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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

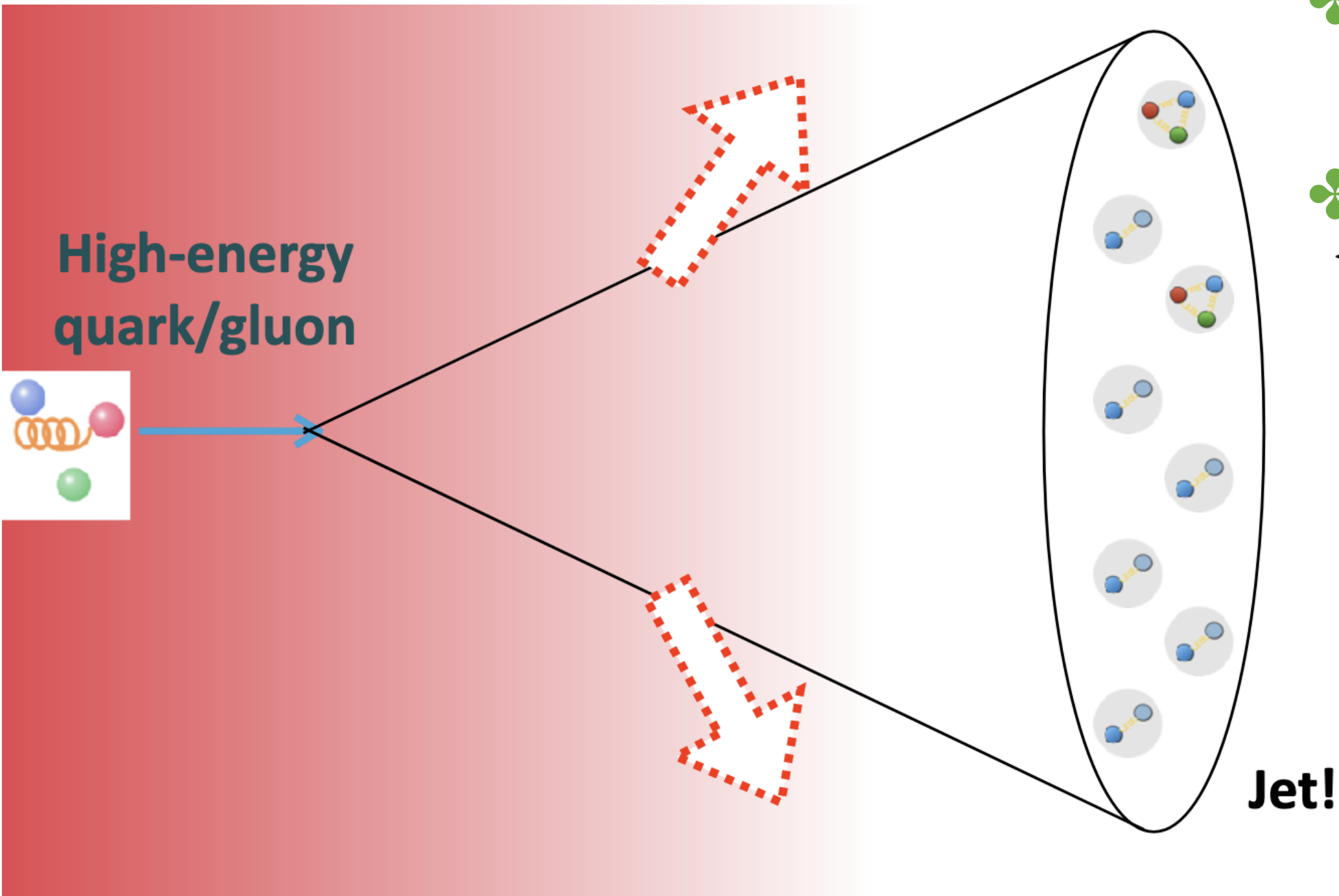
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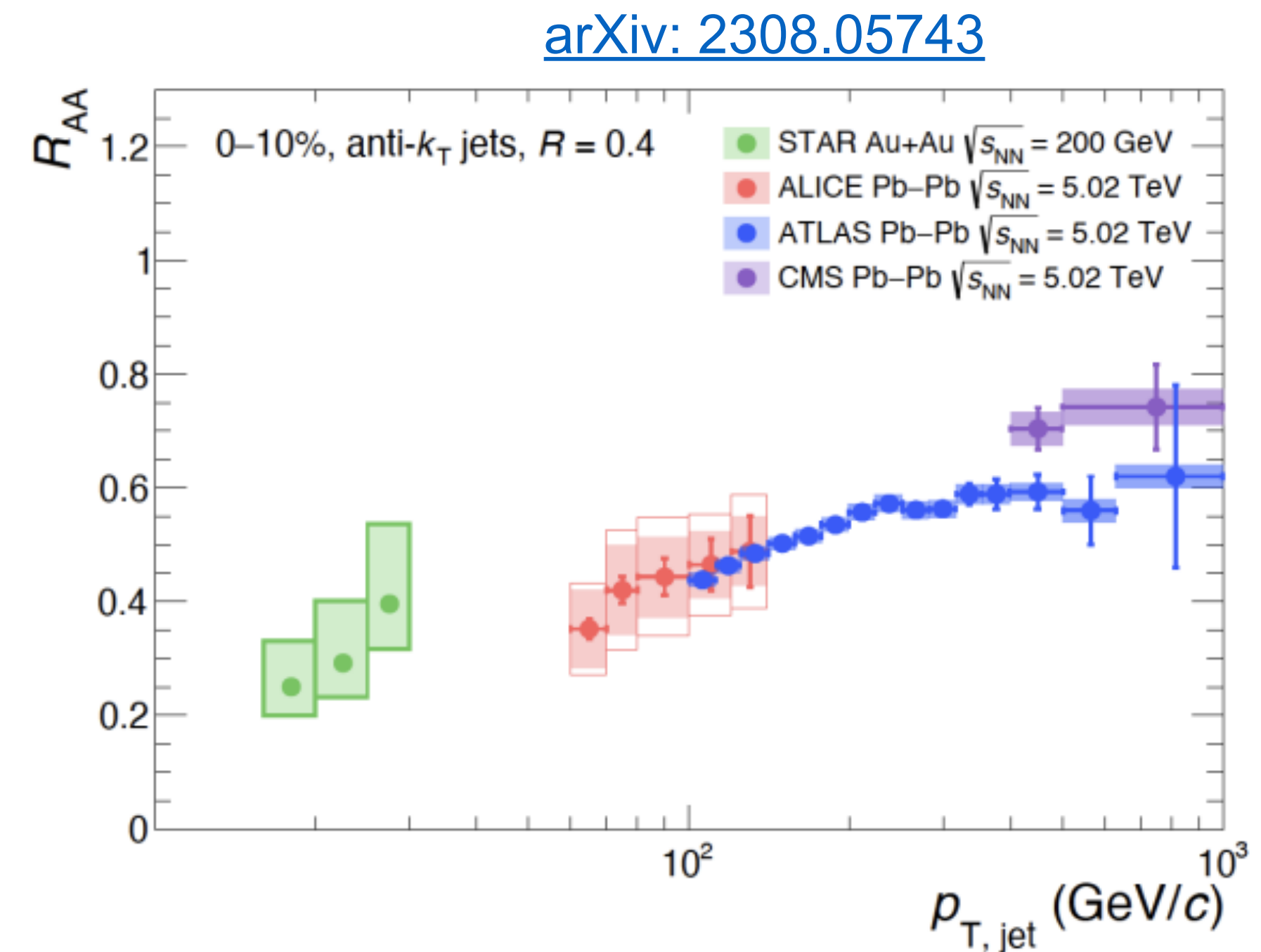
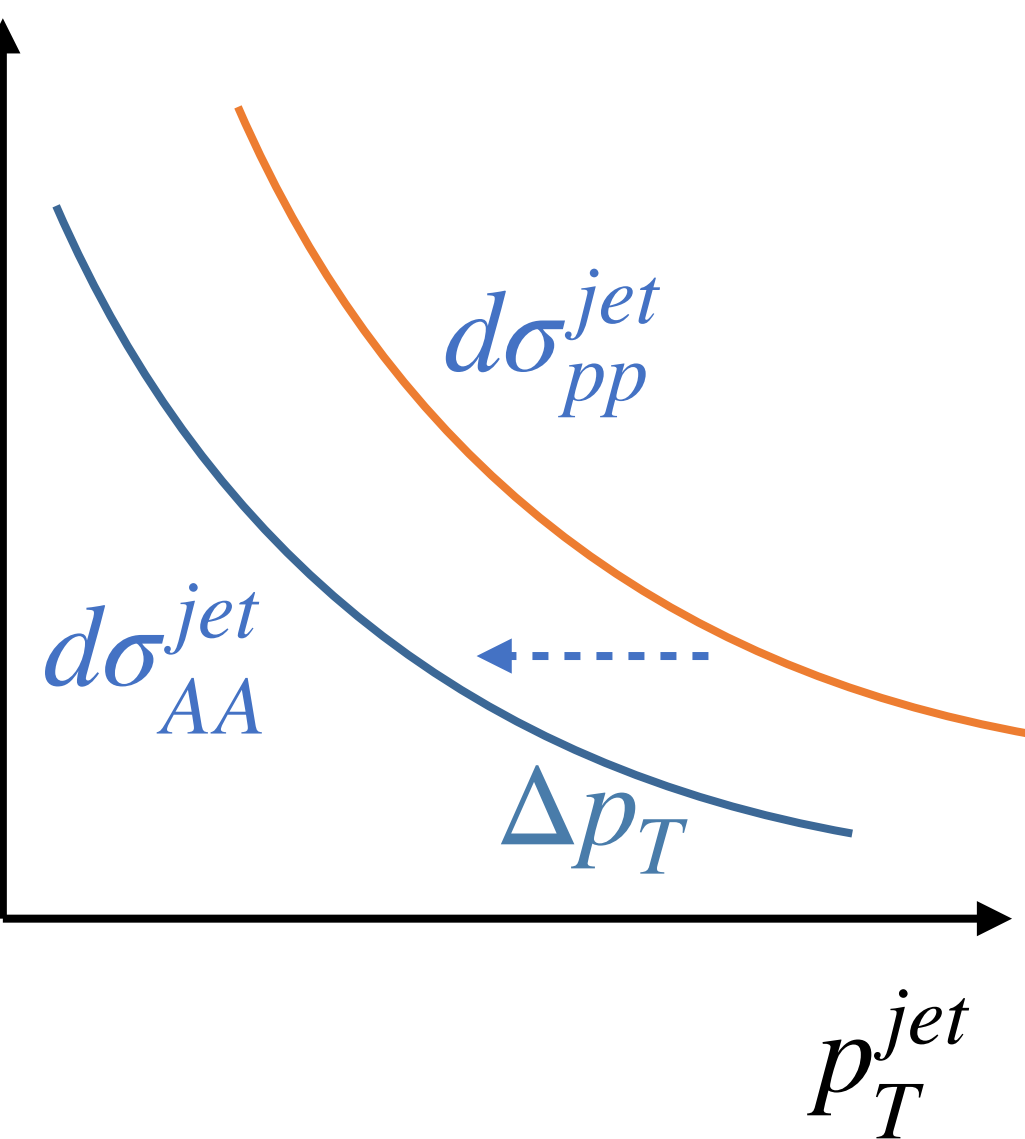
The 3rd Edition of the Spicy Gluons (胶麻) Workshop for Young Scientists on the Quark-Gluon Matter in Extreme Conditions, October 17–20, 2026, Pujin Hotel, Wuhan

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



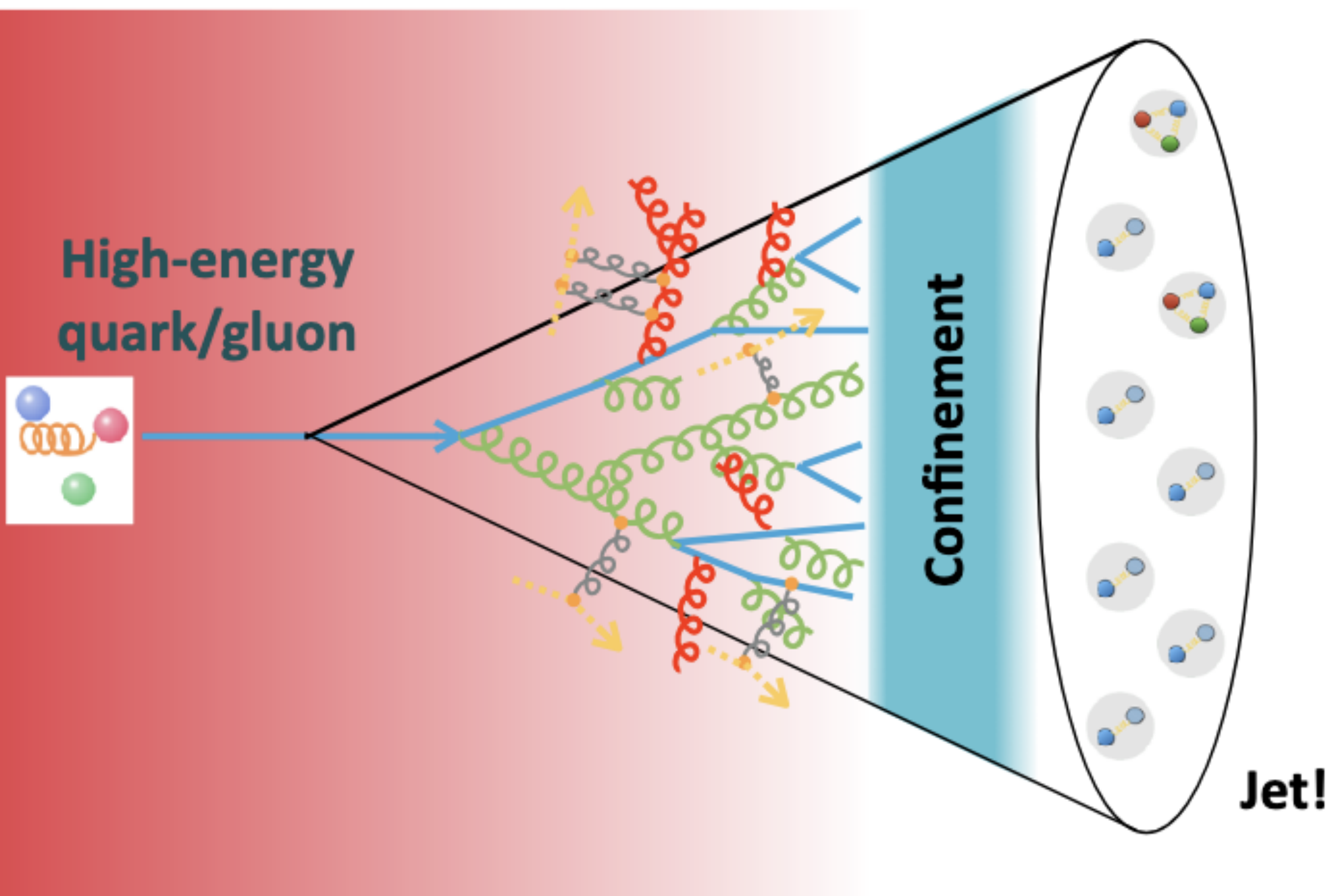
Jets “lose” (redistribute) energy when going through the QGP

- ✿ 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).



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

Energy-Energy Correlators

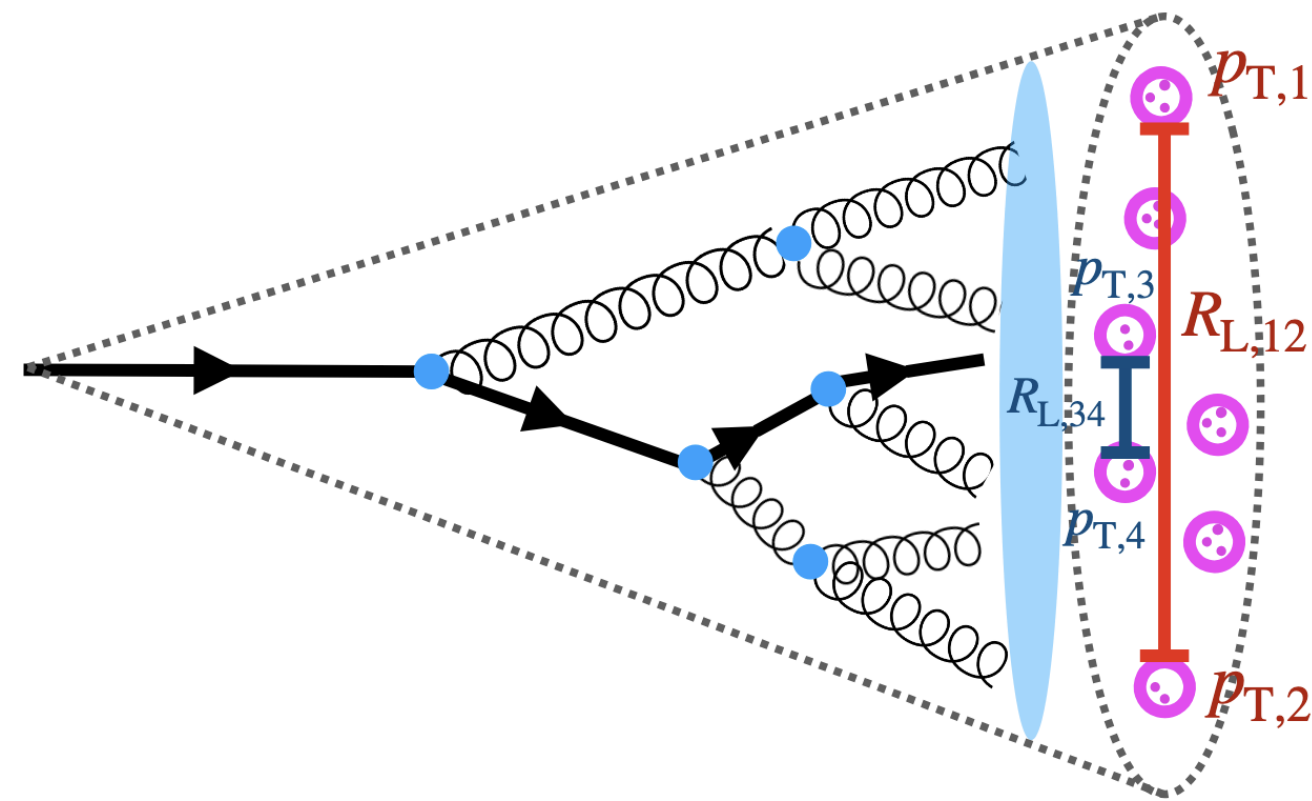


Figure from [Preeti Dhankher\(QNP 2024\)](#)

