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Energy-energy correlators from large to small systems

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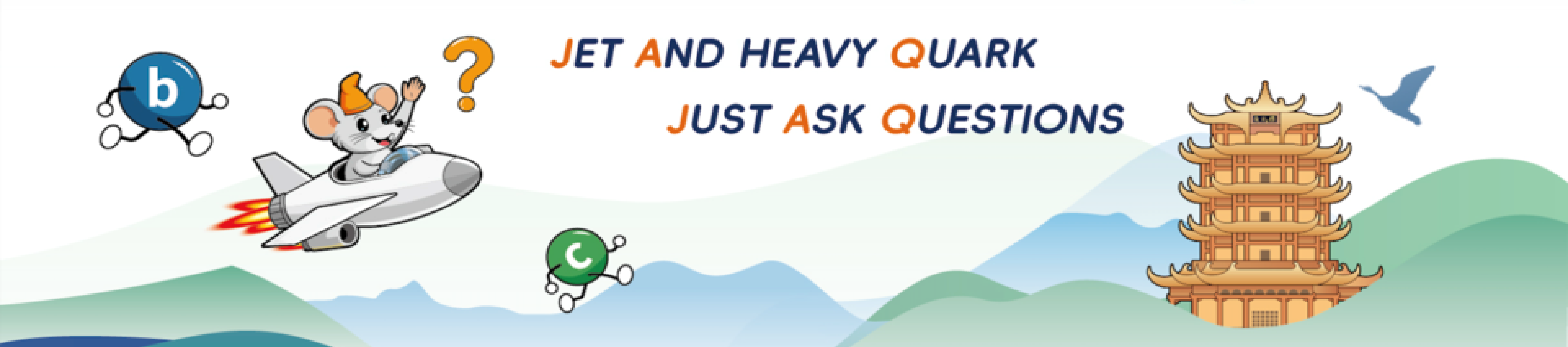
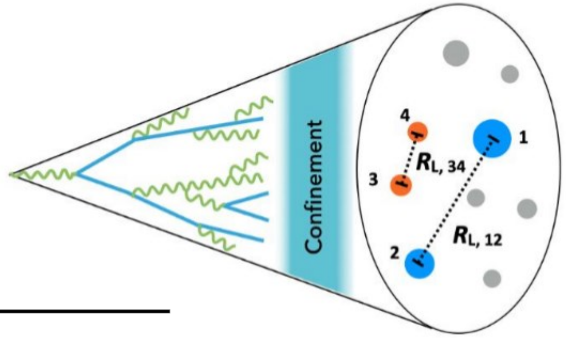


Energy-Energy Correlators

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



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

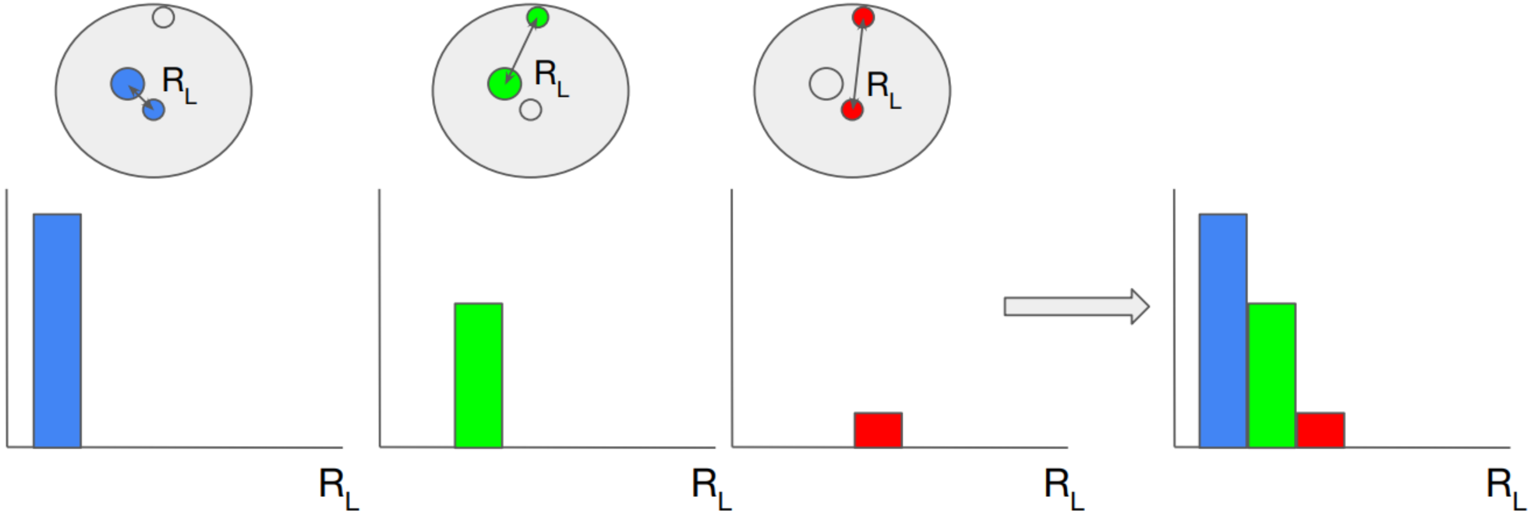


Figure from Arjun Kudinoor (quark matter 2025)

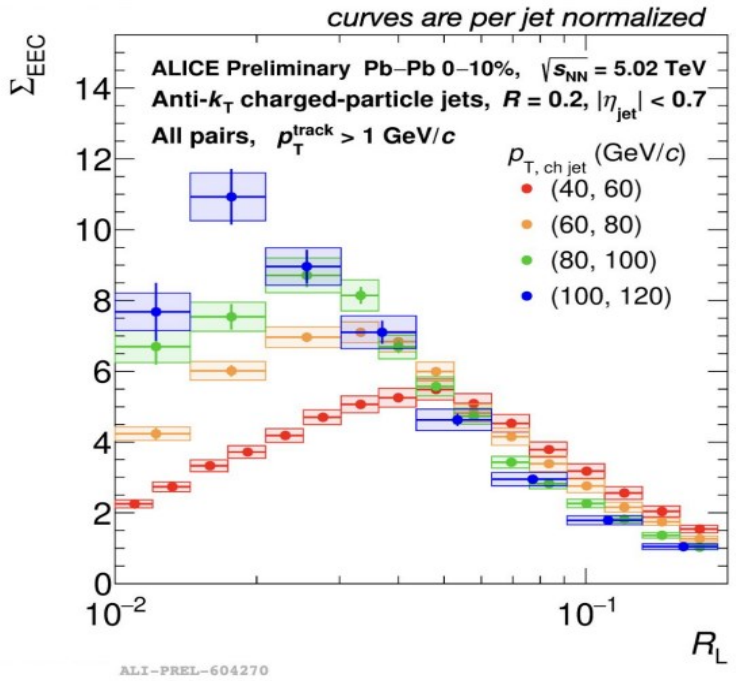
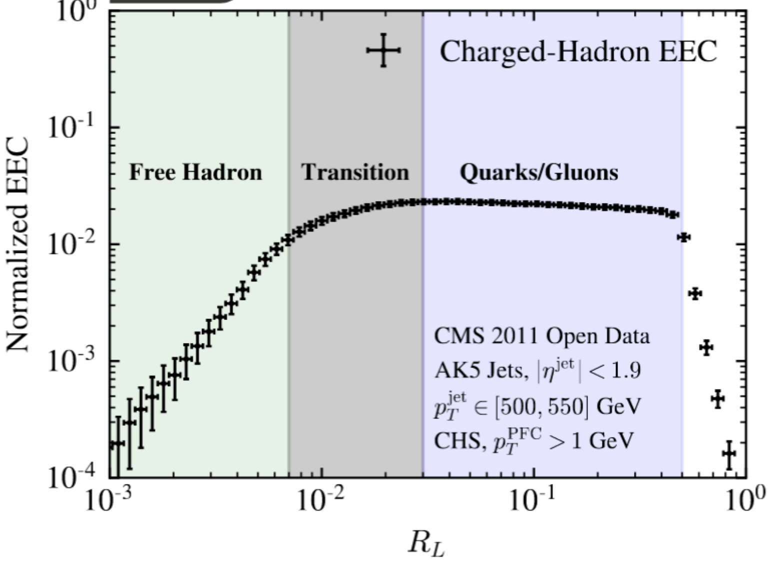


