

# Probing the Short-Distance Structure of the Quark-Gluon Plasma through Energy-energy Correlators

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**Abstract.** Energy-energy correlators (EECs) are promising observables for probing the dynamics of jet evolution in the quark-gluon plasma (QGP). By studying jet propagation in a uniform QGP medium, we isolate and examine the individual effects of jet energy loss, jet-induced medium response, and medium-induced gluon radiation on the EECs. We find that the enhancement of EECs at large angles arises predominantly from medium response via elastic scatterings, rather than from medium-induced gluon radiation. In contrast, EECs are suppressed at small angles due to energy loss and transverse momentum broadening of the jet shower partons. We further present the first complete calculation of EECs in high-energy heavy-ion collisions using realistic simulations. These medium-induced modifications are shown to be sensitive to the angular scale of in-medium interactions, as characterized by the Debye screening mass. Experimental measurements of such modifications can thus provide insight into this scale and reveal the short-distance structure of the QGP.

## 1 Introduction

In high-energy heavy-ion collisions, jets generated in the initial hard scattering are powerful probes of properties of the Quark-Gluon Plasma (QGP). Jet physics has undergone rapid development over the past few decades, with a broad range of measurements carried out at both the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). The interaction between jets and the QGP medium leads to a suppression of the jet production cross section, providing strong evidence for the formation of the QGP in high-energy heavy-ion collisions. The energy lost by jets excites the medium—a phenomenon known as the jet-induced medium response—which in turn modifies the internal jet structure [1], such as the jet shape and fragmentation functions, offering valuable insights into the properties of the QGP.

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Energy–energy correlators (EECs) [2] within jets have emerged as powerful observables for probing jet substructure and accessing the space-time evolution of parton showers. They are constructed from the inclusive cross section for producing two final-state hadrons, weighted by their respective energies. In vacuum, the angular distribution of the EEC exhibits distinct features: at large angles within the jet, it follows a power-law behavior that can be described by perturbative QCD (pQCD). As the angle decreases, the EEC enters a transition region associated with the confinement of quarks and gluons into free hadrons. Recent studies have shown that medium-induced emissions can significantly enhance the EEC at large angles. However, these works often neglect the contributions from jet quenching and the jet-induced medium response, which may play an important role in shaping the final EEC distribution. In this work, we aim to provide a more complete description by calculating the EEC of  $\gamma$ -jets in high-energy heavy-ion collisions using both the linear Boltzmann transport (LBT) and the CoLBT-hydro model [3].

## 2 The LBT and CoLBT-hydro model

The Linear Boltzmann Transport (LBT) [4] model is based on the Boltzmann equation to simulate the transport of parton shower in QGP medium.

$$p_1 \partial f_1 = - \int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |\mathcal{M}_{12 \rightarrow 34}|^2 (2\pi)^4 \delta^4 \left( \sum_i p^i \right) + \text{inelastic} \quad (1)$$

where  $f_i (i = 1, 3)$  are the phase-space density before and after scattering.  $f_i (i = 2, 4)$  are the thermal parton phase-space distribution in the QGP. The elastic scattering amplitude  $|\mathcal{M}_{12 \rightarrow 34}|^2$  are taken from leading-order pQCD calculations for all possible scattering channels. The inelastic scattering is modeled by High-Twist approach. In the LBT model, a jet parton can interact with the QGP medium by scattering off a thermal parton, effectively “kicking” it out of the medium. This kicked thermal parton is referred to as a recoil parton, while the corresponding hole left in the thermal distribution is treated as a negative parton. To ensure energy–momentum conservation, the information of the negative parton is also recorded. The medium response in the LBT thus consists of both recoil and negative partons. Additionally, the jet parton can radiate gluons during this interaction. Both the recoil and radiated partons are allowed to undergo further interactions with the medium, similar to the jet parton itself. However, interactions among the jet, recoil, and radiated partons are neglected, which is why the model is referred to as linear.

