

Theory overview of medium response and hard-soft correlation

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Abstract. Overview of recent theoretical advances presented at Quark Matter 2025 in the study of medium response and hard-soft correlation in heavy ion collisions and small systems.

1 Introduction

The observation of jets has been instrumental in driving our understanding of Quantum Chromodynamics (QCD) in both proton-proton and heavy-ion collisions. In proton-proton (p - p) collisions, jet observables are essential for probing the internal structure of protons and validating the predictions of perturbative QCD. Due to this understanding of jets in vacuum, the observation of jet modification in heavy-ion collisions provides a strong indication of the presence of a hot and dense QCD medium. These highly energetic partons can then be used as tomographic probes of the quark-gluon plasma (QGP) created in such collisions.

Due to the large momentum transfer involved, jet production occurs at short timescales during the early stages of the collision. These off-shell excitations must undergo a series of splittings to reduce their virtuality. While in vacuum, the whole jet shower collimates into a jet of hadrons observed in the detector, in the presence of a medium, the jet shower interacts with the QGP leading to energy loss and modification of the jet substructure.

The rapid formation of vacuum-like emissions generally allows them to be factorized from the medium interactions [1]. However, as the shower evolves, the medium's resolution scale becomes increasingly comparable to the transverse size of the jet. Several studies have investigated how and when medium effects begin to influence the vacuum-like shower [1–3]. These works highlight that the onset of medium interactions is essential for accurately describing the suppression of hard partons and the correlation of their azimuthal structure with the medium asymmetries [4].

Once the medium resolves individual prongs within the jet, it can interact with each of them independently. This interaction broadens the jet core through scattering and induces radiation as hard partons are driven off-shell. Theoretical models describing jet-medium interactions typically follow one of two approaches: a strong coupling framework based on the AdS/CFT correspondence [5] or a weak coupling framework grounded in perturbative QCD (pQCD), which is the subject of this manuscript.

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The QGP evolves through multiple stages following its formation, eventually reaching a state of local thermal equilibrium where it is effectively described using hydrodynamic simulations. The energy and momentum deposited by hard partons in the medium create perturbations that modify the hydrodynamic background itself.

In smaller systems like proton-nucleus (p - A) or proton-proton (p - p) collisions, recent measurements of the elliptic flow coefficient v_2 have revealed collective flow patterns similar to those observed in heavy-ion collisions [6–8]. However, measurements of the nuclear modification factor R_{AA} in these small systems do not show significant jet quenching effects [9, 10]. Given the limited energy budget in small systems, understanding the interplay between the hard and soft sectors is key to interpreting these observations.

2 Jets in heavy ion collisions

Jet-medium interactions can be described using an effective kinetic theory, where the partons are treated as on-shell quasi-particles. The evolution of the phase-space distribution is described by the Boltzmann equation [11–13]

$$\left(\partial_t + \frac{\mathbf{p}}{|\mathbf{p}|} \nabla_x \right) f_a(\mathbf{p}, \mathbf{x}, t) = C_a^{2 \leftrightarrow 2}[\{f_i\}] + C_a^{1 \leftrightarrow 2}[\{f_i\}], \quad (1)$$

At leading order of pQCD, two main processes contribute to the energy loss of hard partons: number conserving elastic scatterings $C_a^{2 \leftrightarrow 2}$ and radiation induced by the medium which can be resummed into an effective collision term $C_a^{1 \leftrightarrow 2}$ [11–13].

In the weak coupling approach, the processes responsible for energy loss are the same that drive the initial highly energetic plasma to local equilibrium [14]. Accordingly, the evolution of the medium component f^{med} can itself be described by the same Boltzmann equation. The phase-space distribution can be separated into medium and jet components

$$f(\mathbf{p}, \mathbf{x}, t) = f^{\text{med}}(\mathbf{p}, \mathbf{x}, t) + \delta f^{\text{jet}}(\mathbf{p}, \mathbf{x}, t). \quad (2)$$

We will integrate out the position dependence \mathbf{x} and follow the evolution of the momentum distribution $f(\mathbf{p}, t)$. Since the jet is dilute compared to the dense QGP, the jet distribution is treated as a perturbation on top of the medium distribution. The Boltzmann equation can be linearized around the medium, ignoring any subleading jet-jet interactions.

Energy loss has typically been studied using MonteCarlo stochastic approaches [15–20]. In order to describe medium response, one then needs to couple the jet evolution to hydrodynamical simulations. By introducing a source term in the hydrodynamic simulation, the energy-momentum lost by the jet is deposited in the medium [21–25]. Another approach is to directly solve the linearized Boltzmann equation. This allows the treatment of the full energy cascade from the high energy partons $\sim E$ to medium scales $\sim T$ using the same framework [26–28].

Static background:

The evolution of the jet energy distribution $D(x) = \int dp \delta(p - xE) p^3 \delta f(p)$, with initial energy E in a static equilibrium background is depicted in Fig. 1. The collinear emissions dominate the energy loss, leading to efficient transport of energy from the hard scales $\sim E$ to the medium scales $\sim T$ without deposition in the intermediate scales. The energy cascade can be described using Kolmogorov-Zakharov [29] wave turbulence characterized by a stationary solution in the intermediate scales $D(x) \simeq 1/\sqrt{x}$ [30, 31]. Elastic scatterings are responsible for the redistribution of the energy deposited in the medium out to large angle.