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

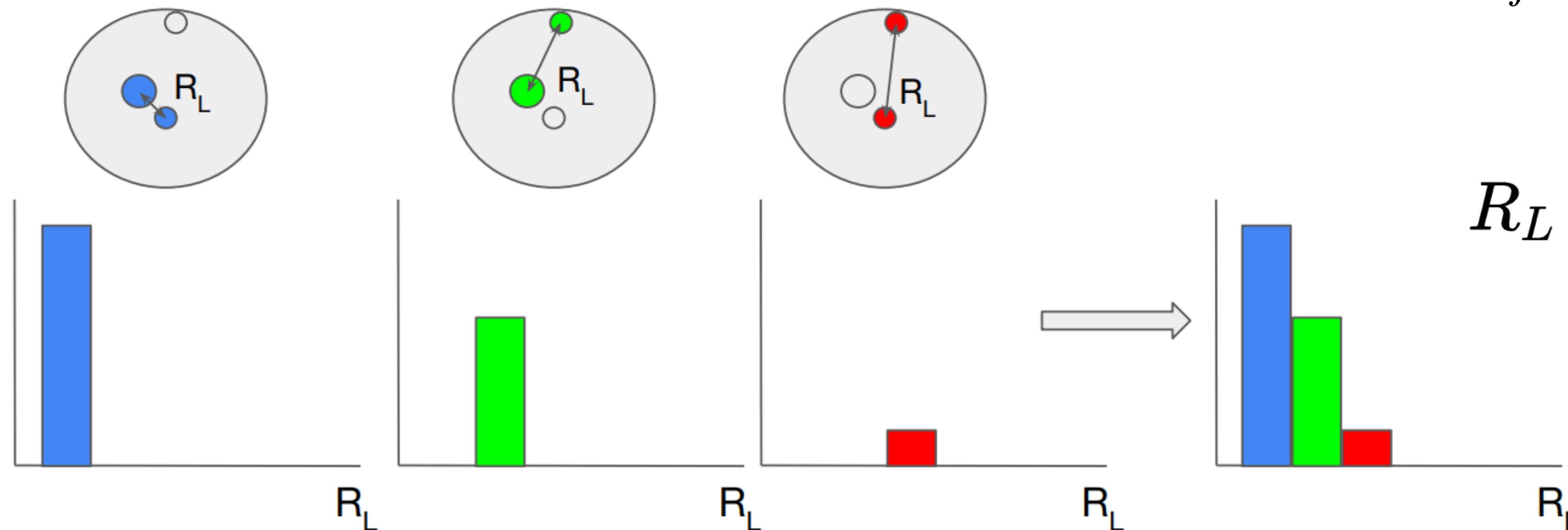
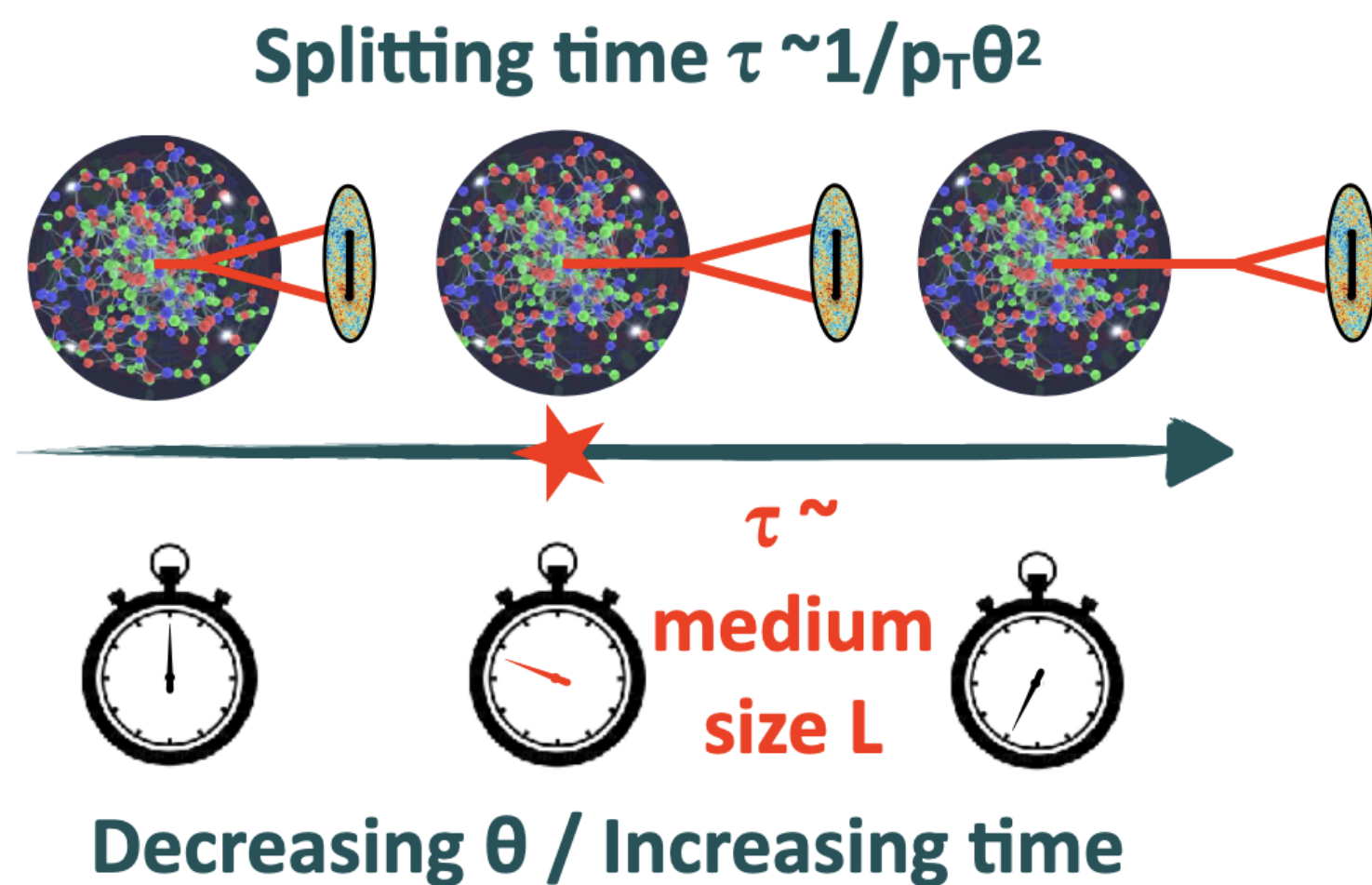


Figure from [Arjun Kudinoor \(quark matter 2025\)](#)

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

Why do we study energy-energy correlator?

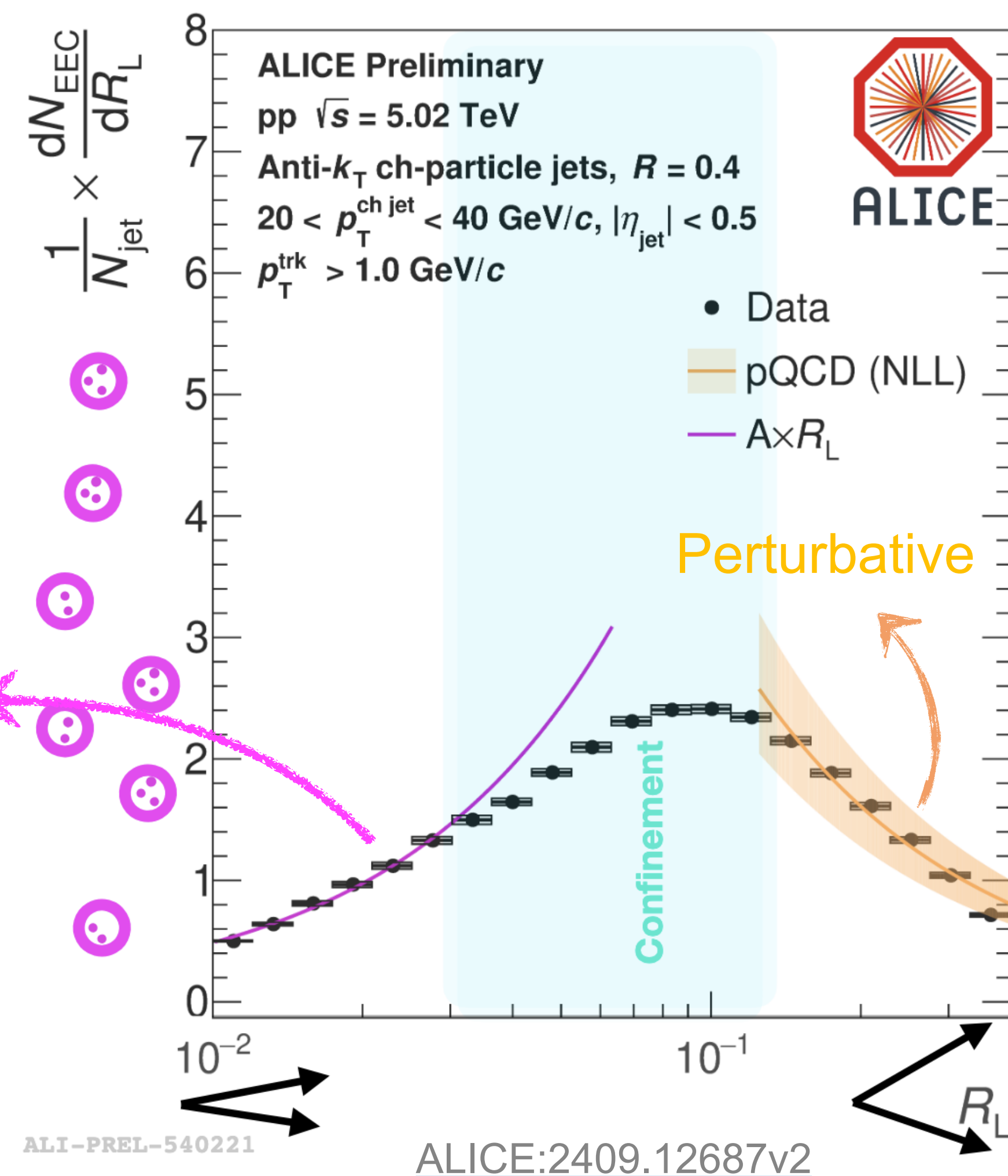
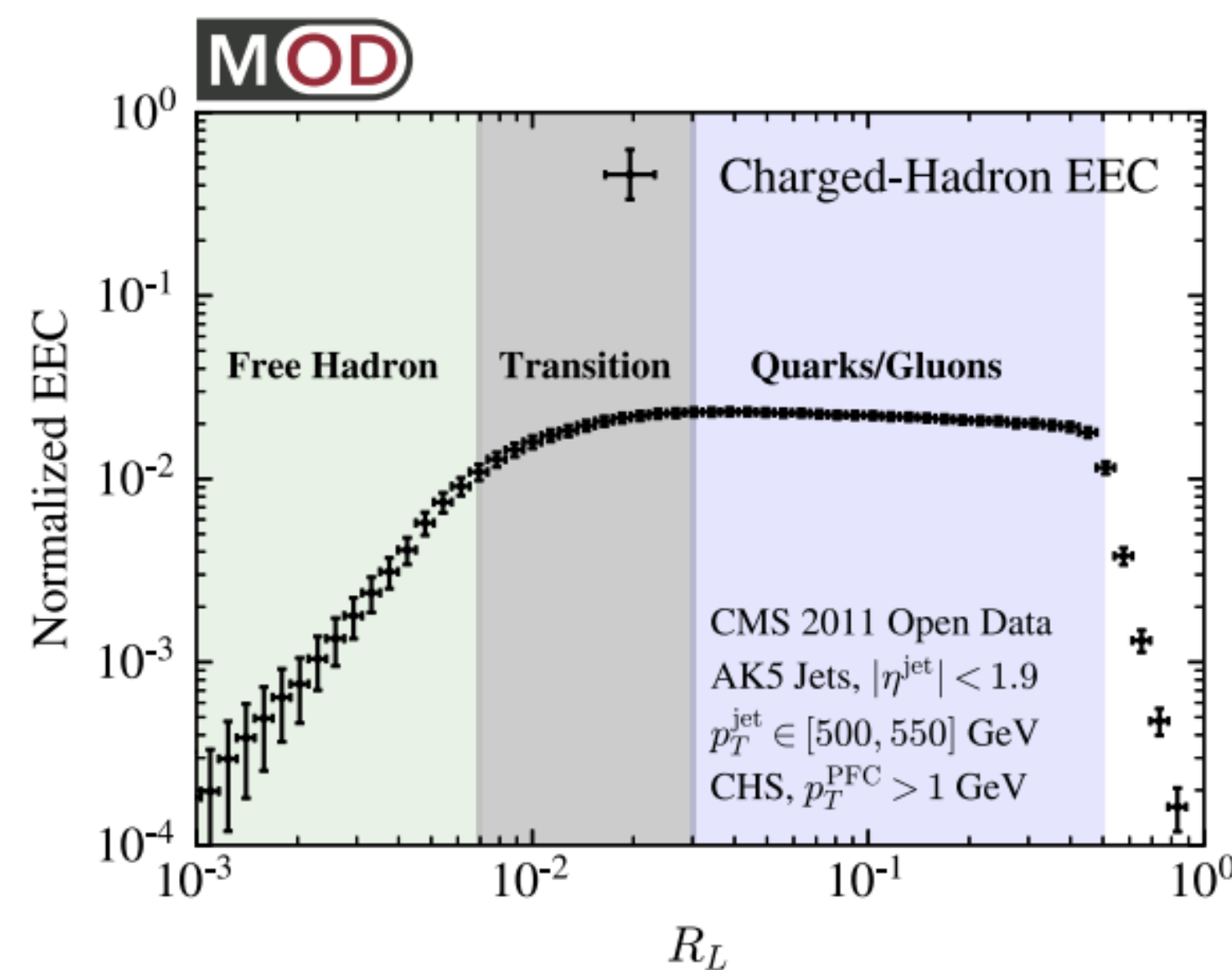


Wenqing Fan ([Quark Matter 2025](#))

➤ 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



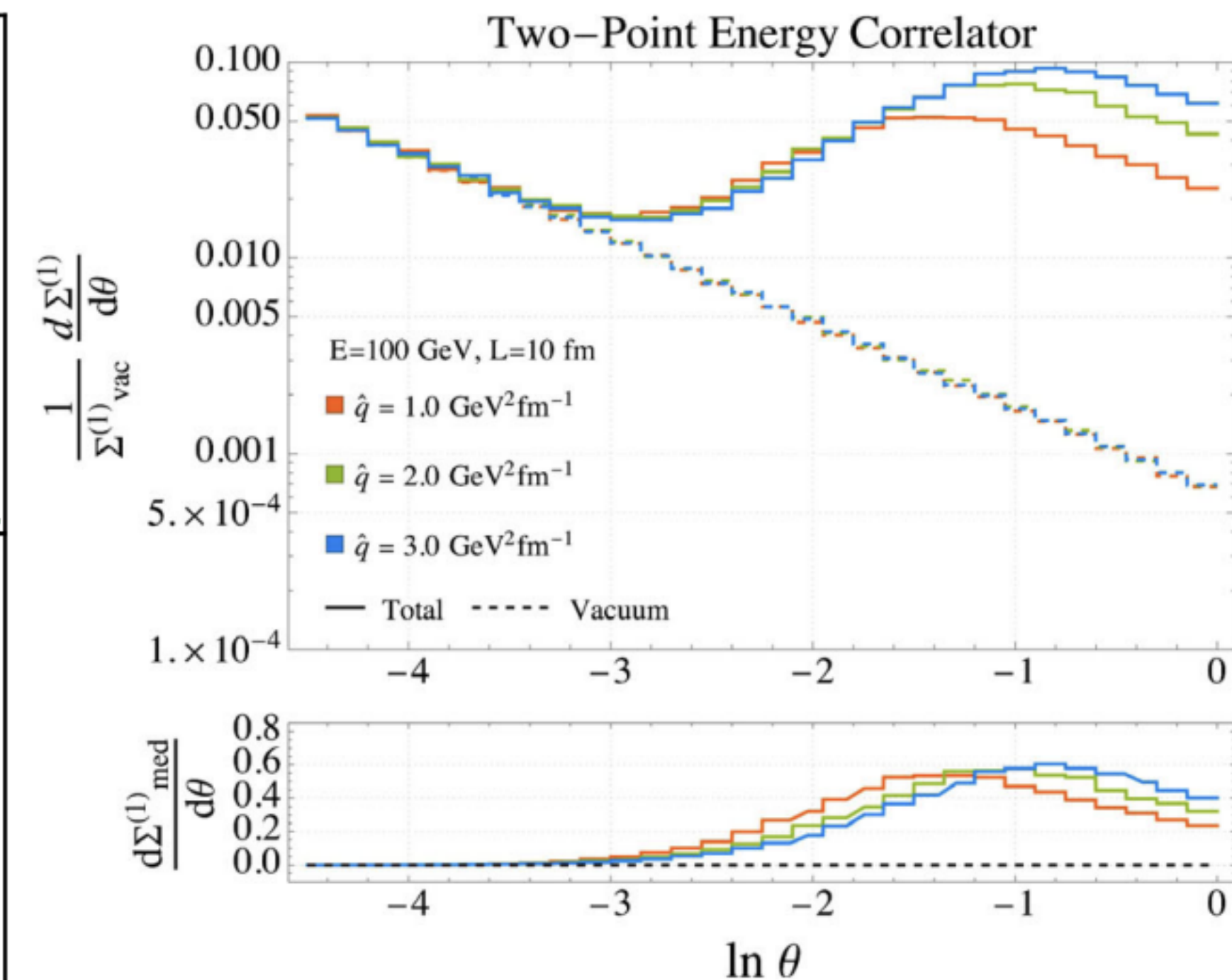
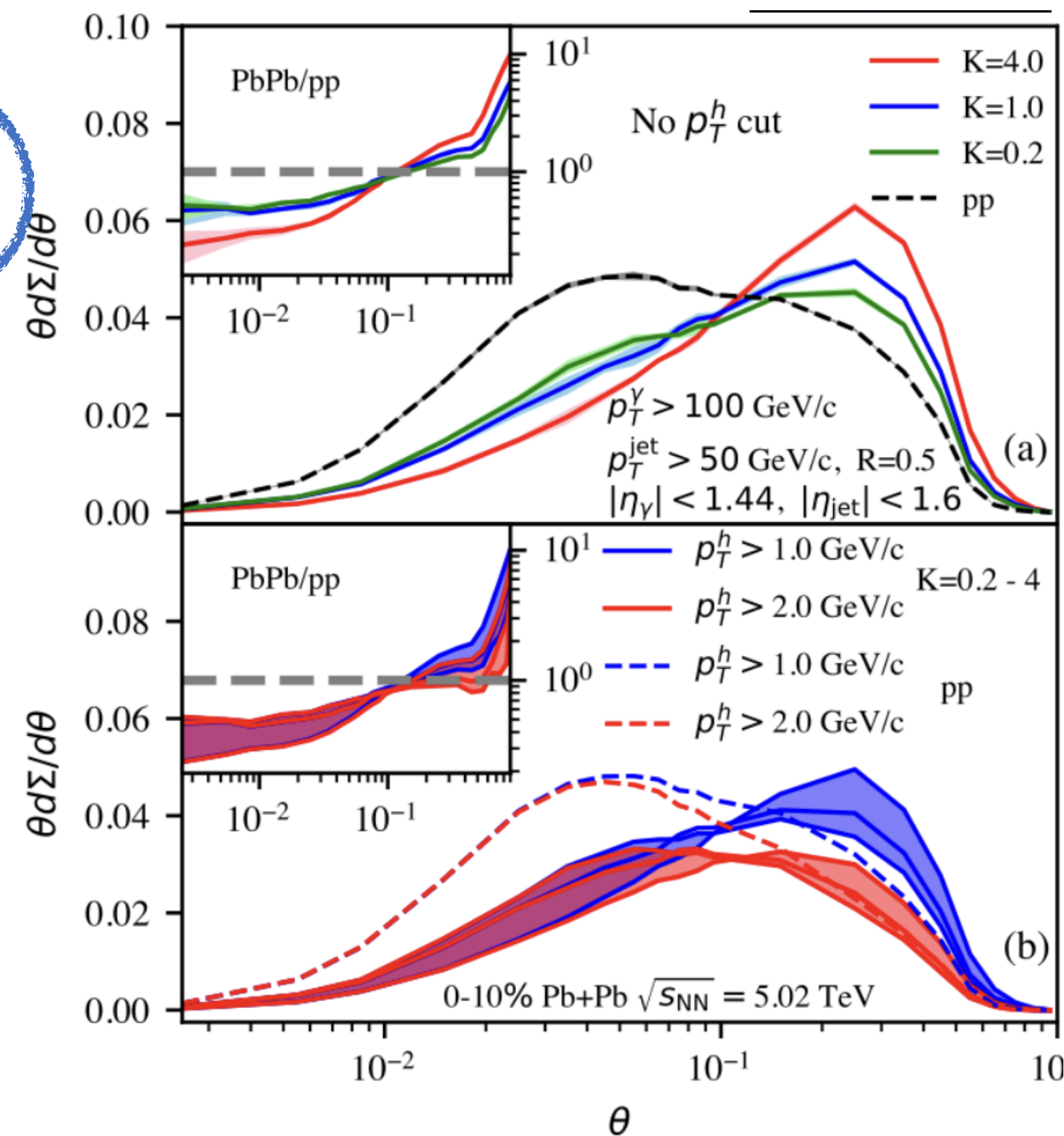
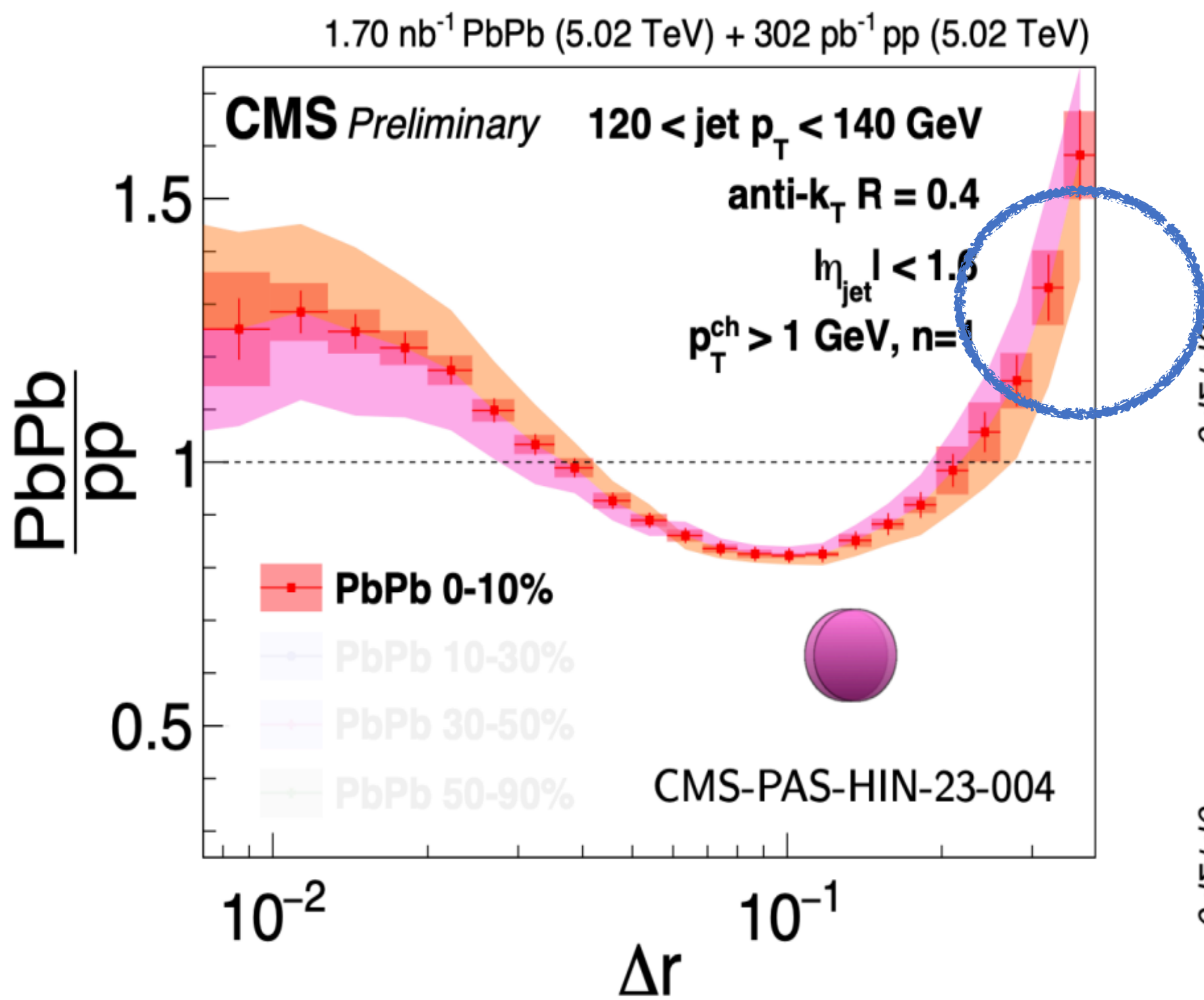
EEC of single jet in Pb+Pb collisions at CMS

