Study Energy Correlators in high-energy heavy-ion collisions

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Hot Jets: Advancing the Understanding of High Temperature QCD with Jets

Jet in heavy-ion collisions

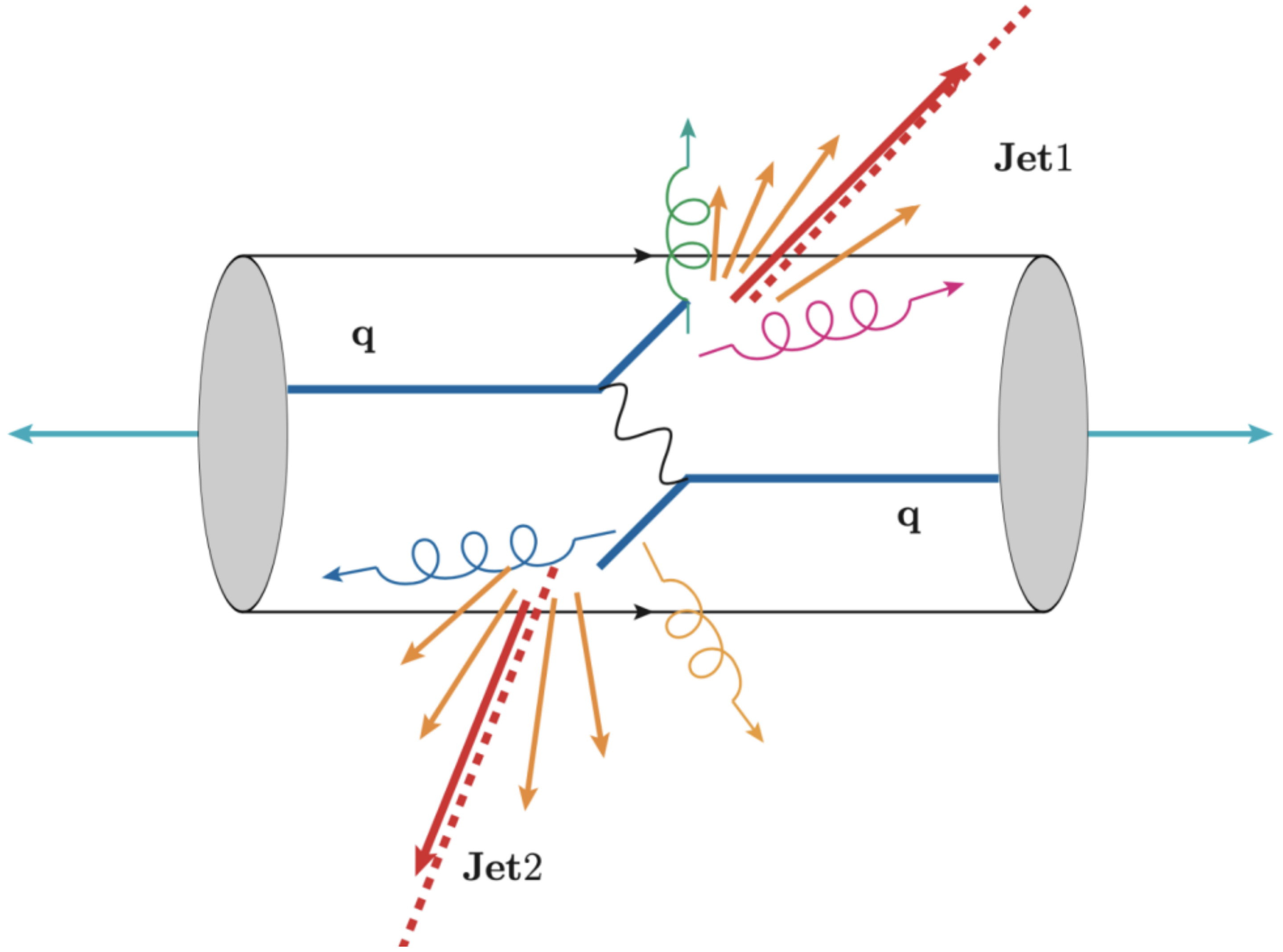
Jet: a collimated cluster of hadrons produced by the fragmentation of high-energy quarks or gluons.

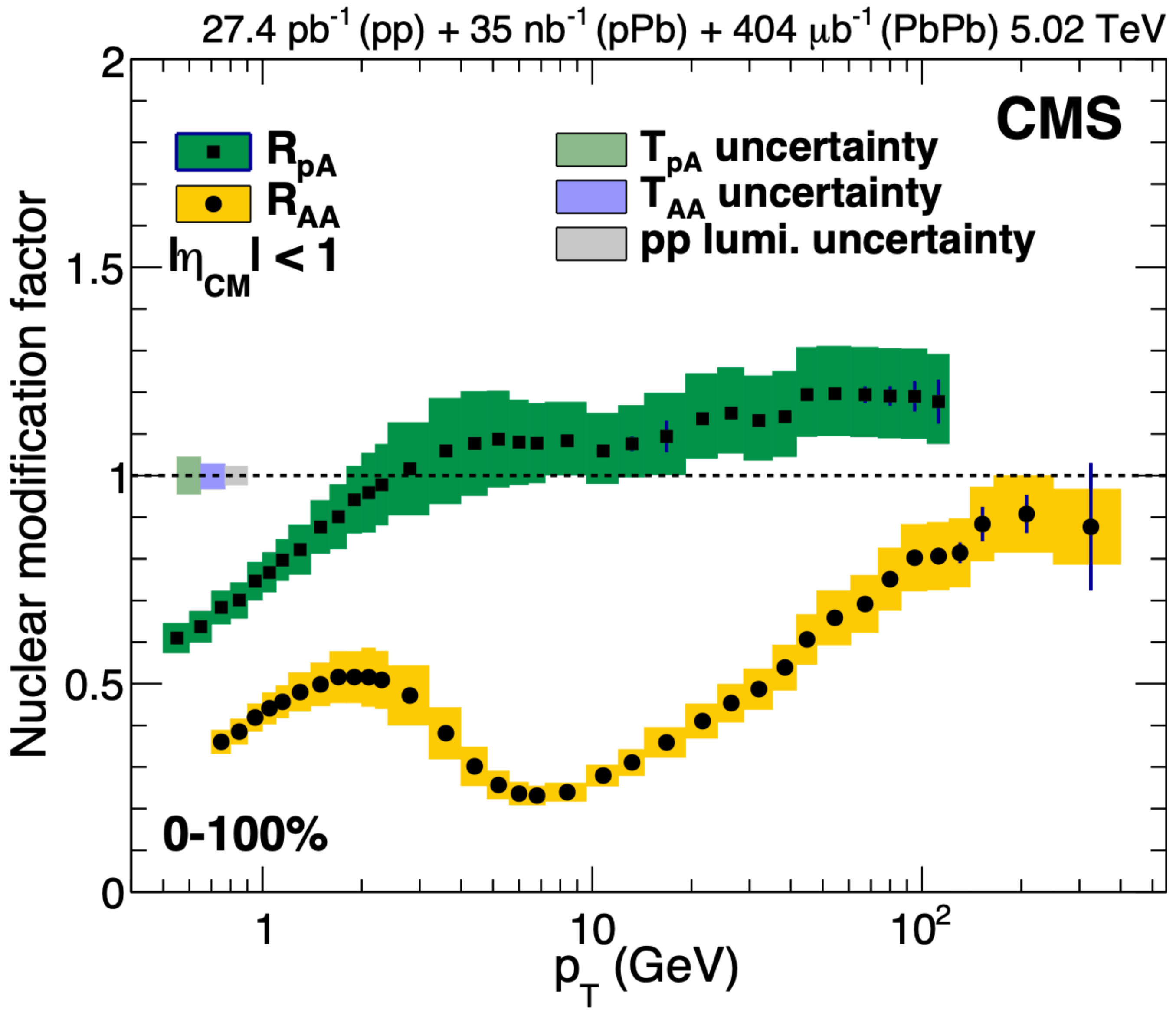
$$d\sigma_{\text{jet}} = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab\to jd} \otimes J_i$$

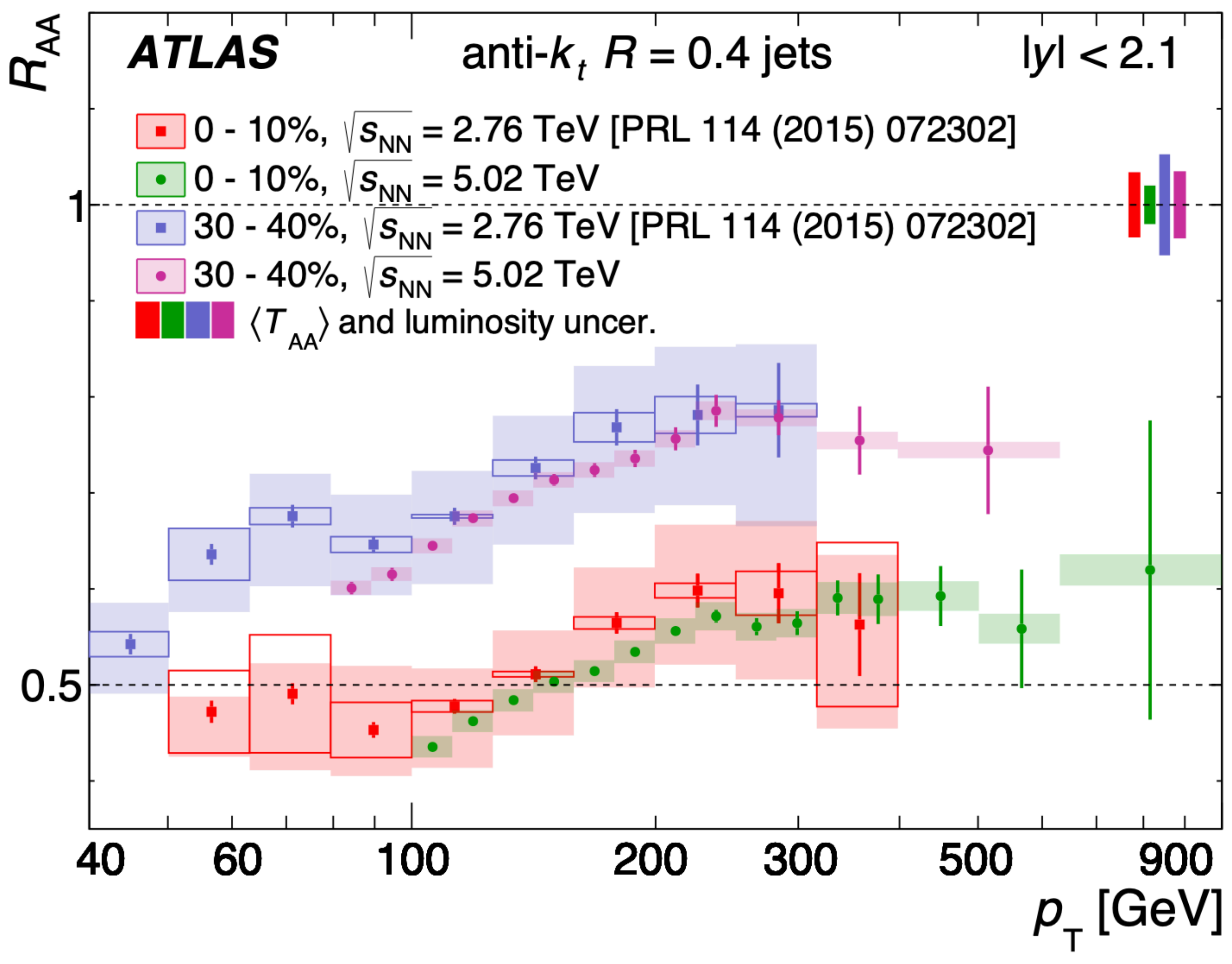
Jet quenching: jet energy loss caused by interaction between jet and QGP medium.

Nuclear modification factor: $R_{AB} = \frac{1}{N_{coll}} \frac{d^2N_{AB}/dp_T dy}{d^2N_{pp}/dp_T dy}$

Khachatryan V, et al. *JHEP* *04* (2017) 039
ATLAS, *Phys.Lett.B* 790 (2019) 108-128
Shreyasi Acharya,et al. *PRC* 101 (2020) 3, 034911