In the LBT model, all particles—including soft ones—are described using pQCD, which becomes unreliable in the soft regime. To address this limitation, we developed the CoLBT-hydro model [5] based on the LBT. In this hybrid model, jet shower, recoil, and radiated partons are sorted after each interaction according to an energy threshold  $p_{\text{cut}}^0 = 2.0$  GeV. Partons whose energy in the local rest frame exceed this threshold called hard partons continue to evolve according to the LBT model. In contrast, partons with energy below the cutoff called soft partons are treated as source terms for the hydrodynamic model and are used to update the information of background. Therefore, the final hadron spectra of CoLBT-hydro have two components, one is hadronization of hard partons from LBT within parton recombination model, the other is hydro response from Cooper-Frye formula.

## 3 EECs in vacuum and medium-induced emissions

First we study the EEC in vacuum case. We focus on the normalized two-point energy correlator  $\langle \mathcal{E}_1(\vec{n}_1) \mathcal{E}_2(\vec{n}_2) \rangle / Q^2$  of final state particles with the angular scale  $\cos \theta = \vec{n}_1 \cdot \vec{n}_2$ . 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 correlator,

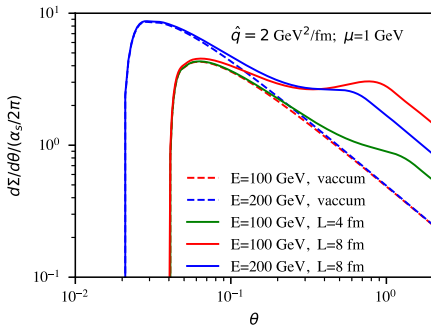
$$\frac{d\Sigma_q^{\text{vac}}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz z(1-z) P_{qg}(z) \int_{\mu^2}^{Q^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2} \delta\left(\theta - \frac{|\mathbf{k}_\perp|}{z(1-z)E}\right), \quad (2)$$

where  $\mathbf{k}_\perp$  is the transverse momentum of the emitted gluon,  $P_{qg}(z) = [1+(1-z)^2]/z$  is the splitting function, and  $\mu \ll Q$  denotes the collinear cut-off scale below which non-perturbative effects become dominant. Since the momentum fraction  $0 < z < 1$  in the splitting, the energy correlator,

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

is proportional to  $1/\theta$  which is consistent with other studies when  $\theta > 4\mu/E$ . If  $\theta < 4\mu/E$ , non-perturbative effects take over and its behavior will be influenced by hadronization processes.

We further investigate the contribution of medium-induced gluon radiation to the EEC using the High-Twist approach. Figure 1 shows the angular distribution of the energy-energy correlator from a single parton propagating in vacuum and in a static medium, respectively. We consider two values of initial parton energy and two different path lengths in the medium.



**Figure 1.** The leading-order vacuum (dashed) and vacuum + medium-induced (solid) two-particle energy correlators, normalized by  $\alpha_s/2\pi$ , for different parton energies  $E$  and medium path lengths  $L$ . The collinear cut-off for vacuum radiation is set to  $\mu = 1$  GeV.

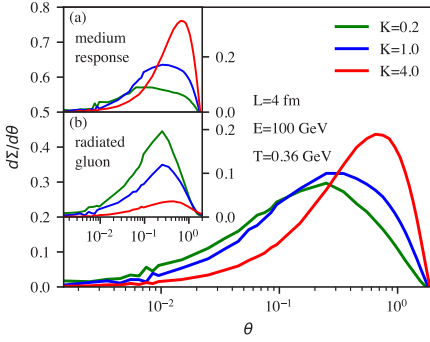
The dashed curves represent vacuum splittings, which exhibit a characteristic power-law behavior. The solid curves include both vacuum and medium-induced radiations. A significant enhancement is observed at large angles compared to the vacuum case, consistent with previous studies. Furthermore, both the position and magnitude of the enhancement are found to be sensitive to the medium path length and the initial parton energy.

