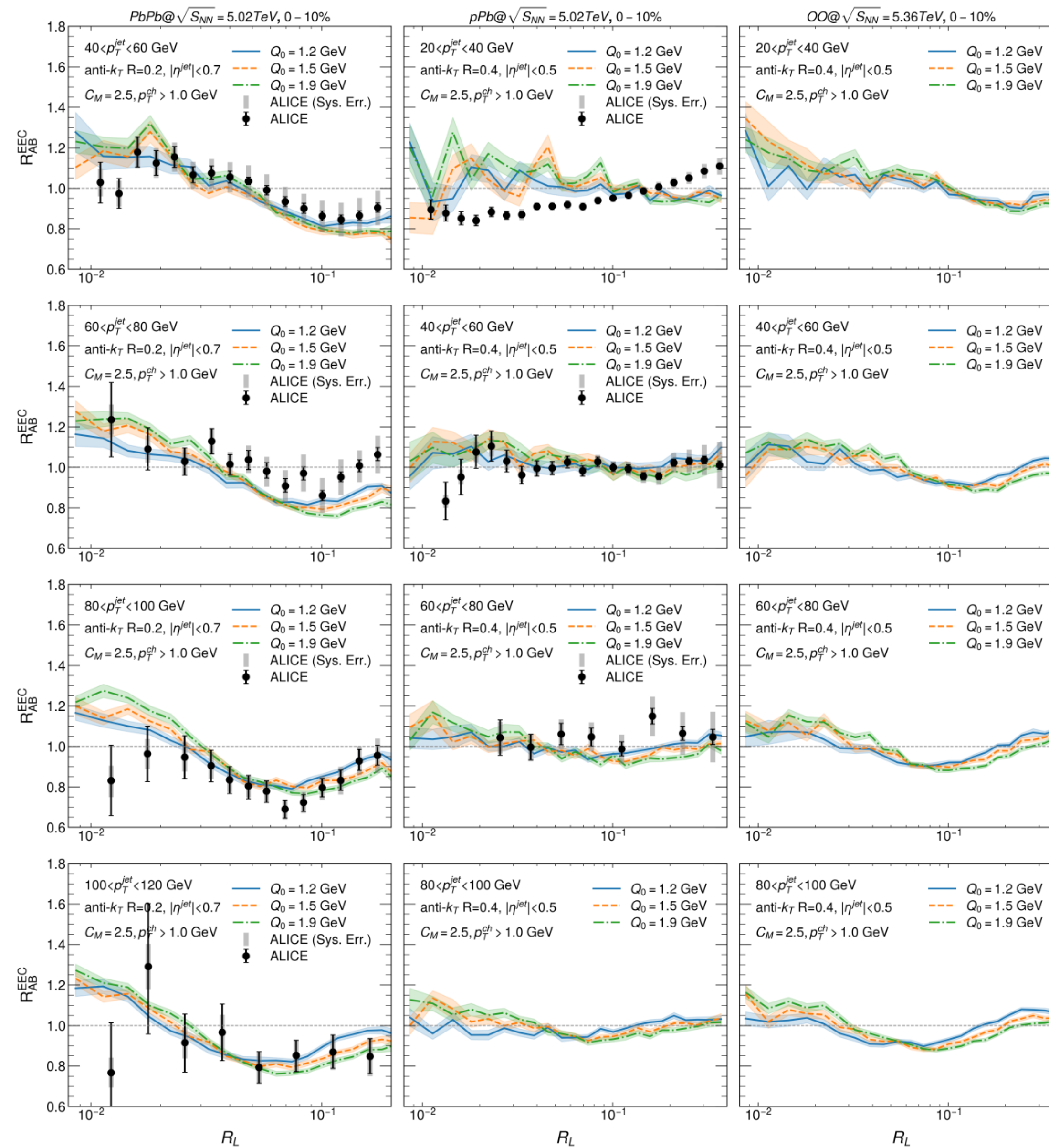
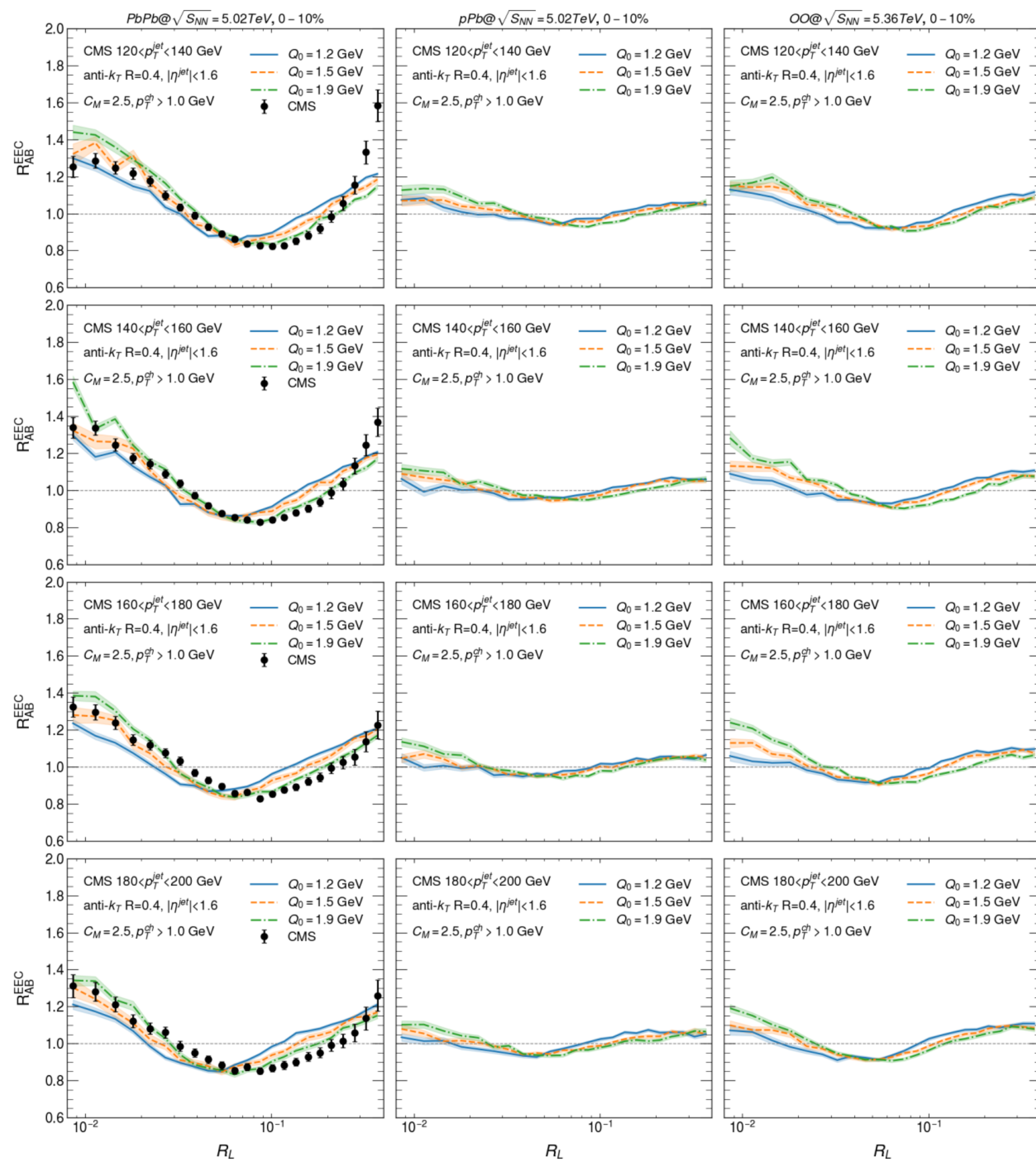
➤ O--O : Similar structure but smaller magnitude than Pb-Pb.

➤ p--Pb : Even smaller than O-O

⇒ The shape of the EEC ratio is the similar across systems, with only an overall change in magnitude.



Pb-Pb, p-Pb, O-O EEC: vs. Experiment



- The EEC is a sensitive probe of the vacuum–medium transition scale Q_0 .
- **A smaller Q_0 suppresses small-angle enhancement and enhances large-angle medium-induced correlations.**
- The EEC modification shows a similar trend across Pb–Pb, p–Pb, and O–O systems, with only an overall change in magnitude.
- Our model describes CMS and ALICE data at high p_T and provides predictions for O–O collisions