Figure from Komiske et al., 2022



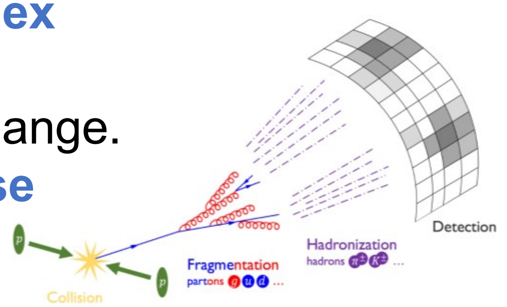
From Hadrons to Jets to Substructures

High-p_T hadrons:

✓ Single-particle observables show **overall energy loss**.

Jets:

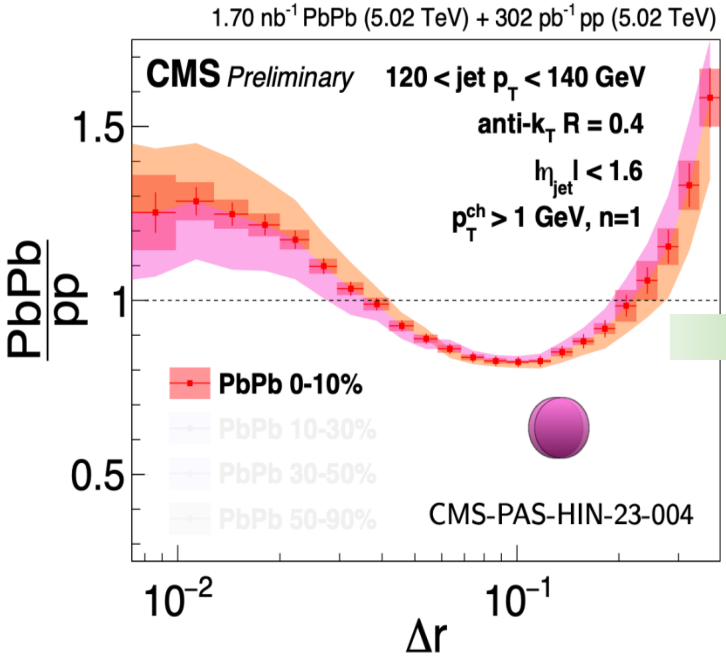
- Collections of many particles → **more complex modifications**.
- Substructure and particle composition can change.
- Traditional observables **cannot capture these details**.



EEC (Energy–Energy Correlator):

- Measures **energy correlations between particle pairs** inside a jet.
- Reveals **how energy is distributed angularly** within the jet.

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



- **Large angle:**

  Medium response

  Medium-induced radiation

- **Small angle:**

  Jet p_T selection bias,

  Falvor dependence of jet

- **Intermediate angles:** Both effects contribute, but the dip is mainly due to radiation.

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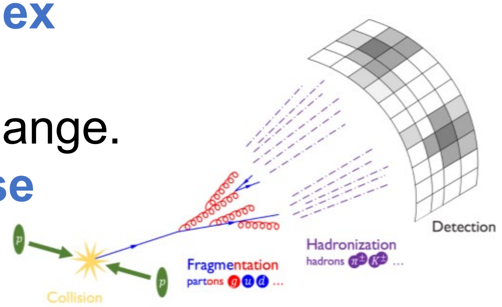

EEC (Energy–Energy Co

- Measures **energy corre** **between particle pairs** jet.
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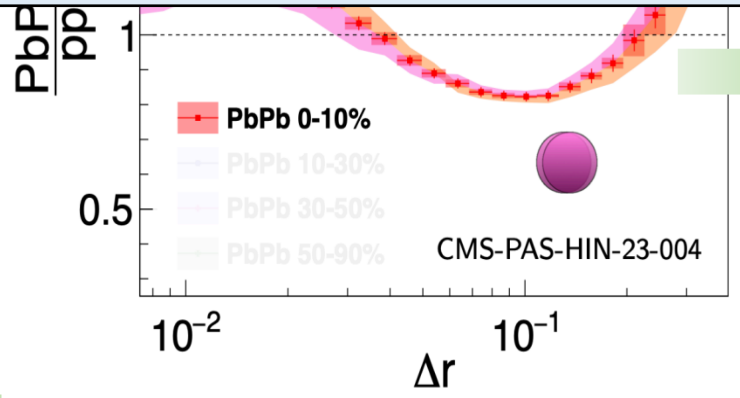
This work: employ the LIDO partonic transport model + hydrodynamic description of QGP + linear medium response model to study jet substructure via the EEC.



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ced radiation

Jet p_T selection bias,

Falvor dependence of jet

➢ Intermediate angles: Both effects contribute, but the dip is mainly due to radiation.