## 4 Effects of jet energy loss and medium response on EEC

When a parton goes through QGP medium, it will experience energy loss and induce medium response. These should also modify the EEC inside jet. Here we use LBT model simulate jet propagation in the static medium. LBT model has a cut-off in the transverse momentum transfer in terms of the Debye screening mass. We have introduced a  $K$  factor to characterize this scale.

$$\mu_D^2 = \frac{3}{2} K g^2 T^2, \quad (4)$$

We examine the sensitivity of the modification of the energy-correlator to this scale due to jet-medium interaction by varying  $K$ . In Figure 2, we present the angular distribution of the

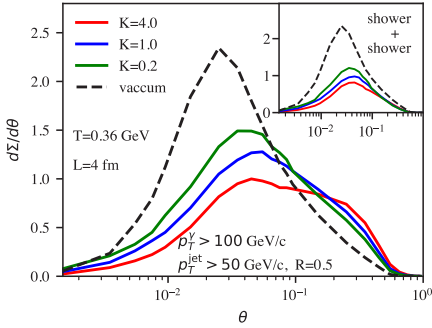


**Figure 2.** Energy-correlators initiated by a single quark with  $E = 100$  GeV going through a QGP brick with length  $L = 4$  fm and at temperature  $T = 0.36$  GeV for three values of  $K$ . The inserts show contributions from (a) medium response and (b) radiated gluons.

EEC generated by a single quark propagating through a QGP brick. Three different values of the Debye screening mass  $\mu_D$  are considered in the simulation. Two inset panels are included: the upper panel shows the correlation between the leading parton and the medium response (recoil and negative partons) from the LBT model, while the lower panel shows the correlation between the leading parton and the radiated gluons.

We observe that the EEC contribution from the medium response exhibits a clear dependence on  $\mu_D$ . Since the typical transverse momentum transfer scales as  $q_\perp \sim \mu_D$ , and the energy transferred to the medium is approximately  $\delta E \sim \mu_D^2/T$ , increasing  $\mu_D$  results in a larger angle between the leading and recoil partons. At the same time, the recoil partons carry more energy, leading to an enhanced correlation strength. As a result, increasing  $\mu_D$  shifts the EEC distribution from medium response toward larger angles and increases its overall magnitude. For EEC distribution from radiated gluon, increasing  $\mu_D$  leading to more energy loss of leading jet, which in turn reduces the magnitude of correlation between the leading parton and the radiated gluons. Nevertheless, the overall distribution still shifts toward larger angles. The main panel shows the total energy-energy correlator, which includes all possible correlations among the leading quark, medium response, and radiated gluons. Its dependence on  $\mu_D$  follows the same trend as the medium response contribution, indicating that the medium response dominates over the radiated gluons in our model simulation.

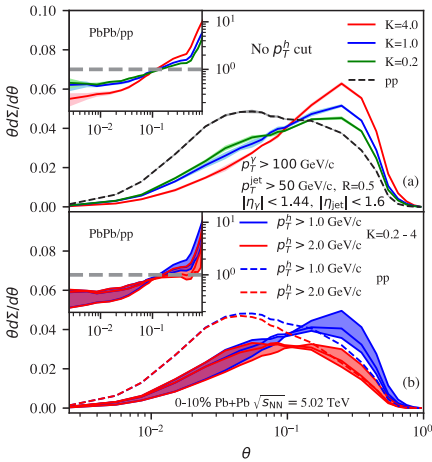
Since a parton produced in the initial hard scattering undergoes multiple splittings to form a parton shower, we also utilize the LBT model to simulate the in-medium transport of the entire parton shower, rather than that of a single parton. Shown in Figure 3 are modified EEC distributions for partons inside  $\gamma$ -triggered jets with cone size  $R = 0.5$ ,  $p_T^\gamma \geq 100$  GeV/ $c$  and final state  $p_T^{\text{jet}} \geq 50$  GeV/ $c$  after going through a QGP brick at a temperature  $T = 0.36$  GeV with length  $L = 4$  fm, as compared to the EEC in vacuum (dashed) without multiple scatterings in the QGP medium. EEC's for jets are all calculated as  $\Sigma = \langle \sum_{ij} p_T^i p_T^j / p_{T,\text{jet}}^2 \rangle$  in this study. Similar to the single-parton case, we also investigate the dependence of the EEC on  $\mu_D$ . We observe that the EEC distributions from correlations among shower partons—excluding contributions from the medium response and medium-induced radiation—are suppressed at both small and large angles compared to the vacuum result, for all values of  $\mu_D$ . This suppression arises from jet energy loss and transverse momentum broadening in the medium. The main panel presents the total EEC, which includes contributions from shower partons, medium response, and radiated gluons within the modified jet. It exhibits a significant enhancement at large angles due to correlations involving the medium modification, and shows a clear dependence on  $\mu_D$ .