➤ Large angle:

Medium response

Medium-induced radiation

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



Carlota Andres.el [PRL 130, 262301](https://arxiv.org/abs/2503.19993)

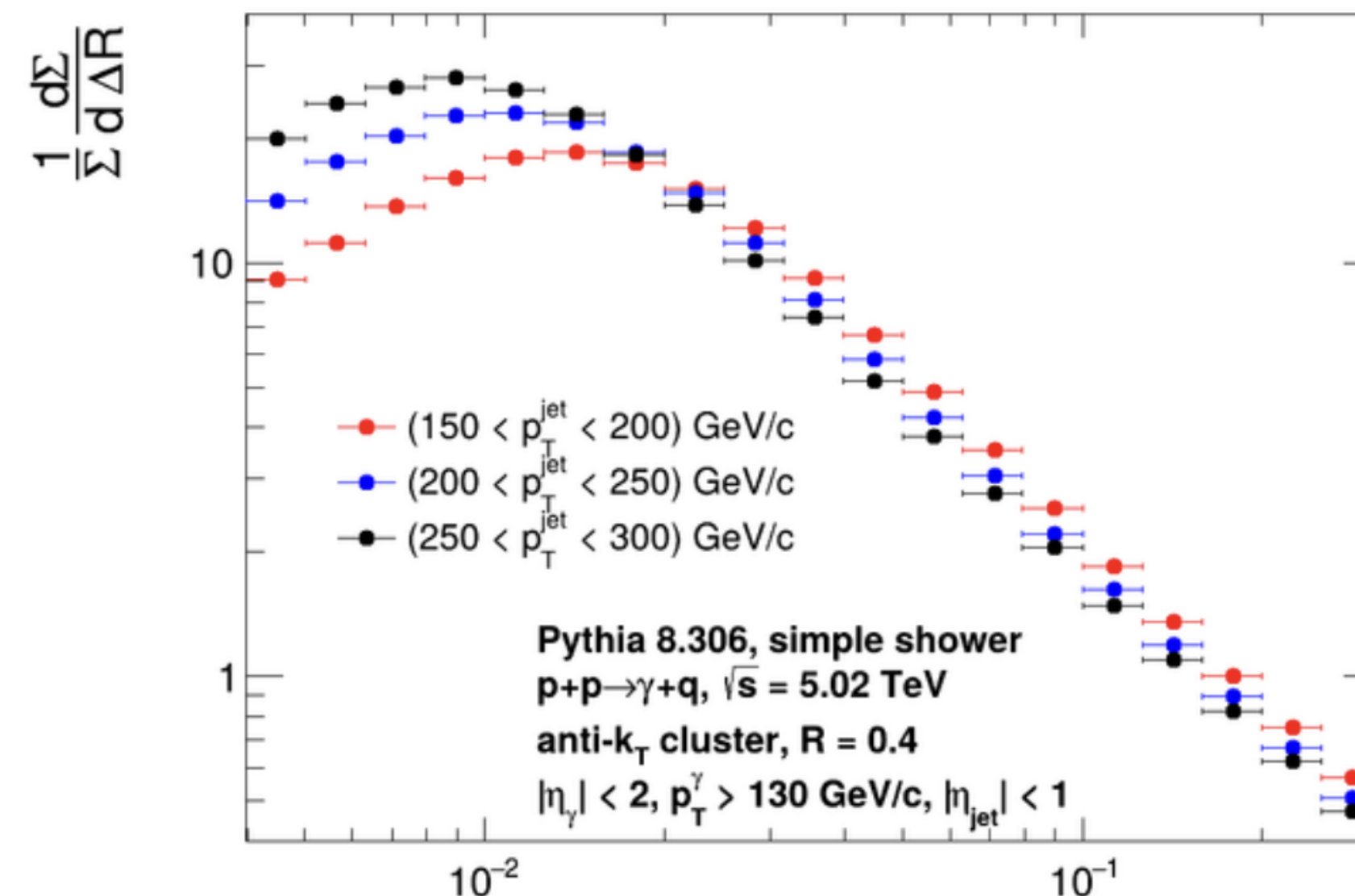
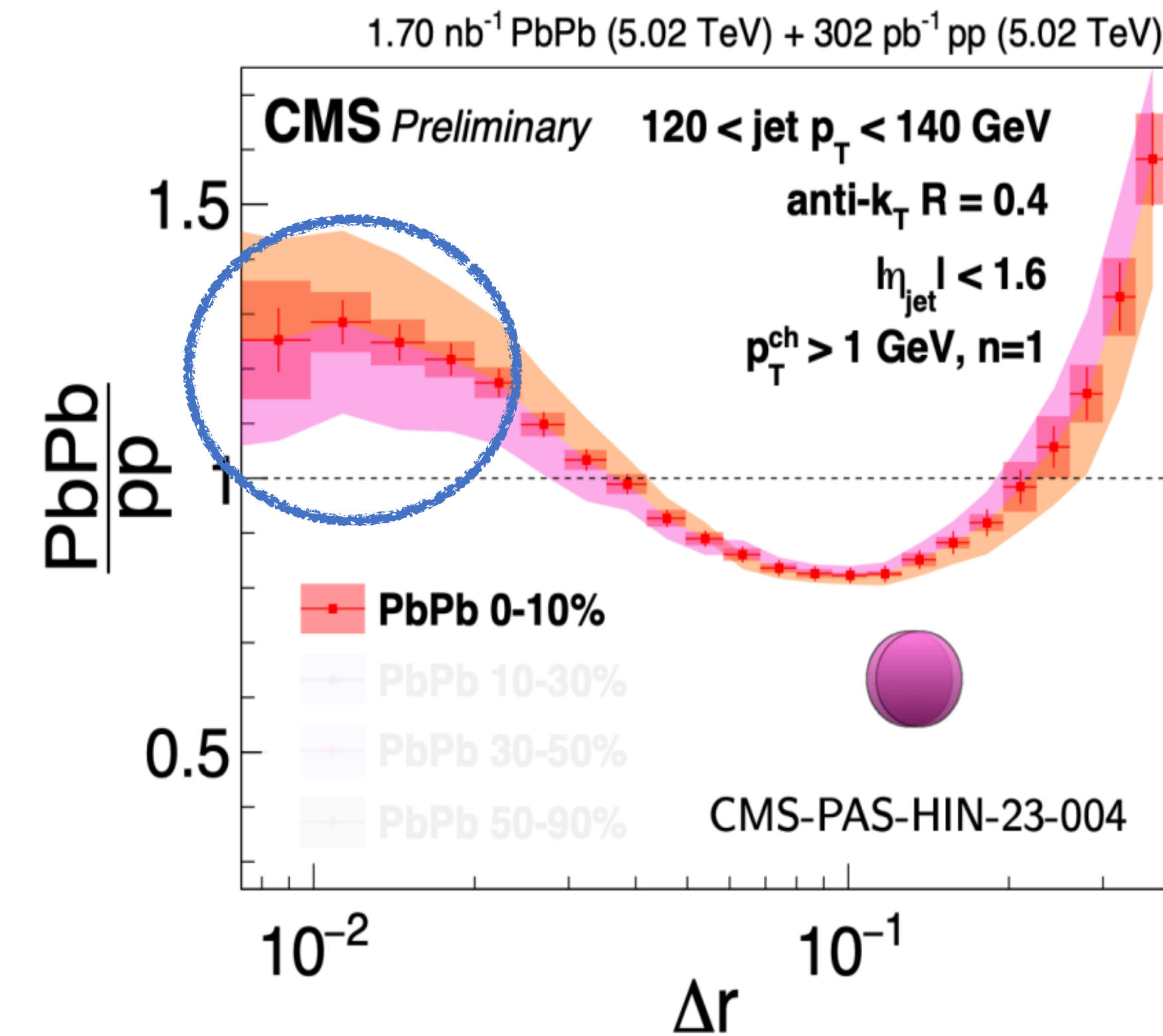
zhong.Y PRL 132 (2024) 1, 011901

EEC of single jet in Pb+Pb collisions at CMS

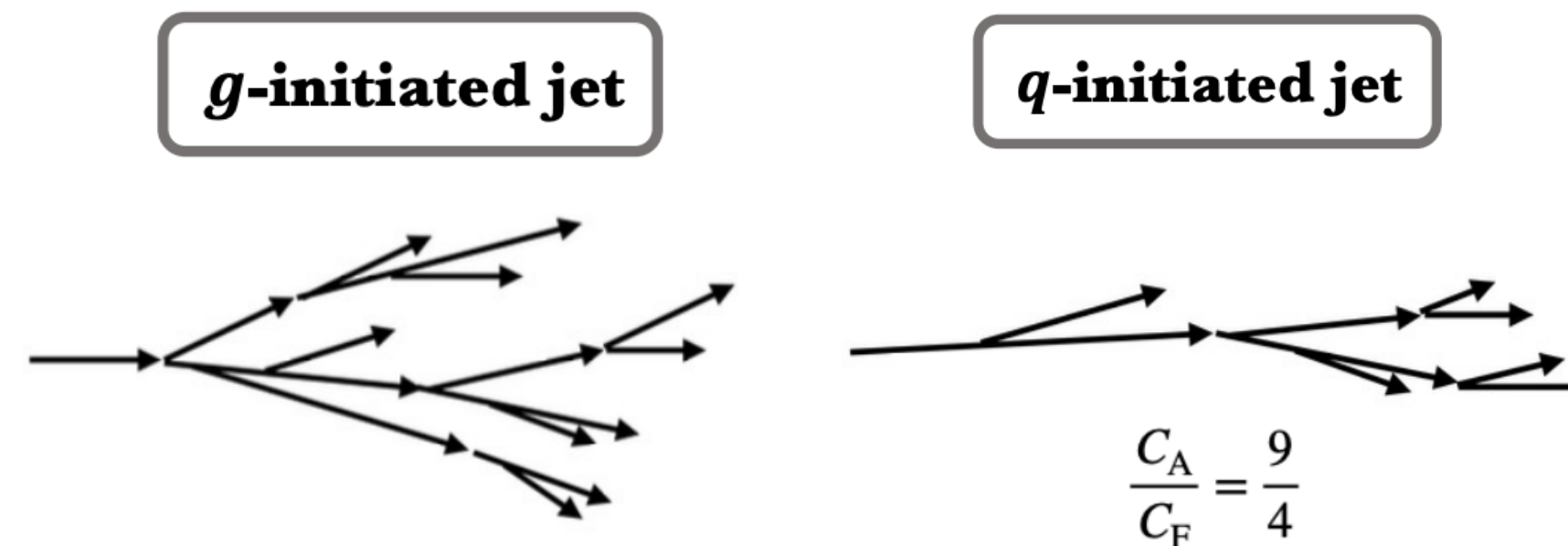
➤ Small angle:

● Jet pT selection bias

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

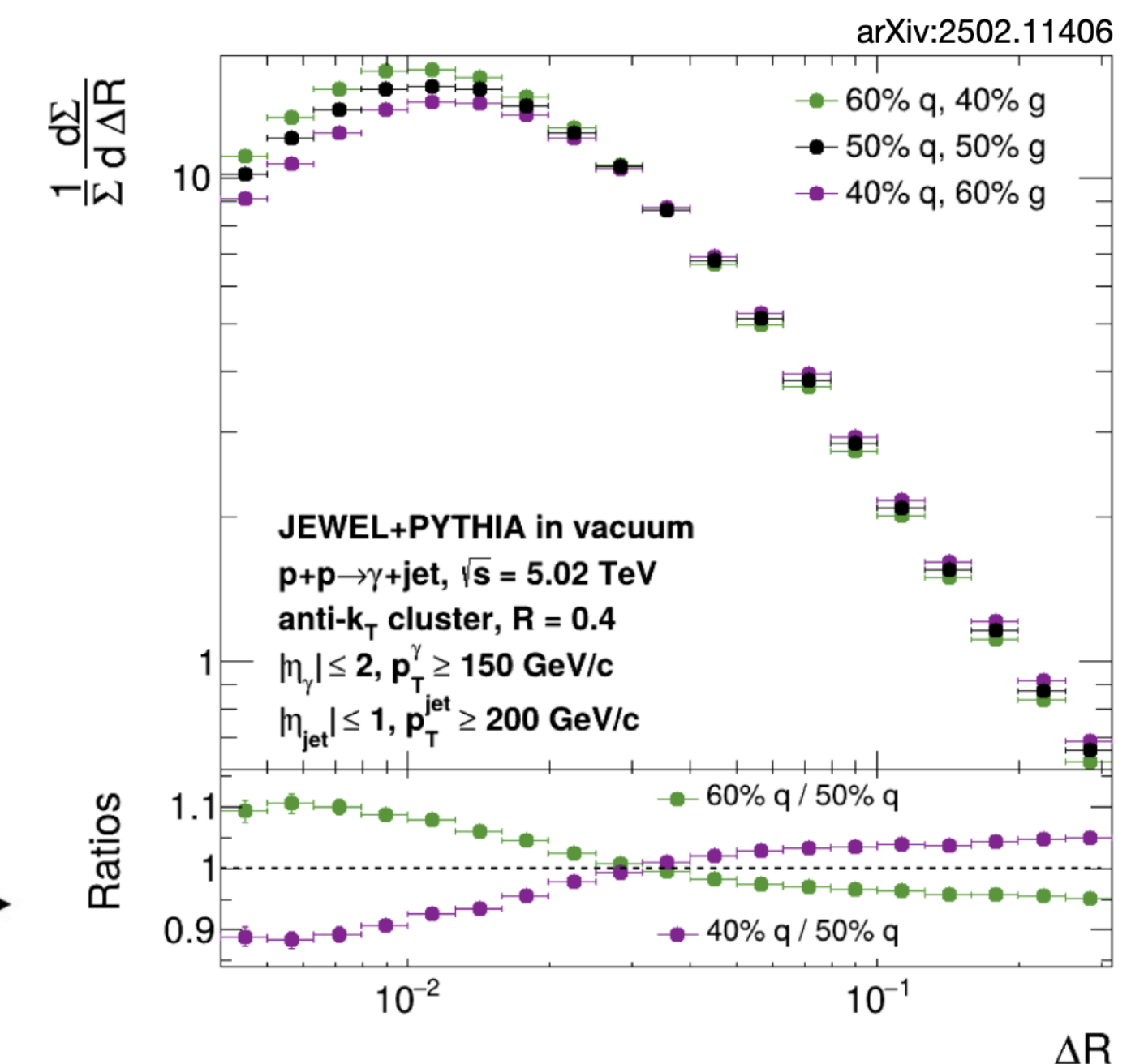
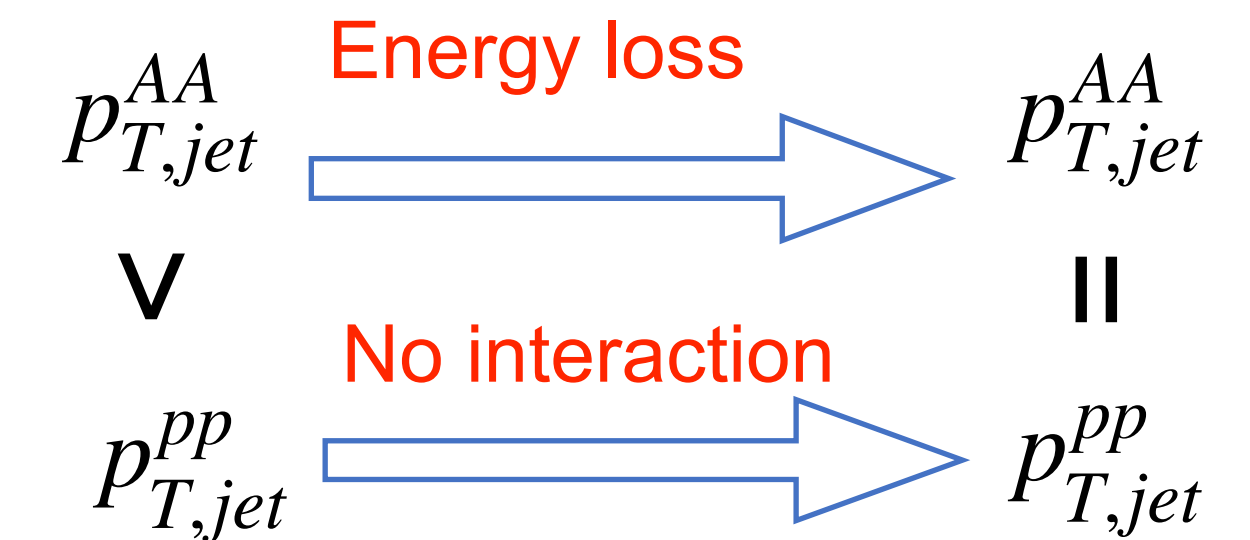