LIDO Model: Jet Evolution Framework

PYTHIA8
Vacuum shower
$Q^{hard} \to Q_0$

→

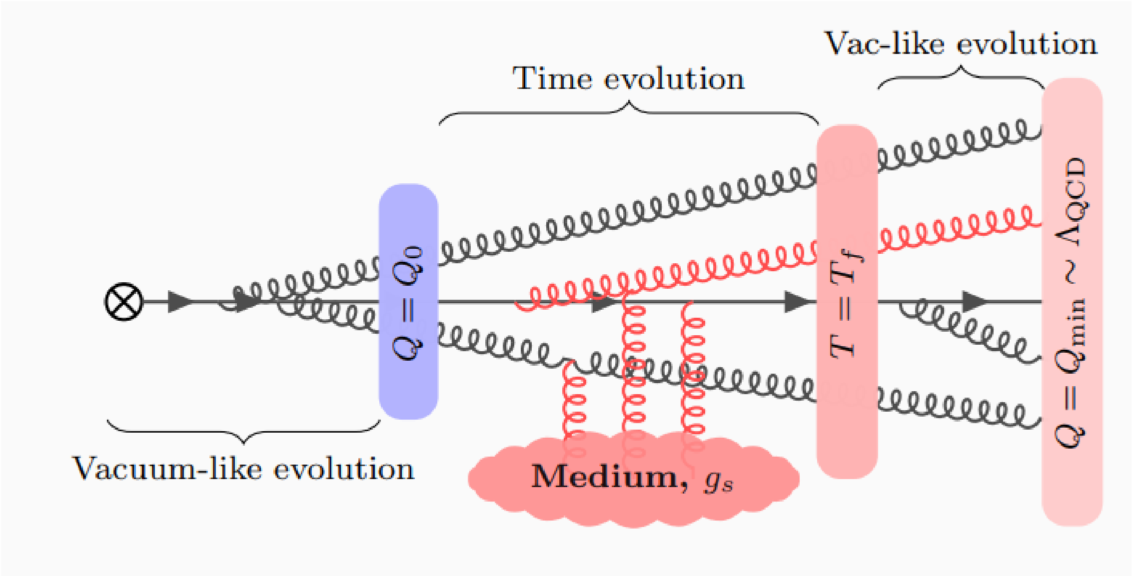
LIDO Transport
Parton-Medium
Interactions
$\sim Q_0$

→

PYTHIA8
Final Shower +
Hadronization
$Q_0 \to Q_H \sim 0.5GeV$

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

Transport Equation in the Incoherent Limit

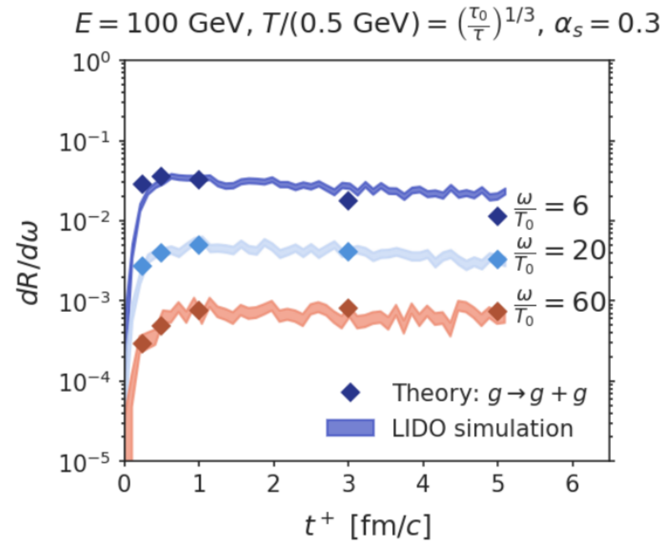
The semiclassical transport equation for hard partons ($p \cdot u > E_{min}$) in the incoherent and independent-collision limit is:

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

The distribution function of a hard parton evolves under the influence of :

PRC 82 (2010) 064902
PRC 58 (1998) 1706

- Diffusion term: $D[f]$
- Large- $\hat{q}$ elastic collisions: $C_{2\to 2}[f]$
- Diffusion-induced small-$\hat{q}$ parton splitting/merging: $C_{1\to 2}[f]$
- Large- $\hat{q}$ inelastic collisions: $C_{2\to 3}[f]$
- $E_{min} = \theta T$,θ is a Parameter



☺ The strong coupling α_s(Q, T) ceases to run for momentum transfers below the thermal scale, and is given by:

$$\alpha_s(Q,T) = \frac{4\pi}{9} \cdot \frac{1}{\ln\left(\frac{\max\{Q^2, \mu^2_{\min}\}}{\Lambda^2_{\rm QCD}}\right)} \qquad \mu_{\min} = C_M \times \pi T$$

Linear Medium Response Model

- Energy-momentum deposition to soft sector:

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

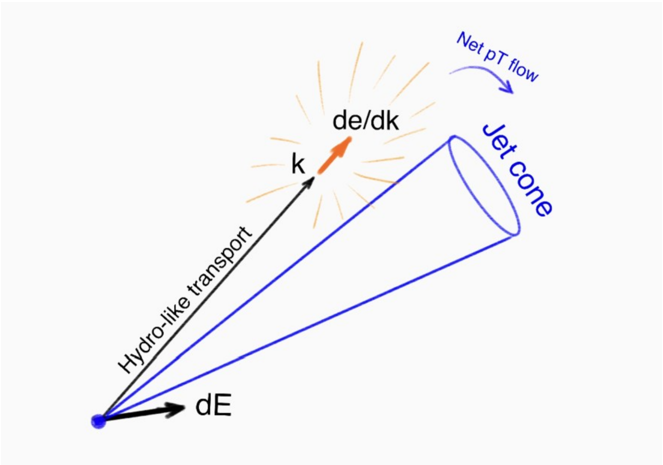
- An ideal-hydro response (no transverse flow)

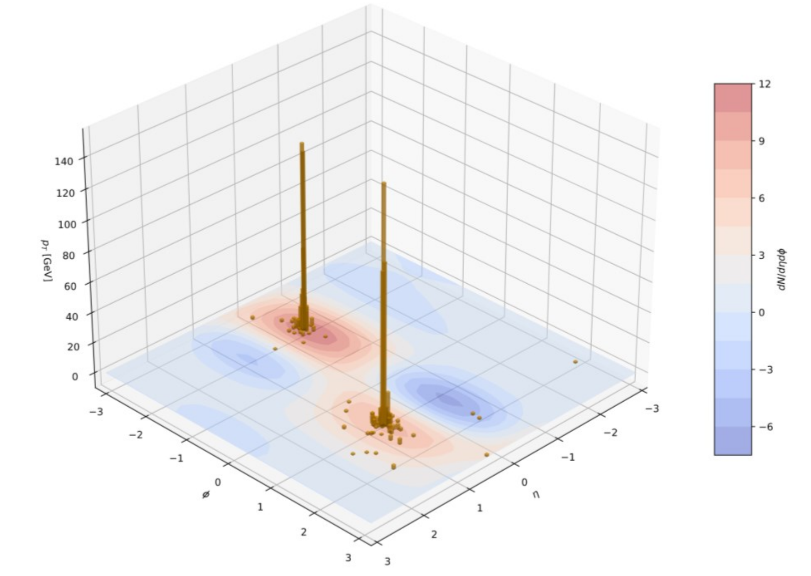
$$\frac{de}{d\Omega'_k} = \frac{\delta p^0 + \hat{k}' \cdot \delta\vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega'_k} = \frac{3(c_s\delta p^0 + \hat{k}'\cdot\delta\vec{p})\hat{k}'}{4\pi}$$

