Probing the Short-Distance of the Quark-Gluon Plasma with Energy Correlators

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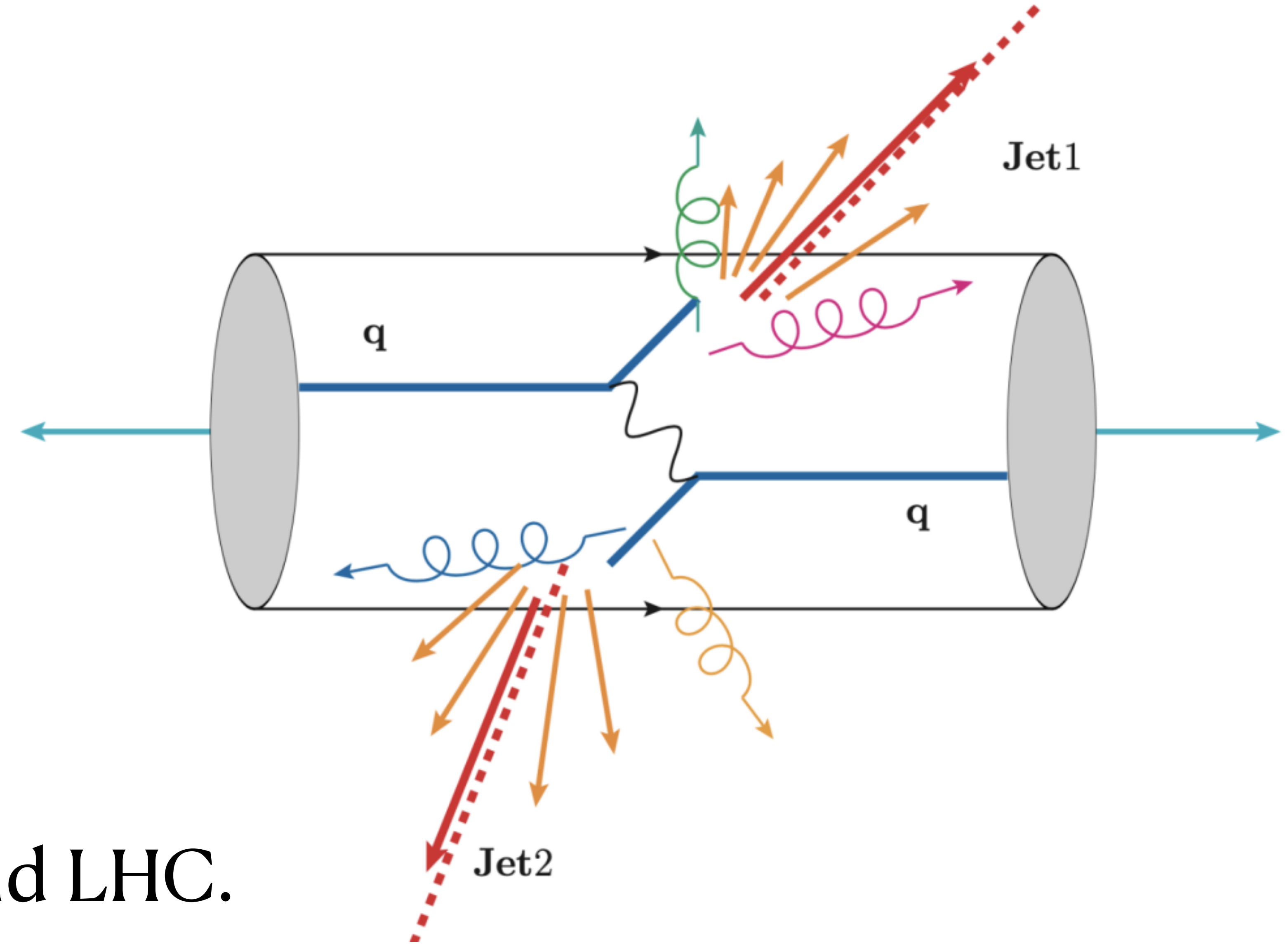
Jet physics

Jets generated in the initial hard scattering are powerful probes of properties of the quark-gluon plasma

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



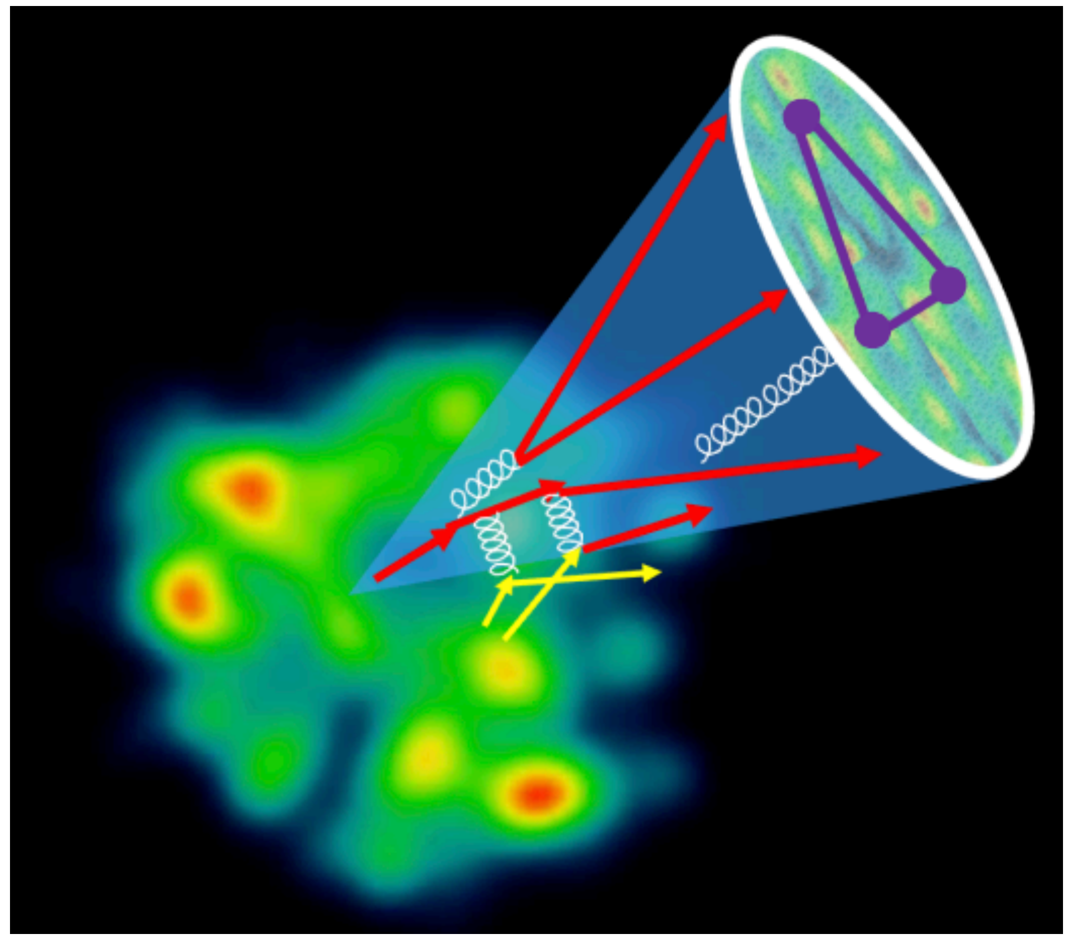
1. The suppression of the jet product cross section on RHIC and LHC.
   (Jet quenching, Jet-induced medium response)

2. The modification of the internal structure of jets, such as jet shape and jet fragmentation function.

3. There are many studies of jet substructure observables. They are analyzed in the hope of revealing the space-time structure of medium-induced splittings.

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.



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

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

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

The n-th weighted normalized two-point correlation:

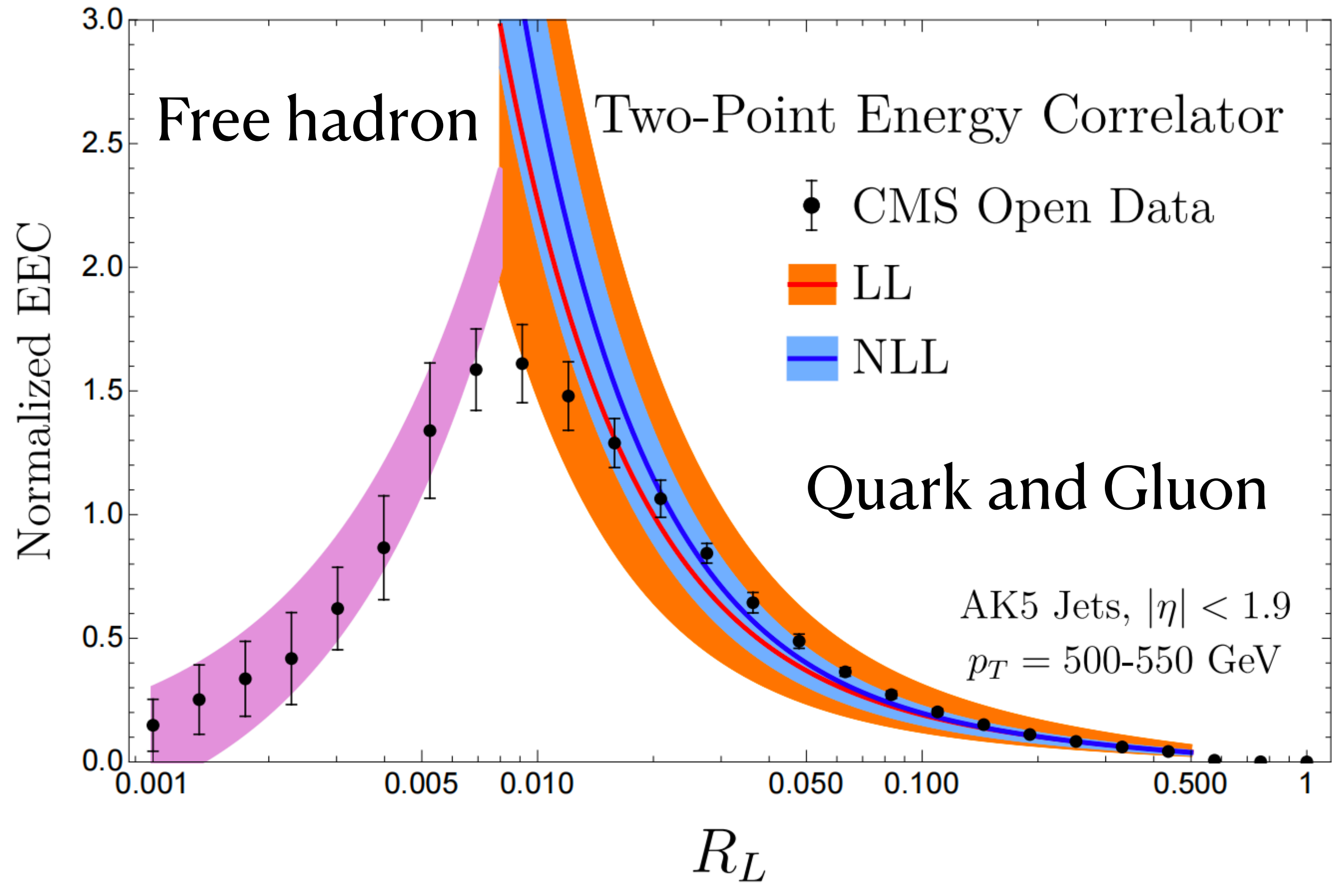
$$\frac{\langle \varepsilon^{(n)}(\overrightarrow{n_1})\varepsilon^{(n)}(\overrightarrow{n_2})\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\frac{d\sigma_{ij}}{d\overrightarrow{n_i}d\overrightarrow{n_j}}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\overrightarrow{n_i} - \overrightarrow{n_1})\delta^{(2)}(\overrightarrow{n_j}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