● Flavor dependence of jet



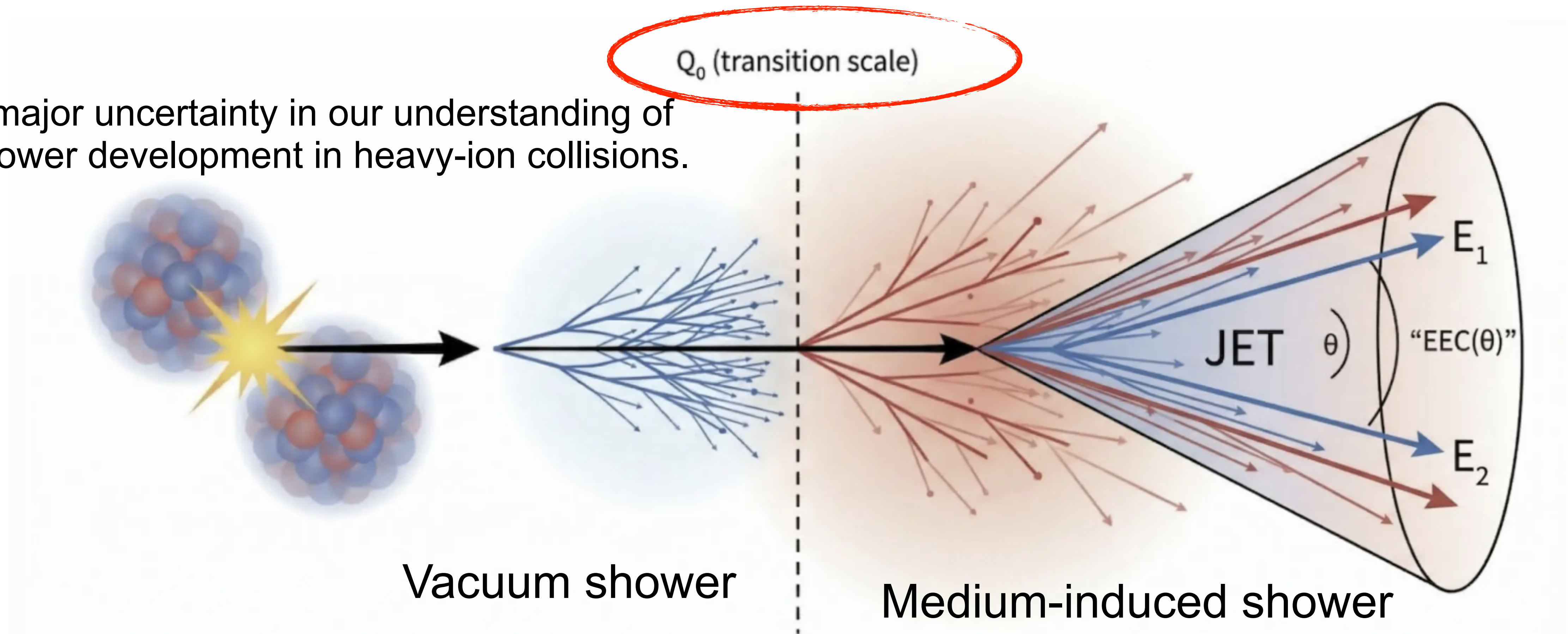
Initial

Final



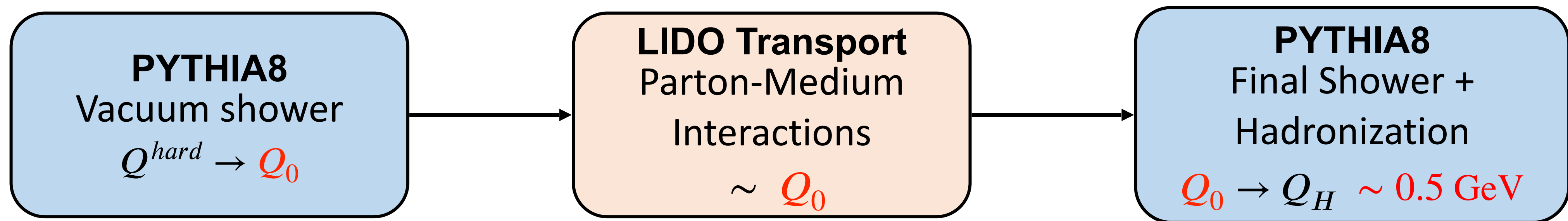
What else can EEC tell about parton shower in the medium?

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



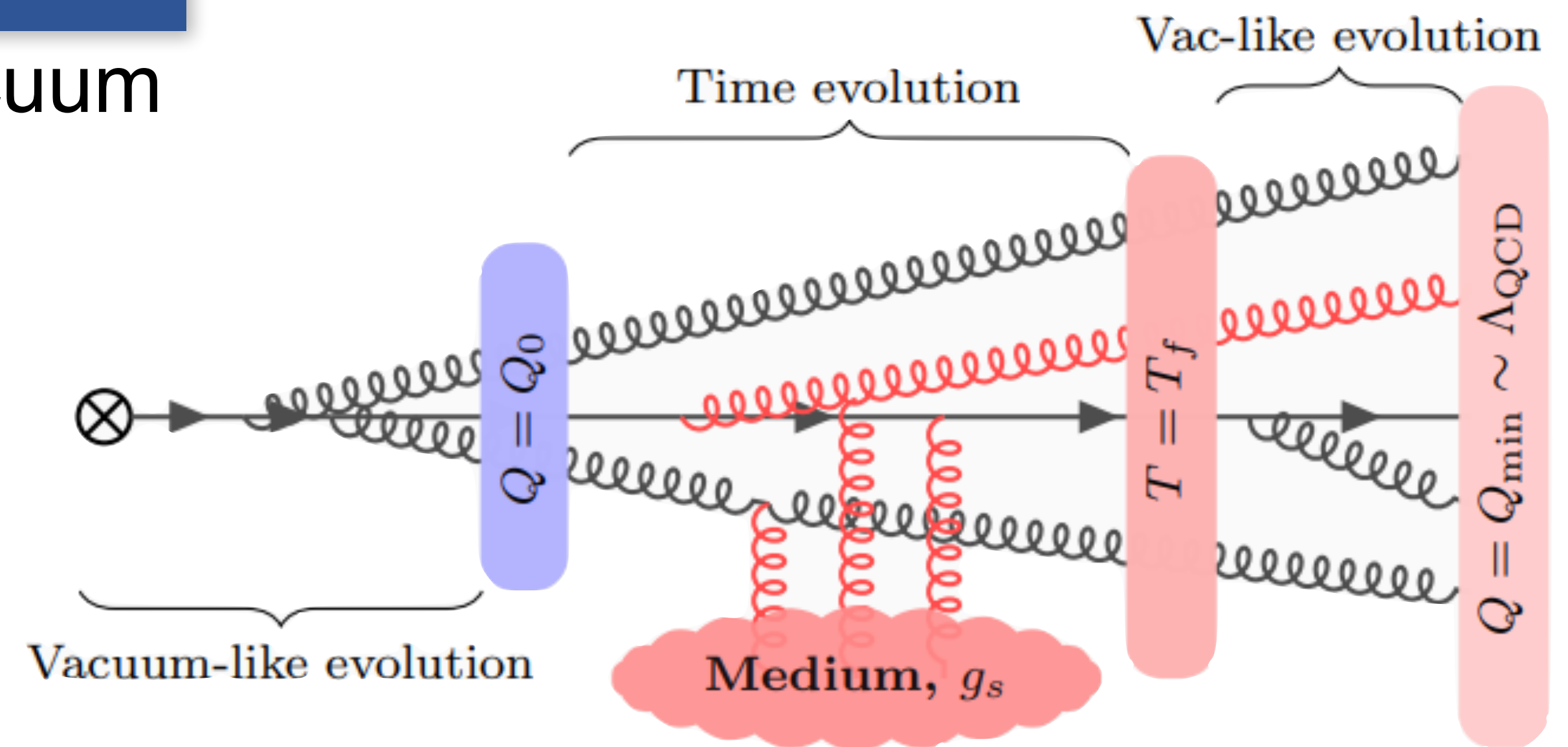
Use EEC to probe the impact of the transition scale Q_0 between vacuum and medium-induced showers.

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](#)

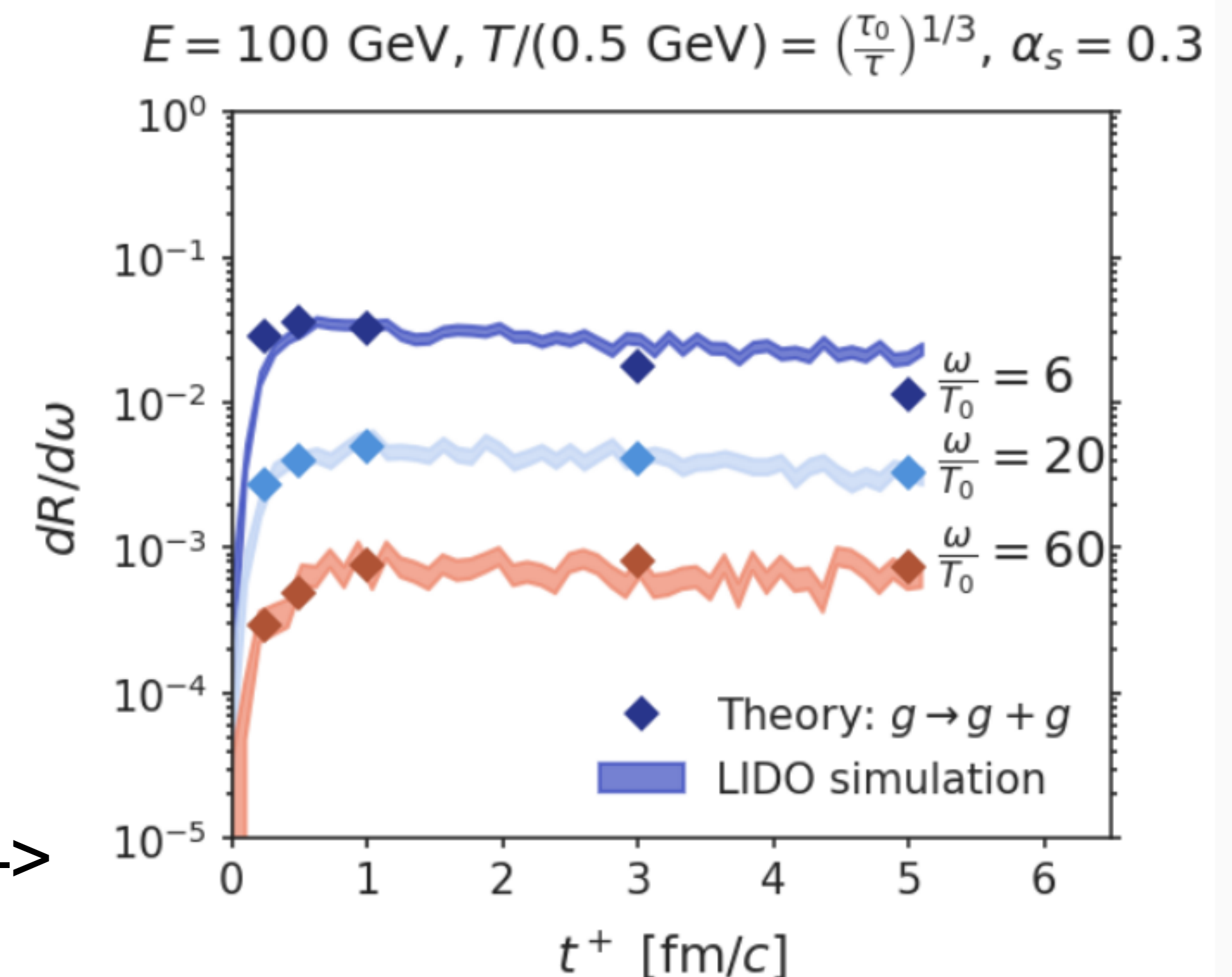
LIDO modeling: 1. hard parton transport

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](#)

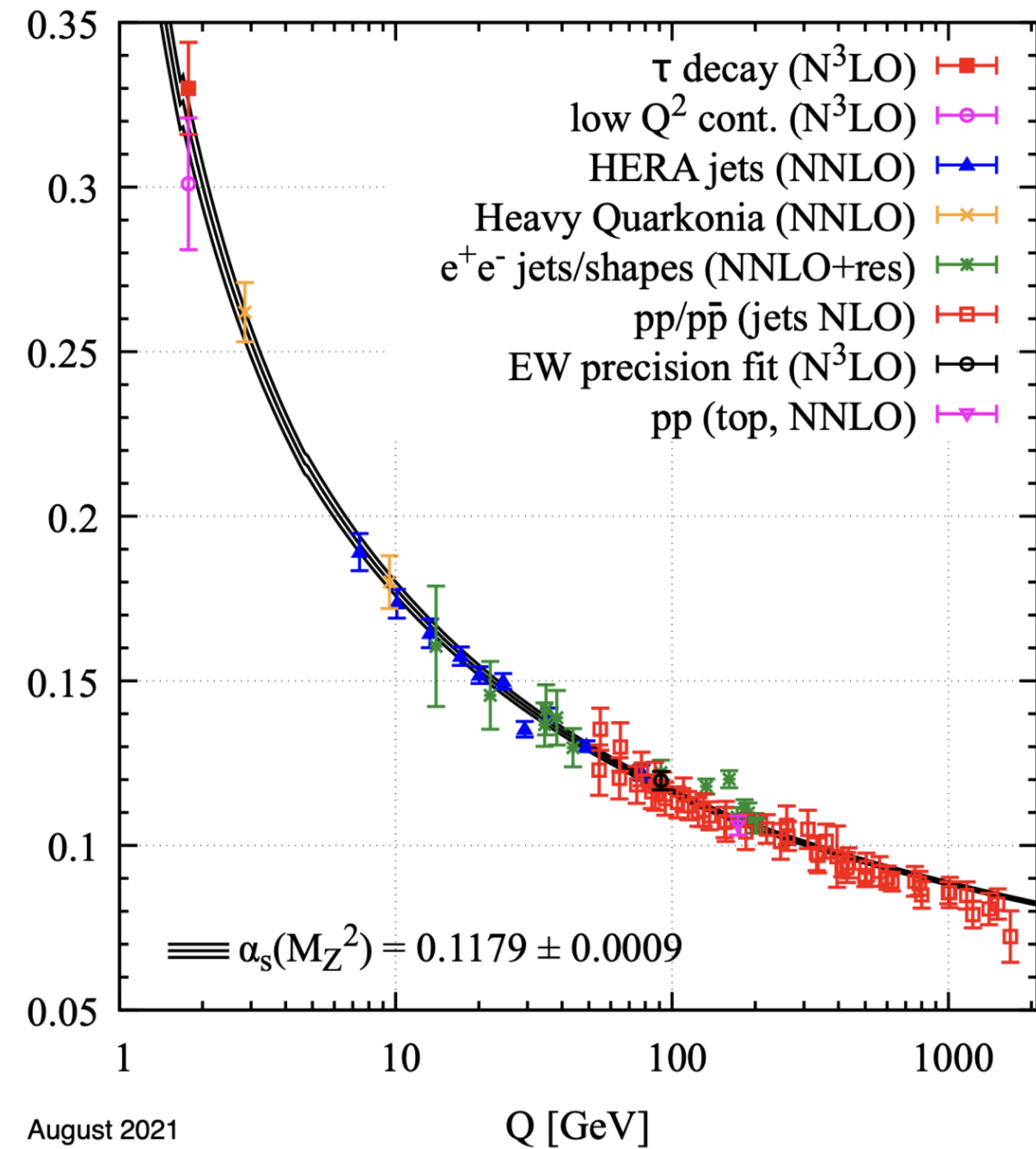
[PRC 58 \(1998\) 1706](#)

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:

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

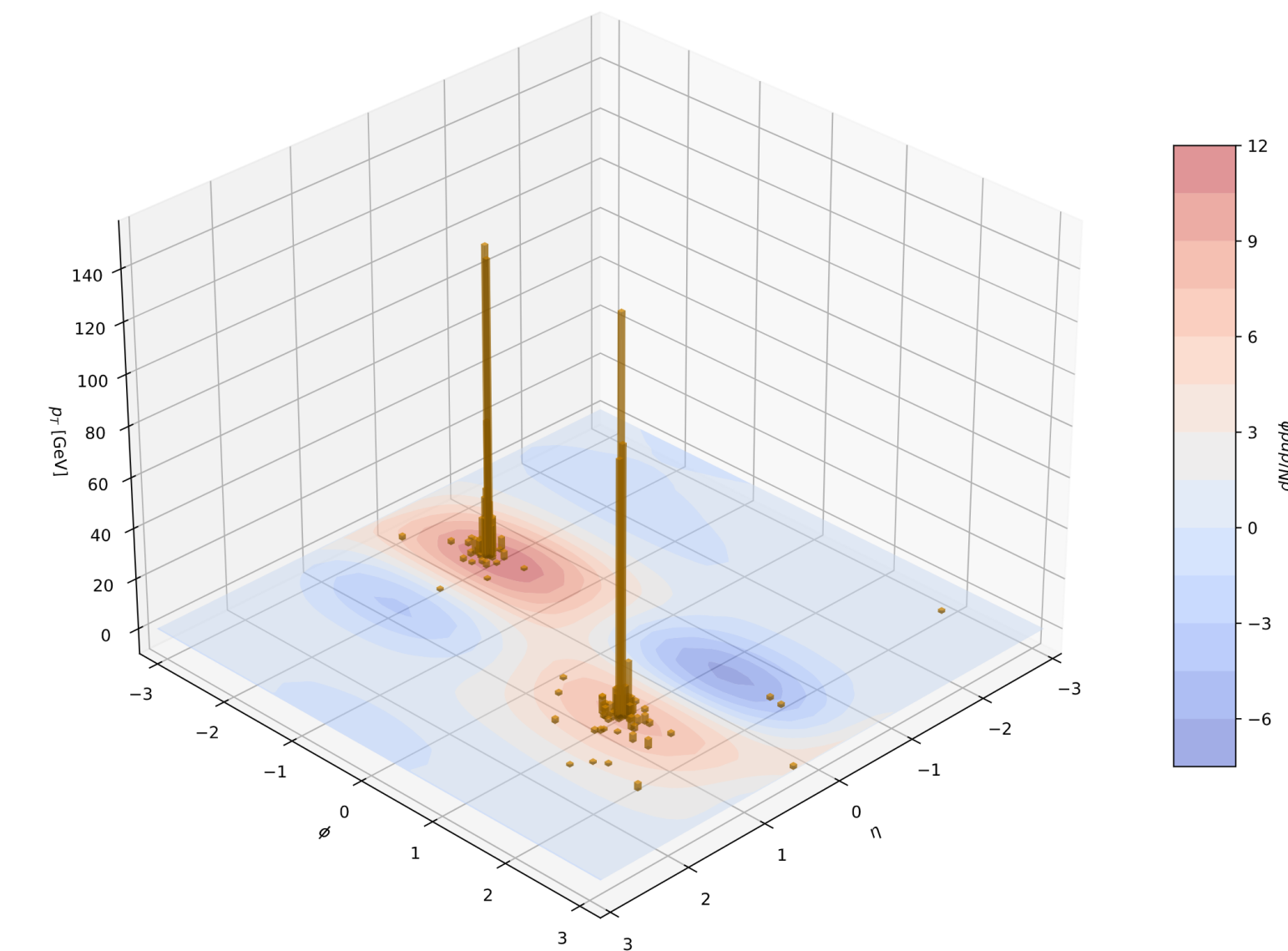
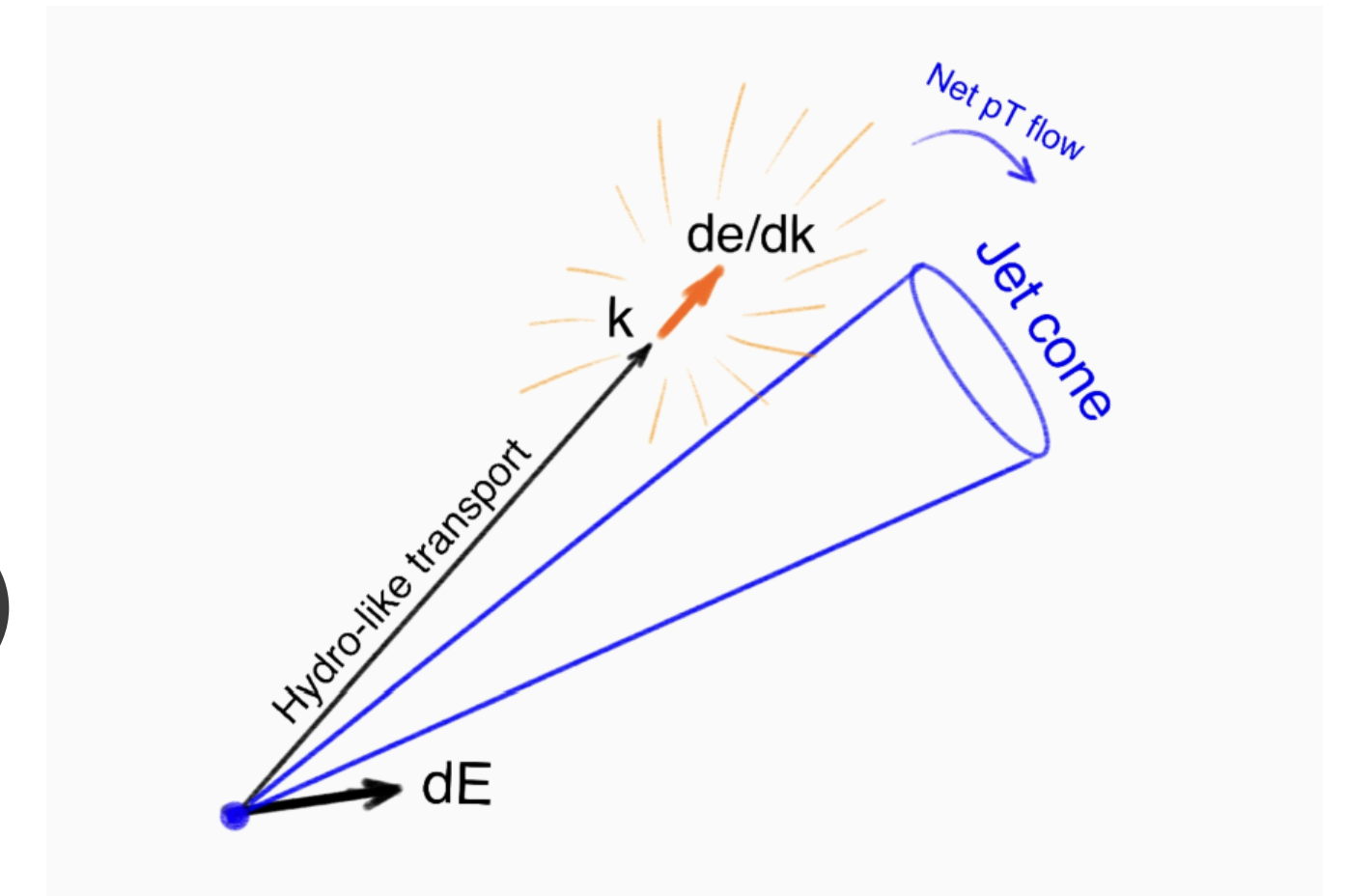
- Ideal-hydro response in real space (no transverse flow)

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

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

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

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

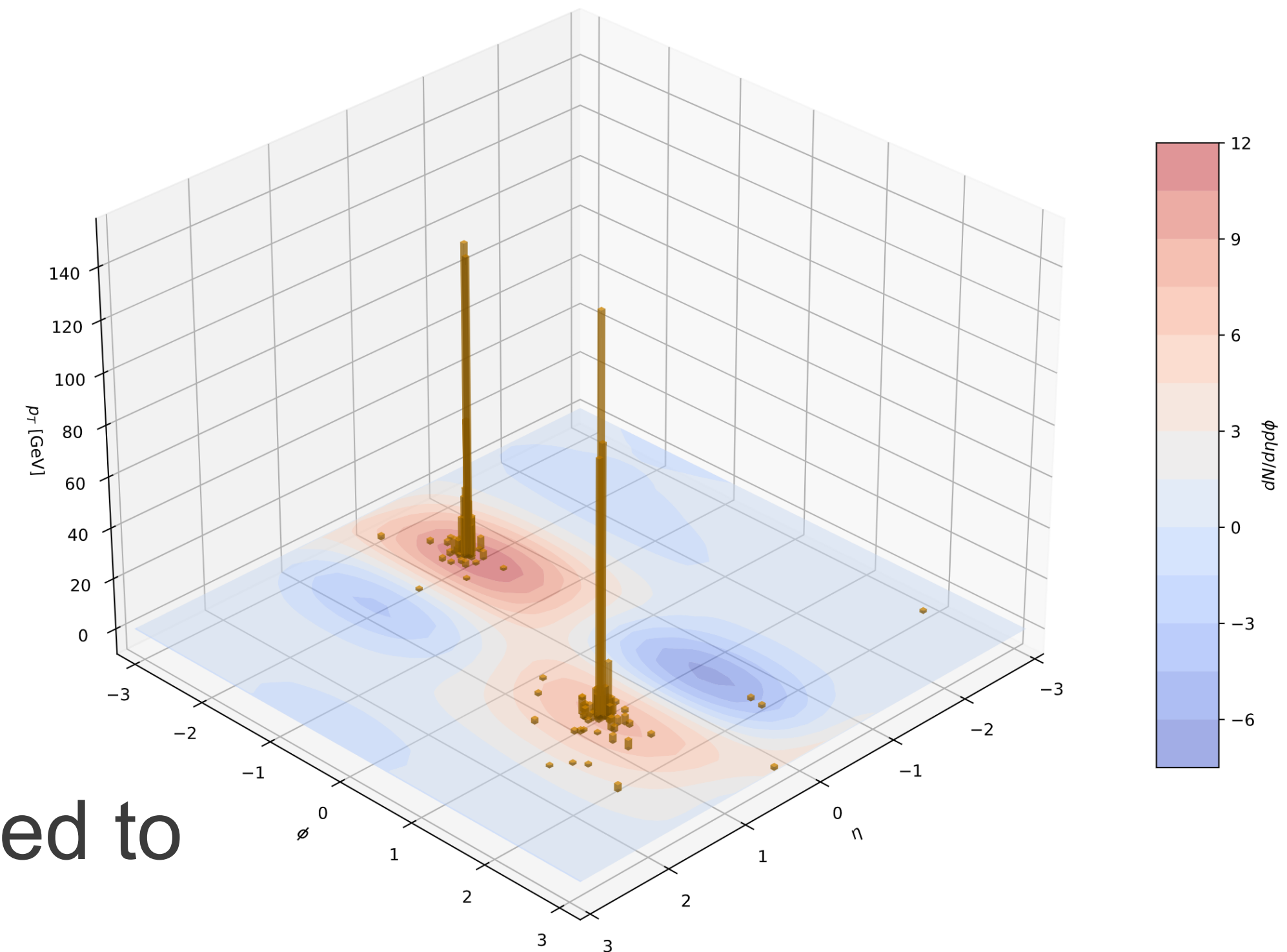


Jet definition in LIDO with medium response

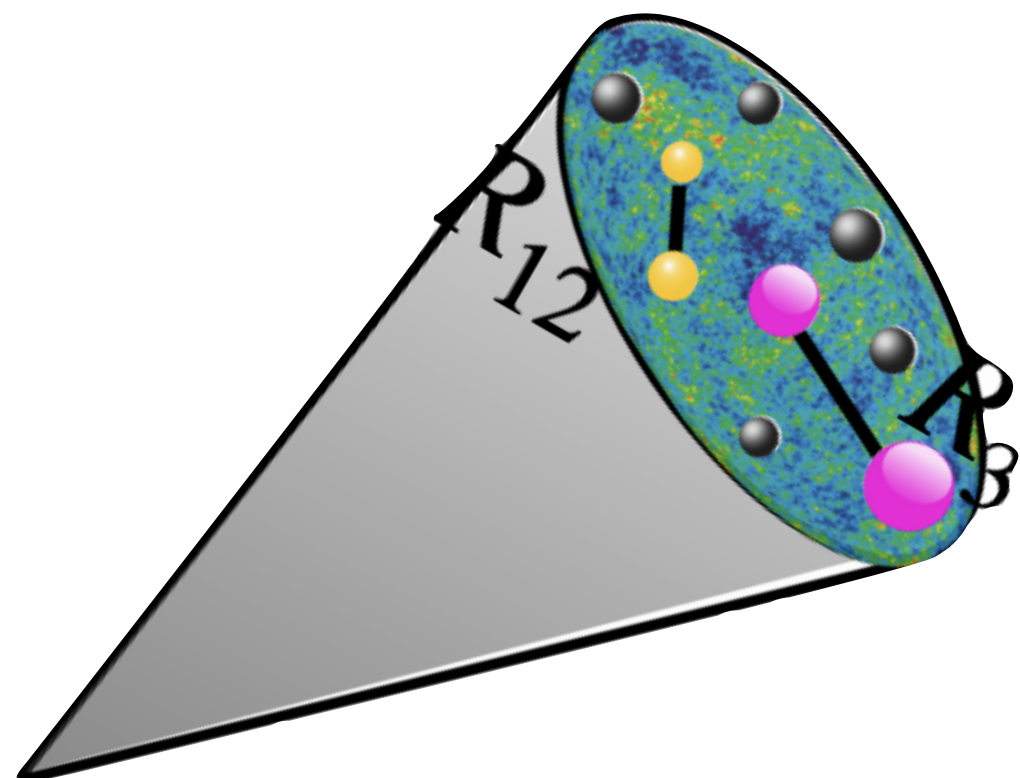
- Jets (anti- K_T) are reconstructed from energy bins $E_{T,ij}$, defined by

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

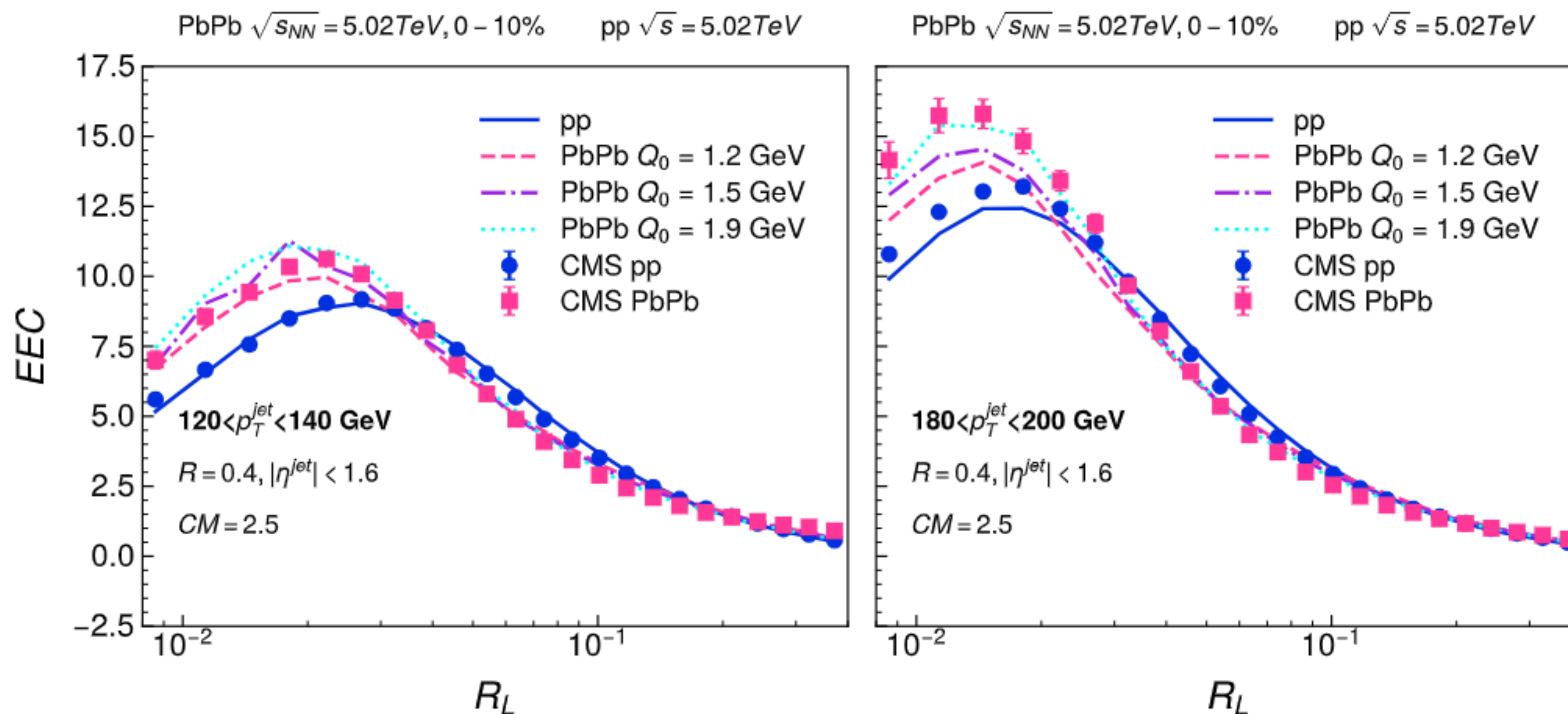
- Uncorrelated medium background are assumed to be perfectly subtracted.