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

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

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

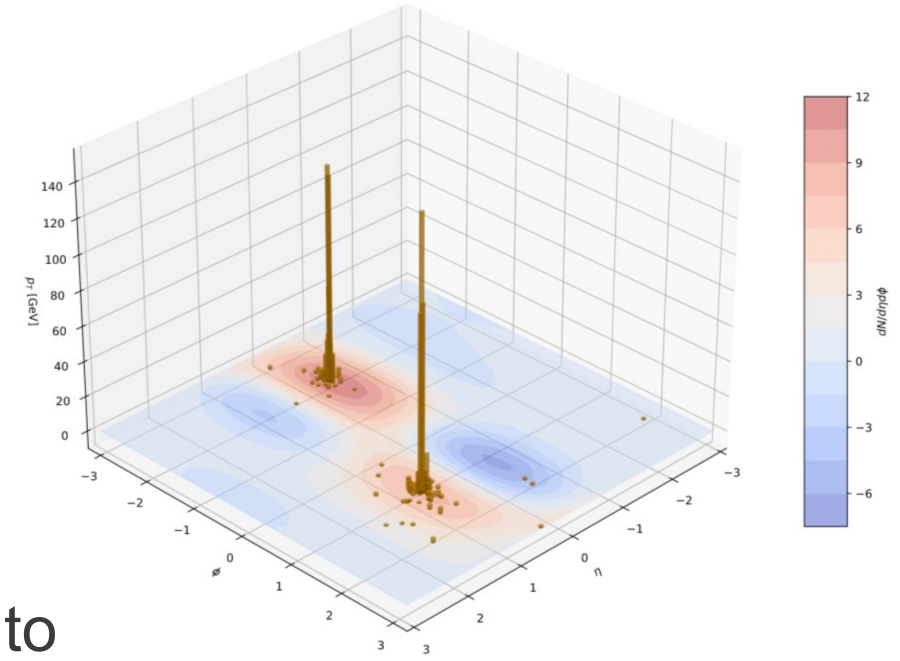




Jet Definition in LIDO with medium response

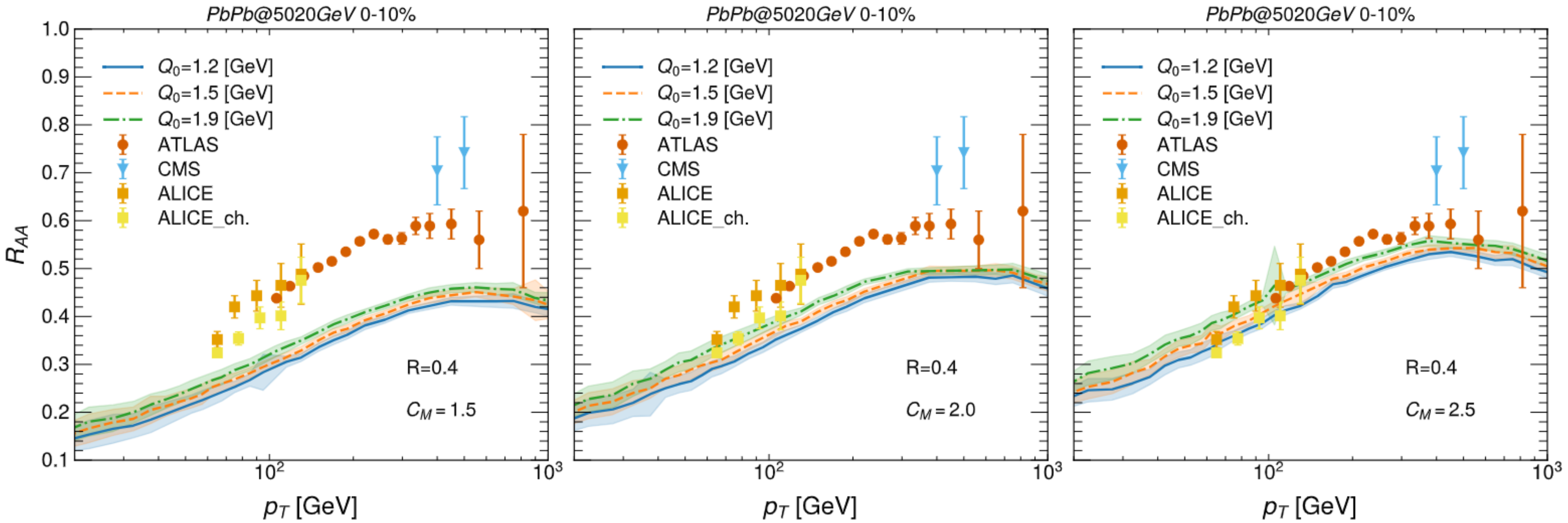
- Jets (anti-K_T) are reconstructed from energy bins $E_{T,ij}$, defined by

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



- Uncorrelated medium background are assumed to be perfectly subtracted.

Parameter sensitivity: effective coupling and initialization scale



Q_0 modulates jet quenching magnitude

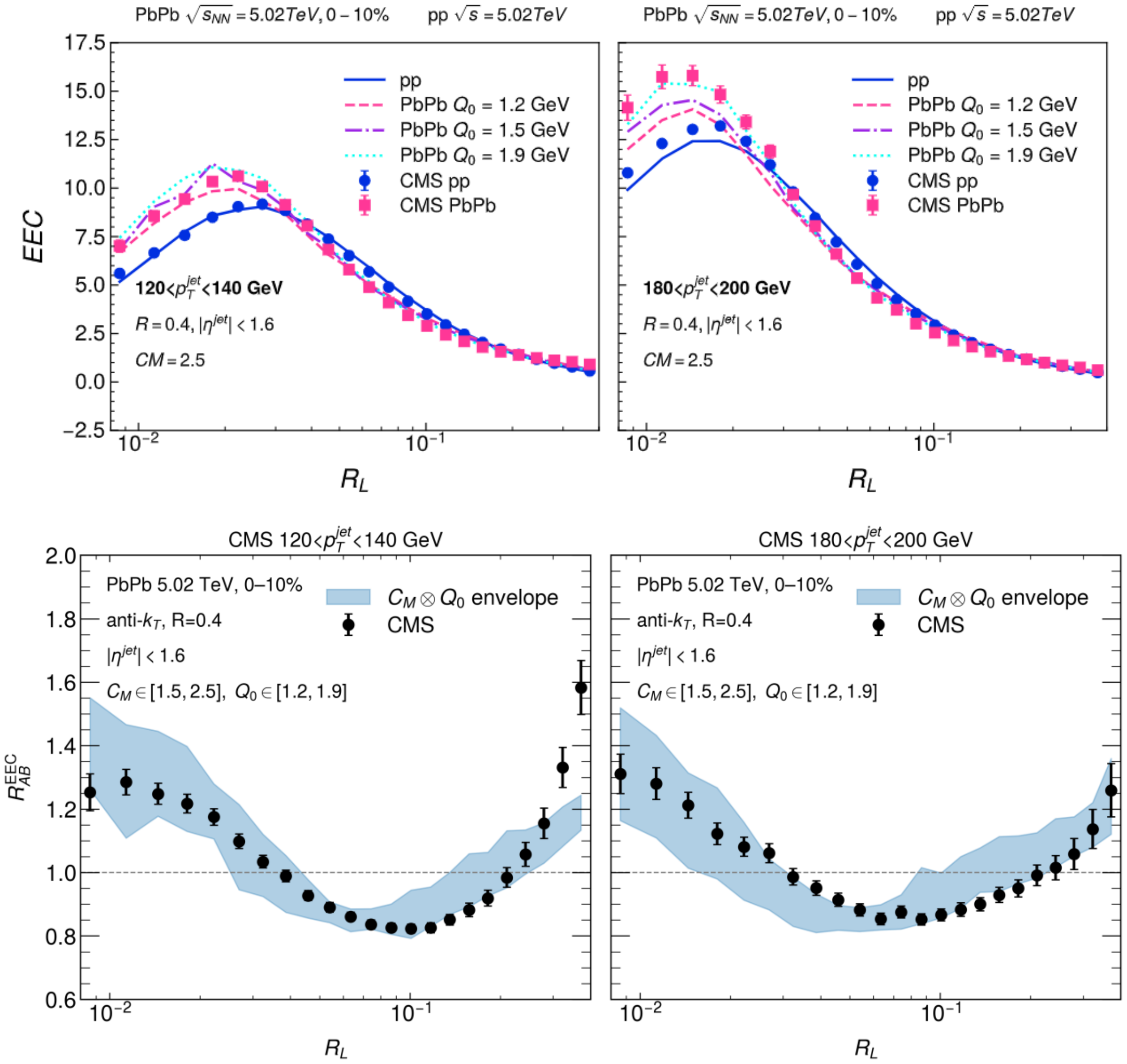
increasing $C_M \Rightarrow$ decreasing jet-medium coupling at T ⇒ less suppression