$$n = 1$$

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

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

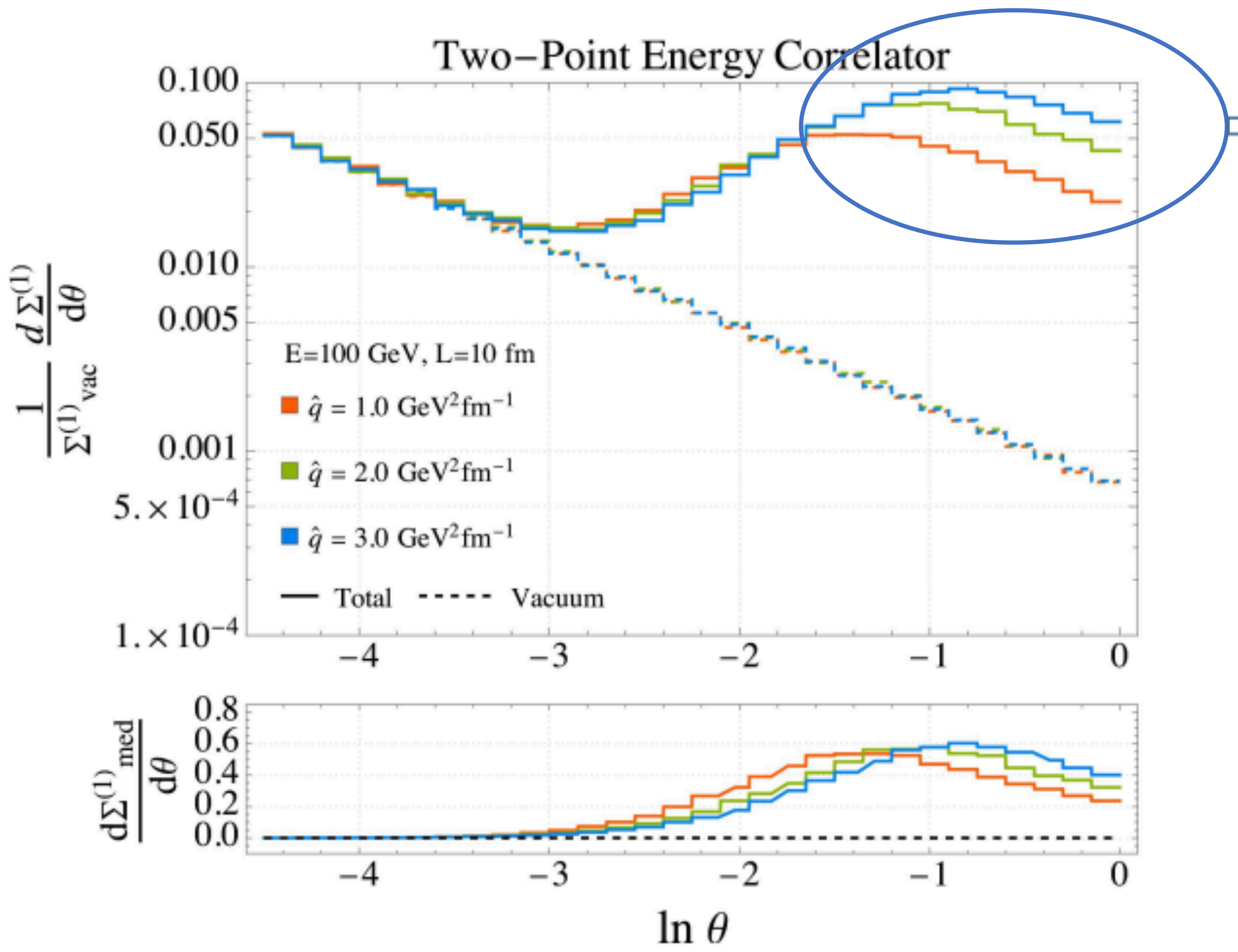
Previous studies of EECs



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 modification leads to significant enhancement of EEC at large angle.

Static medium
No Jet energy loss
No Jet-indcued medium response

Carlota A, et al. *Phys.Rev.Lett.* 130 (2023) 26, 262301
Patrick V, *et al. Phys.Rev.Lett.* 130 (2023) 5, 051901
Carlota A, et al. arXiv:2307.15110

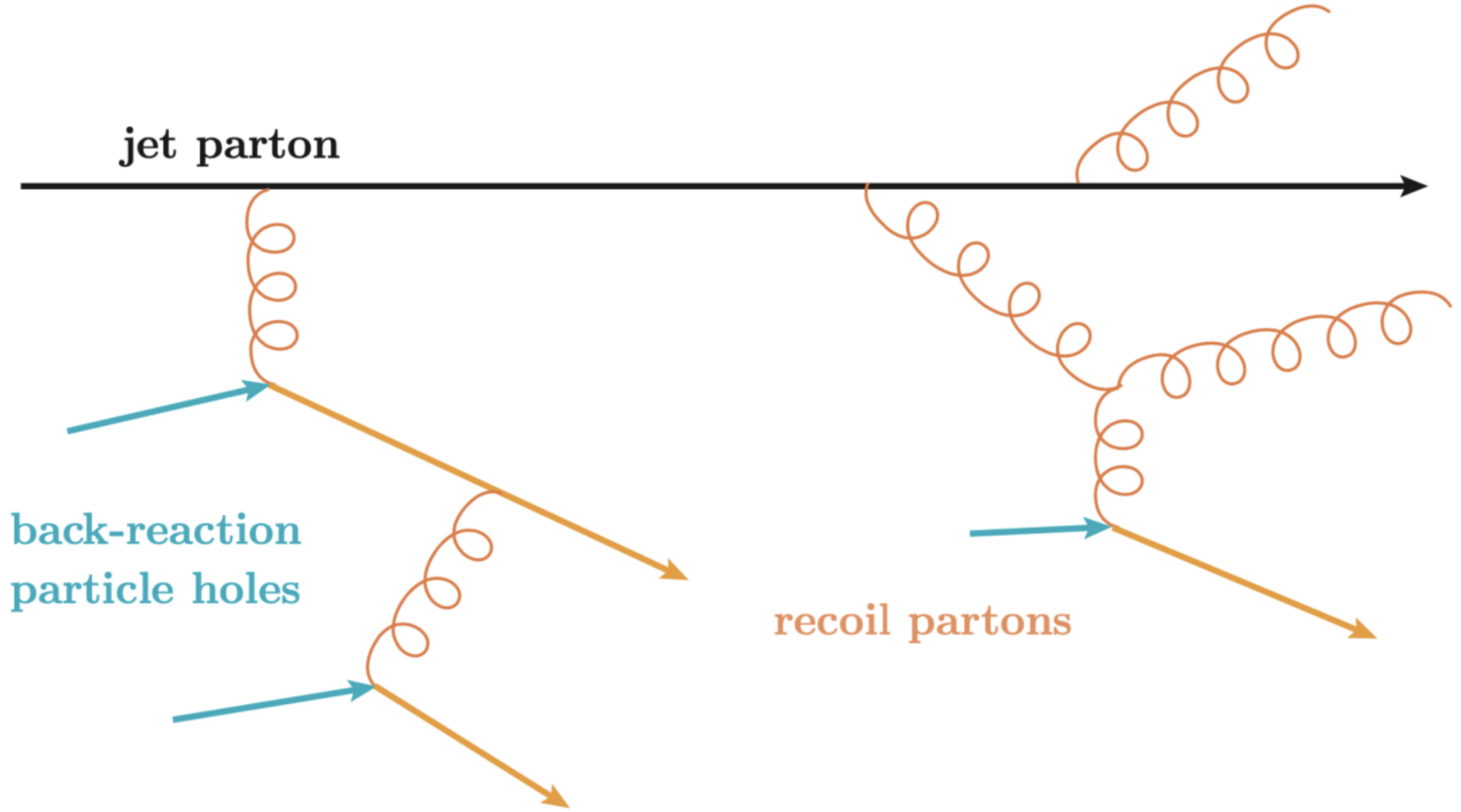
Linear Boltzmann Transport model

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

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(Back reaction induced by energy-momentum conservation)

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:

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

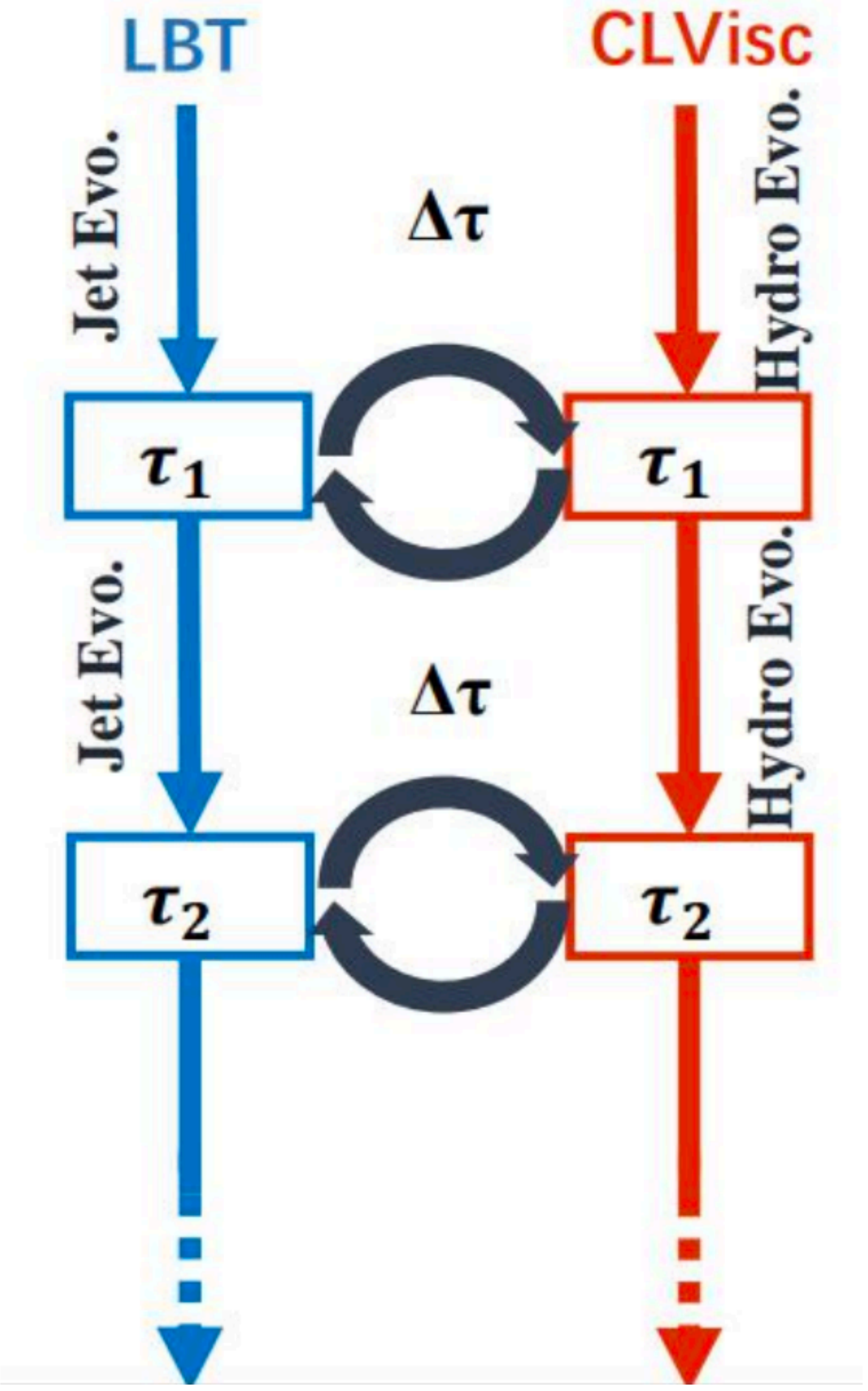
4. Updating medium information by solving the hydrodynamics equation with source term

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

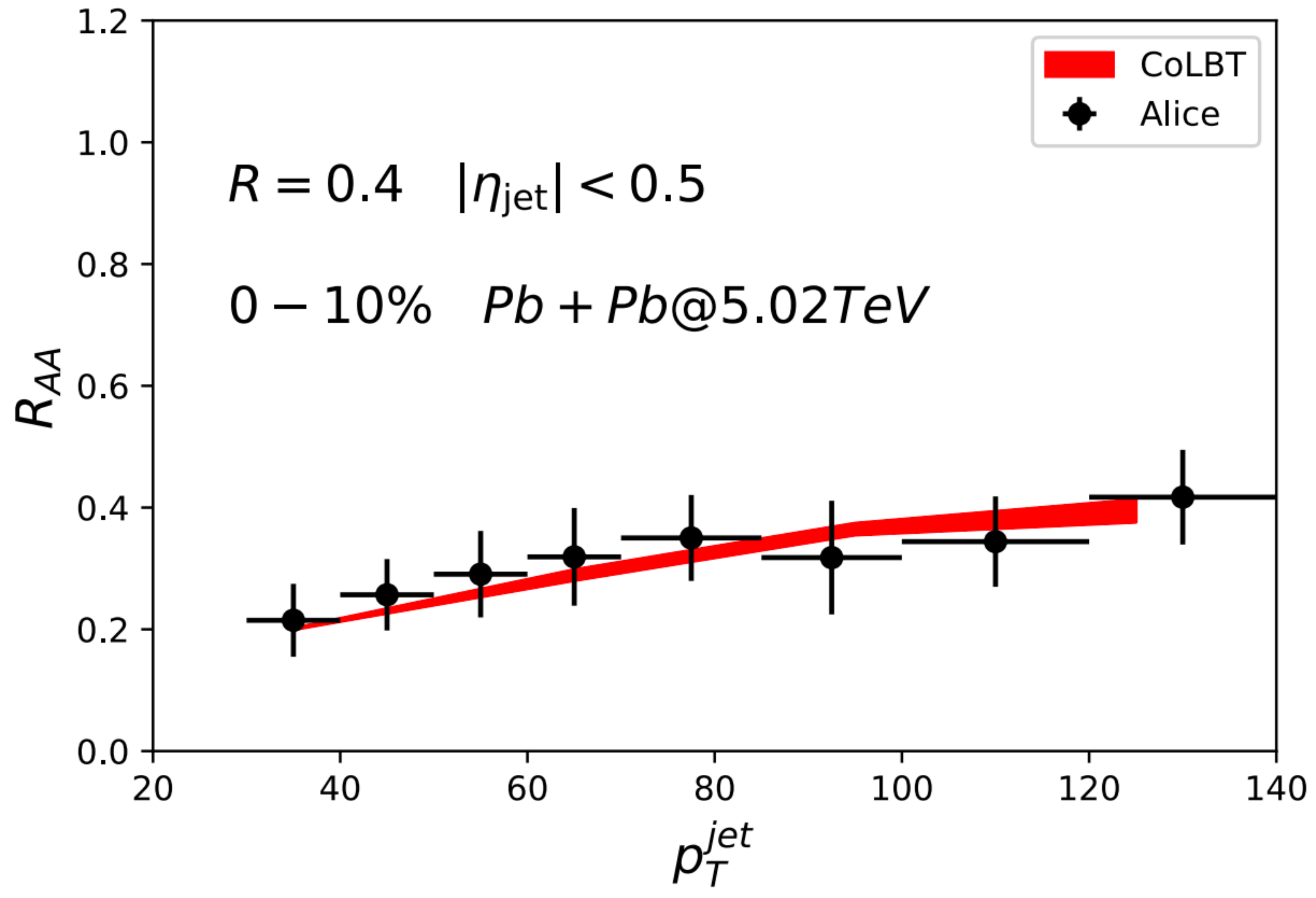
5. The final hadron spectra:

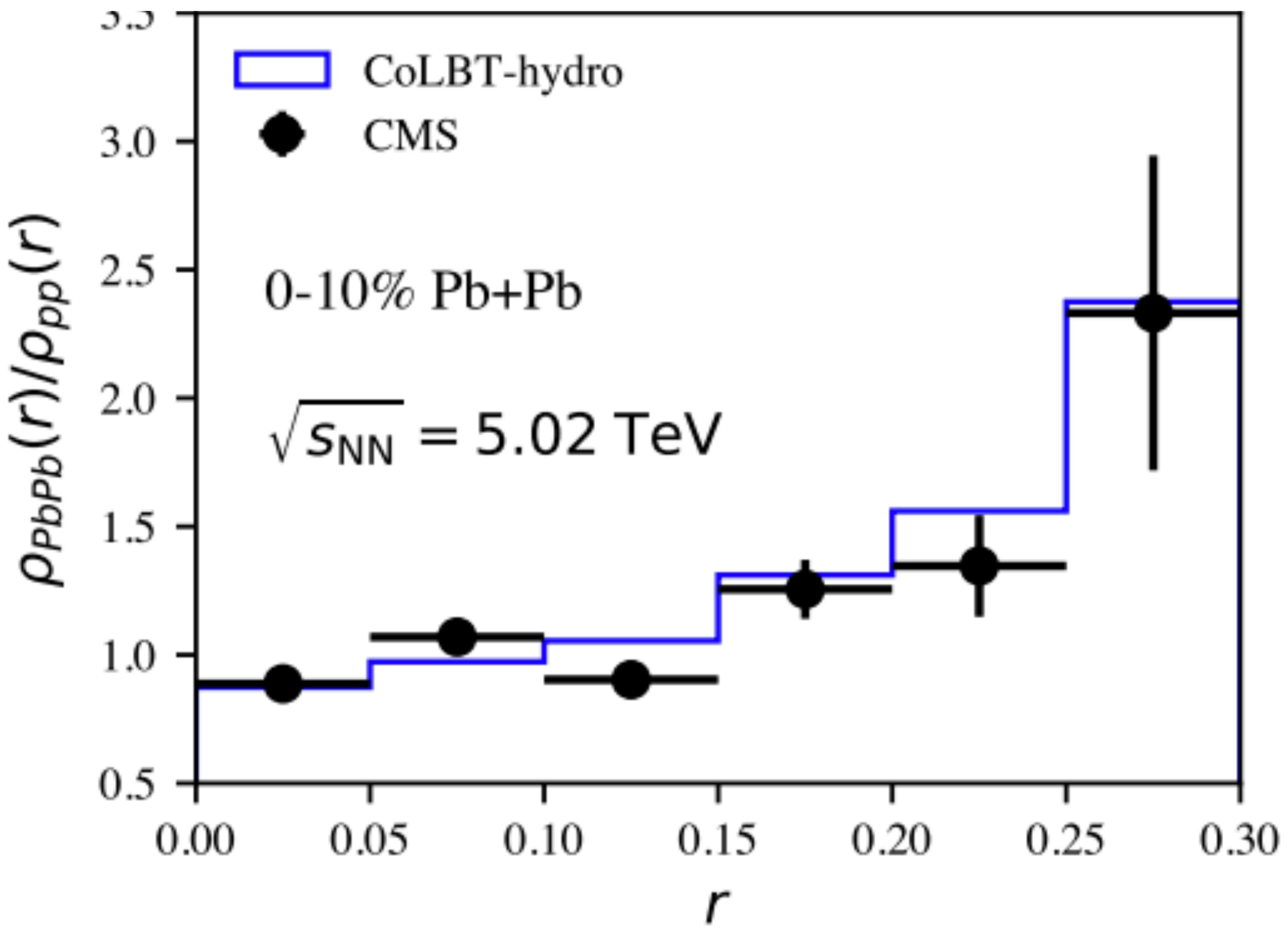
   (1) hadronization of hard partons within a parton recombination model