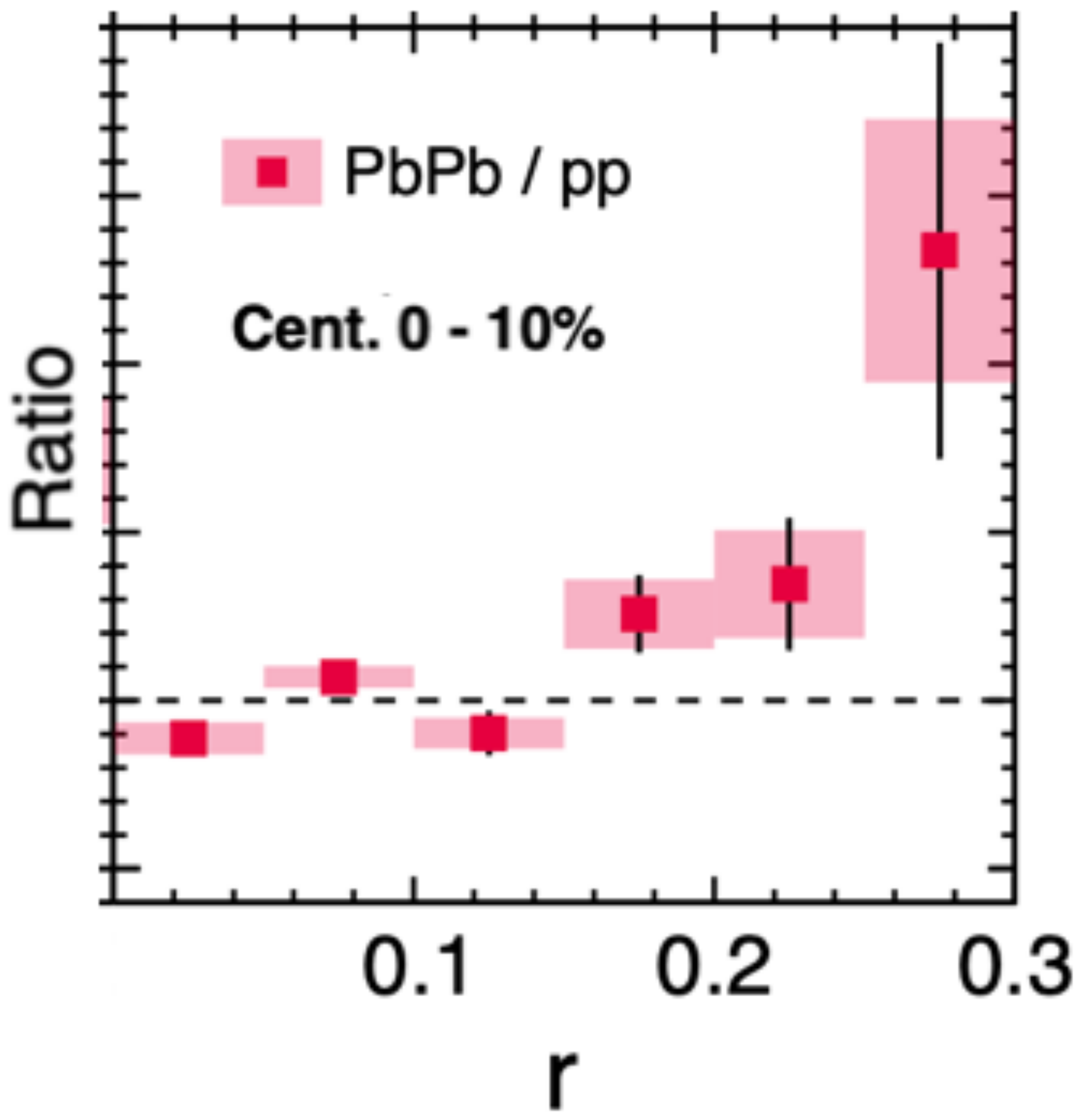


Jet substructure

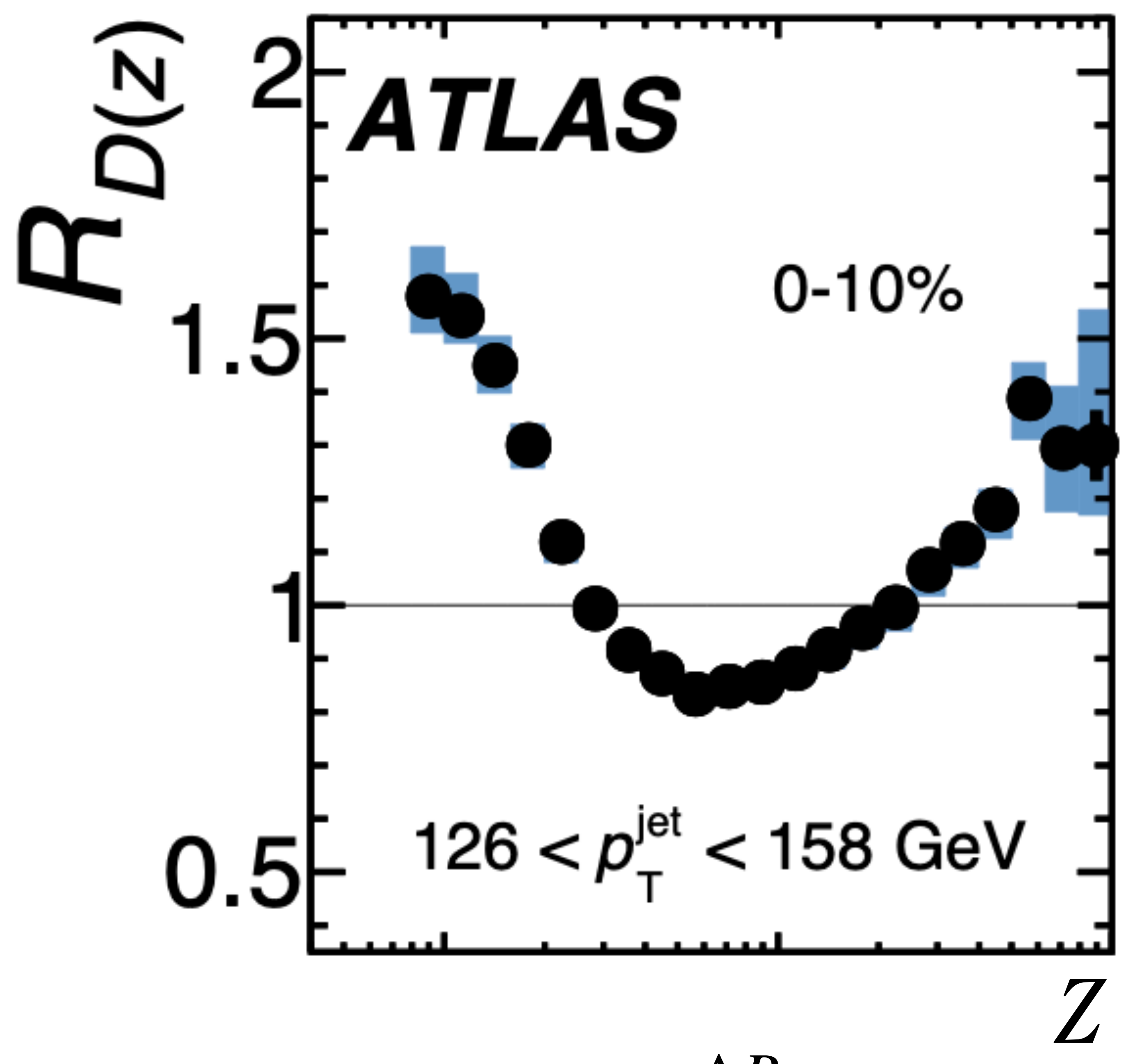
Jet shape, jet fragmentation, groomed jet …

ALICE, *Phys.Rev.Lett.* 128 (2022) 10, 102001
ATLAS, *Phys.Rev.C* 98 (2018) 2, 024908
CMS, *Phys.Rev.Lett.* 122 (2019) 15, 152001

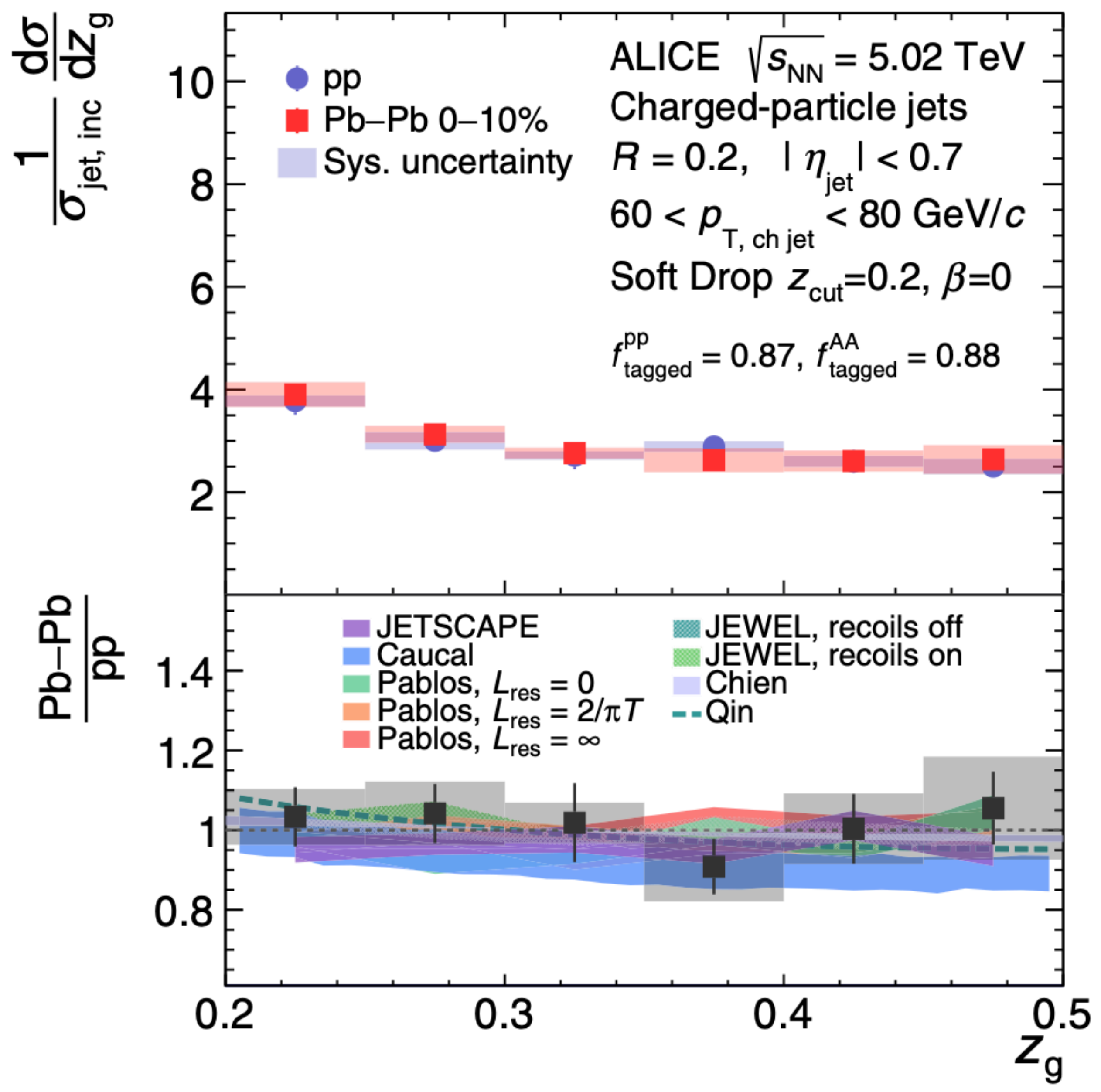
Medium-induced emissions, jet-induced medium response



$$r = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



$$z = \frac{p_T \Delta R}{p_T^{jet}}$$

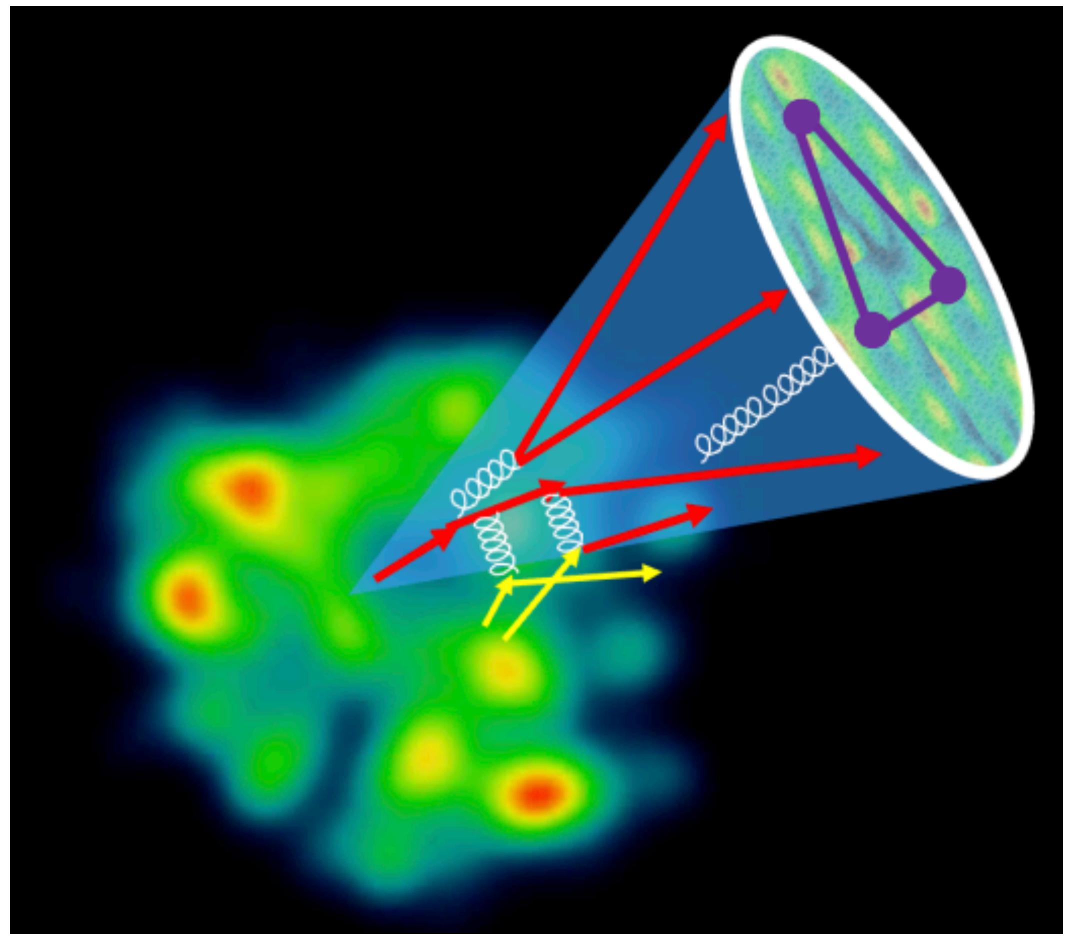


$$z_g = \frac{p_{T,sub-leading}}{p_{T,sub-leading} + p_{T,leading}}$$

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. [Komiske, Moult, Thaler, Zhu, 2023]

$$\langle \varepsilon^{(n)}(\vec{n_1}) \dots \varepsilon^{(n)}(\vec{n_k}) \rangle$$



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

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

The n-th weighted normalized two-point correlation:

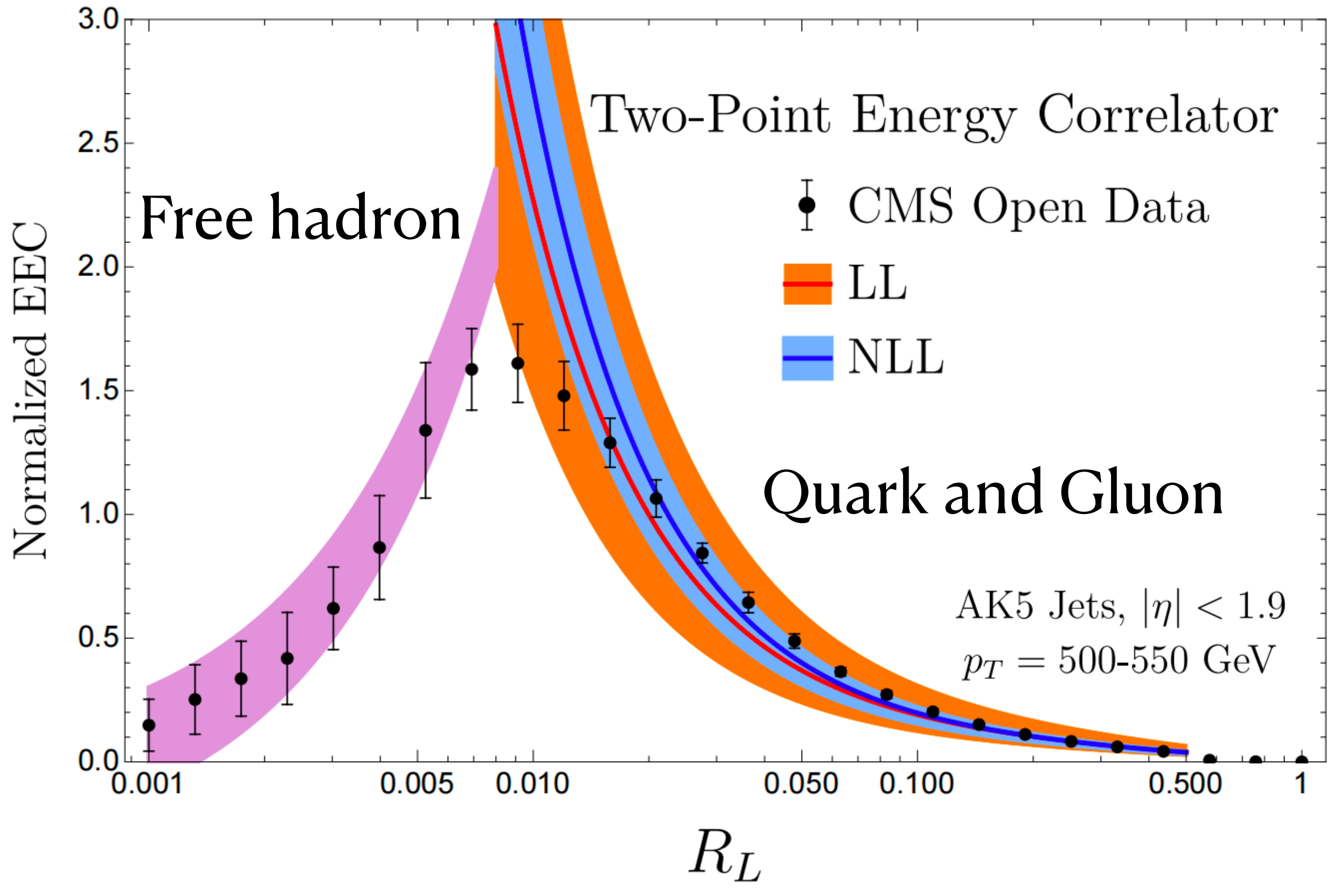
$$\frac{\langle \varepsilon^{(n)}(\vec{n_1}) \varepsilon^{(n)}(\vec{n_2}) \rangle}{Q^{2n}} = \frac{1}{\sigma} \sum_{ij} \frac{d\sigma_{ij}}{d\vec{n_i} d\vec{n_j}} \frac{E_i^n E_j^n}{Q^{2n}} \delta^{(2)}(\vec{n_i} - \vec{n_1}) \delta^{(2)}(\vec{n_j} - \vec{n_2})$$