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

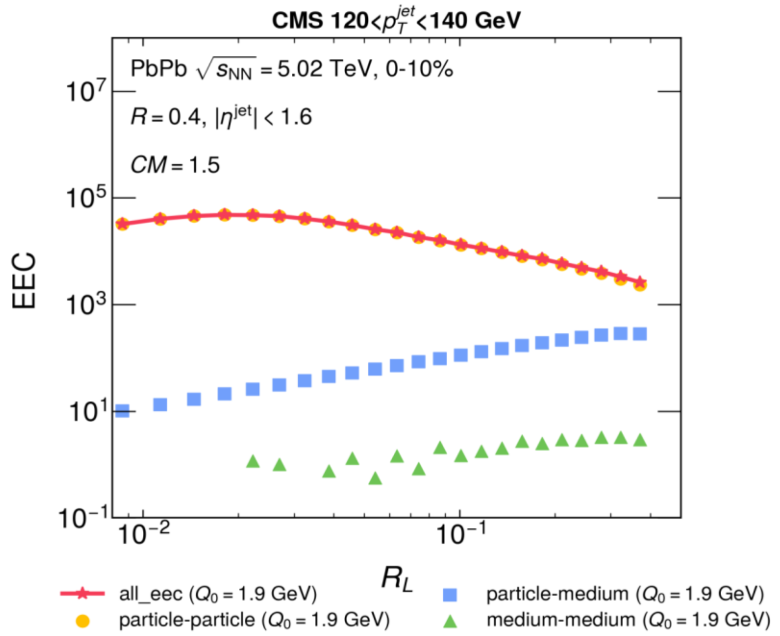
EEC in Pb-Pb: Theory vs. CMS Data

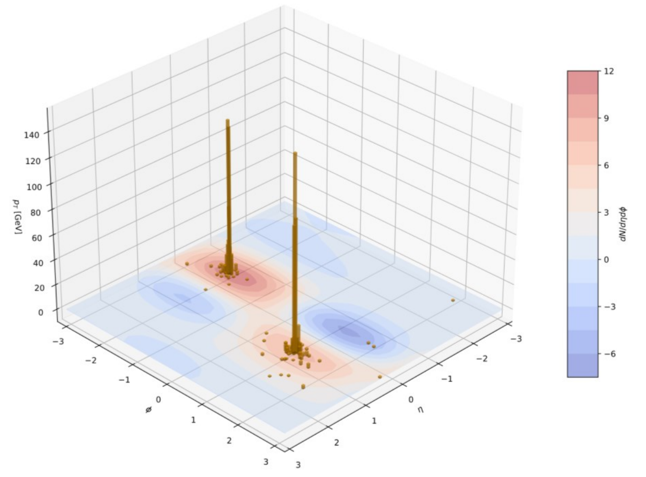
$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{\mathrm{pairs}}} \frac{1}{\delta r} \sum_{\mathrm{jets} \in [p_{T,1}, p_{T,2}]} \sum_{\mathrm{pairs} \in [\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})^n$$

- Normalize with the number of pairs W_{pairs}
- Exponent values n = 1 used in this analysis



The Full EEC with medium response



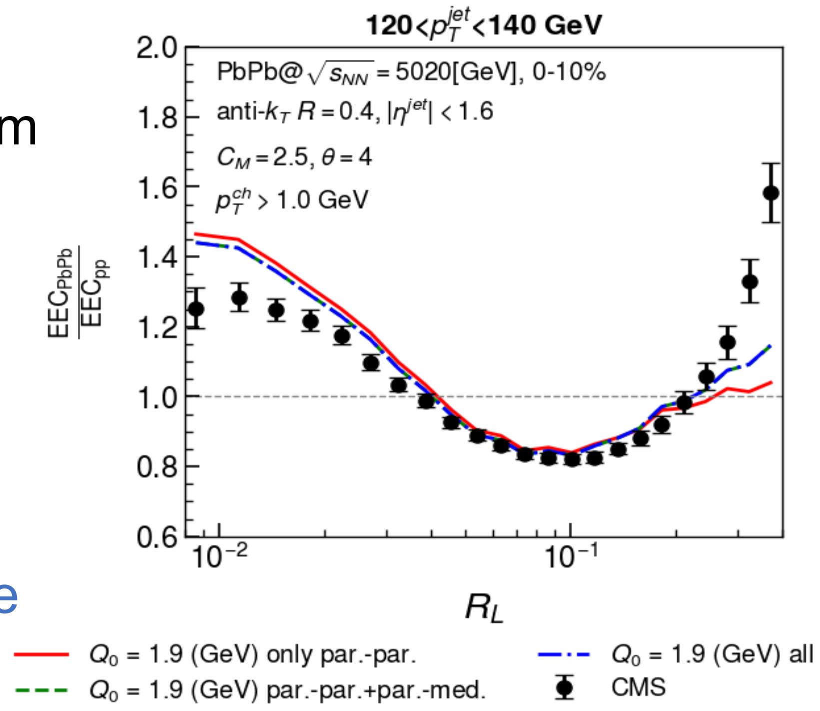


- Medium particles generated from transverse momentum density:

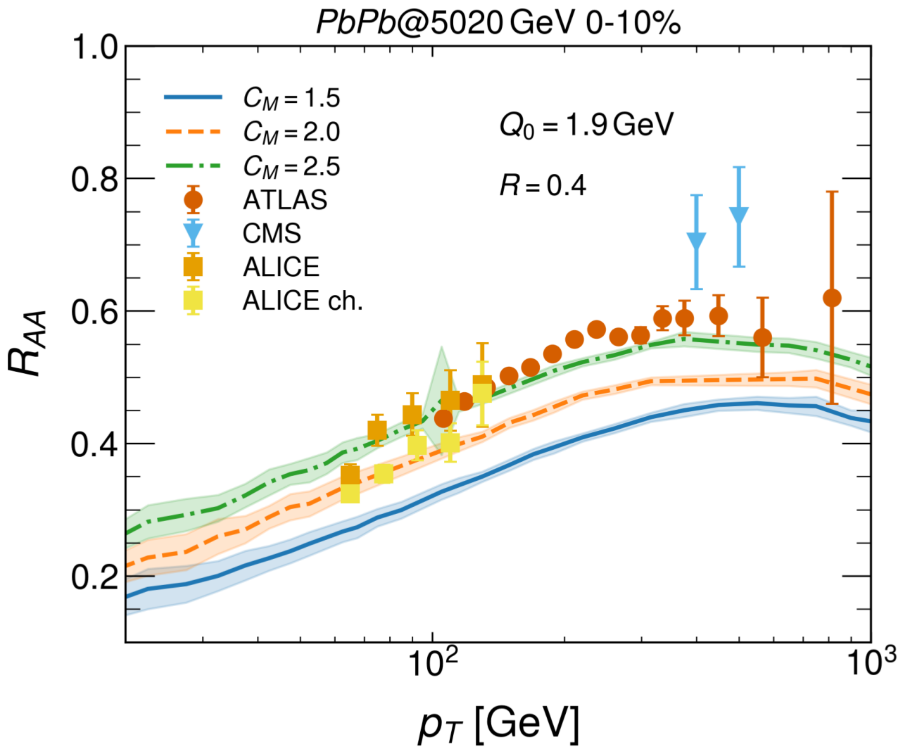
$$\frac{dp_T}{d\eta d\varphi}\Delta\eta\Delta\varphi$$

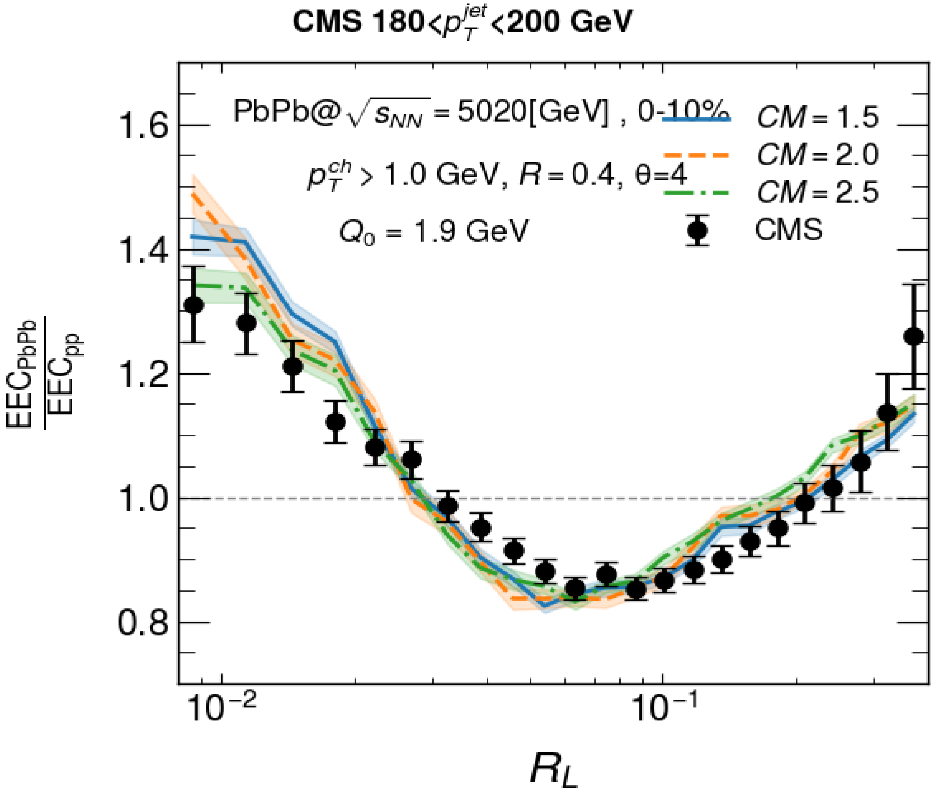
  via energy-tower method

- EEC include:
  ① Hard particle – Hard particle correlations
  ② Medium response – Hard particle correlations
  ③ Medium response – Medium response correlations.