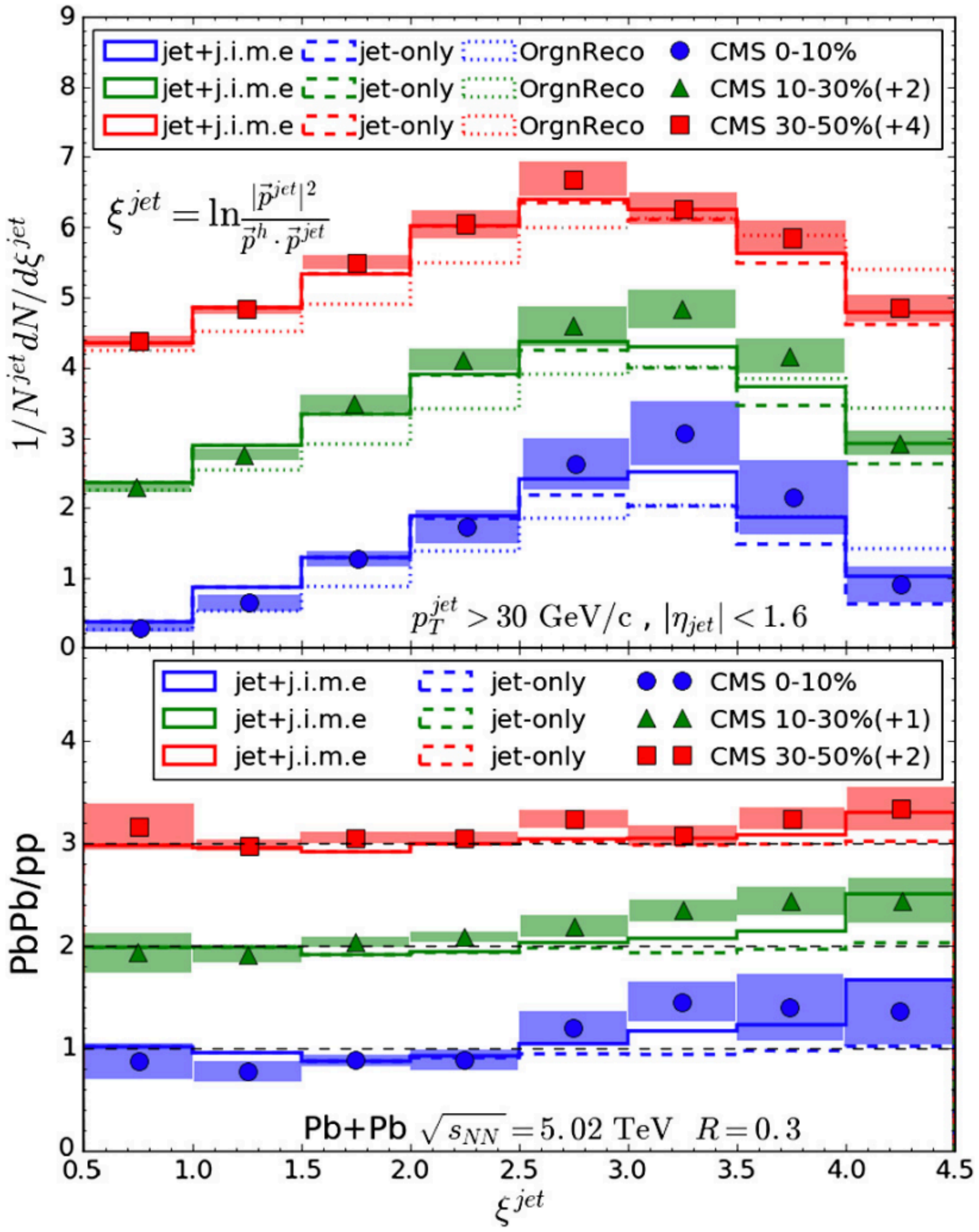
   (2) jet-induced hydro response via Cooper-Frye freeze-out



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 first complete calculations of EECs using realistic simulations of high-energy heavy-ion collisions within LBT and CoLBT model

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

EECs in vacuum and medium-induced emissions

We focus on the normalized two-point energy correlates

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

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

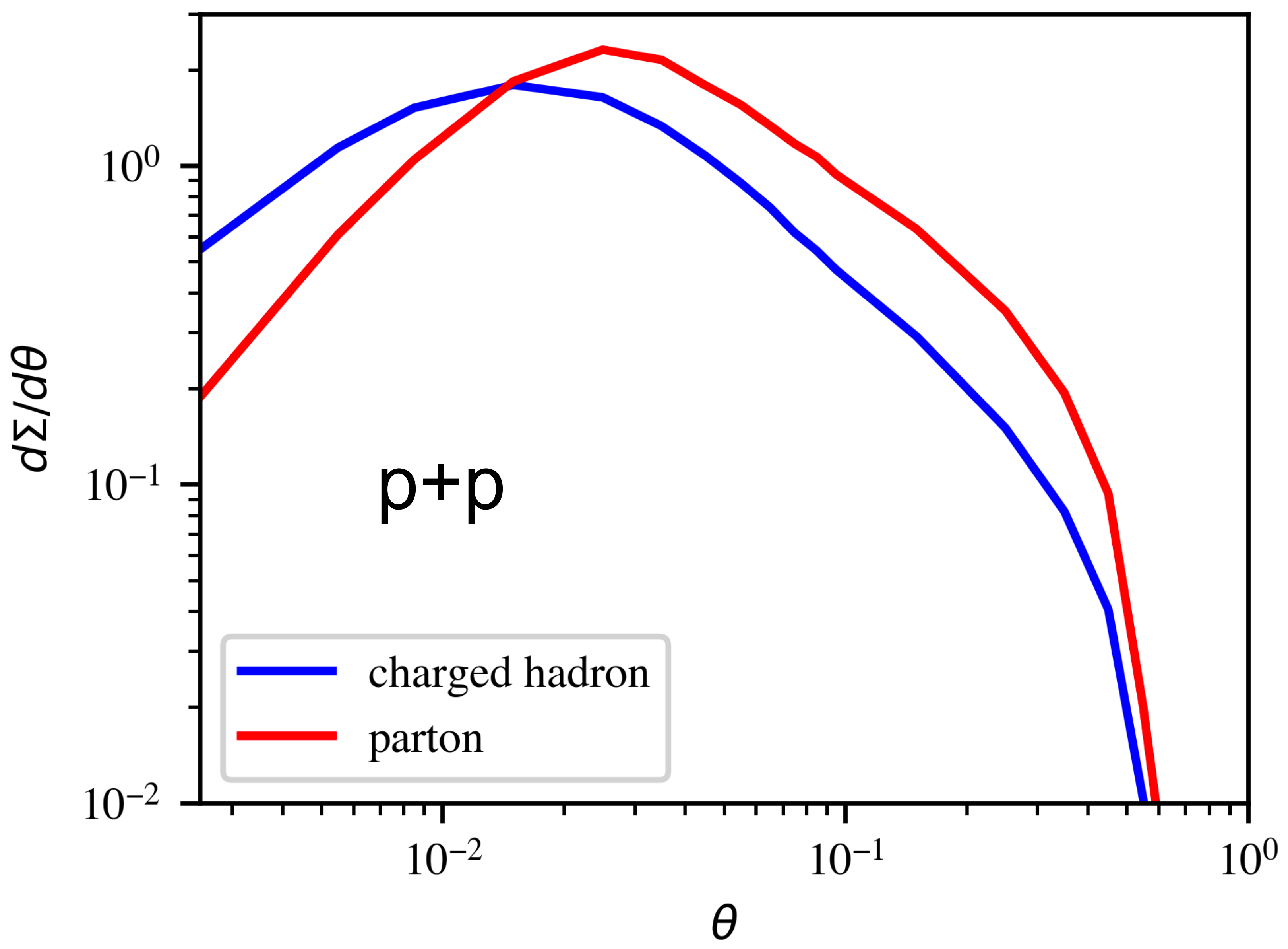
$$P_{qg}(z) = \frac{1+(1-z)^2}{z}$$ Splitting function