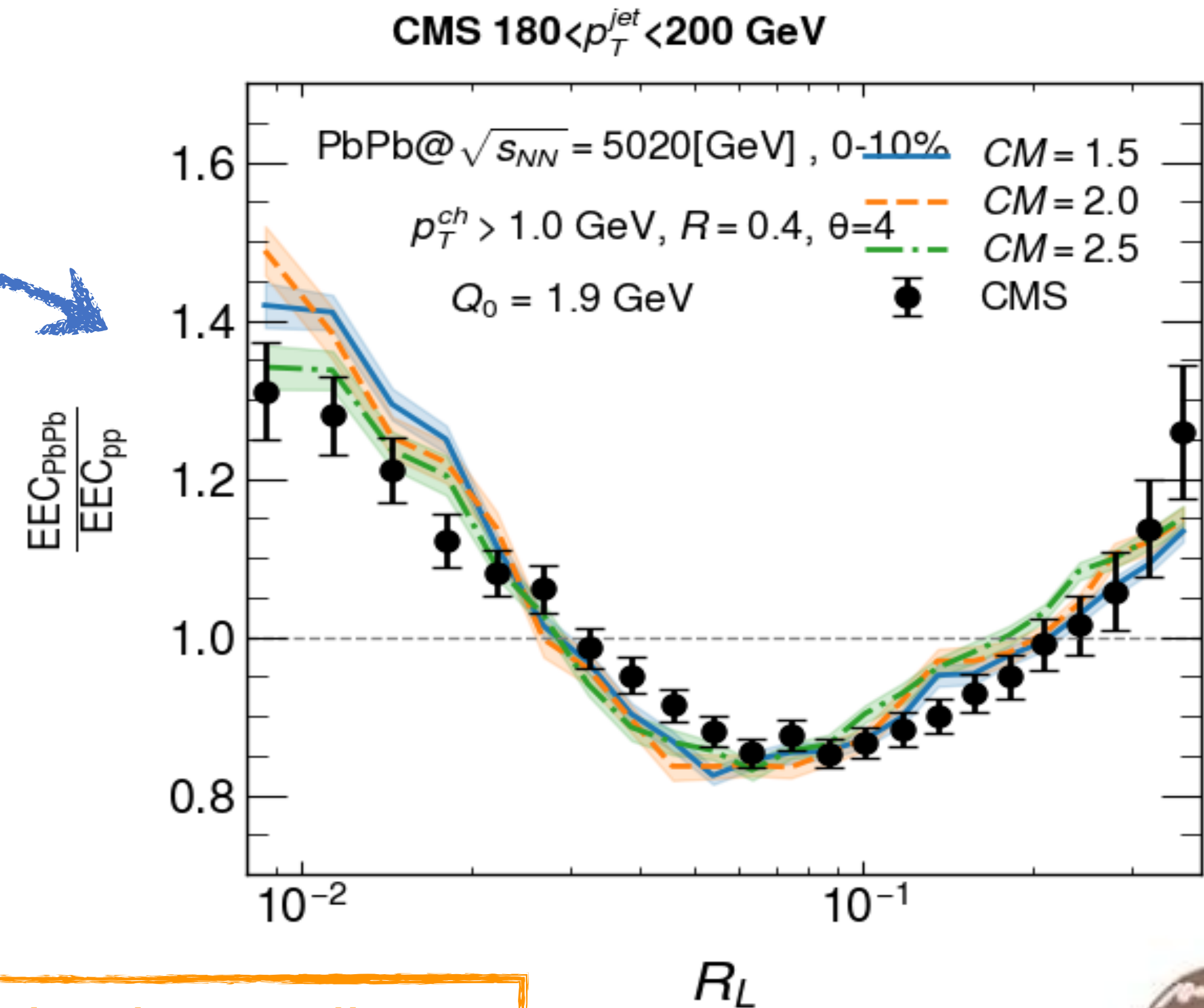
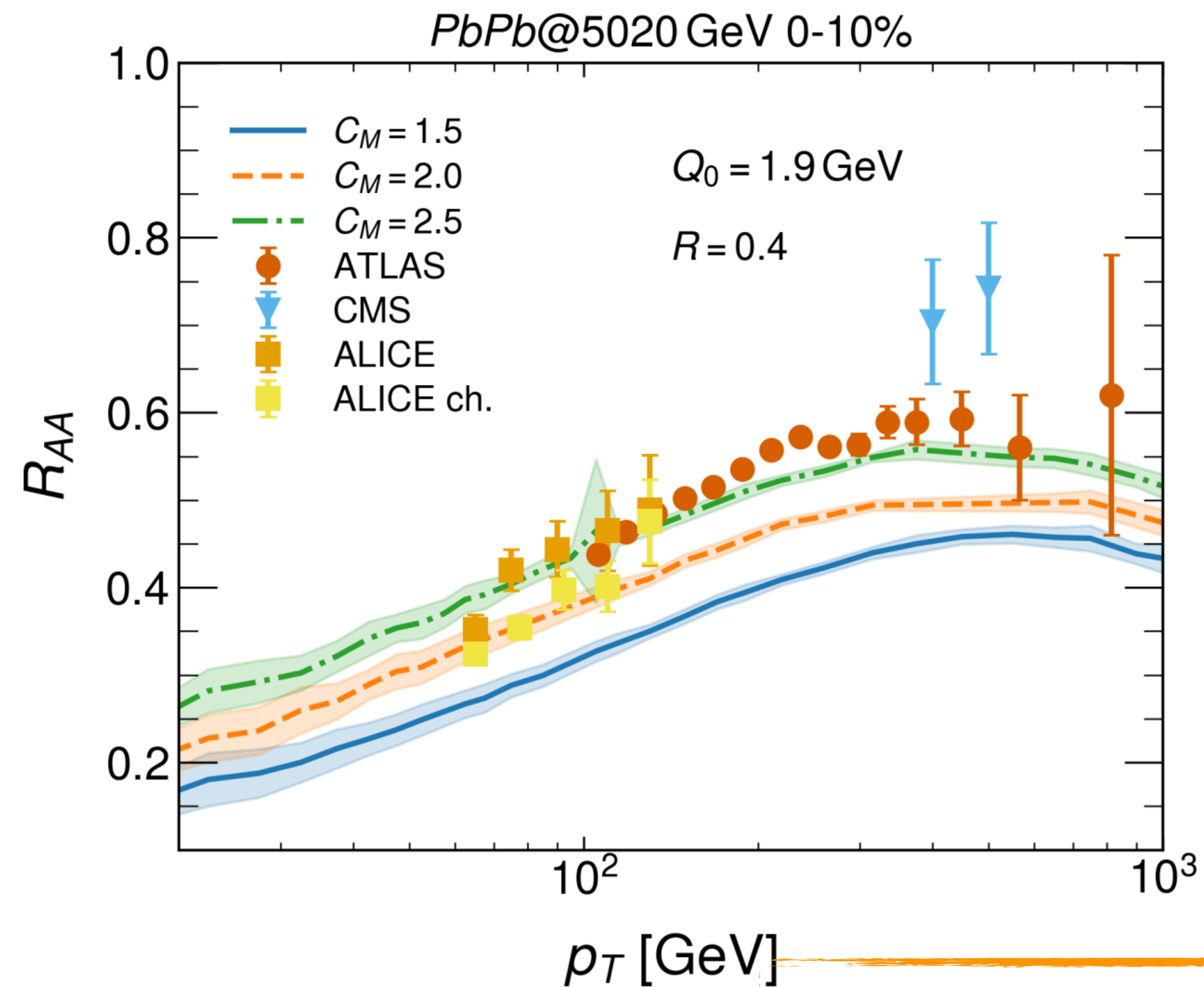
0. EEC in pp baseline: Theory vs. CMS Data



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



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

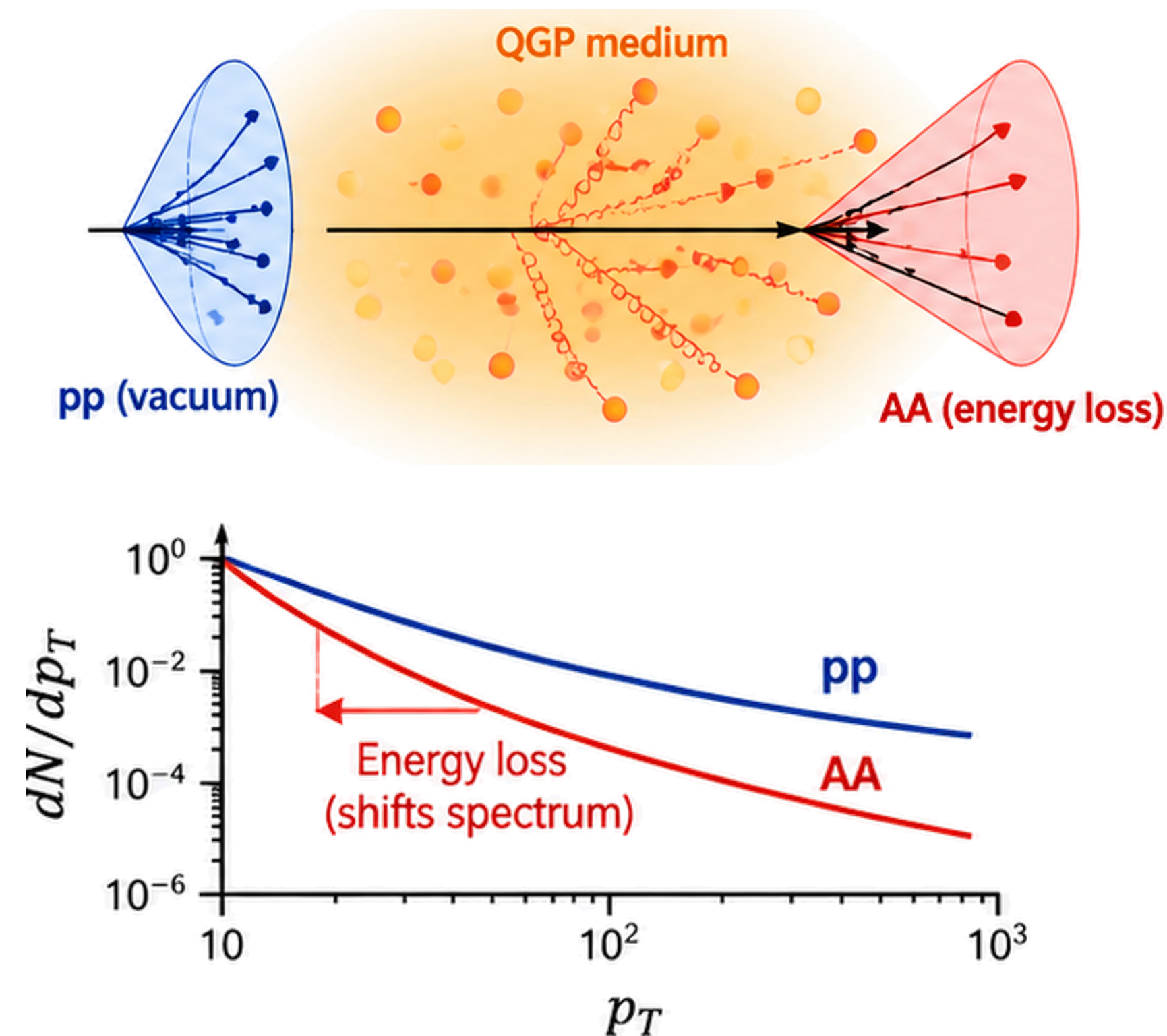
$$\alpha_s(Q, T) = \frac{4\pi}{9} \cdot \frac{1}{\ln\left(\frac{\max\{Q^2, \mu_{\min}^2\}}{\Lambda_{\text{QCD}}^2}\right)} \quad \mu_{\min} = C_M \times \pi T$$



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

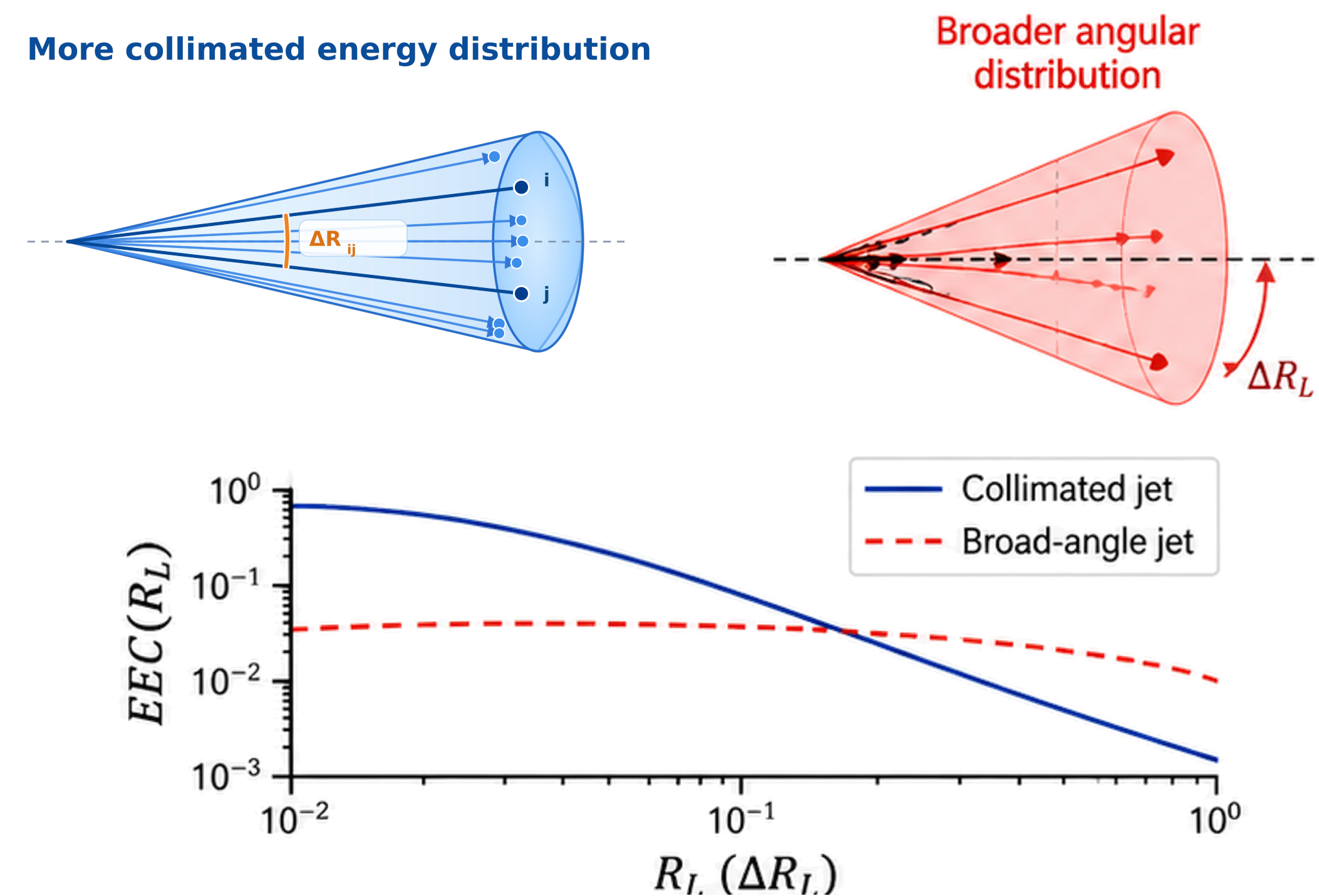
Jet nuclear modification factor:

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



Energy-energy correlator:

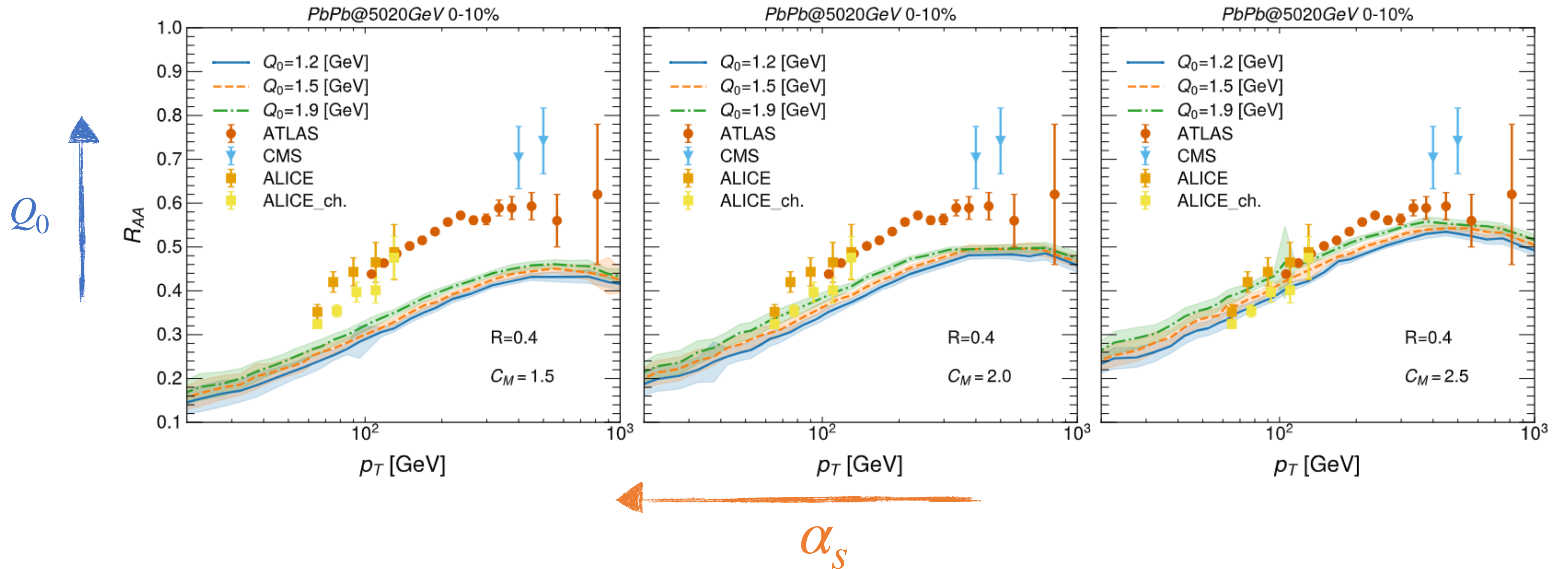
$$\text{EEC}(\Delta r) = \frac{1}{W_{\text{pairs}}} \frac{1}{\delta r} \sum_{\text{jets} \in [p_{T,1}, p_{T,2}]} \sum_{\text{pairs} \in [\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})^n$$



➤ R_{AA} : Governed by total energy loss
→ Stronger sensitivity

➤ **EEC**: Probes relative angular structure in jets →
Normalized & energy-weighted → weak sensitivity