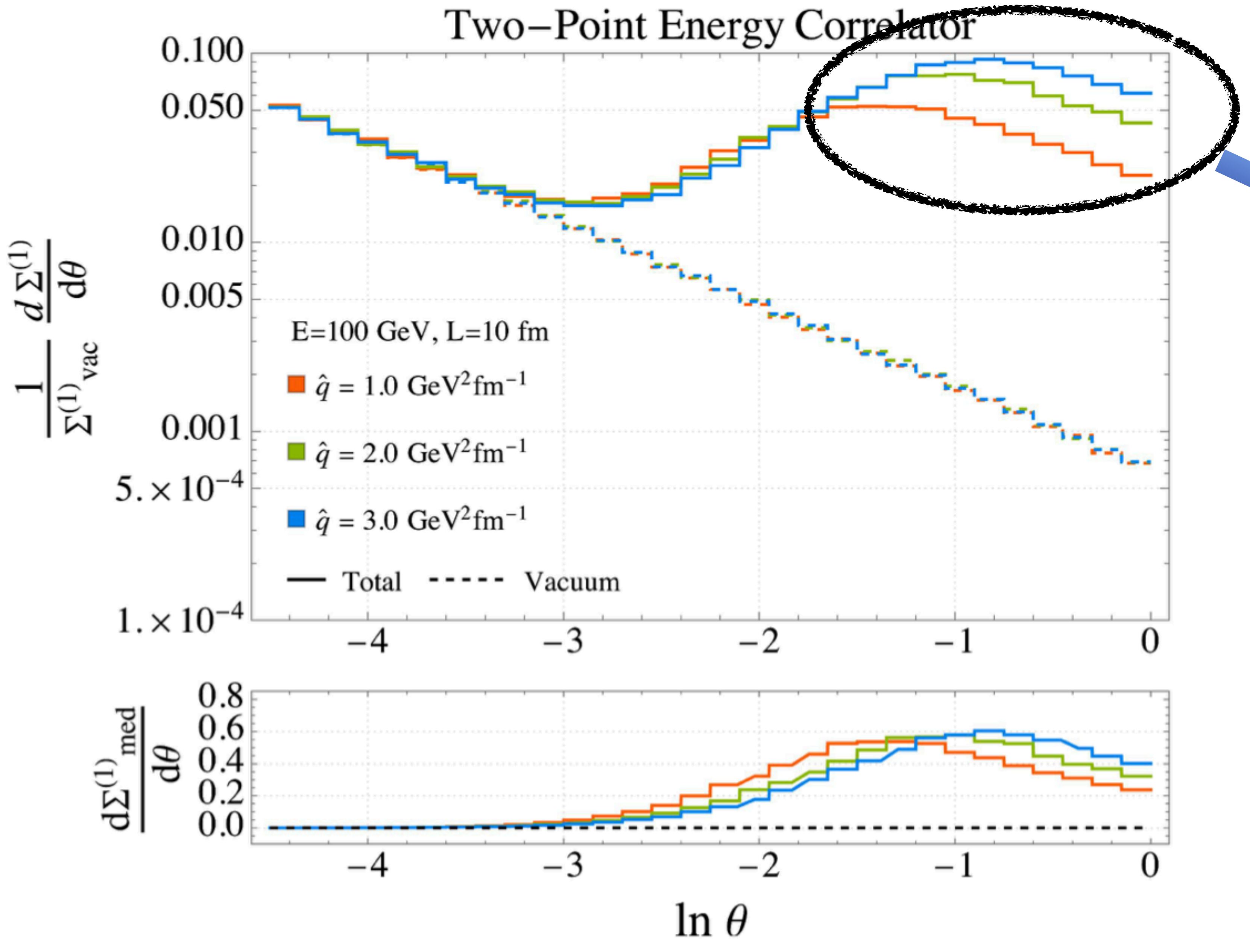
$$n = 1$$

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

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

Previous studies of EECs





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

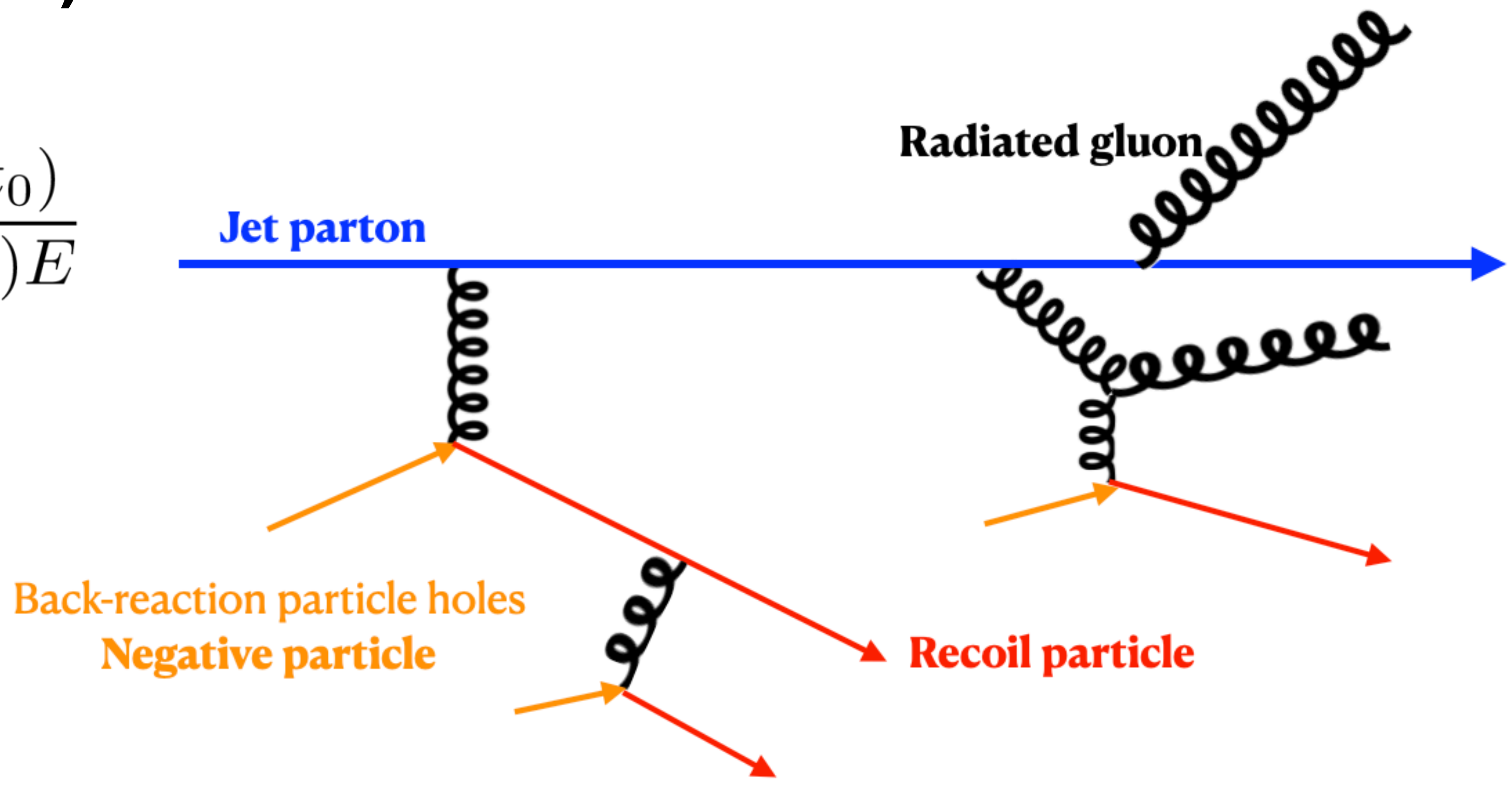
Linear Boltzmann Transport (LBT) model

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

Medium-induced gluon(High-Twist):

[Wang, Guo, 2001]

$$\frac{dN_g}{dz d^2k_\perp dt} \approx \frac{2C_A\alpha_s}{\pi k_\perp^4} P(z)\hat{q}(\hat{p}\cdot u) sin^2 \frac{k_\perp^2 (t-t_0)}{4z(1-z)E}$$



Tracked partons:

- Jet shower partons
- Thermal recoil partons
- Radiated gluons
- Negative partons

LBT: Pure pQCD description of parton transport

CoLBT-hydro model

1. LBT for energetic partons(jet shower and recoil)

2. Hydrodynamic model for bulk and soft hadrons: CLVisc

3. Sorting jet and recoil partons according to a cut-off parameter p^0_{cut}

   Hard partons: $p\partial f(p) = -C(p) \quad (p \cdot u > p^0_{cut})$

   Soft and negative partons:

$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

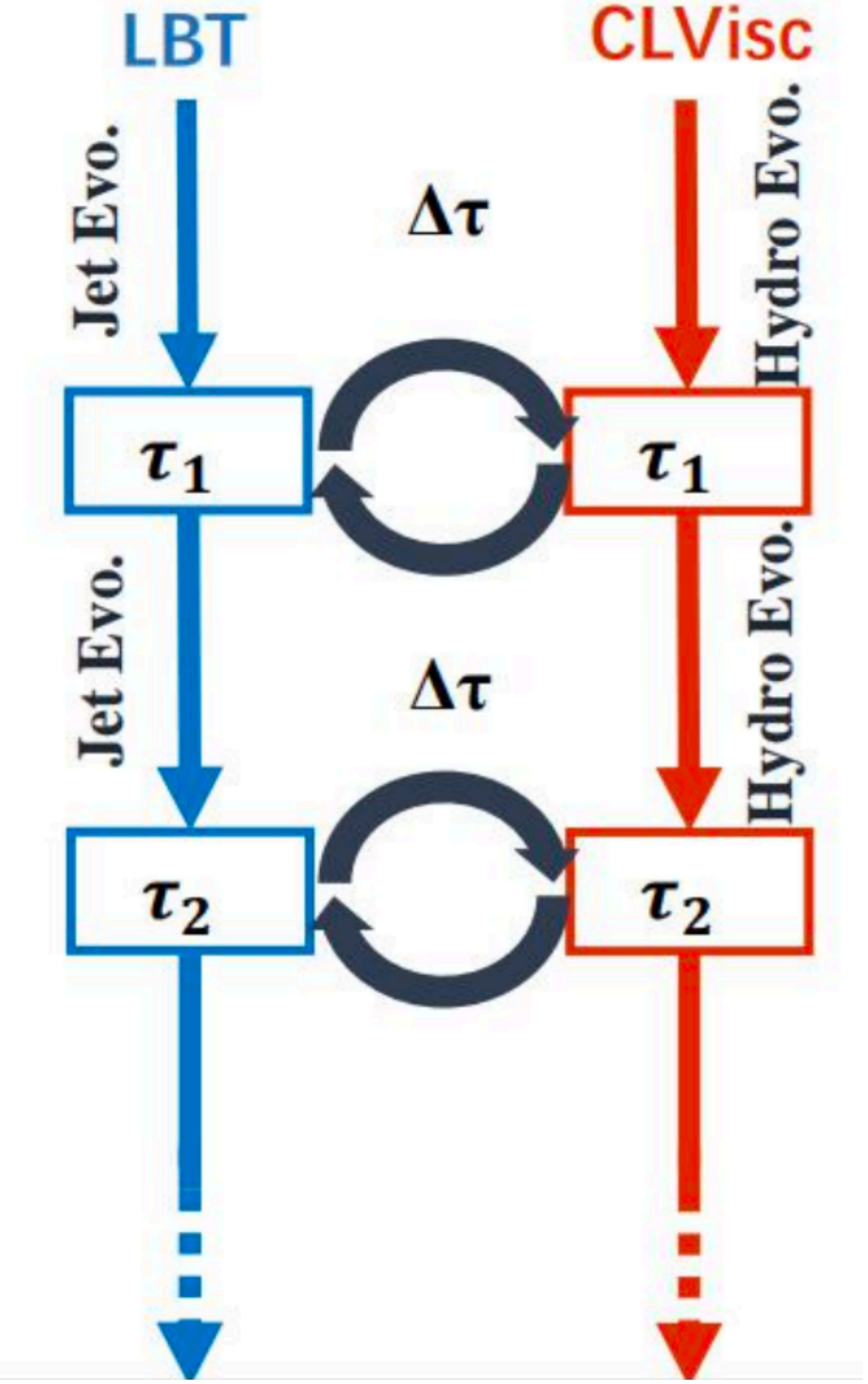
4. Updating medium information by solving the hydrodynamics equation with source term