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

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

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

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



EECs in vacuum and medium-induced emissions

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

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

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

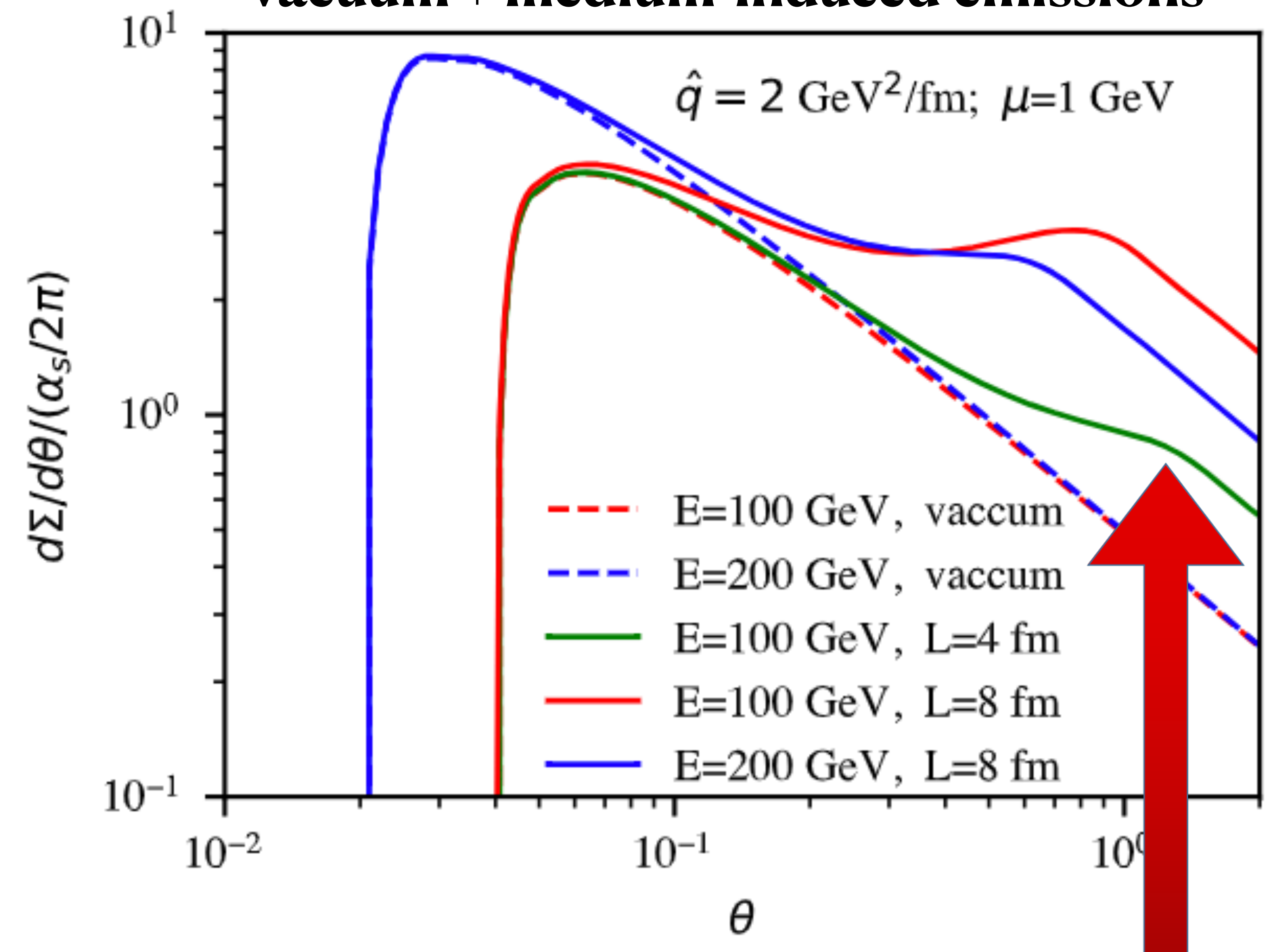
The corresponding angular contribution to EEC is,

$$\frac{d\Sigma_q^{\rm med}}{d\theta} = \frac{16\alpha_{\rm s}C_A}{\pi E^2\theta^3}\int dx dz \frac{\hat{q}P_{qg}(z)}{z(1-z)}\sin^2\left(\frac{x}{2\tau_f}\right)$$
$$= \frac{L^{5/2}\hat{q}}{\pi\sqrt{E}}\frac{8\alpha_{\rm s}C_A}{(\sqrt{EL}\theta)^3}\int dz \frac{P_{qg}(z)}{z(1-z)} \times \left[1 - \frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]$$

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

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

vacuum + medium-induced emissions



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

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

Medium response and jet energy loss

EECs from a quark going through the QGP brick

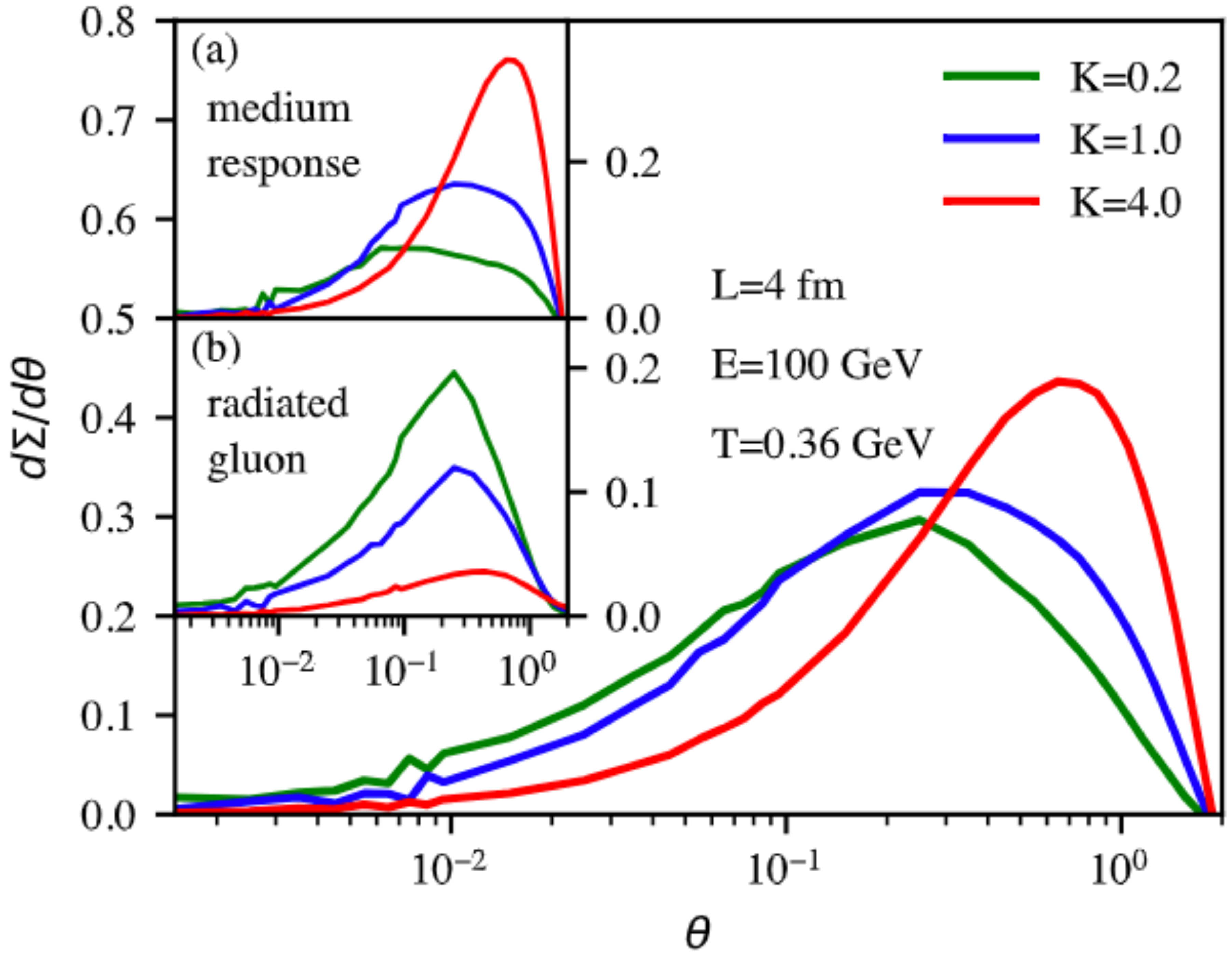
Interaction with QGP → Parton energy loss → **Modified EEC**

Interaction with QGP → Medium response (recoil and negative) → **Modified EEC**

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.



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.