Sensitivity of EEC and Jet R_{AA} to the Jet–Medium Coupling Cutoff C_M

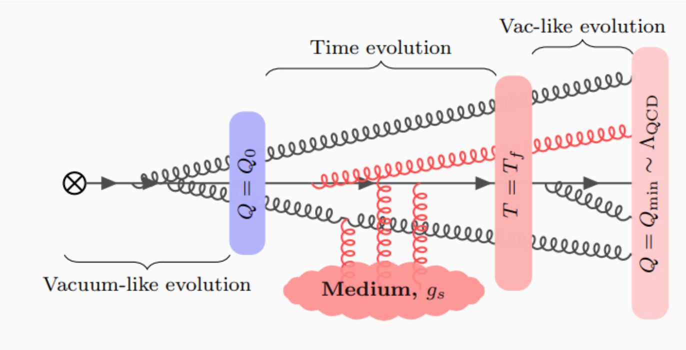




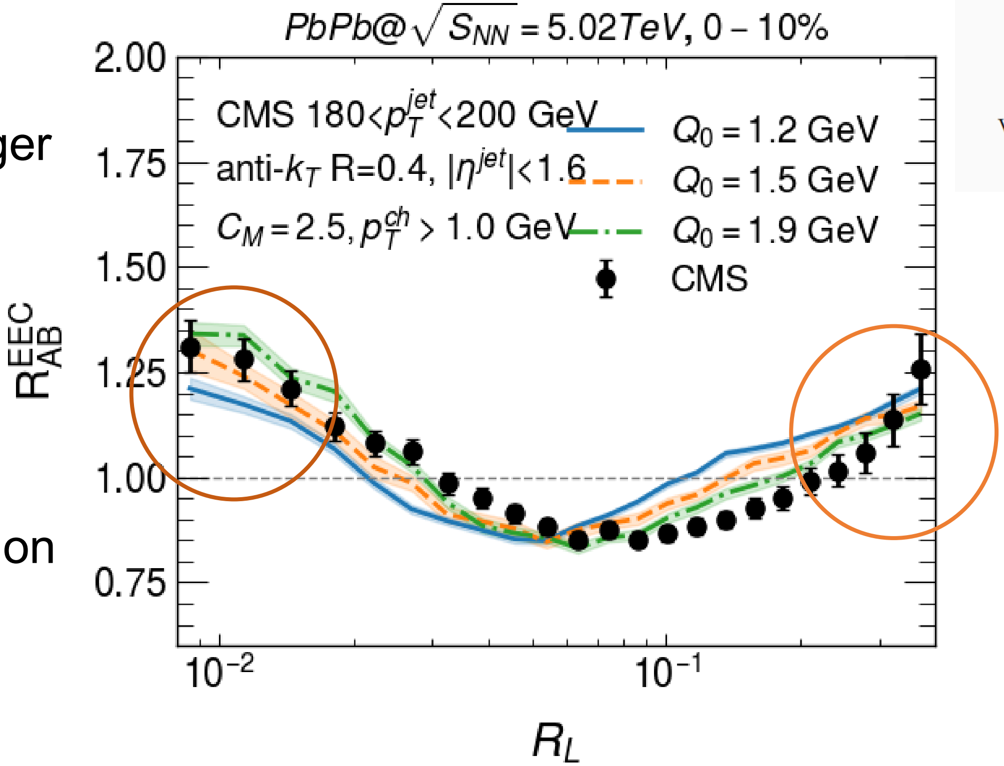
- ➢ R_{AA}: Governed by total energy loss → Strongly affected by soft interactions → Stronger sensitivity
- ➢ **EEC:** Probes relative angular structure in jets → Normalized & energy-weighted → weak sensitivity

Sensitivity of EEC to the Vacuum–Medium Transition Scale Q_0

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



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

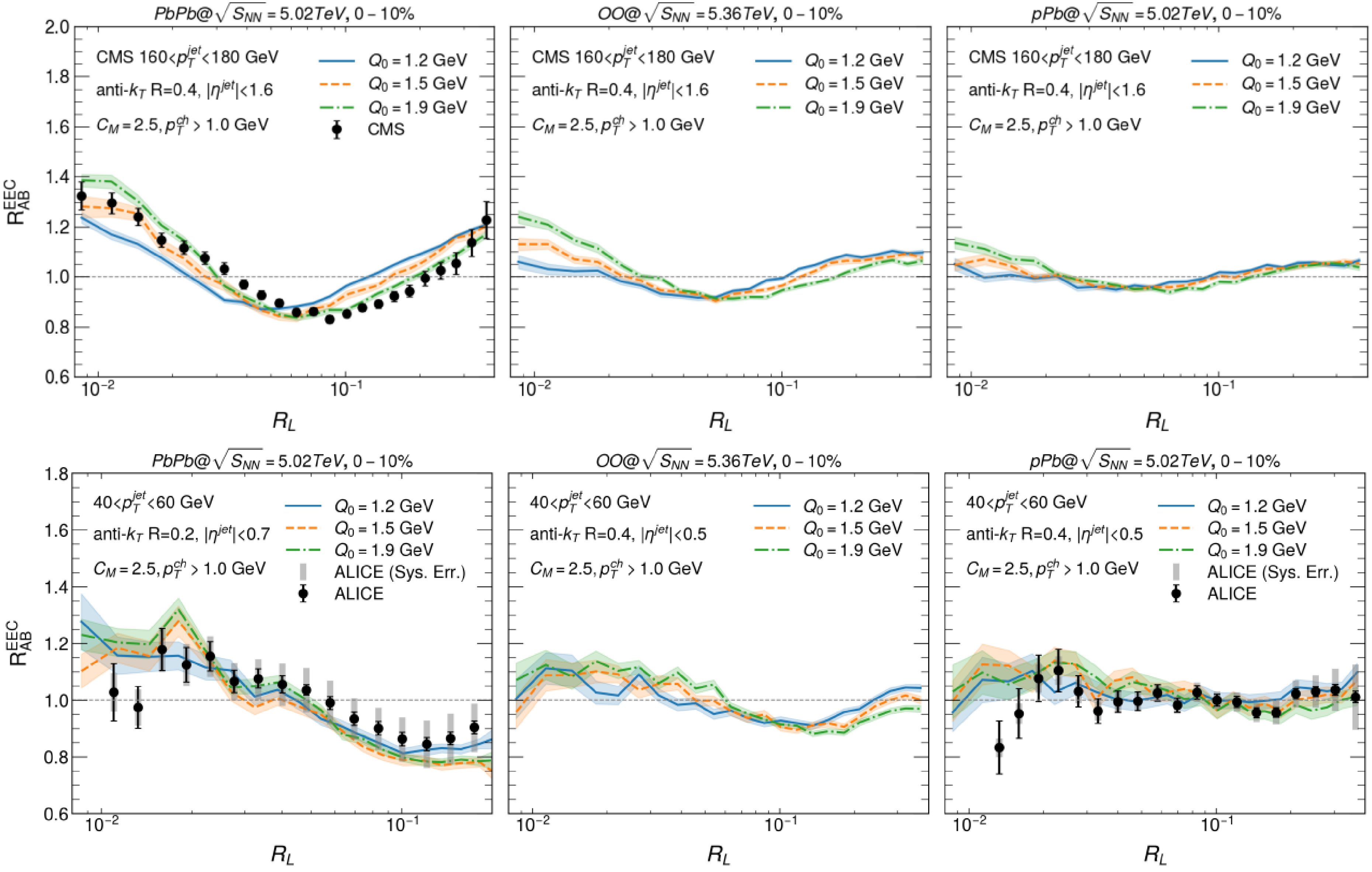


- At small angles, a smaller Q_0 leads to a richer vacuum shower reduces the quark-gluon energy-loss difference thereby suppressing their selection bias.
- At large angles, a smaller Q_0 leads to more shower particles, resulting in stronger medium-induced radiation.