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

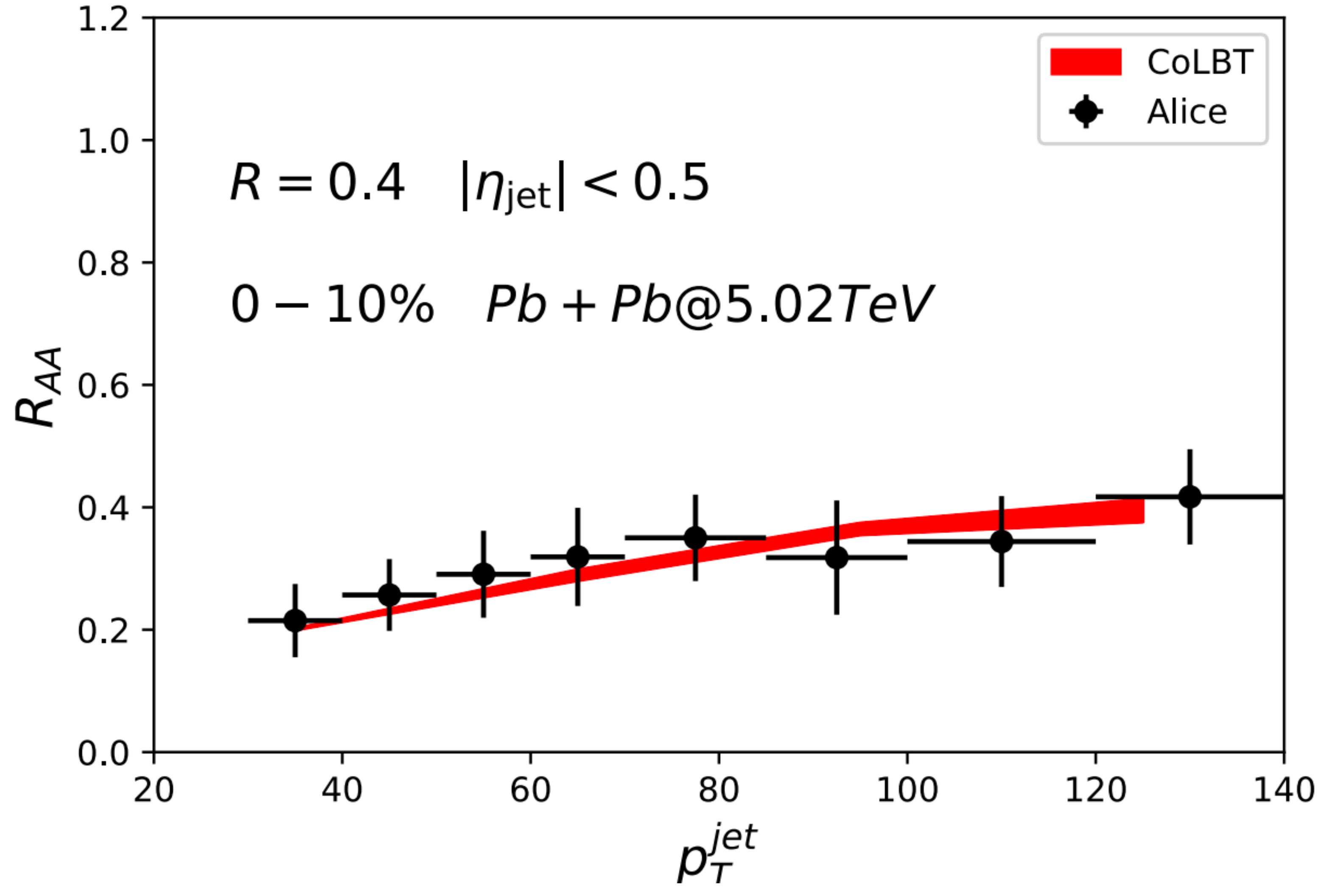
5. The final hadron spectra:

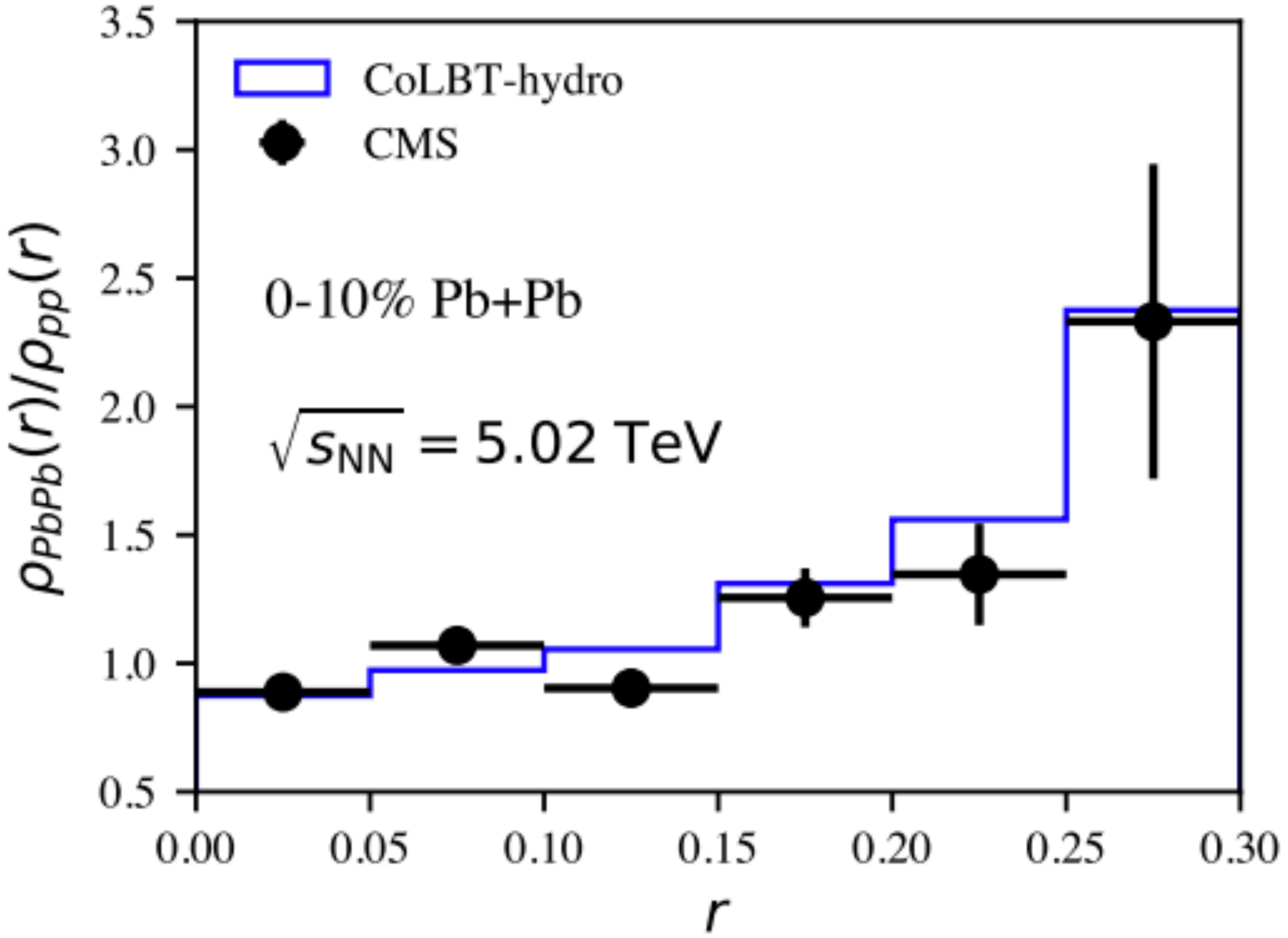
   (1) hadronization of hard partons within a parton hadroniztion model

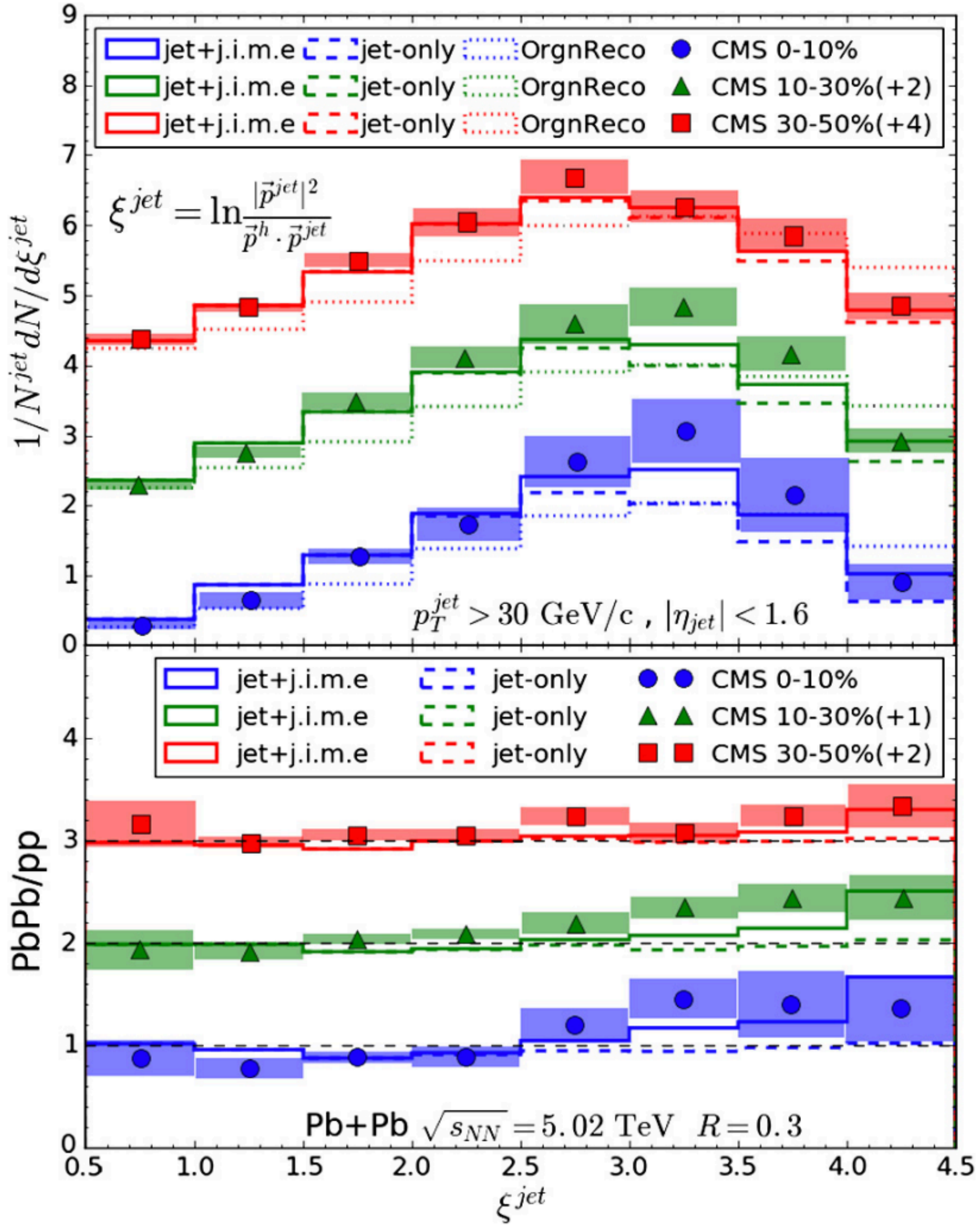
   (2) jet-induced hydro response via Cooper-Frye freeze-out



Medium modifications of jets







CoLBT/LBT are effective models to study jet-medium interaction and jet-induced medium response

We plan to carry out the complete calculations of EECs using realistic simulations of high-energy heavy-ion collisions within LBT and CoLBT.

Zhong Y, et al. arXiv:2203.03683
Wei C, et al. arXiv:2005.09678

EECs in vacuum

We focus on the normalized two-point energy correlates

For a quark with energy E and initial virtuality Q=E, the vacuum splitting $q \to q + g$ at small angles and leading order (LO) in pQCD leads to the angular distribution of the energy correlators

$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz\; z(1-z) P_{qg}(z) \int_{\mu^2}^{Q^2} \frac{d\mathbf{k}_\perp^{\,2}}{\mathbf{k}_\perp^{\,2}} \delta(\theta - \frac{|\mathbf{k}_\perp|}{z(1-z)E})$$

$\mu \ll Q$ the collinear cut-off scale below which non-perturbative effects become dominant.

$$P_{qg}(z) = \frac{1+(1-z)^2}{z}$$

Splitting function

$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi}\frac{C_F}{2\theta}\left(3 - \frac{2\mu}{E\theta}\right)\sqrt{1 - \frac{4\mu}{E\theta}} \longrightarrow$$

$\theta > 4\mu/E :$ $\quad d\Sigma_q^{vac}/d\theta \sim 1/\theta$

$\theta \to 4\mu/E :$ **non-perturbative effects take over and its behavior will be influenced by hadronization processes.**

EECs from medium-induced emissions

The medium-induced gluon radiation is modeled by high-twist approach

For a massless parton, the formation time of radiated gluon is

$$\theta_{12} = \frac{2\ell_\perp}{Ez(1-z)} \qquad \tau_f = \frac{2Ez(1-z)}{\ell_\perp^2} = \frac{8}{\theta_{12}^2 z(1-z)E}$$

The corresponding angular contribution to EEC is,

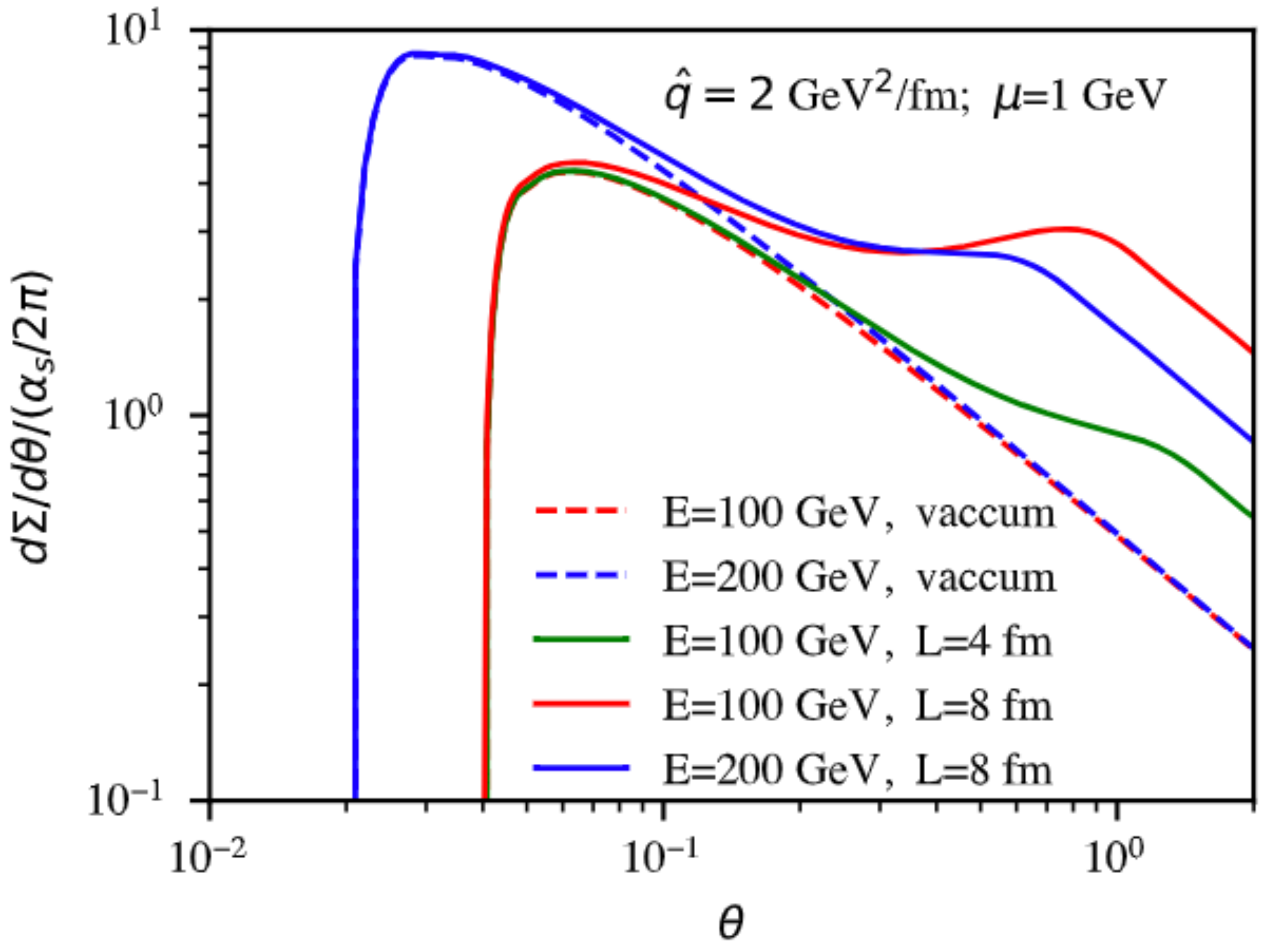
$$\frac{d\Sigma_q^{\rm med}}{d\theta} = \frac{16\alpha_{\rm s}C_A}{\pi E^2\theta^3}\int dx dz \frac{\hat{q}P_{qg}(z)}{z(1-z)}\sin^2\left(\frac{x}{2\tau_f}\right)$$