2. Parameter sensitivity: transition scale Q_0

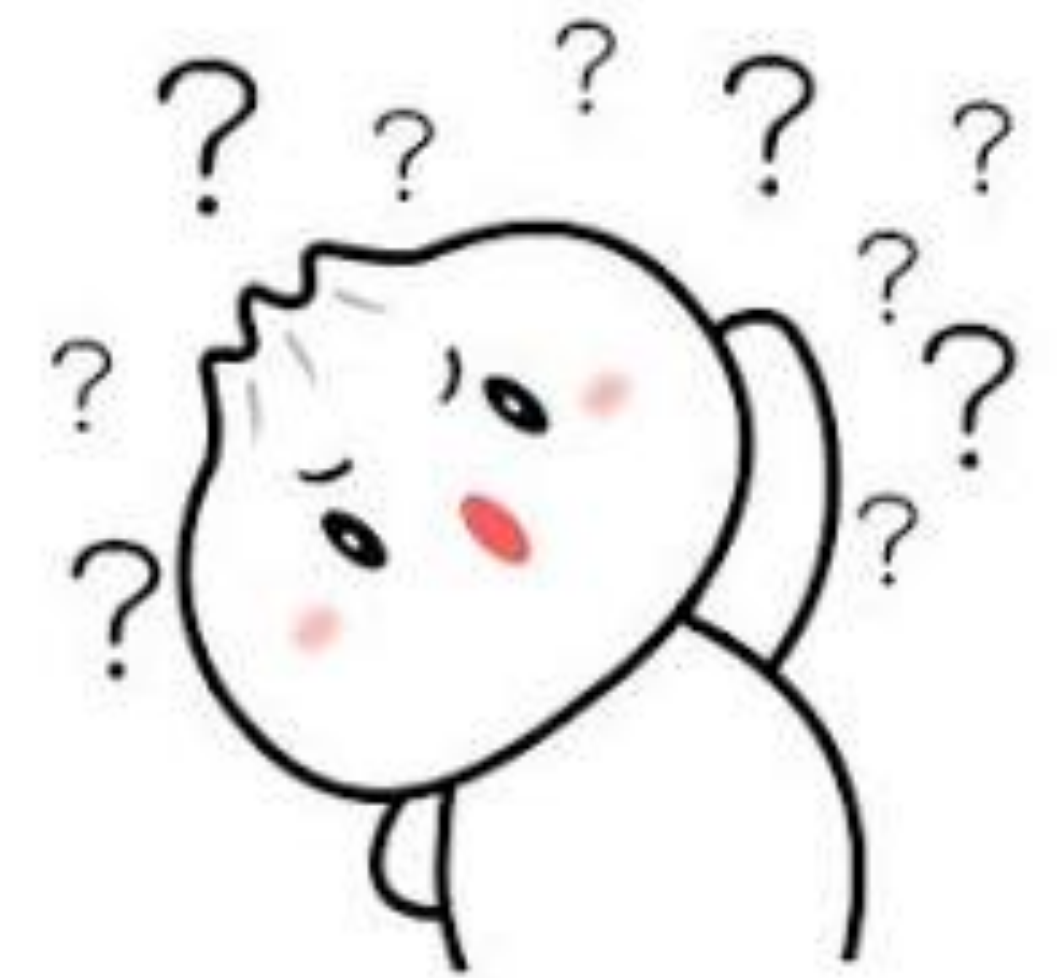
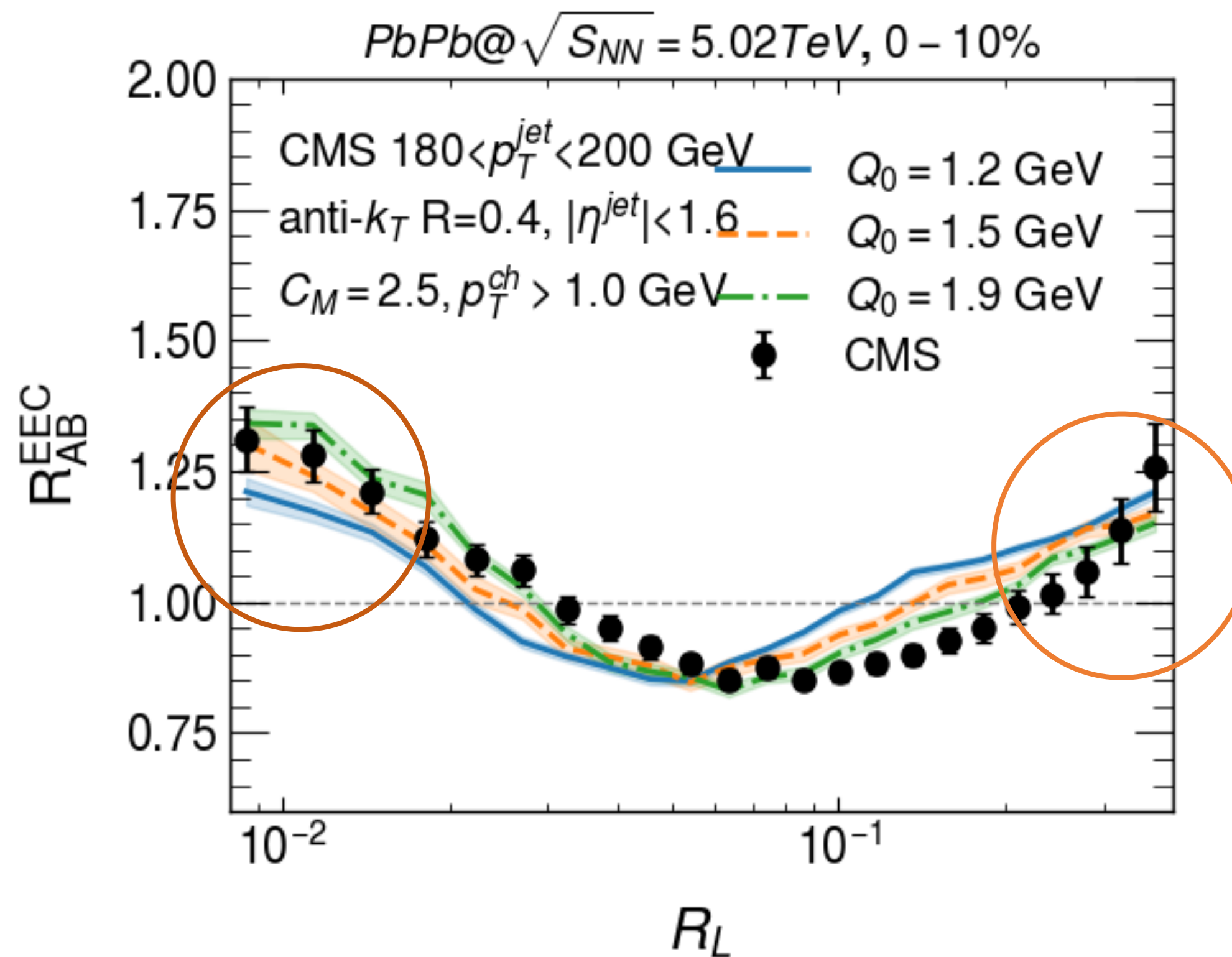
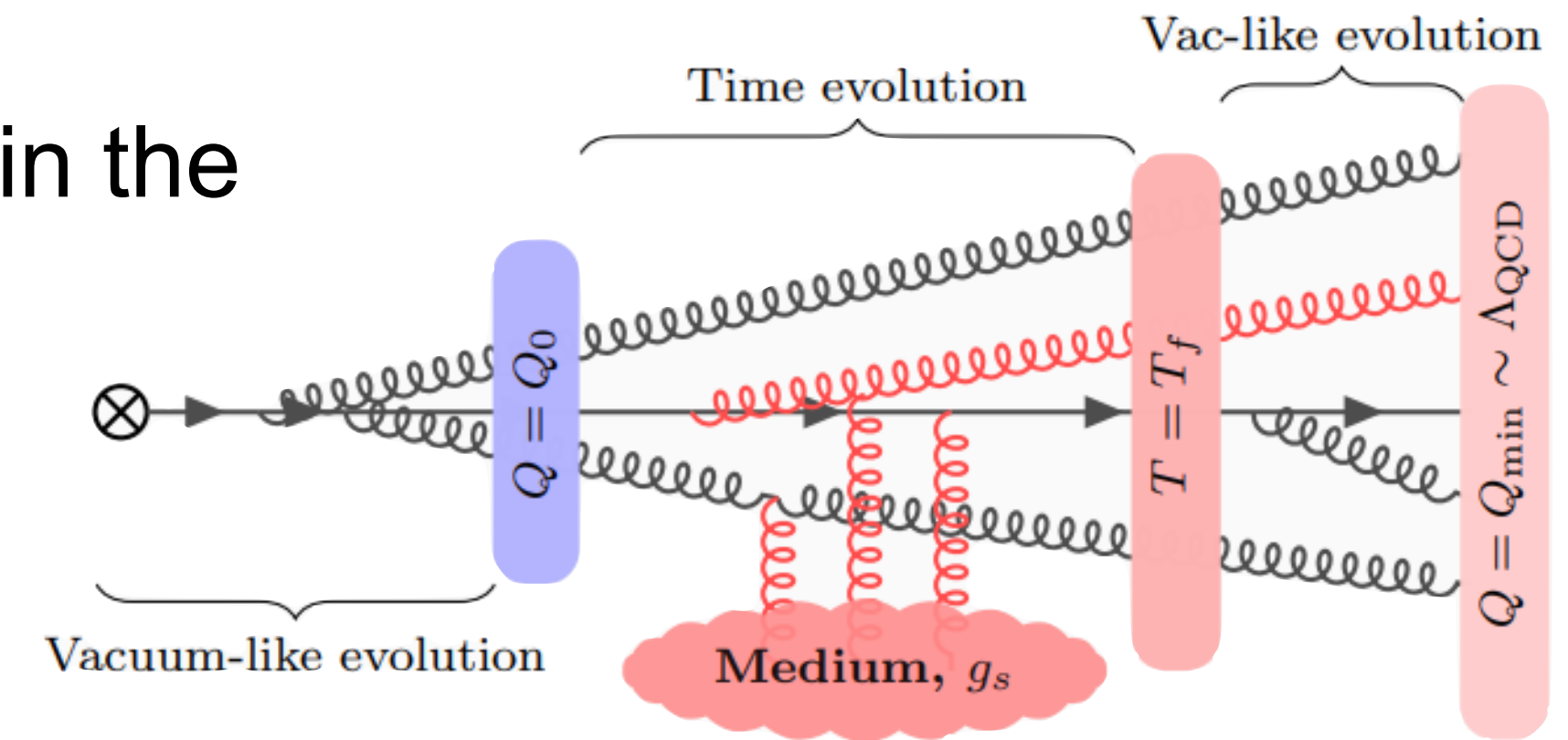


Q_0 modulates jet quenching magnitude with a weaker dependence

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

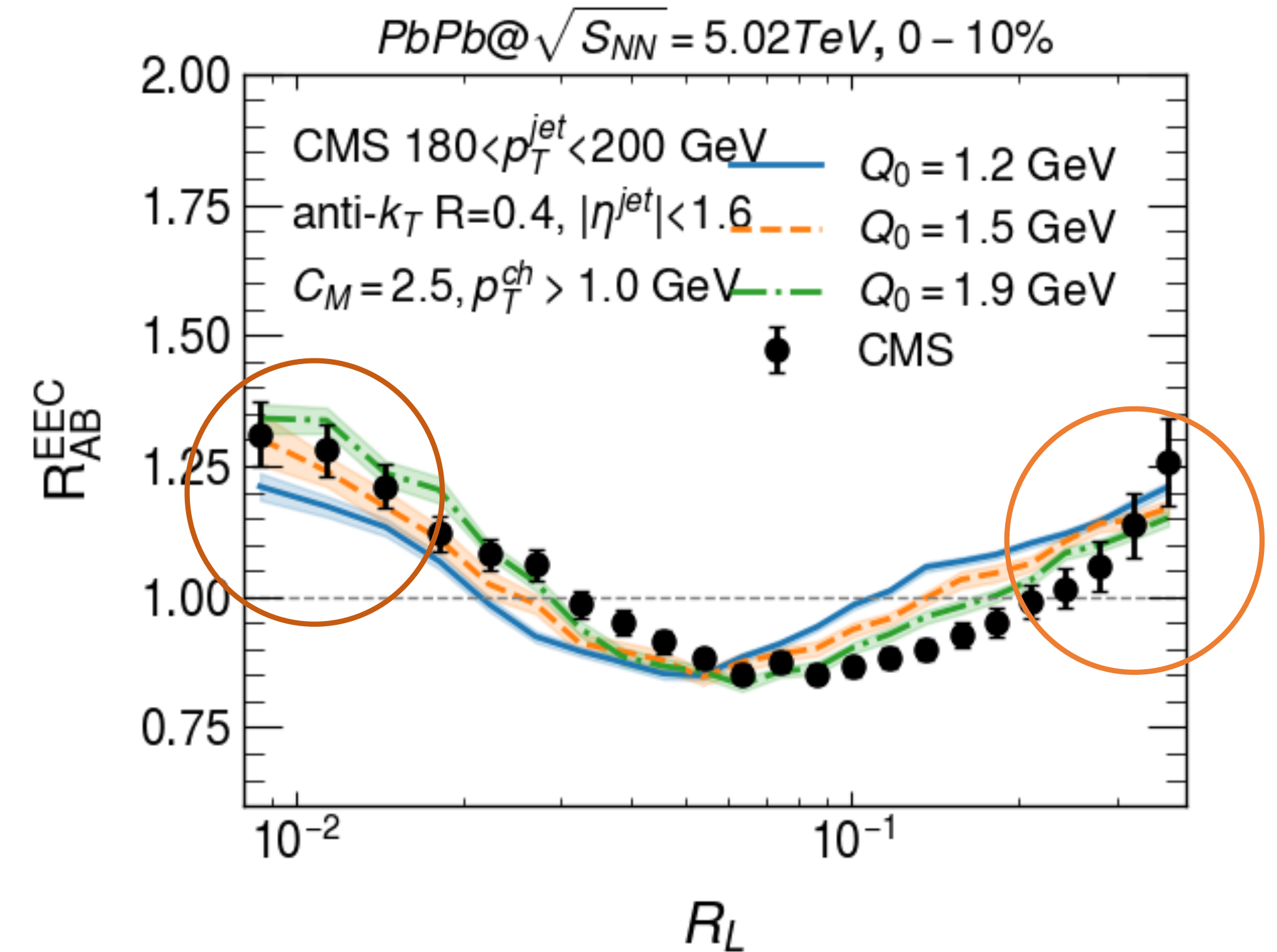
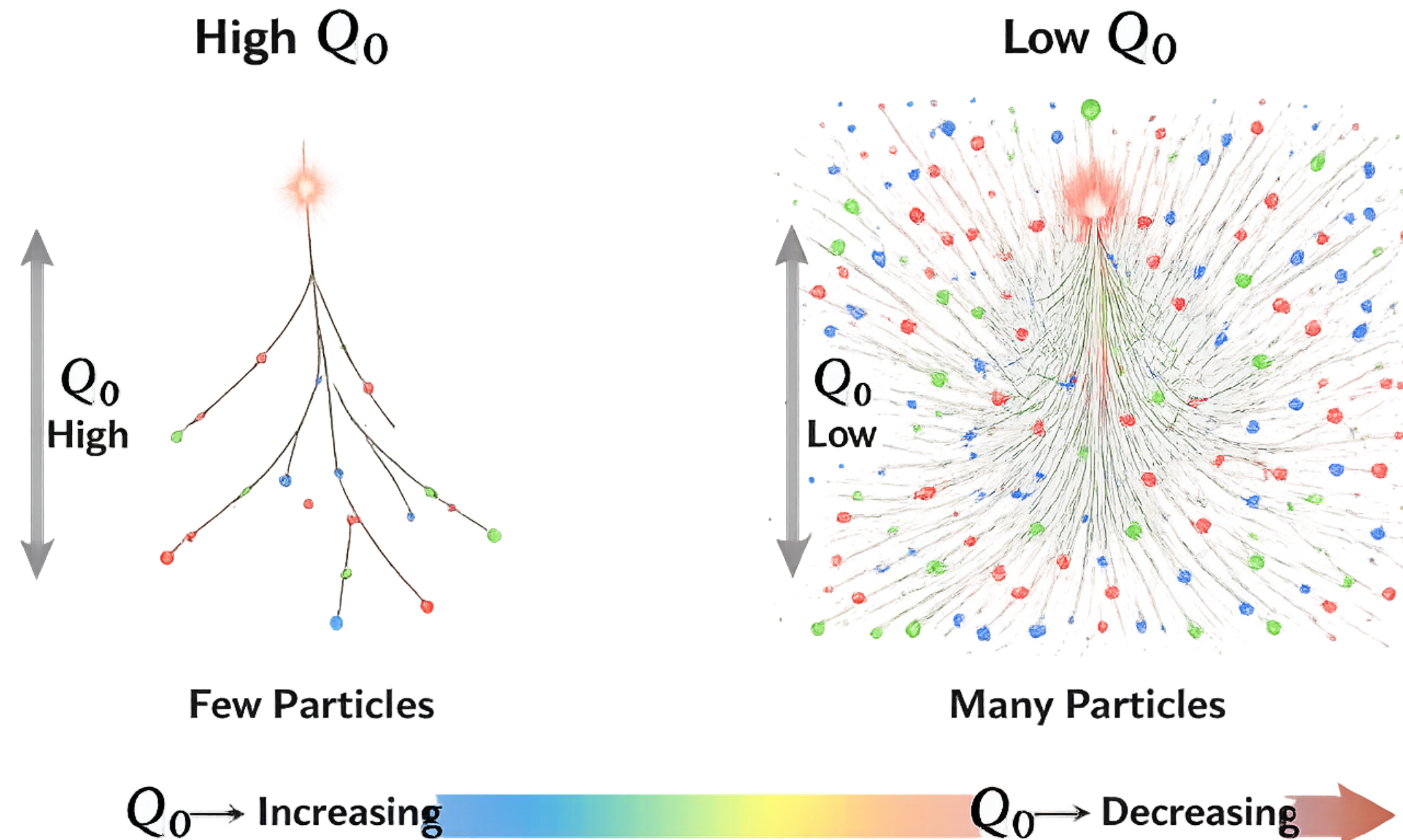
Q_0 (Scale separating vacuum & medium shower) $\uparrow$: fewer partons in the shower, interacting earlier with the medium.

- **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.



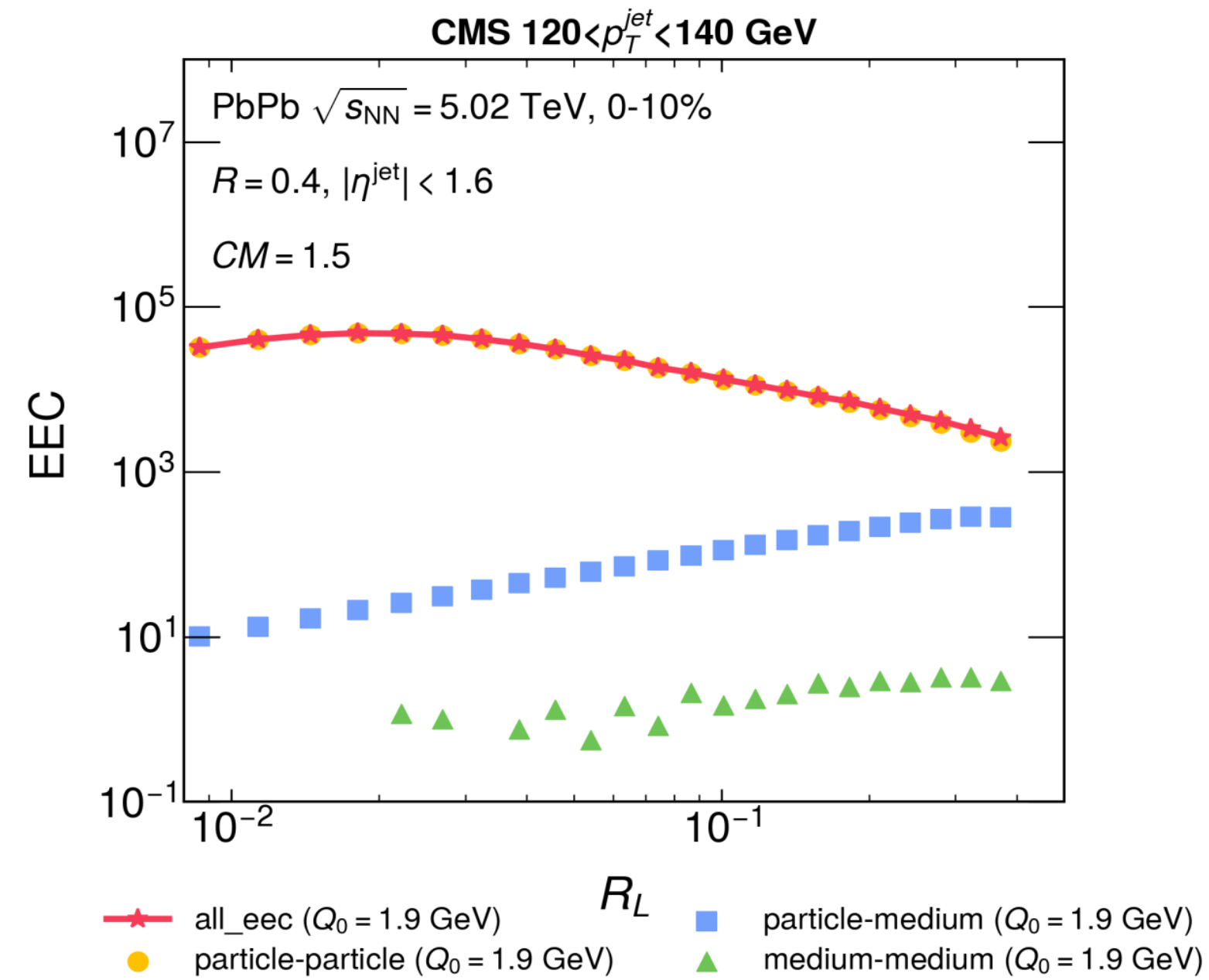
2. Sensitivity of EEC to the Vacuum–Medium Transition Scale Q_0

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.