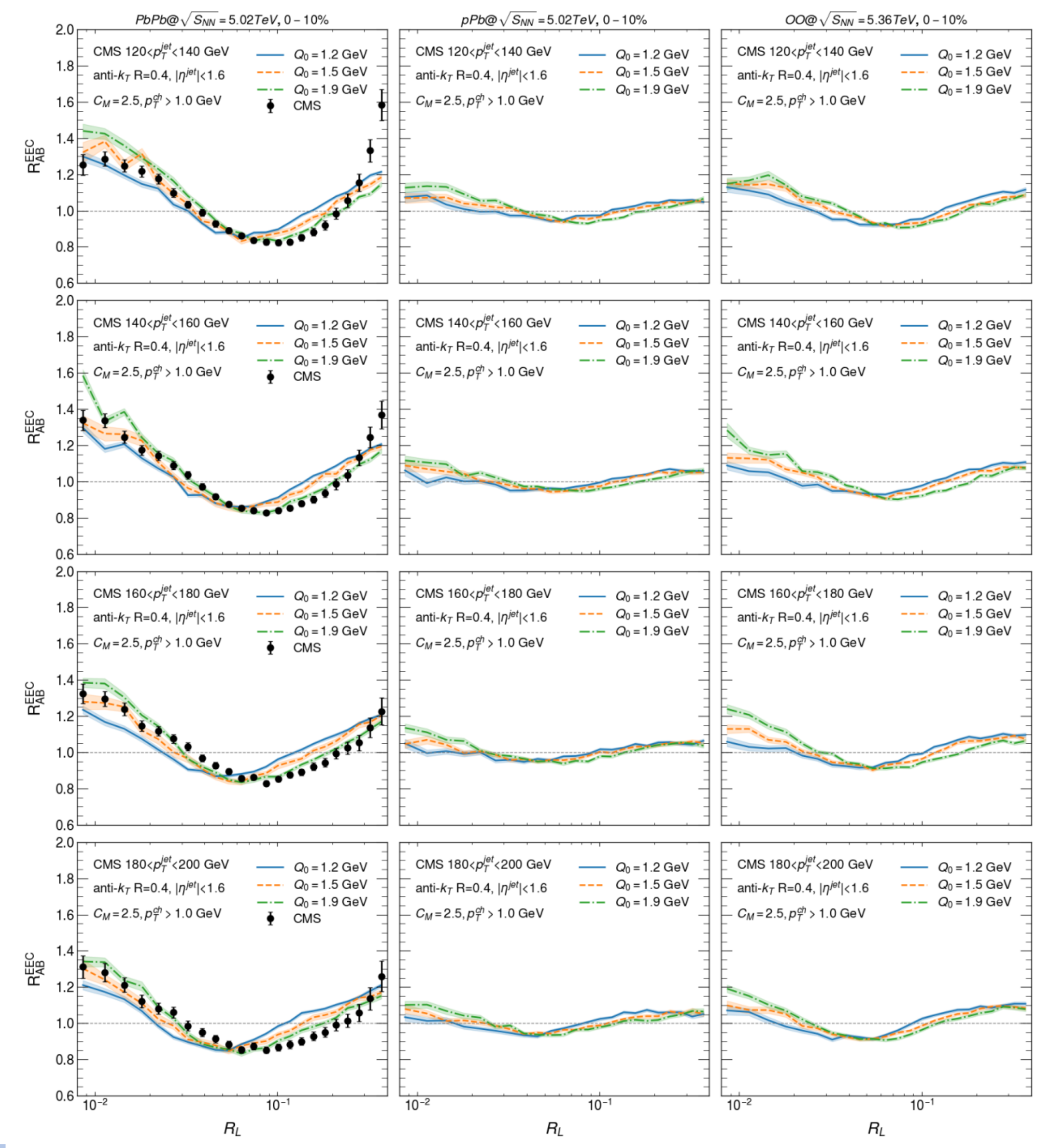
EEC from large to small systems: Pb-Pb, O-O and p-Pb

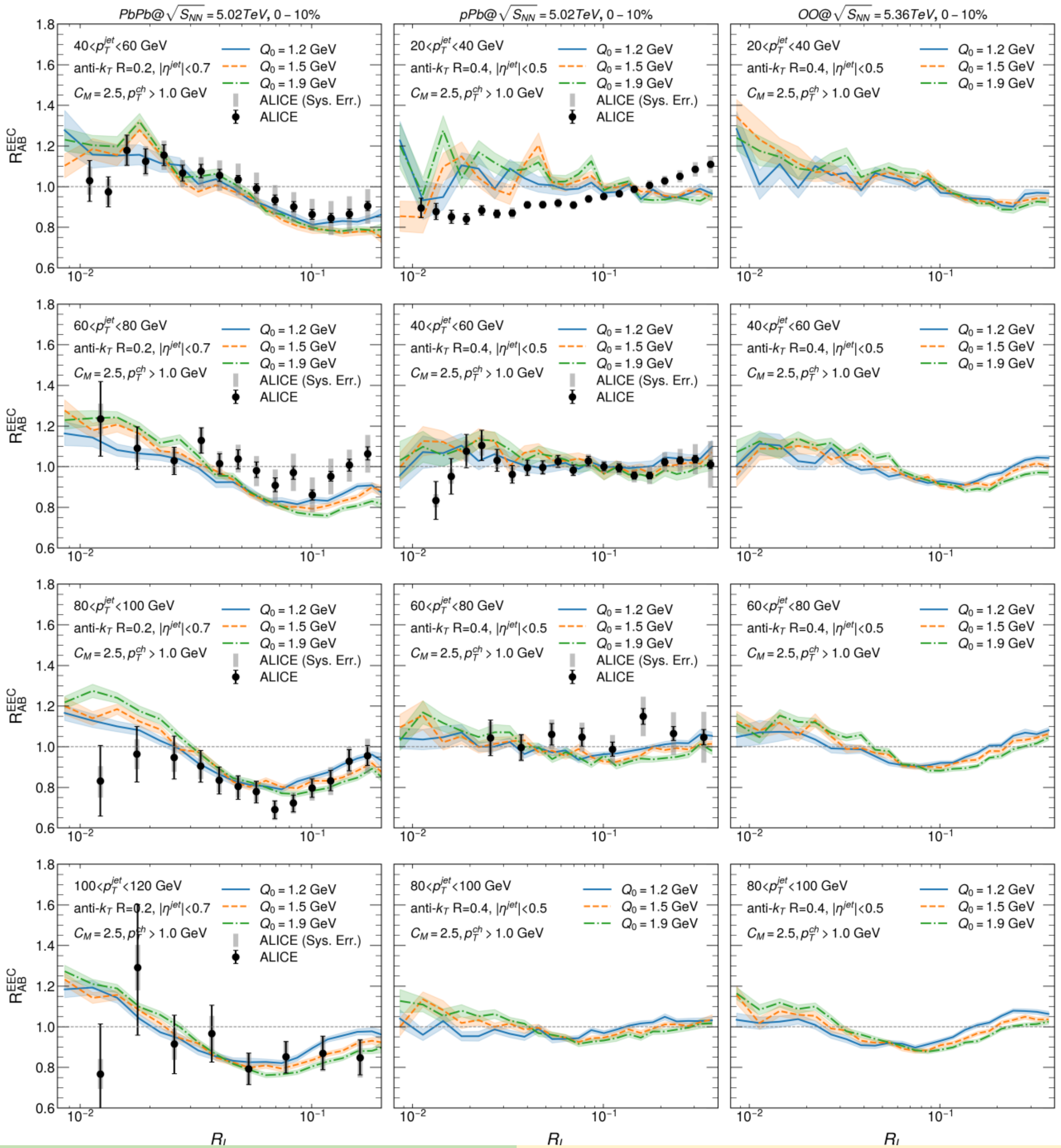
- O--O : Similar structure but smaller magnitude than Pb-Pb.
- p--Pb : Even smaller than O-O

⇒ 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





Summary

- 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