$$= \frac{L^{5/2}\hat{q}}{\pi\sqrt{E}}\frac{8\alpha_{\rm s}C_A}{(\sqrt{EL}\theta)^3}\int dz \frac{P_{qg}(z)}{z(1-z)} \times \left[1 - \frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]$$

$$\theta < \sqrt{8\pi/EL}: \qquad d\Sigma_q^{\rm med}/d\theta \approx L^3\hat{q}\alpha_s C_A\theta/(64\pi) \sim \theta$$

$$\theta > \sqrt{8\pi/EL}: \qquad \frac{d\Sigma_q^{\rm med}}{d\theta} \approx \frac{L^2\hat{q}}{2E}\frac{\alpha_s C_A}{\theta}\left[1 + \mathcal{O}\left(\frac{1}{EL\theta^2}\right)\right] \sim 1/\theta$$

vacuum + medium-induced

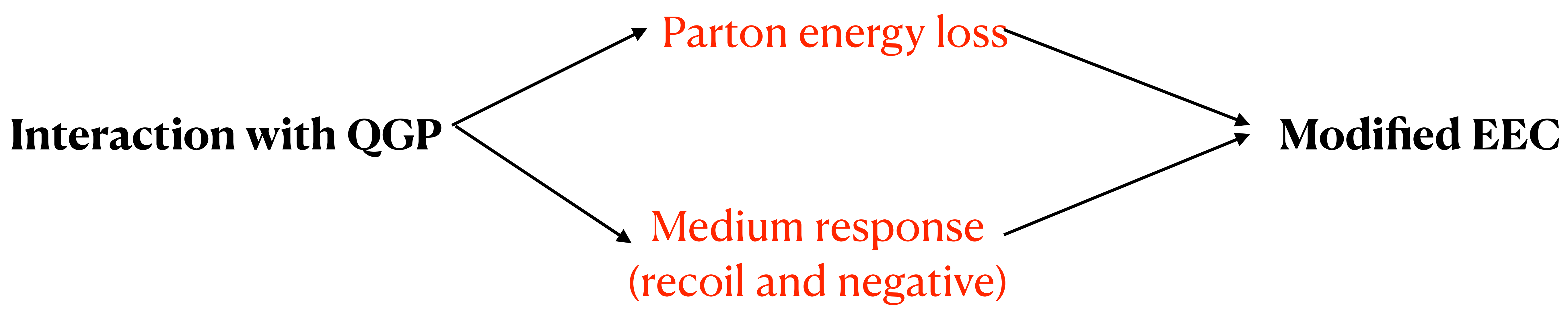


$$\theta_{\rm peak}^{\rm med} \sim \sqrt{8\pi/EL}$$

$$\Sigma_{\rm peak}^{\rm med} \sim \alpha_s\hat{q}L^{5/2}/\sqrt{E}$$

EECs from a quark going through the QGP brick

EECs from a quark going through the QGP brick

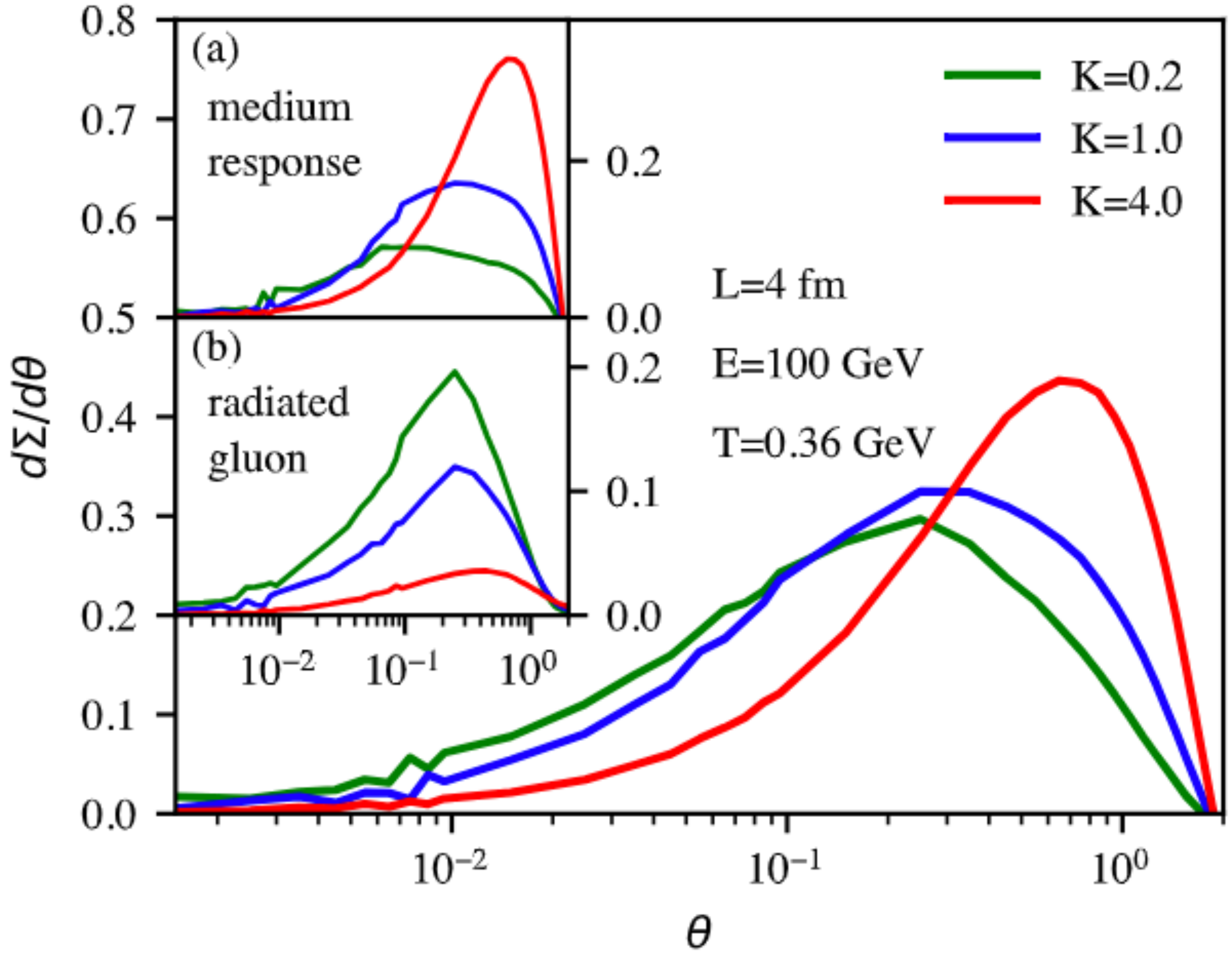


LBT model has a cut-off in the transverse momentum transfer in terms of the Debye screening mass.

$$\mu_D^2 = \frac{3}{2} K g^2 T^2 \qquad K = 1(default), 0.2, 4.0$$

It determines the typical momentum and angular scale of the in-medium interaction.

EECs from a quark going through the QGP brick



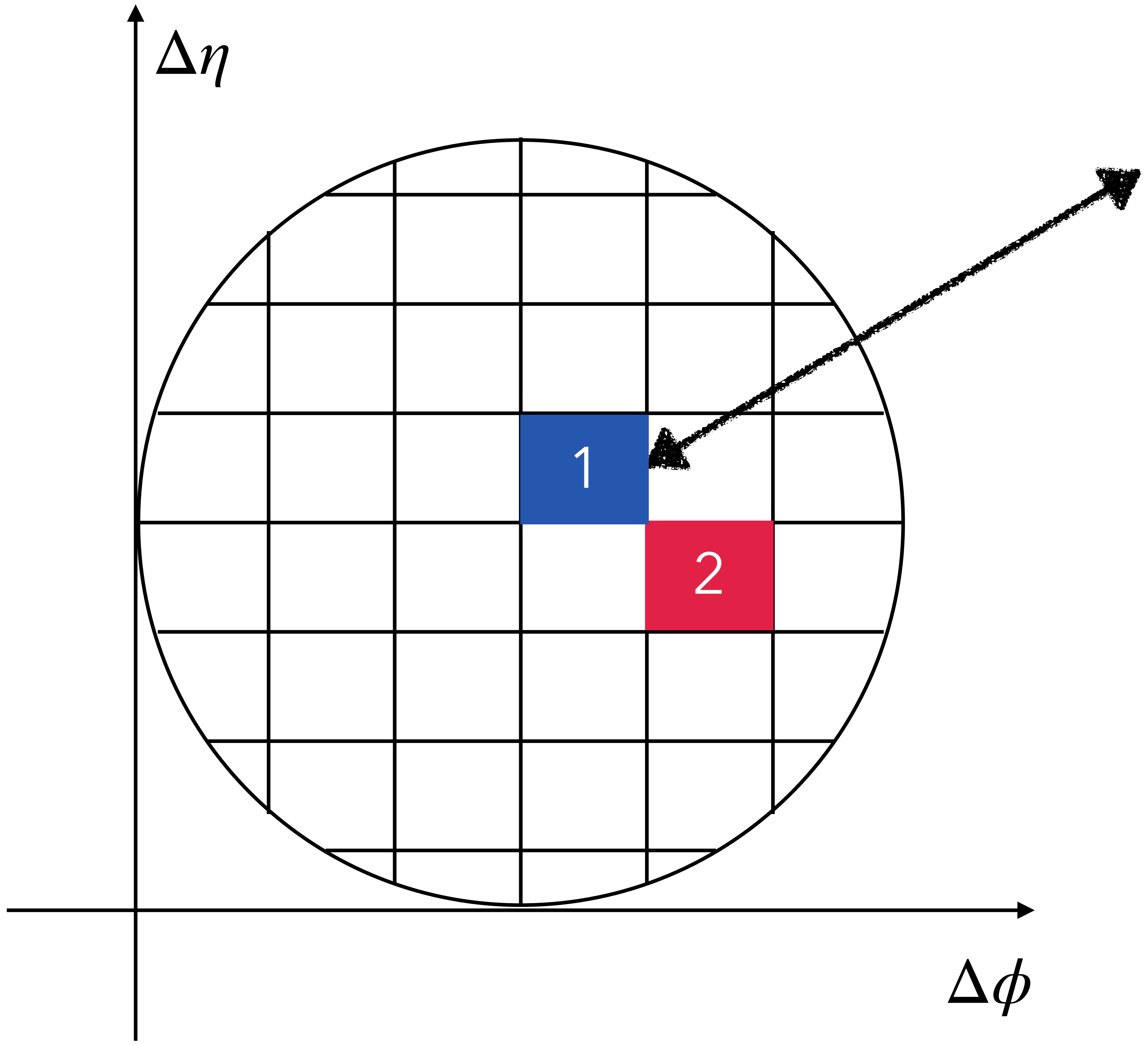
Transverse momentum transfer: $q_\perp \sim \mu_D$

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

The EEC distribution from the medium response shifts to a larger angle with an enhanced magnitude if μ_D increases. While the quark-radiated-gluon correlator decreases with μ_D and peak shifts slightly to large angles.

How to deal with negative partons

How to deal with the negative parton



The energy deposited in this cell equal $E_{pos} - E_{neg}$

Therefore, energy correlation between different cells is $(E^1_{pos} - E^1_{neg})(E^2_{pos} - E^2_{neg})$

Sign	Pair
+	**pos+pos**
-	**pos+neg**
+	**neg+neg**

It does not directly subtract the contributions of all negative particles.

EECs from jet shower going through the QGP brick

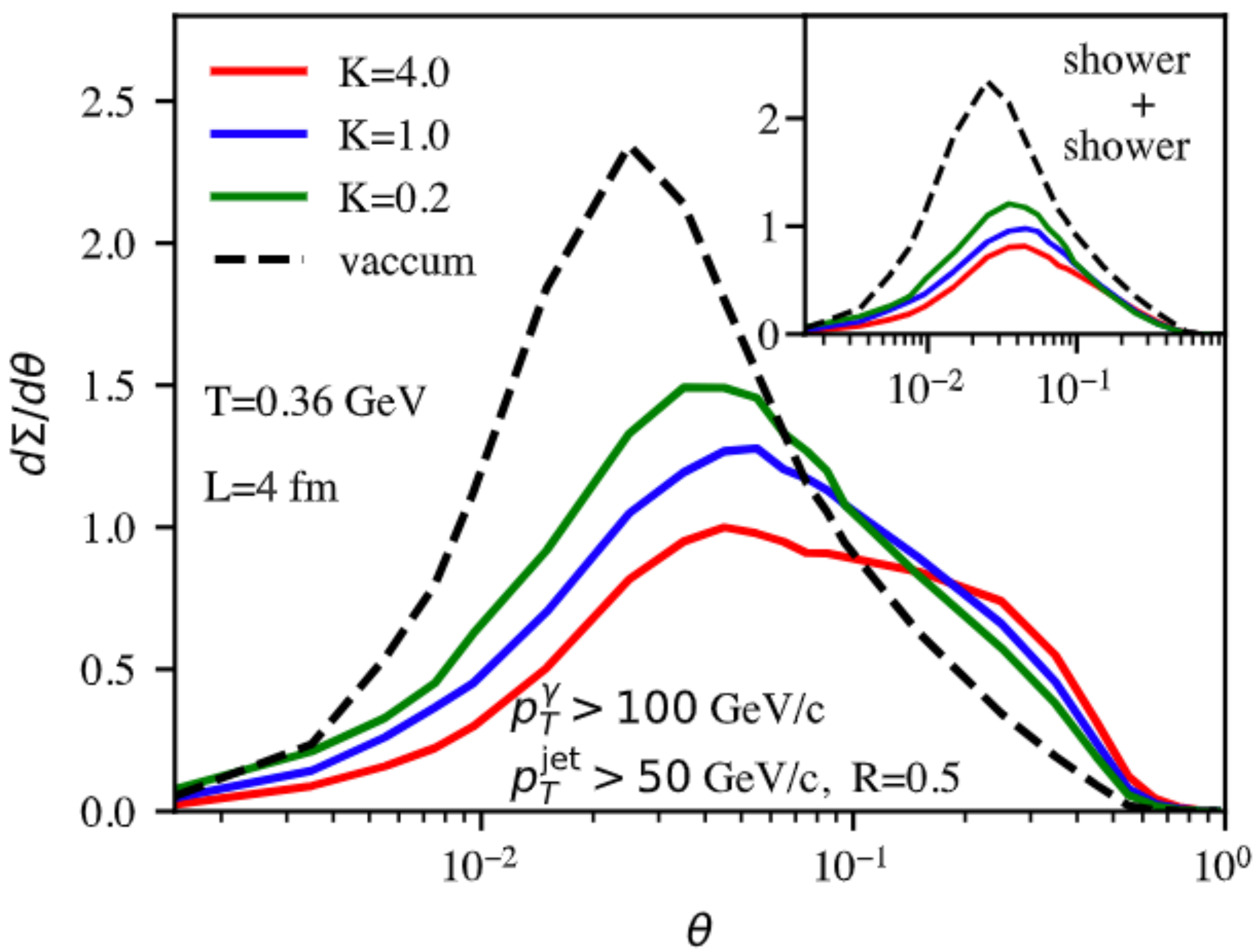
EECs from a parton shower going through the QGP brick

$R = 0.5 \quad p_T^\gamma \geq 100 GeV/c \quad p_T^{\text{jet}} \geq 50 GeV/c$

Jet → Parton showers → Multiple elastic and inelastic scatterings

↓

Transverse momentum broadening and energy loss



EEC distributions from correlation between shower partons suppressed at both small and large angles relative to the vacuum EEC (dashed).
The total correlator of all partons (shower, medium-response and radiated gluons) inside the modified jet enhanced at large angles due to correlations involving medium response or/and radiated gluons.