**Figure 3.** EEC for partons inside  $\gamma$ -jets with cone-size  $R = 0.5$ ,  $p_T^\gamma \geq 100$  GeV and  $p_T^{\text{jet}} \geq 50$  GeV/c propagating through a uniform QGP at temperature  $T = 0.36$  GeV for a length  $L = 4$  fm for three values of  $K$ , as compared to the vacuum (dashed). The insert shows contributions from shower-shower correlations as compared to the vacuum (dashed).

## 5 EECs in Pb+Pb collisions at LHC

We now shift our focus to studying how the QGP medium modifies the EEC distribution inside  $\gamma$ -jets in realistic high-energy heavy-ion collisions. Figure 4 shows the energy-energy correlators  $d\Sigma/d\ln\theta$  for (a) all charged hadrons inside  $\gamma$ -triggered jets in 0–10% central Pb+Pb collisions at  $\sqrt{s} = 5.02$  TeV from CoLBT simulations with  $K = 0.2, 1, 4$  (solid), compared to p+p collisions (dashed), and (b) for charged hadrons with  $p_T > 1$  GeV/c (blue) and  $p_T > 2$  GeV/c (red). Inserted figures show the ratio of EECs in Pb+Pb to p+p collisions. Similar to the QGP brick case, EECs in Pb+Pb are suppressed at small angles due



**Figure 4.** EEC for (a) charged hadrons in  $\gamma$ -jets with cone-size  $R = 0.5$ ,  $p_T^\gamma \geq 100$  GeV/c and  $p_T^{\text{jet}} \geq 50$  GeV/c in 0-10% central Pb+Pb collisions at  $\sqrt{s} = 5.02$  TeV from the CoLBT simulations for  $K = 0.2, 1, 4$  (solid) as compared to p+p (dashed) collisions and (b) for charged hadrons with  $p_T > 1$  (blue) and 2 GeV/c (red) where bands highlight variations due to different values of  $K = 0.2, 1$  and 4.

to jet energy loss and transverse momentum broadening, and enhanced at large angles from medium modification. This modification is also sensitive to the  $\mu_D$ , which sets the angular scale of jet-medium scatterings and encodes the QGP structure in CoLBT. Moreover, when a  $p_T^h > 1$  GeV/c cut is applied, the large-angle enhancement is reduced but remains clearly visible. This  $p_T^h$  cut is chosen because it helps suppress the hydrodynamic background in experimental measurements. However, this enhancement nearly disappears with a  $p_T^h > 2$  GeV/c cut, except in the case of  $K = 4$ .

In summary, we have studied the EEC arising from both vacuum splittings and medium-induced radiation. We further investigated the effects of medium response and jet quenching on the jet EEC. We find that energy loss and transverse momentum broadening lead to a

suppression of the EEC at small angles in the medium, compared to the vacuum case, while medium response and medium-induced gluon radiation result in an enhancement at large angles. We also explored the dependence of the EEC angular distribution on the Debye screening mass  $\mu_D$ , which determines the angular scales of each jet-medium scattering and characterizes the structure of the QGP medium. Finally, we presented the first complete and realistic calculations of the medium modification of EEC inside  $\gamma$ -triggered jets in high-energy heavy-ion collisions.

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