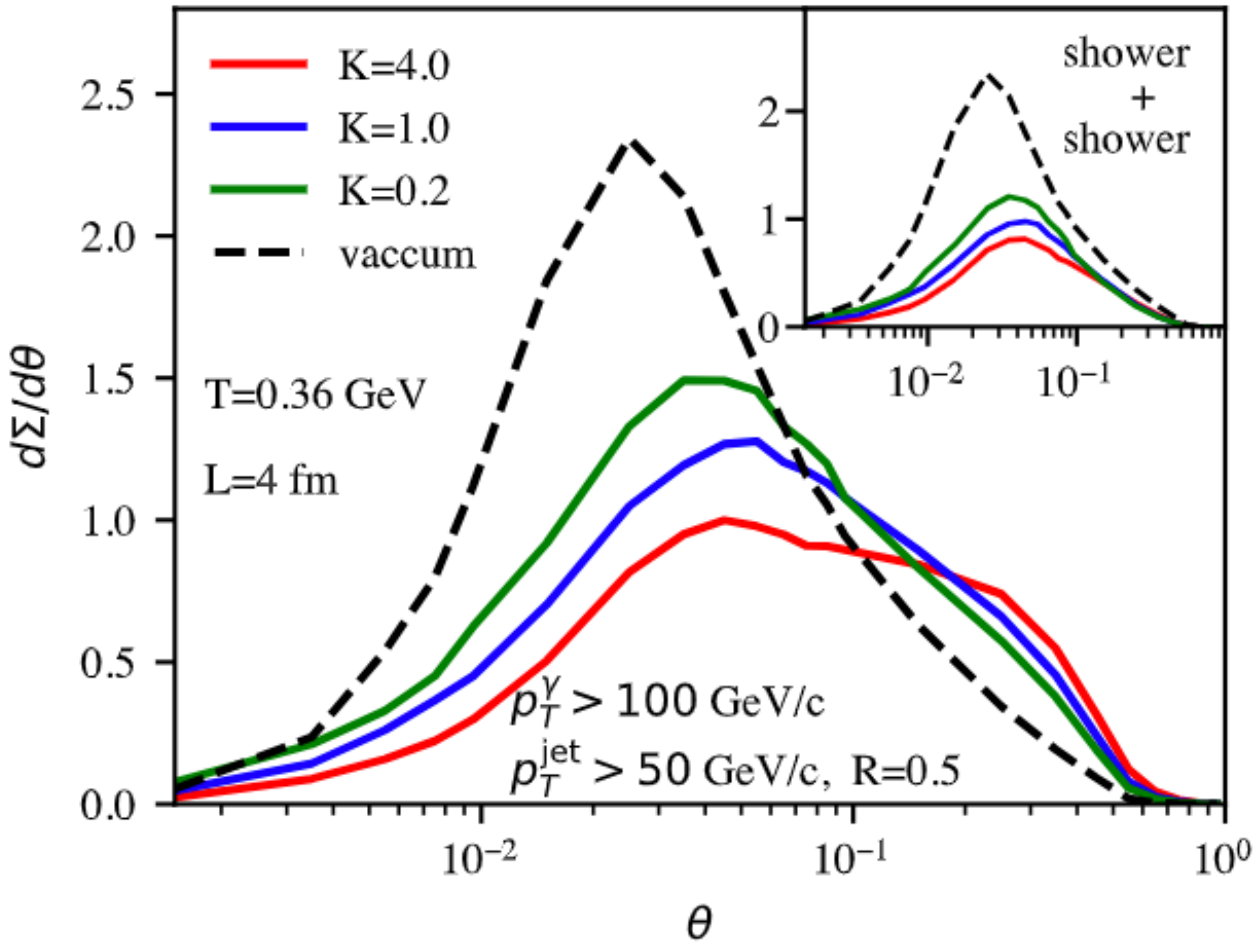
Medium response and jet energy loss

EECs from a parton shower going through the QGP brick

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

Jet $\longrightarrow$ Parton showers $\longrightarrow$ 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.

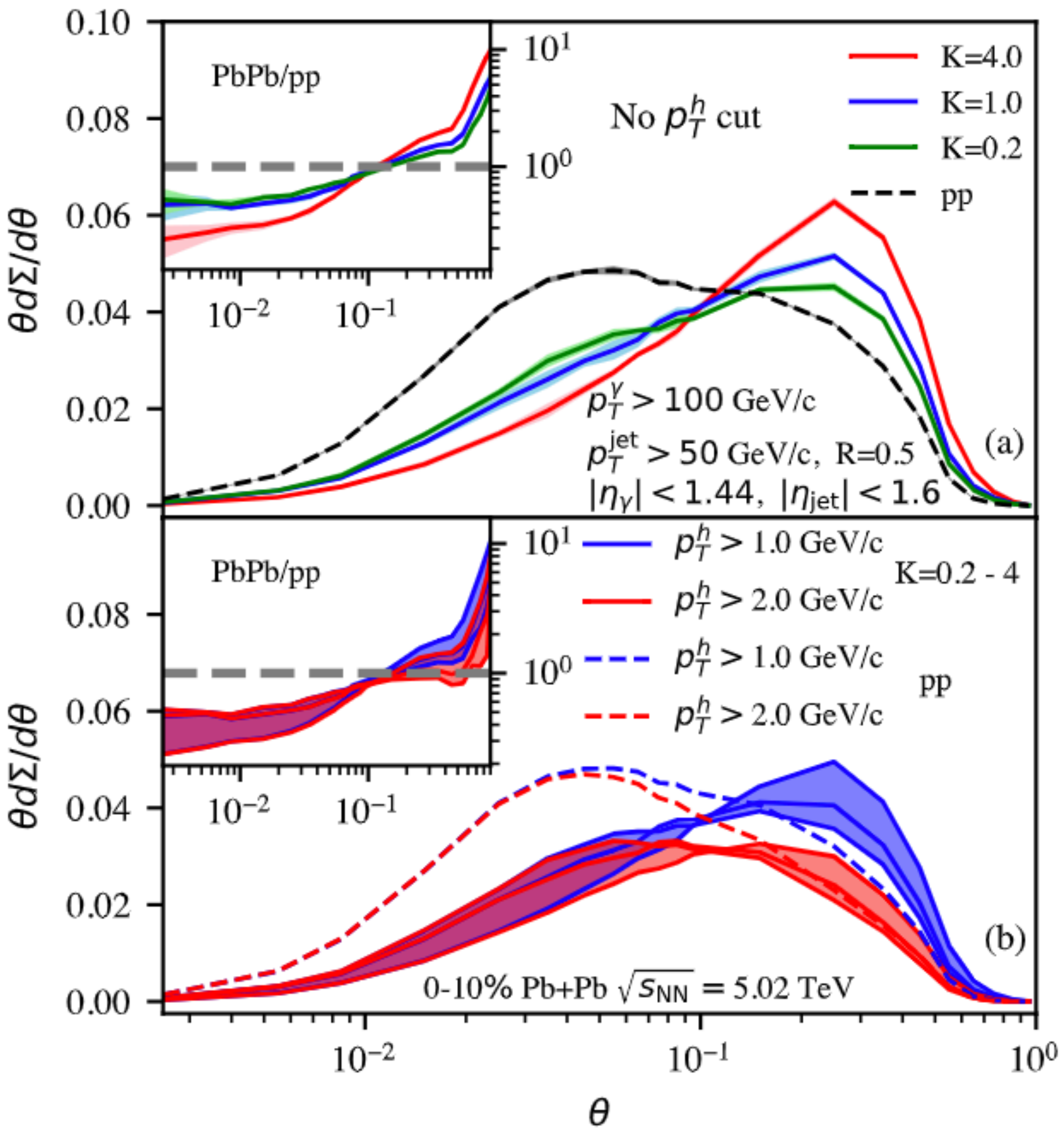
Medium response and jet energy loss

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, while they are enhanced at large angles.

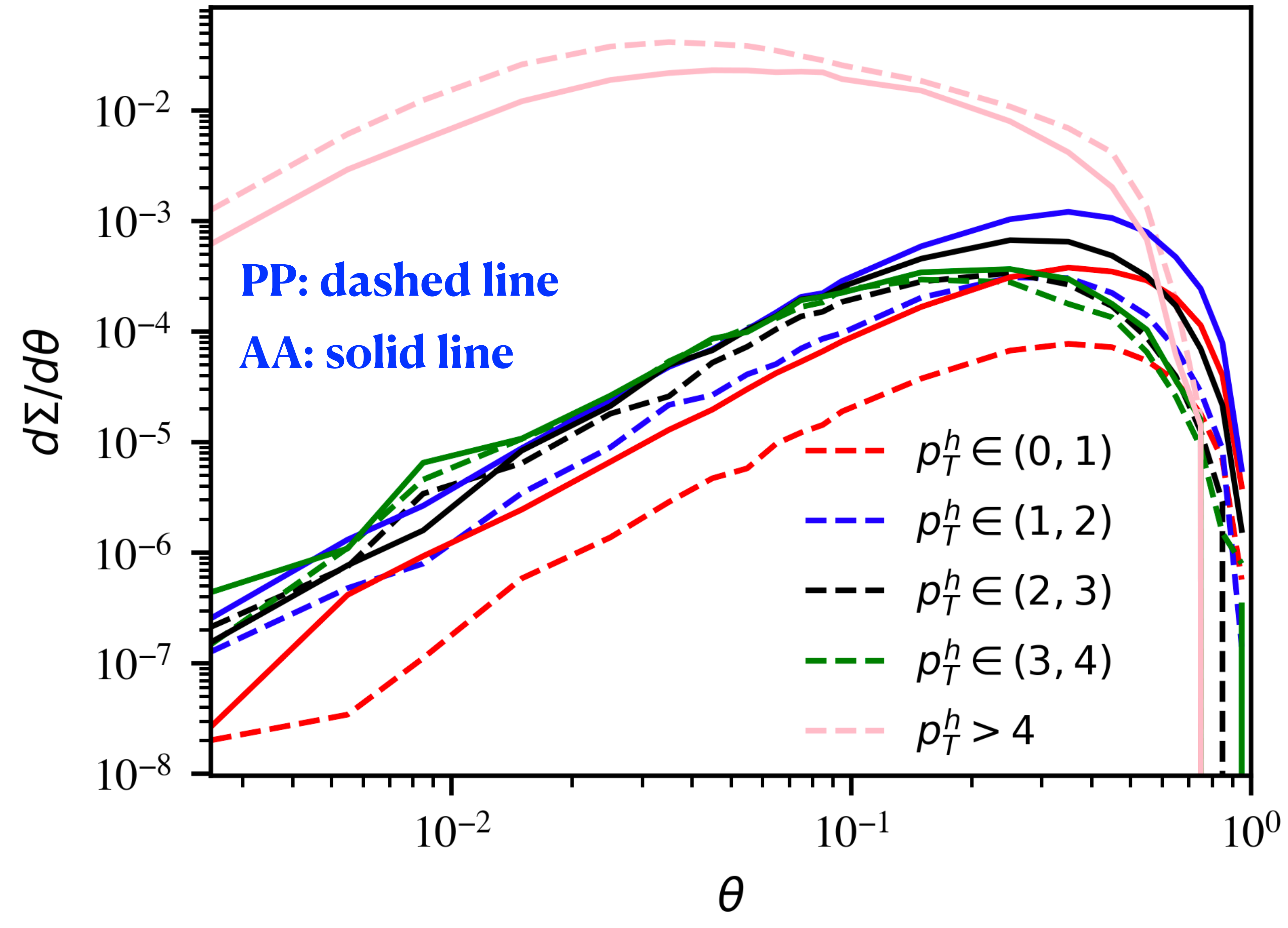
2. This modification is sensitive to the Debye mass, μ_D, which determines the angular scales of each jet-medium scattering and charaterizes the structure of the QGP medium in the CoLBT simulations.

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 $K = 4$.



Medium response and jet energy loss

EEC 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.