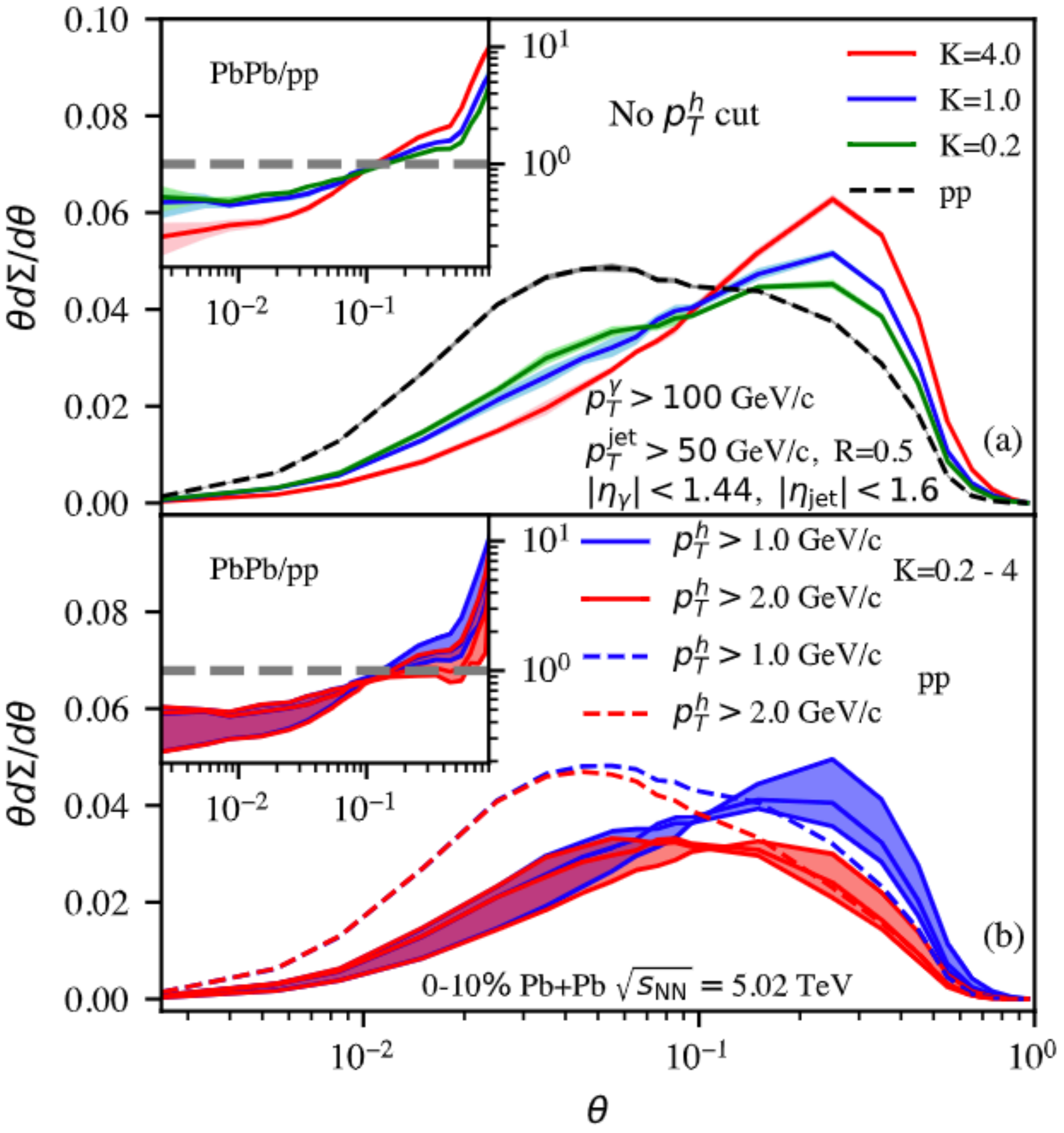
EECs in Pb+Pb collisions at LHC

EEC of γ-jets in Heavy-Ion Collisions.

1. Similar to the case of a QGP brick, the EEC's in Pb+Pb collisions are suppressed at small angles due to energy loss and p_T broadening, while they are enhanced at large angles due to medium modification.

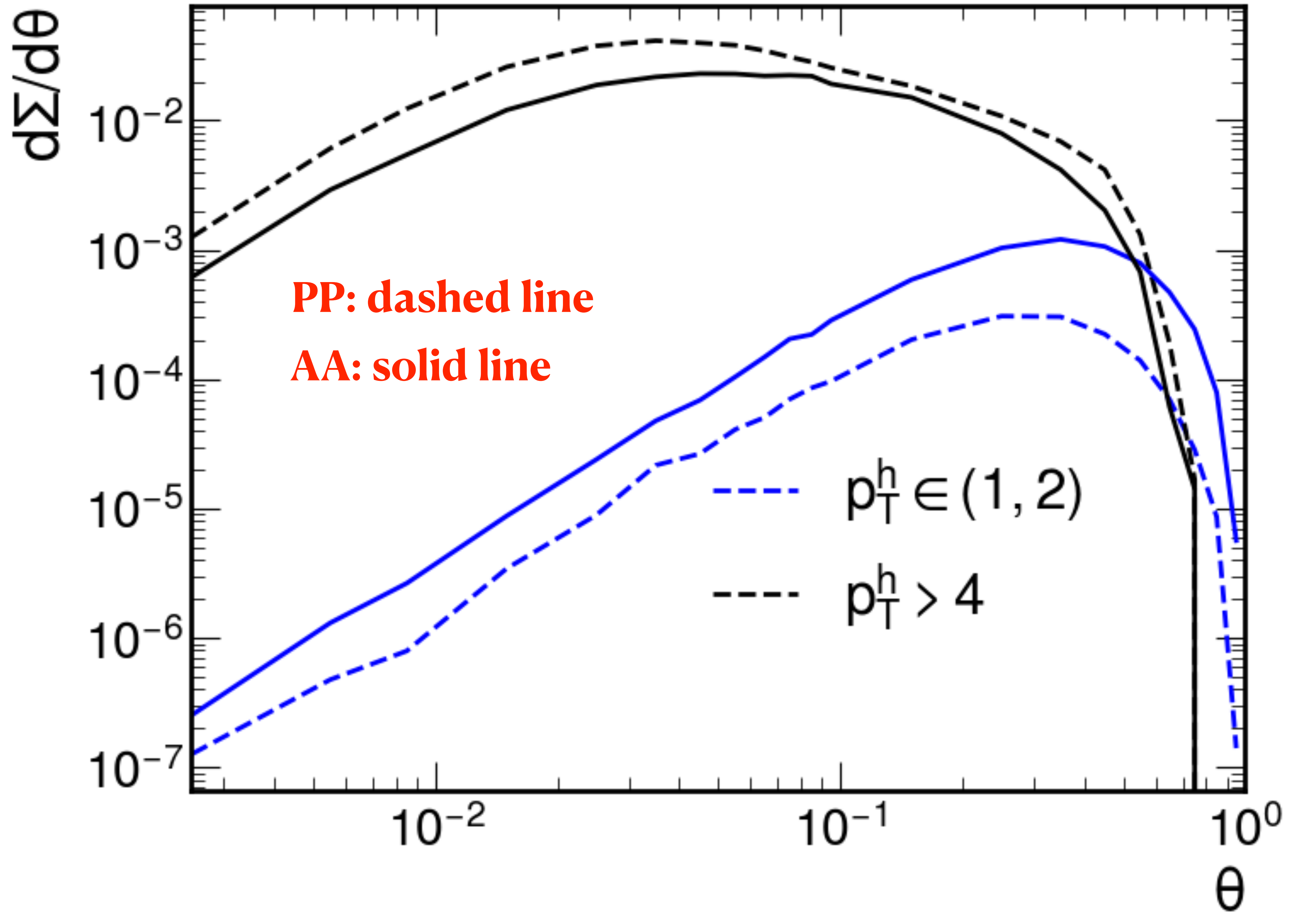
2. This modification is sensitive to the Debye mass, μ_D, which determines the angular scales of each jet-medium scattering and charaterizes the structure of the QGP medium in the CoLBT simulations.

3. The enhancement at large angles is reduced but still survives if a $p_T > 1 GeV/c$ cut is imposed on the final hadrons for the purpose of reducing the background in experimental analyses. If $p_T > 2 GeV/c$ cut is used, the medium enhancement at large angles is mostly gone except for the case of $K = 4$.



Transverse momentum dependence of EECs

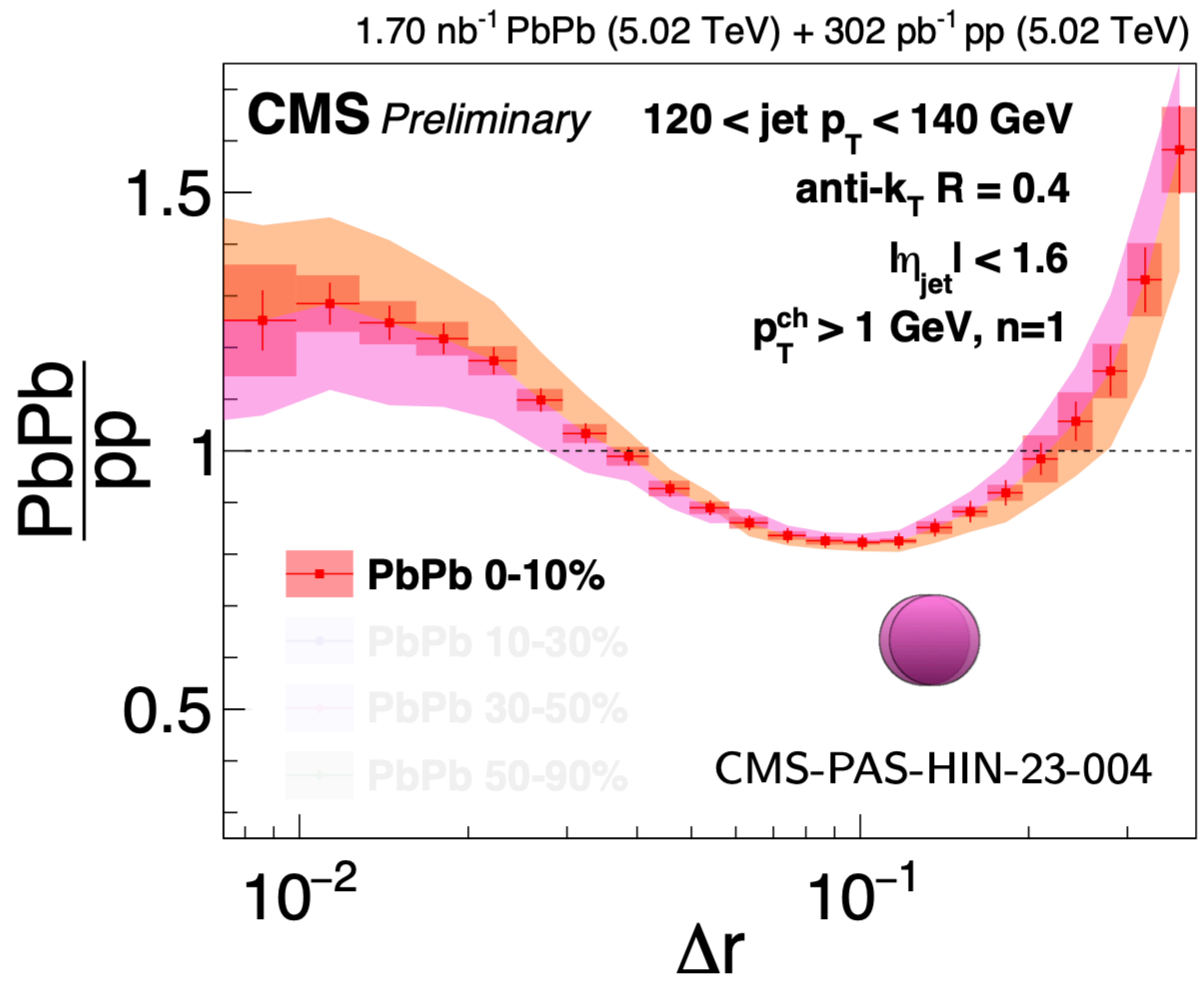
EECs of γ-jets in Heavy-Ion Collisions.



For high p_T hadrons, PP result is greater than AA result.
But, AA results becomes greater when you decrease p_T^h.

EECs of single inclusive jets

EECs of single inclusive jets in Heavy-Ion Collisions.