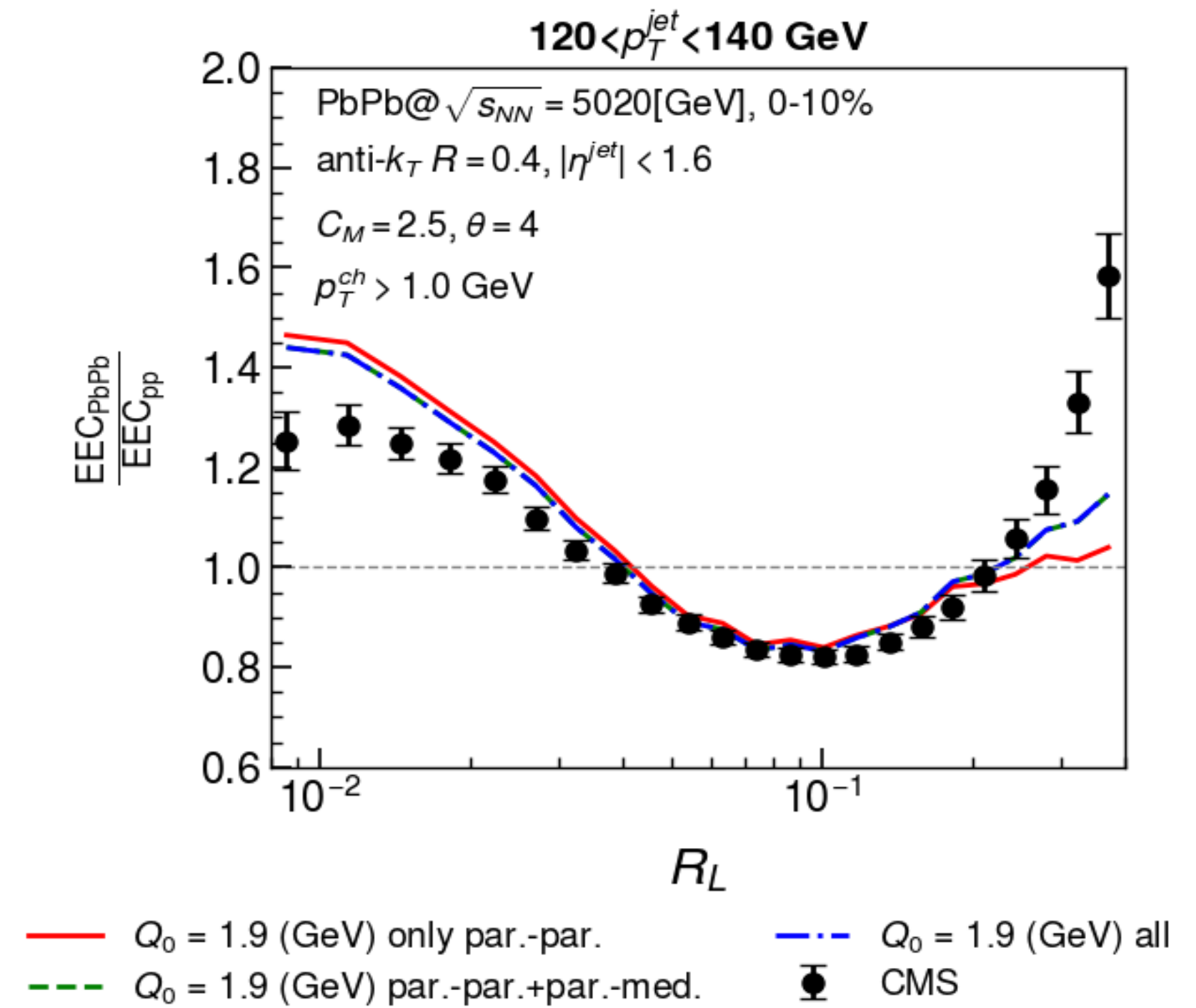
3. Effect of medium response in EEC



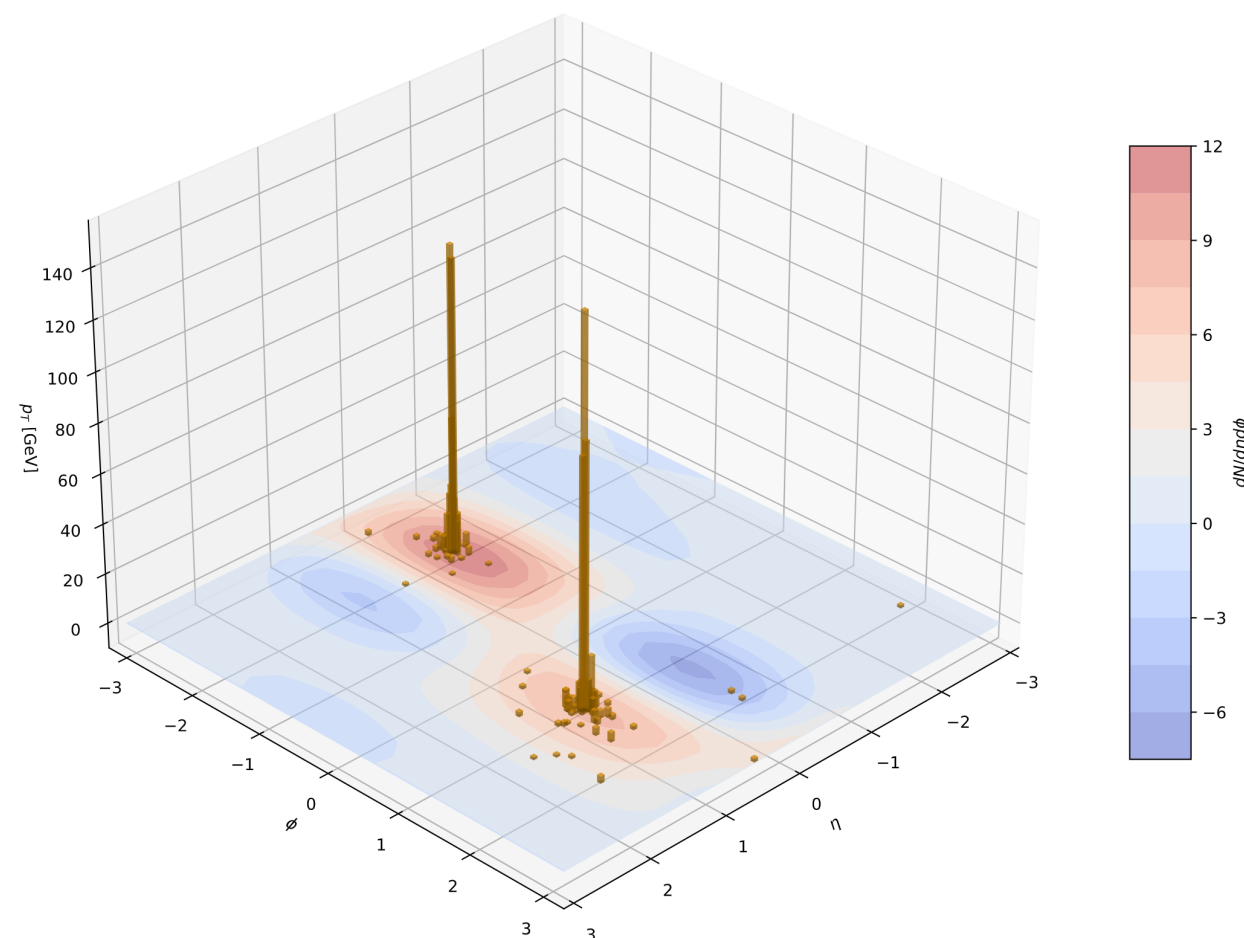
Medium particles generated from transverse momentum density:

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

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

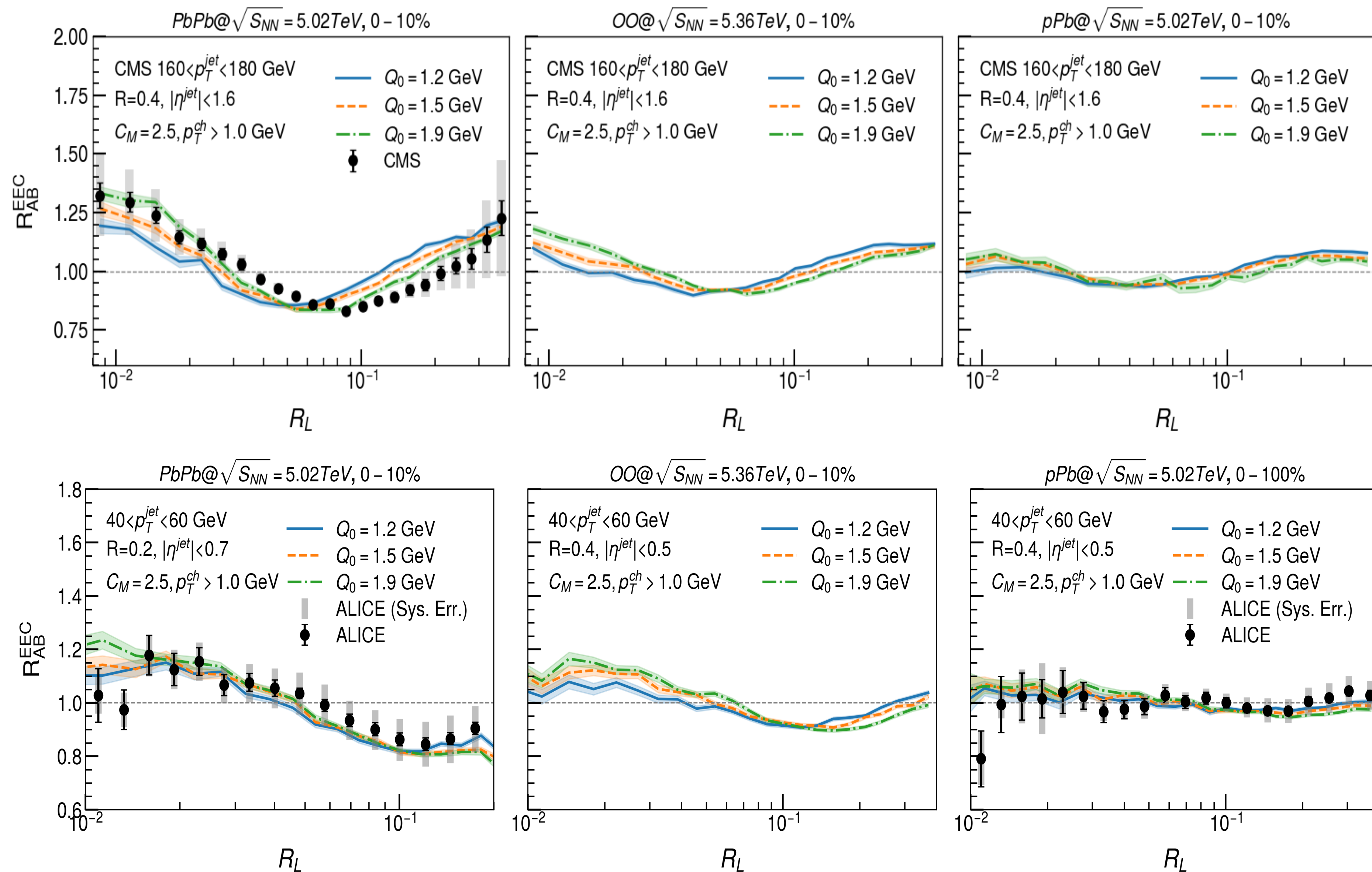


EEC from large to small systems: Pb-Pb, O-O and p-Pb

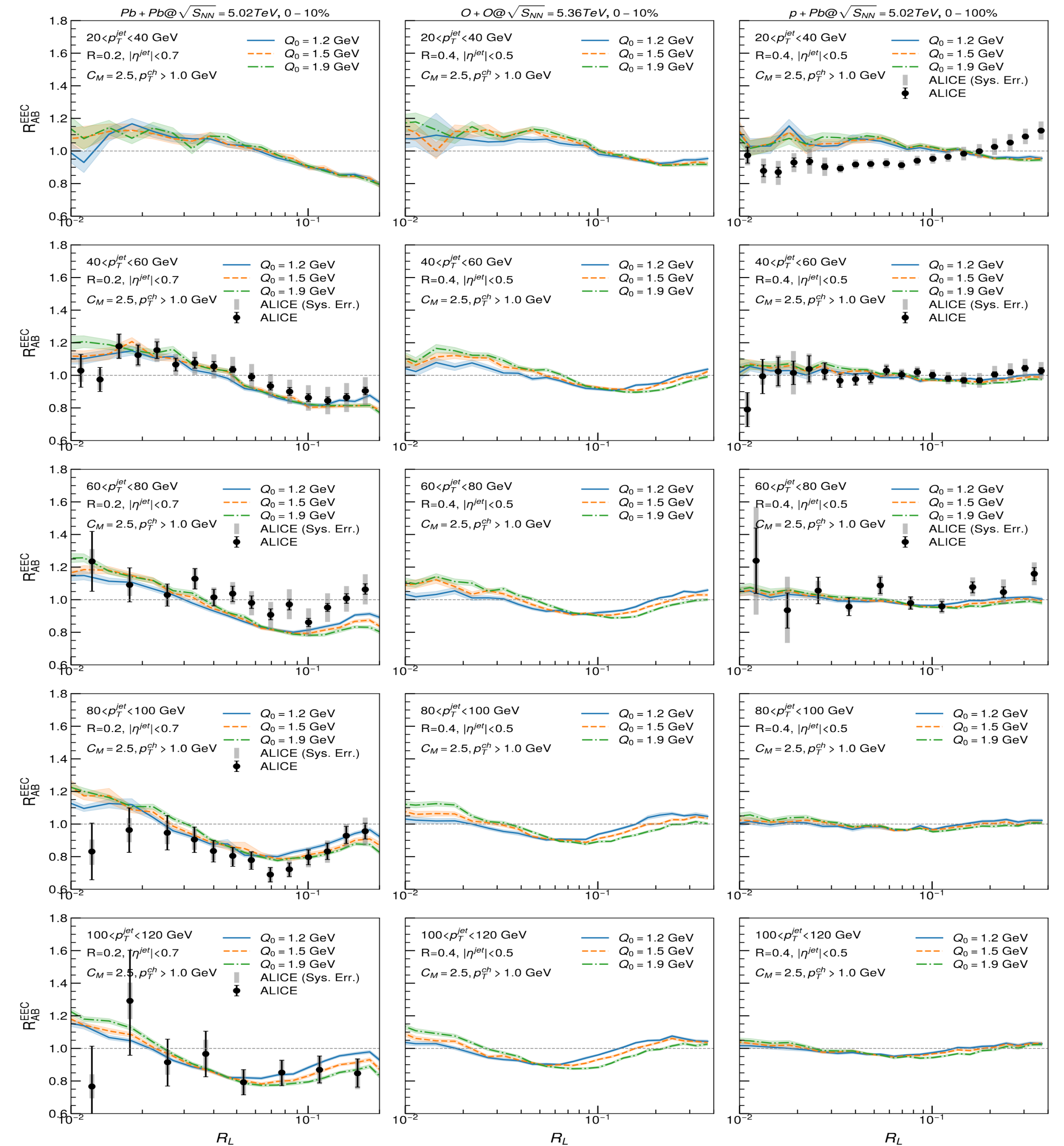
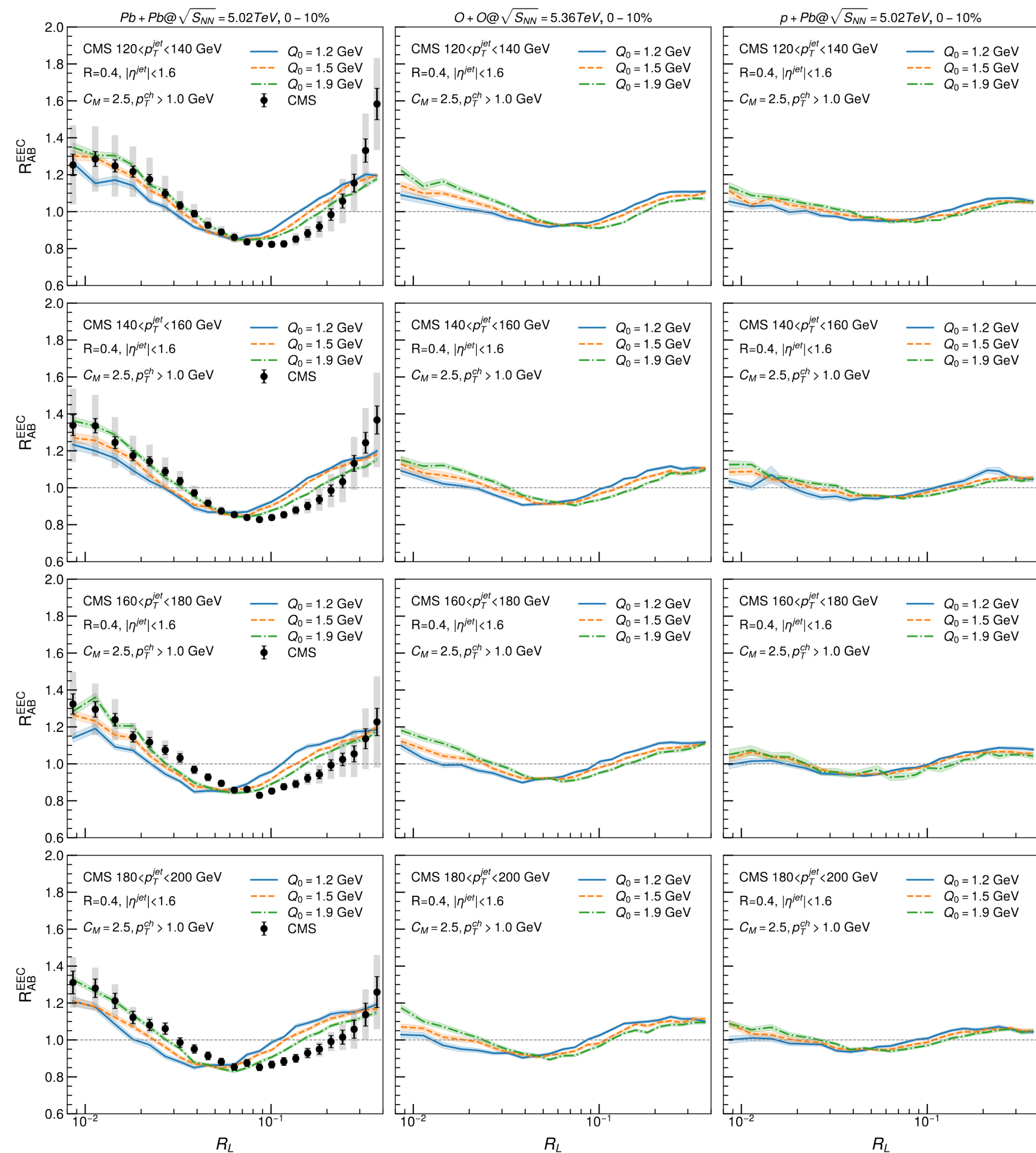
➤ **O--O** : Similar structure but **smaller magnitude** than Pb-Pb.

➤ **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, O-O, p-Pb 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