Summary

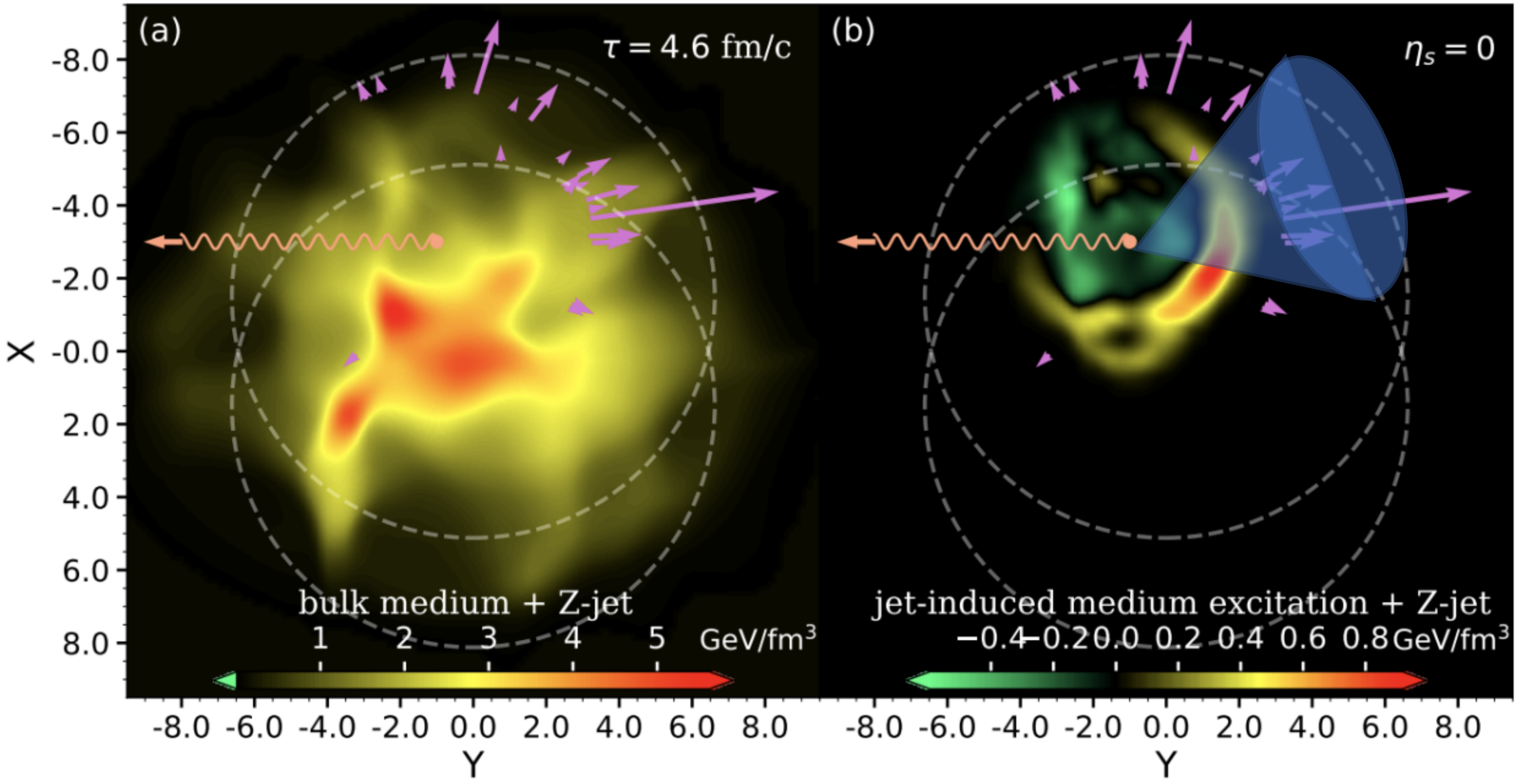
1. EEC is an excellent jet substructure. It exhibits a clear angular separation between the non-perturbative and perturbative regions.

2. Jet-medium interaction will modify the EEC inside jets. The energy loss and transverse momentum broadening lead to the suppression of EEC at small angle in Pb+Pb collisions as compared to the vacuum case. 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.

Back up

CoLBT-hydro model



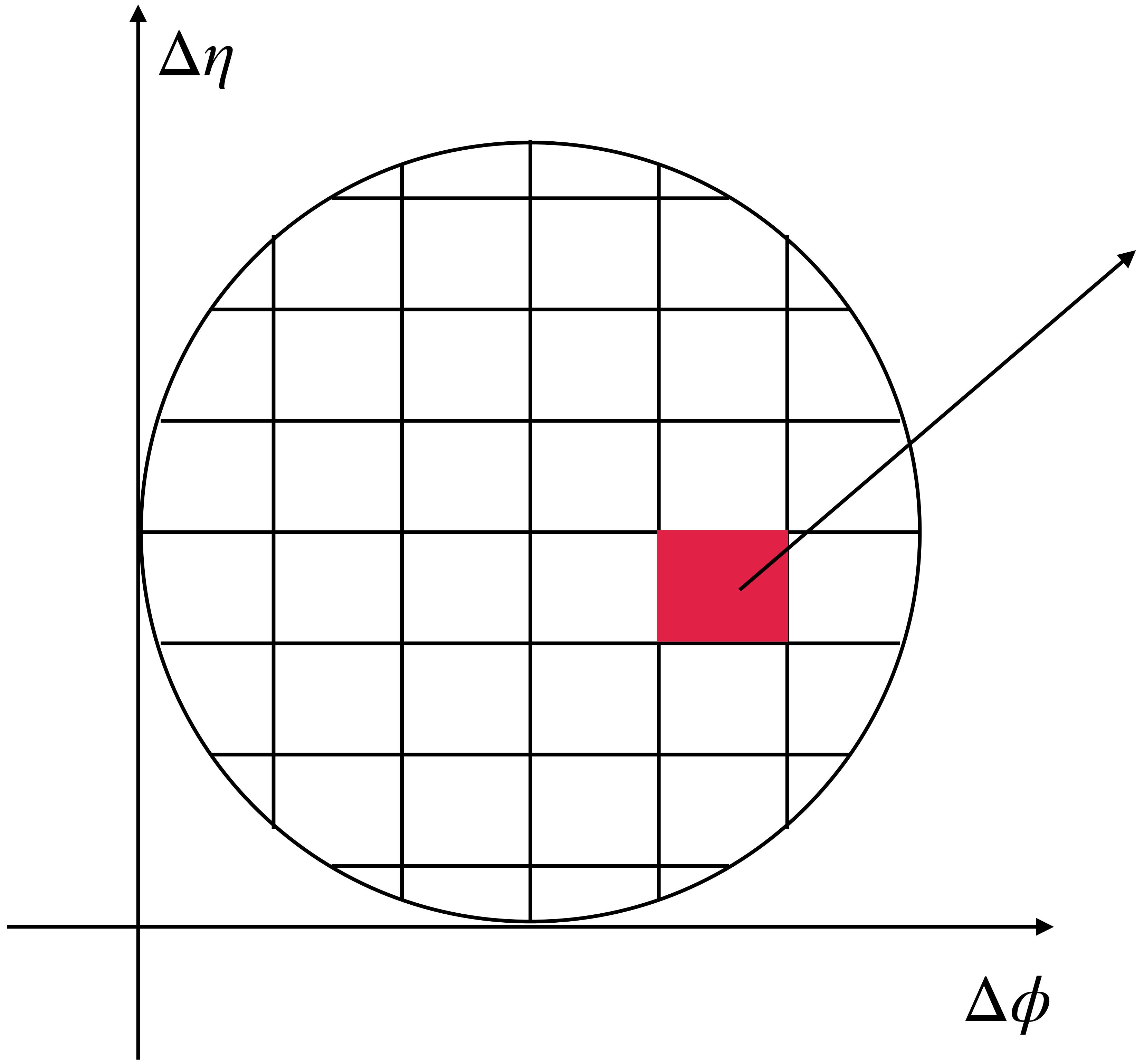
Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

We run model twice with and without jet to subtract hydro background

The Mach-cone-like jet-induced medium response including the diffusion wake is clearly seen in the right panel.

Medium response and jet energy loss

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**

Vacuum splitting

$$
\begin{aligned}
\Sigma_g^{(1)}(\theta^2, E, \mu) &= \frac{\alpha_s}{2\pi}\int_0^1 dx E^2 x(1-x) P_{gg}(x) \int_{\mu^2}^{Q^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2}\delta(\theta^2 - \frac{\mathbf{k}_\perp^2}{[x(1-x)E]^2}) \\
&+ \frac{\alpha_s}{2\pi} N_f \int_0^1 dx E^2 x(1-x) P_{gq}(x) \int_{\mu^2}^{Q^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2}\delta(\theta^2 - \frac{\mathbf{k}_\perp^2}{[x(1-x)E]^2}) \\
&= E^2 \frac{\alpha_s}{2\pi}\frac{C_A}{\theta^2}\int_0^1 dx [1 + x^4 + (1-x)^4]\Theta(\mu^2 < x(1-x)\theta^2 E^2 < Q^2) \\
&+ E^2 \frac{\alpha_s}{2\pi}\frac{N_f T_R}{\theta^2}\int_0^1 dx x(1-x)[x^2 + (1-x)^2]\Theta(\mu^2 < x(1-x)\theta^2 E^2 < Q^2 \\
\xrightarrow{\mu^2/E^2 \ll \theta^2 \ll Q^2/E^2} &\quad E^2 \frac{\alpha_s}{2\pi}\left(\frac{7C_A}{5} + \frac{N_f T_R}{10}\right)\frac{1}{\theta^2}
\end{aligned}
$$