Large angle:

Medium response

Medium-induced emissions

Small angle: 10～40%

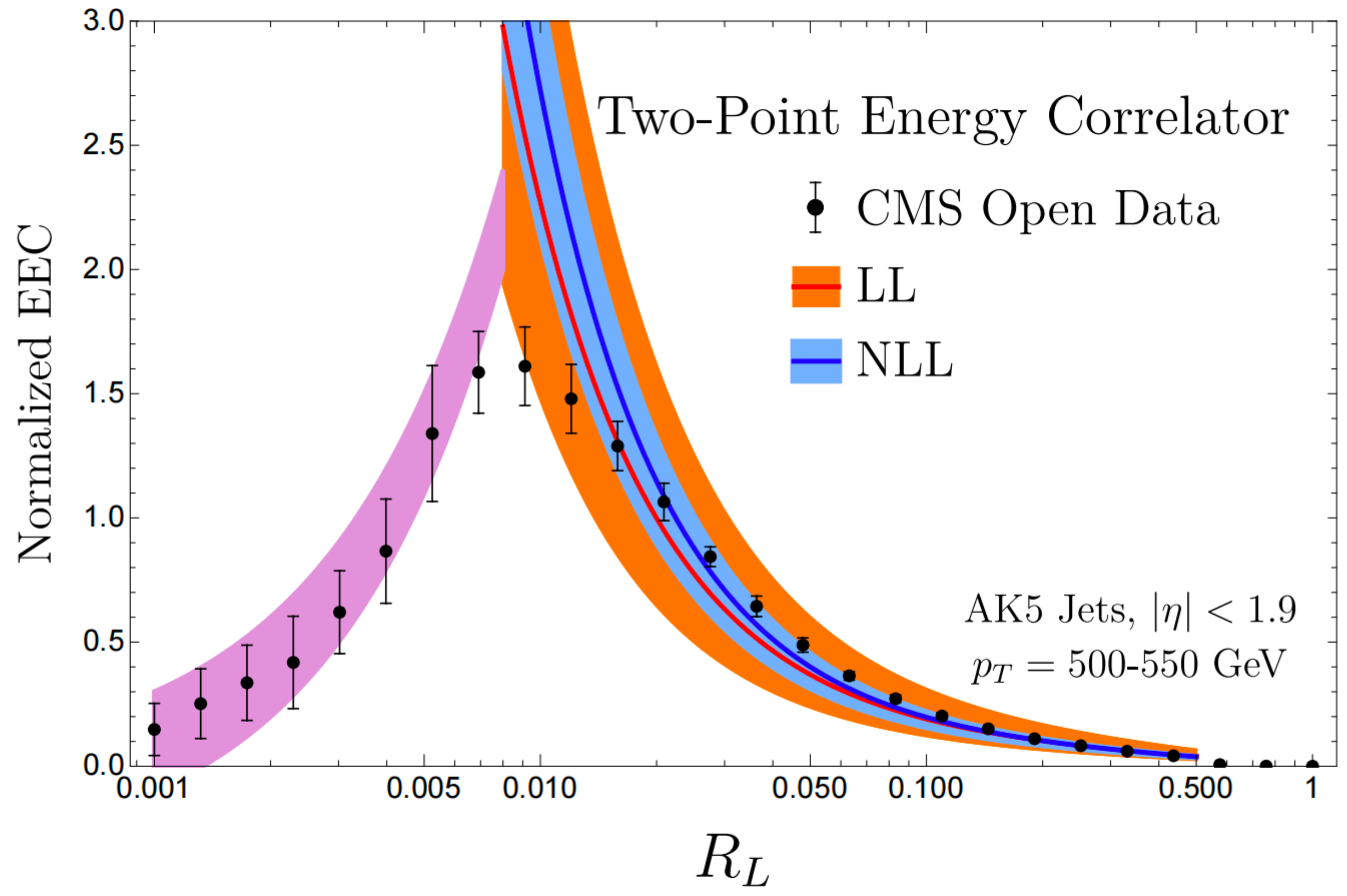
Where does the enhancement come from?

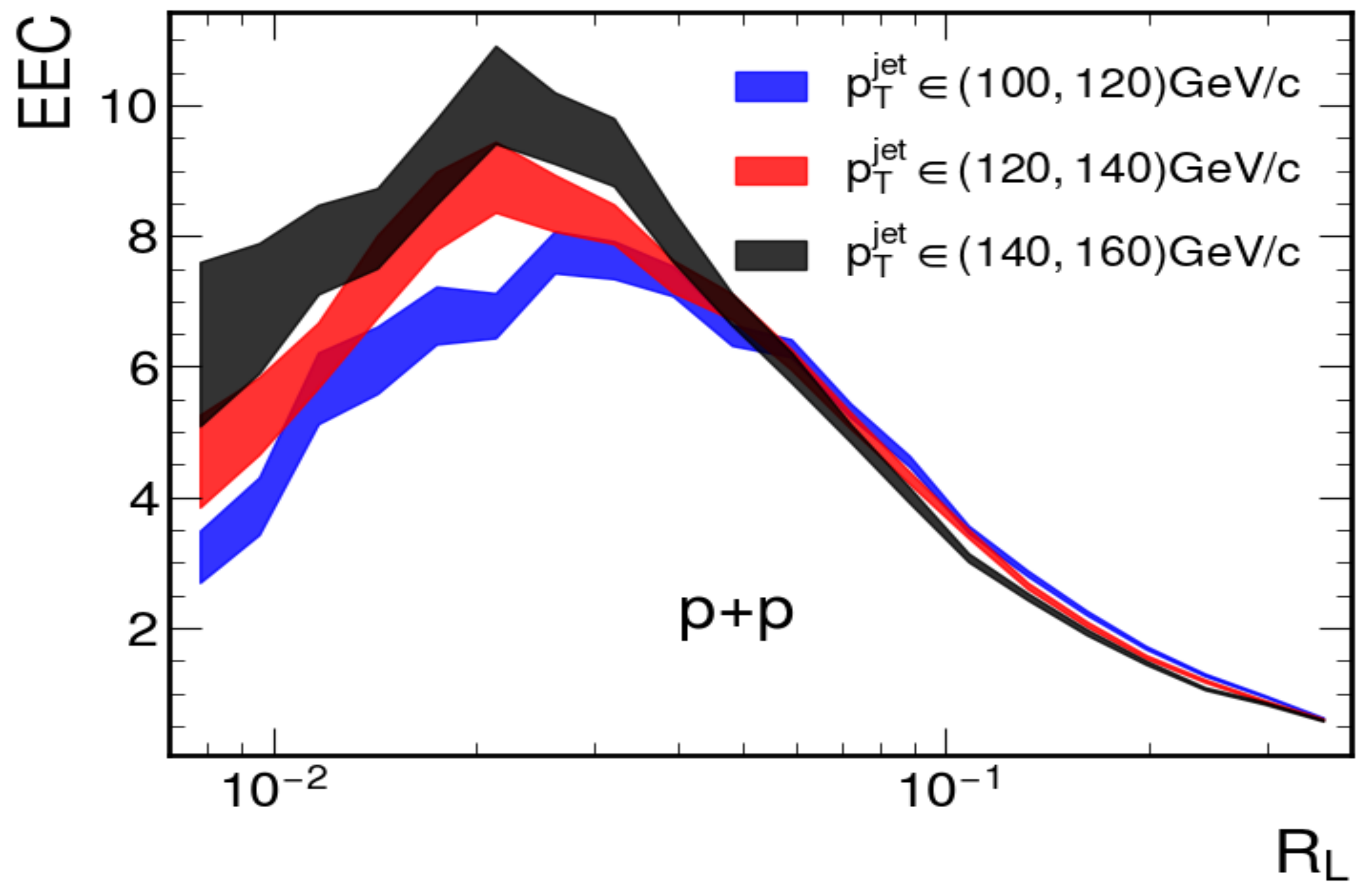
Energy loss or anything else …

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

Jet p_T selection bias

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





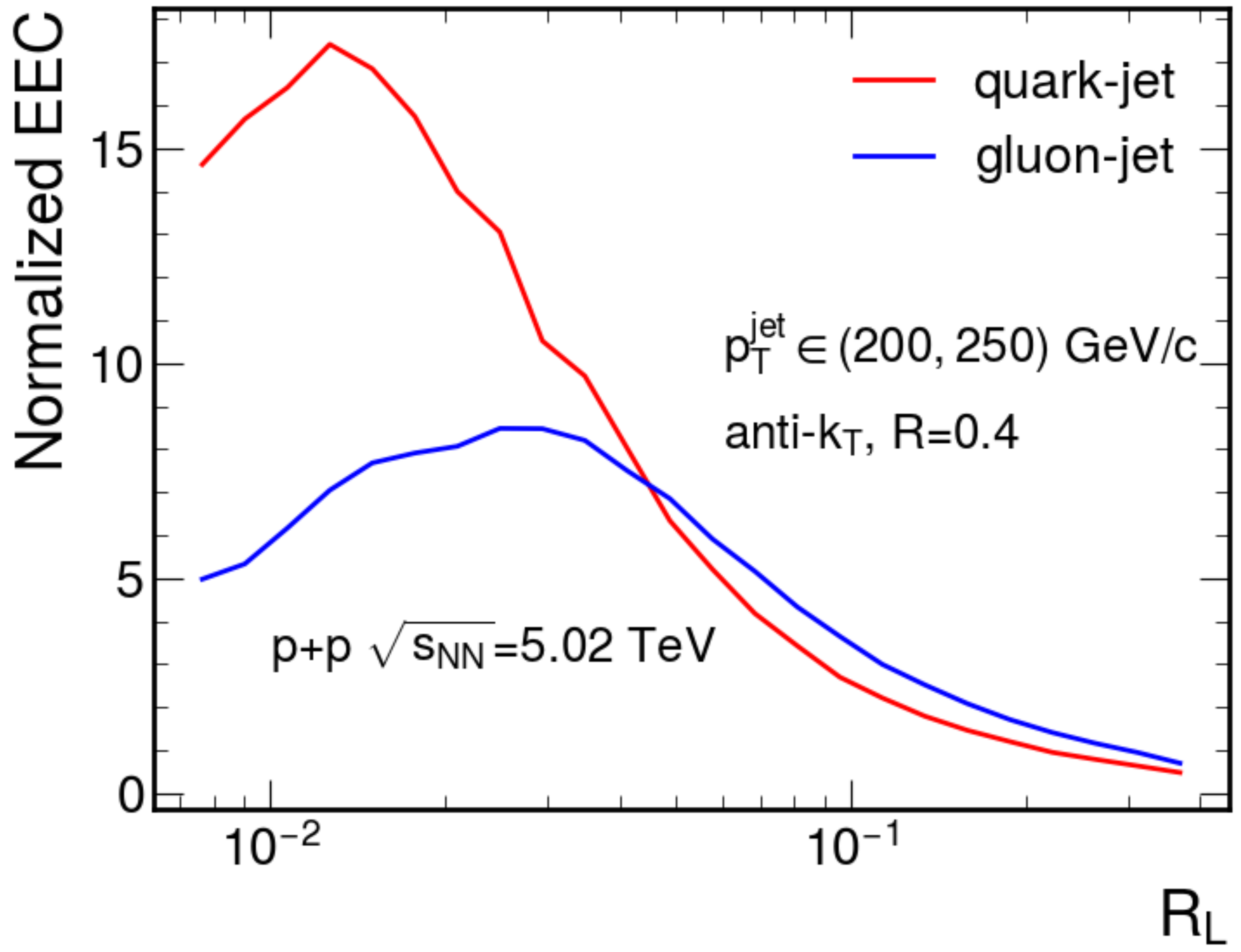
$$R_L \sim \Lambda_{QCD}/p_T^{jet} \sim 10^{-2}$$

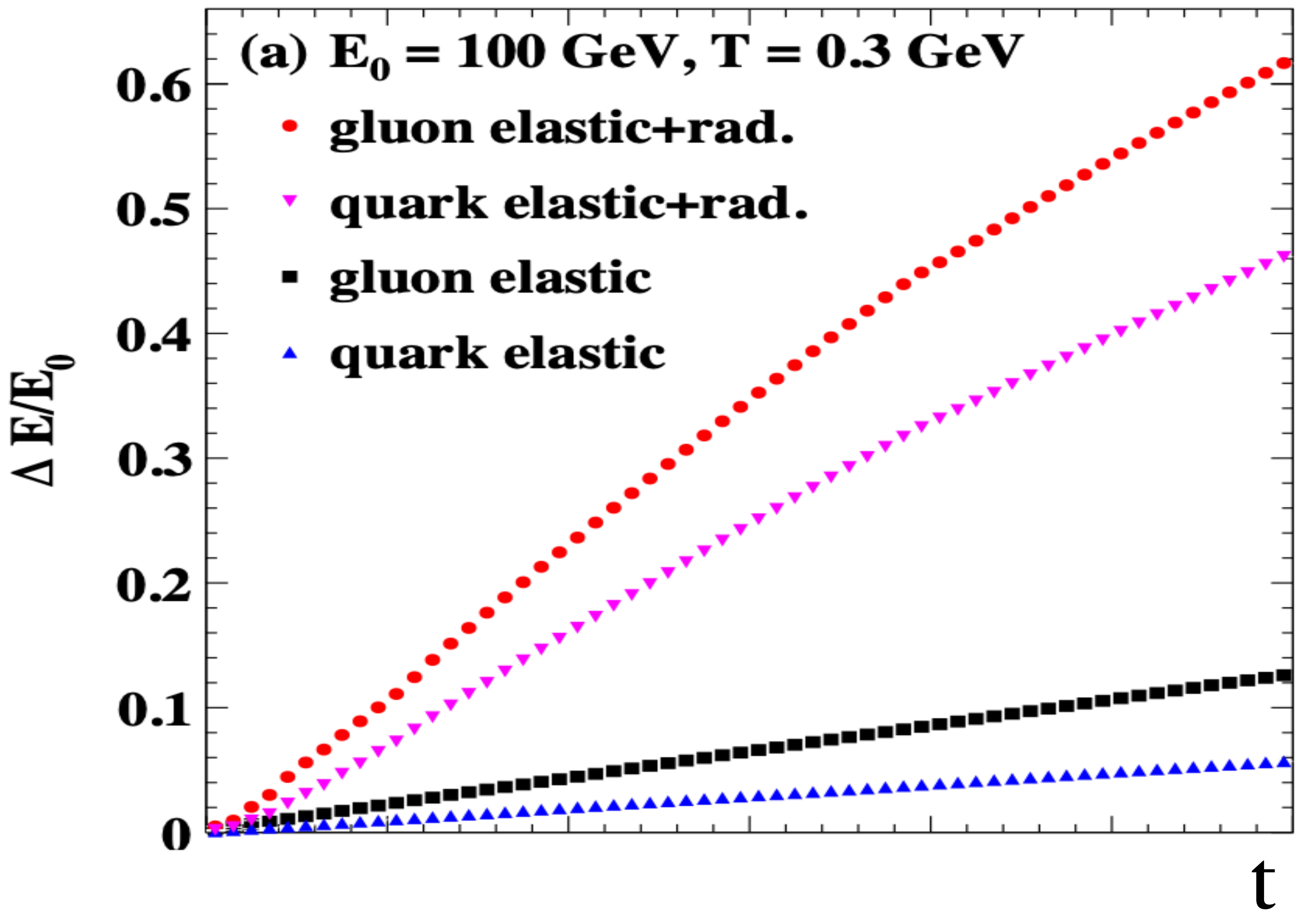
Final		**Initial**
$p_{T,f}^{jet,AA}$	⟵ Energy loss	$p_{T,i}^{jet,AA}$
$\parallel$		$\vee$
$p_{T,f}^{jet,pp}$	⟵ No interaction	$p_{T,i}^{jet,pp}$

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.