High-twist

$$
\begin{aligned}
&\left[\int_0^\delta dz + \int_{1-\delta}^1 dz\right] \frac{8\alpha_s C_A L^- \hat{q}_a(x) P_a(z)}{\pi z(1-z) q^{+2}\theta_{12}^3} \frac{1}{6}[L^- q^+ z(1-z)\theta_{12}^2/8]^2 \\
&= \frac{\alpha_s C_A L^{-3}\hat{q}_a(x)}{6\times 8\pi}\theta_{12}\left[\int_0^\delta dz + \int_{1-\delta}^1 dz\right] z(1-z)P_a(z) \\
&= \frac{\alpha_s C_A L^{-3}\hat{q}_a(x)}{6\times 8\pi}\theta_{12}\left[(2\delta - 2\delta^2 + \delta^3 - \delta^4/4) + \delta^2/2 + \delta^4/4\right] \\
&= \frac{\alpha_s C_A L^{-3}\hat{q}_a(x)}{6\times 8\pi}\theta_{12}\left[2\delta - \frac{3}{2}\delta^2 + \delta^3\right] \approx \frac{\alpha_s C_A L^{-2}\hat{q}_a(x)}{6\pi q^+\theta_{12}}\pi\left[1 - \frac{3\pi}{L^- q^+\theta_{12}^2} + \frac{8\pi^2}{(L^- q^+)^2\theta_{12}^4}\right]
\end{aligned}
$$

where

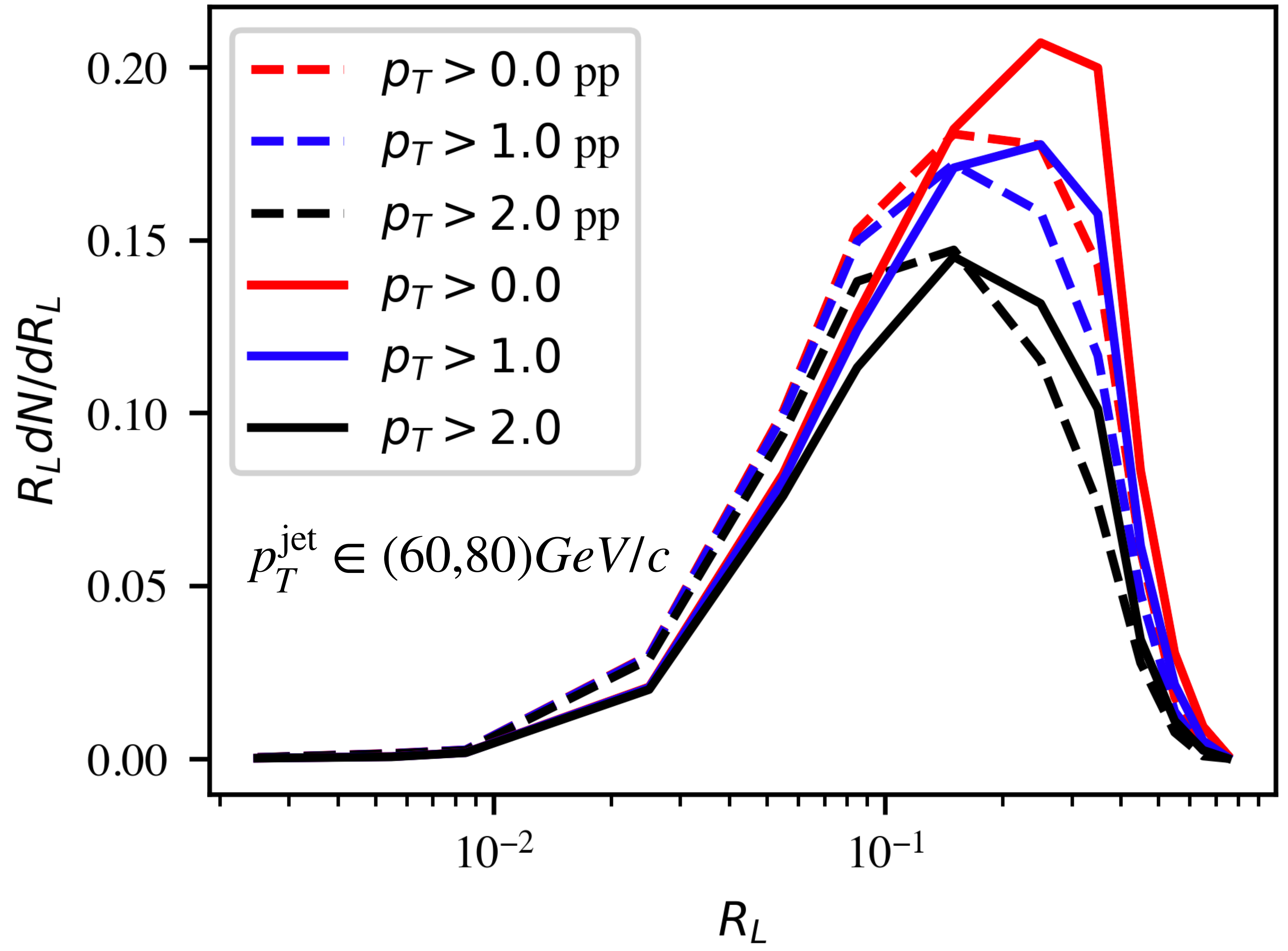
$$
\delta = \frac{1}{2}(1 - \sqrt{1 - 4\epsilon(\theta_{12})}) \approx \epsilon(\theta_{12}) = \frac{4\pi}{L^- q^+\theta_{12}^2}, \quad (L^- q^+\theta_{12}^2 > 8\pi)
$$

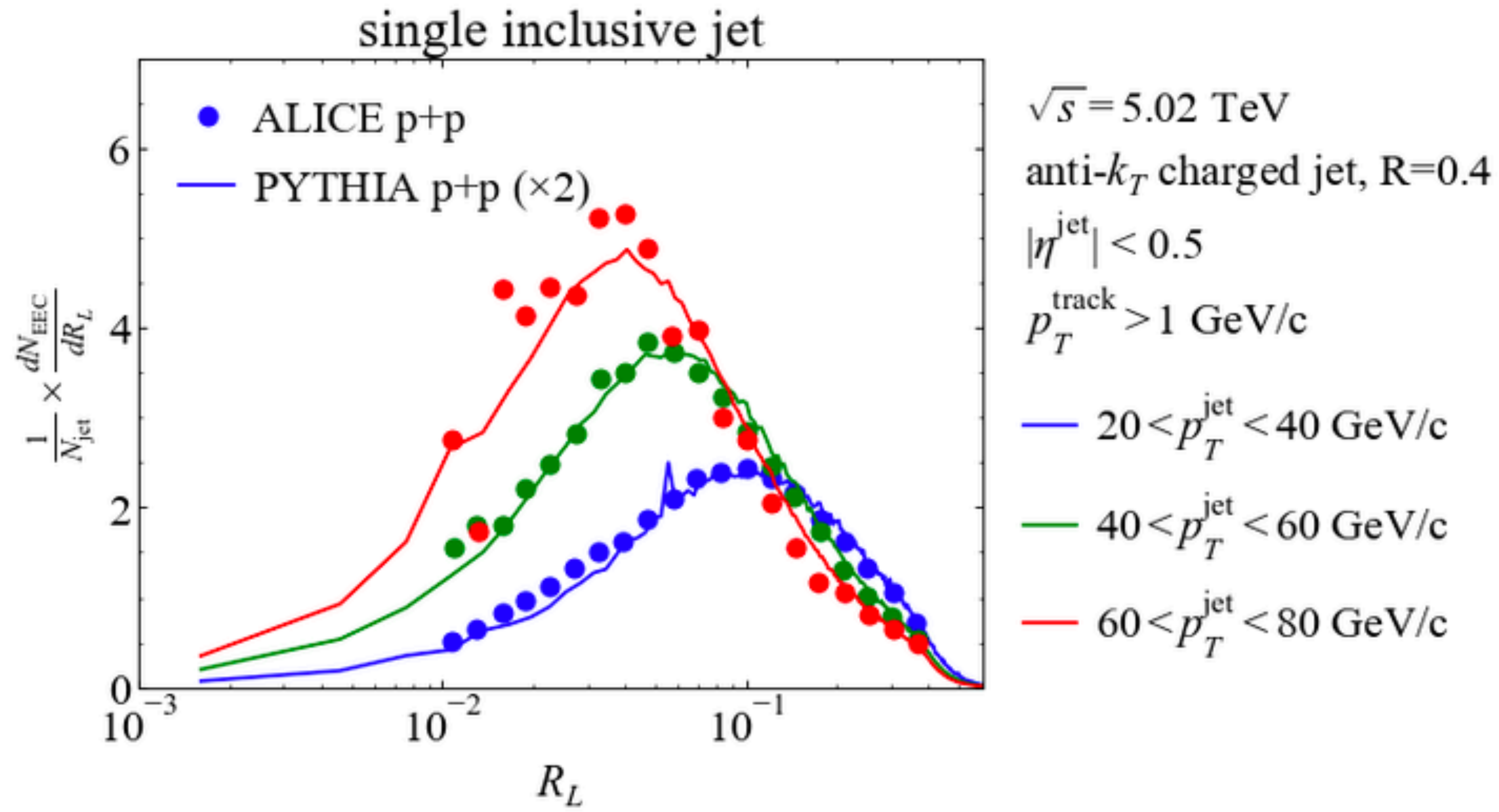
For $L^- q^+ z(1-z)\theta_{12}^2/8 > \pi/2$, or $z(1-z) > 4\pi/L^- q^+\theta_{12}^2$ and $L^- q^+\theta_{12}^2 > 8\pi$,

$$
\begin{aligned}
&\int_\delta^{1-\delta} dz \frac{8\alpha_s C_A L^- \hat{q}_a(x) P_a(z)}{\pi z(1-z) q^{+2}\theta_{12}^3} = \frac{8\alpha_s C_A L^- \hat{q}_a(x)}{\pi q^{+2}\theta_{12}^3}\left[\frac{2}{\delta} - \frac{2}{1-\delta} + \ln\frac{1-\delta}{\delta}\right] \\
&= \frac{8\alpha_s C_A L^{-2}\hat{q}_a(x)}{\pi q^+\theta_{12}}\frac{1}{2\pi}\left[1 - \frac{\delta}{1-\delta} + \frac{\delta}{2}\ln\frac{1-\delta}{\delta}\right] \\
&= \frac{8\alpha_s C_A L^{-2}\hat{q}_a(x)}{\pi q^+\theta_{12}}\frac{1}{2\pi}\left[1 - \frac{4\pi}{L^- q^+\theta_{12}^2} - \frac{3\times 8\pi^2}{(L^- q^+)^2\theta_{12}^4} + \frac{2\pi}{L^- q^+\theta_{12}^2}\ln\frac{L^- q^+\theta_{12}^2}{4\pi}\right]
\end{aligned}
$$

Medium response and jet energy loss

EEC of single inclusive jets in Heavy-Ion Collisions.





The Pythia simulations can well reproduce ALICE measurements in pp collisions.
EEC in single inclusive jets has the similar behavior in γ-jets.