Effects of the quark and gluon jet fraction

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



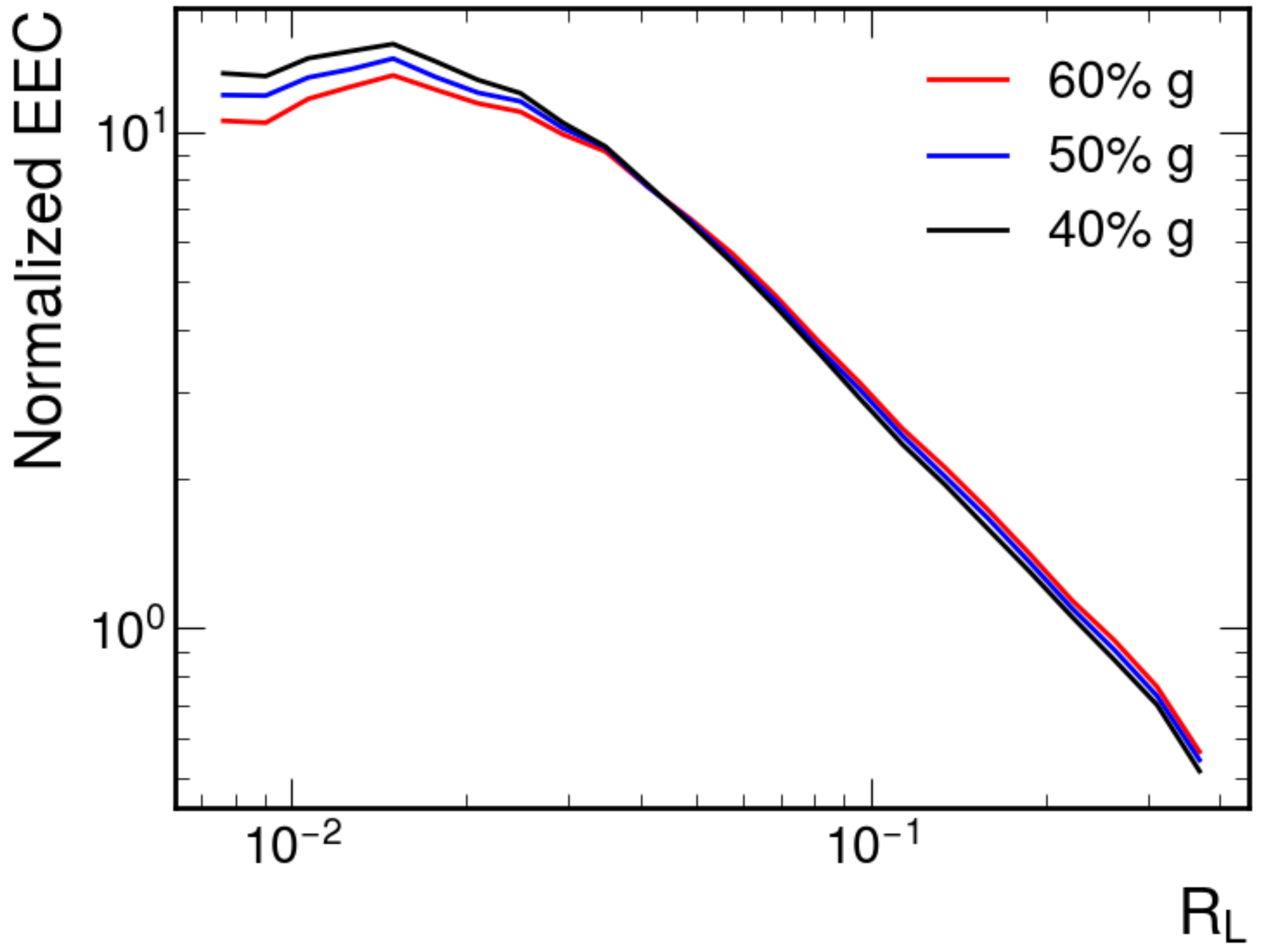


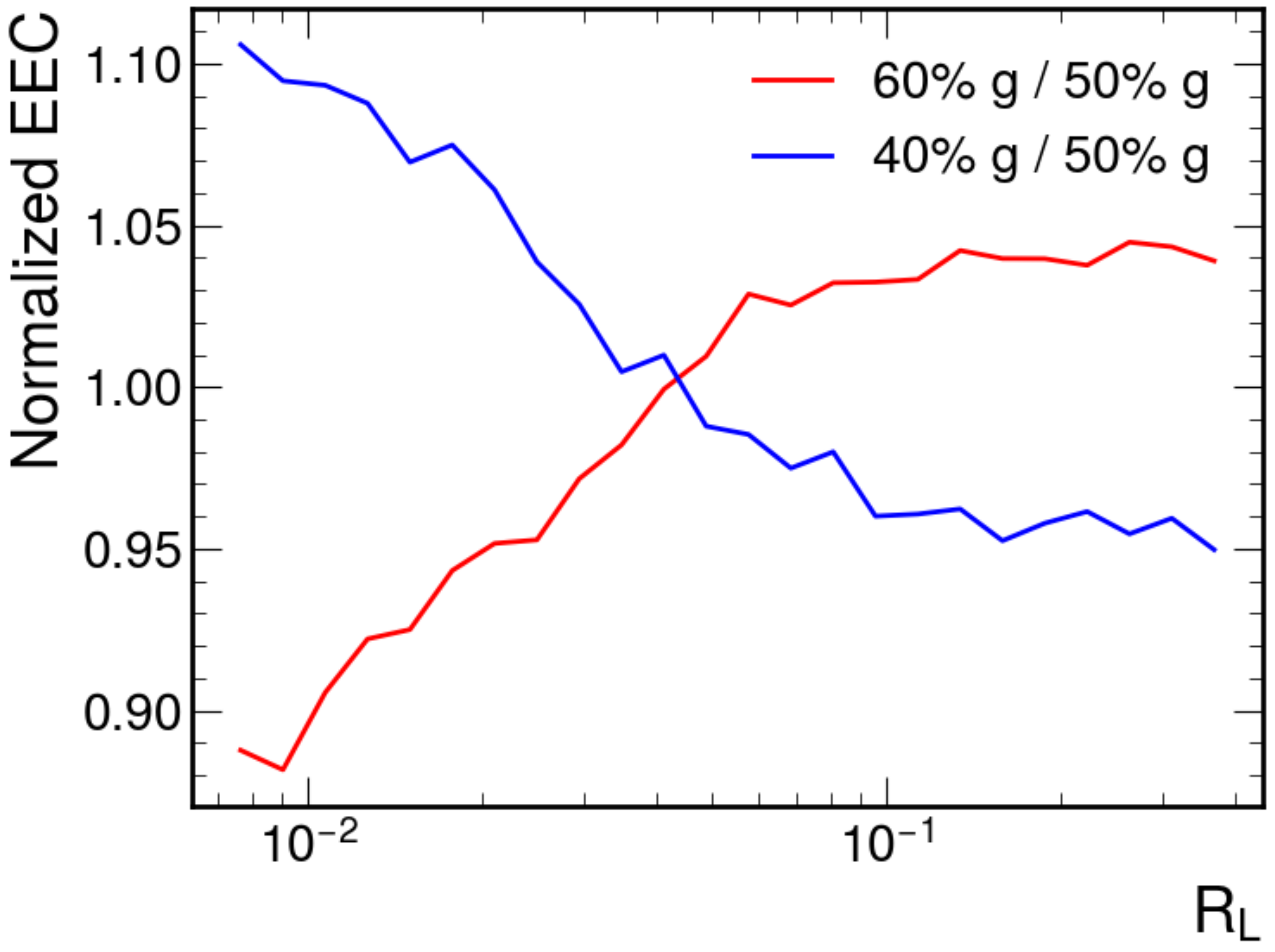
Gluon jet loses more energy during interaction with QGP medium, Therefore, it will reduced the fraction of gluon jet in AA result relative to pp result

The specific amount of the fraction loss is currently under testing.

Fraction of quark and gluon jets

We investigated the impact of the gluon jet fraction on the EEC distribution.



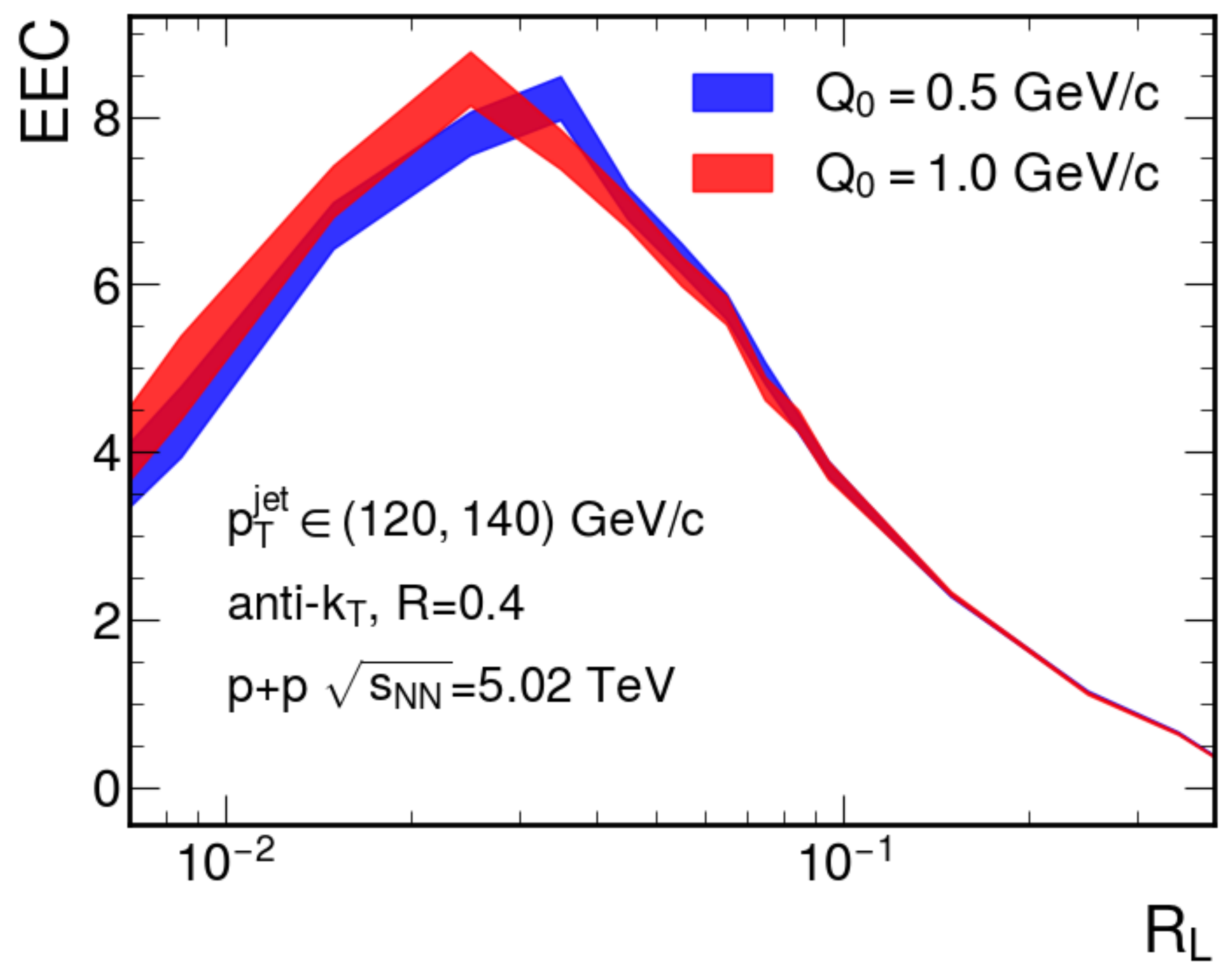


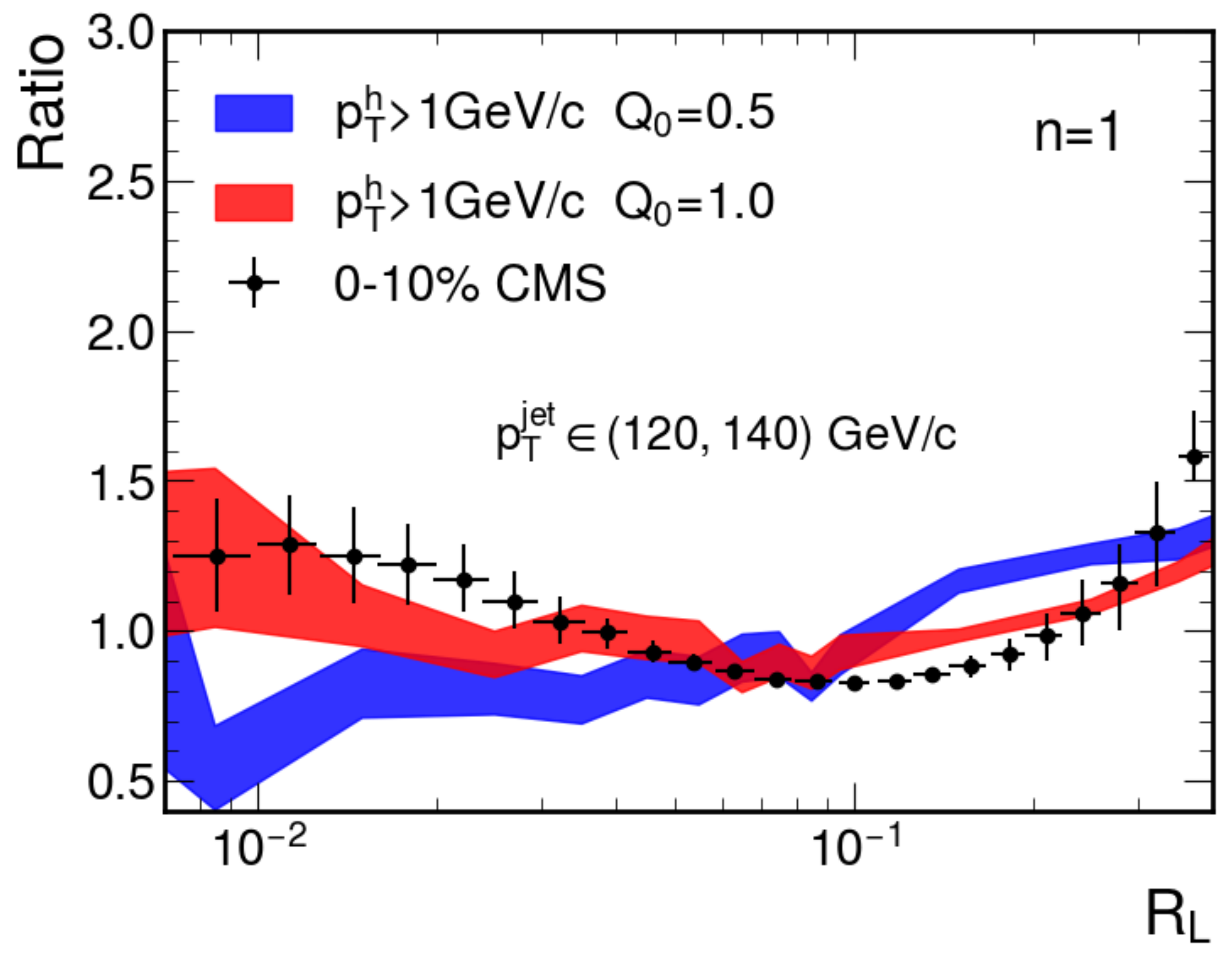
We found that a 10% change in the gluon jet fraction leads to a 10% variation in the EEC distribution at small angles, which is very close to the results reported by CMS.

Effect of hadronization

The small angle (non-perturbative region) —— hadronization

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.

Summary

① EEC is an excellent jet substructure. It exhibits a clear angular separation between the perturbative and non-perturbative regions.

② Jet-medium interaction will modify the EEC inside jets. For gamma-jets, the energy loss and transverse momentum broadening lead to the suppression of EEC at small angle in Pb+Pb collisions compared to pp collisions. While medium response and medium-induced gluon radiation lead to an enhancement at large angle.

③ The medium modification of EEC shows a clear sensitivity to Debye screening mass. The coming experimental result can help constrain this value of models.

④ For single inclusive jet EEC, this is an enhancement at small angle in Pb+Pb collisions relative to pp collisions. Which can be caused by many factors such as initial $p_T^{\rm jet}$ selection bias, gluon jet fraction and some hadronization effects.

Thank You