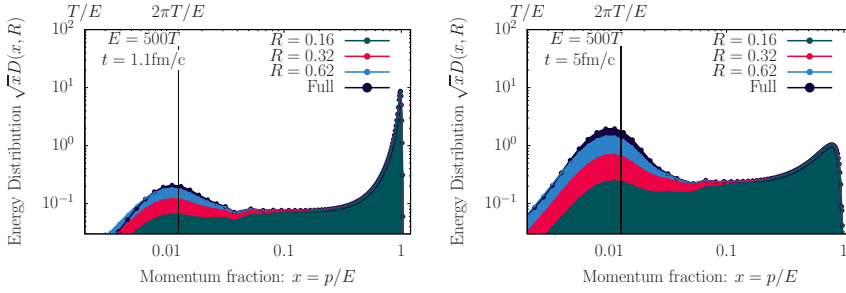


Figure 1. Evolution of the energy distribution with a decomposition into different cone sizes $R = 0.16, 0.32, 0.62$ and π . Figure from Ref. [3].

Dynamic background:

Recent works have studied the equilibration of jets in a dynamic background where the QGP distribution itself is equilibrating [28]. Starting with highly occupied plasma, the QGP undergoes a non-equilibrium evolution approaching a viscous hydrodynamics description. The pressure anisotropy of the jet distribution $A = \frac{\delta P_T - \delta P_L}{\delta e/3}$ is used to characterize the hydrodynamisation. Following jets with different initial momenta at angles θ with respect to the initial QGP anisotropy, they find that the medium expansion leads to a rapid decrease of the longitudinal pressure P_L . The different jets approach the same hydrodynamical limit already at early times.

If the medium is large, all the jet fragments will eventually thermalize with the medium at asymptotic times. The only signal of the hard parton will be a change of the thermodynamic variables (e.g. temperature, flow velocity, ...). For the case of a static background, the asymptotic energy distribution is obtained by matching the leading order Taylor expansion in the thermodynamic variables of the equilibrium distribution [3]

$$D_{a/jet}^{(eq)}(x, \theta) \simeq (1 + 3 \cos \theta) \partial_T n_a(xE) . \tag{3}$$

Here θ is the azimuthal angle of the initial jet momentum and n_a is the equilibrium distribution of the medium. This leads to a boosted energy distribution along the jet direction.

3 Jets in small systems

In heavy ion collisions, the energy carried by the soft sector is much larger than the hard partons' energy. This allows the treatment of hard partons as a small perturbation on top of the medium. However, in small systems, the presence of a hard parton with energy $\gtrsim 100$ GeV significantly alters the remaining energy of the soft bulk.

There has been no observation of suppression in measurements of the R_{AA} for minimum bias p - Pb [9, 10, 32]. However, when selecting for centrality, measurements show suppression for central events and enhancement for more peripheral events [33]. This hints at a possible interplay between the hard and soft particle production.

Hard-soft correlation:

The x-SCAPE-GIM described in [34] employs a multi-stage approach that imposes event-by-event energy-momentum conservation. The energy-momentum consumed in hard processes

is subtracted from that available for bulk medium production. The hadron and jet spectra in minimum-bias p - p and p - Pb collisions reproduce experimental data across the full transverse momentum range at top LHC energies.

Energy loss is found to be negligible in p - Pb collisions, aligning with experimental findings. Correlations between the hard and soft particle production are characterized by measuring the mean transverse energy $\langle E_T \rangle$ as a function of leading jet p_T . At mid-rapidity the mean transverse energy $\langle E_T \rangle$ increases monotonically as a function of leading jet p_T . For forward rapidities, it was shown that the $\langle E_T \rangle$ is peaked at $p_T \simeq 100$ GeV. While it increases with p_T at low p_T , the competition between the hard and soft sector leads to a decrease of $\langle E_T \rangle$ as one selects events with larger jet p_T . These results qualitatively explain the correlations between the centrality selection and hard process triggers observed by ALICE and ATLAS measurements.

TMD-PDFs:

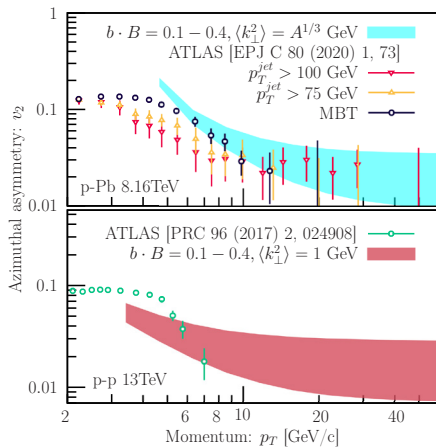


Figure 2. Azimuthal anisotropies obtained using TMD distributions; figure from Ref. [35].

Recent works have shown that azimuthal anisotropies observed in p - p and p - Pb at high- p_T can be attributed to initial state transverse momentum correlations [35, 36]. Consider a hard scattering process with total transverse momentum q_T , due to momentum conservation, it must be balanced by the total transverse momentum of the remaining partons contributing to soft particle production. In the final state, the net transverse momentum of the produced dijet is balanced by the net transverse momentum of the bulk system.

One can then compute the azimuthal anisotropies as the Fourier decomposition of the momentum imbalance of dijet production. Azimuthal correlations generated from transverse momentum dependent parton distribution functions (TMDPDFs) and fragmentation functions (TMDFFs) lead to sizable v_2 at high- p_T as shown in Fig. 2.

4 Summary

Jets constitute a powerful tool to study QCD matter in relativistic hadron colliders. Hard parton energy loss is dominated by medium-induced radiation. Once the inverse energy cascade transports the energy to medium scales, these perturbations are thermalized with the medium. Understanding thermalization of these soft modes is crucial for understanding medium response to hard probes.

In small systems, correlations between the hard and soft particle production become more important. Energy-momentum conservation in x -SCAPE-GIM leads to interplay between the hard and soft particle production. Azimuthal correlations in the initial state can explain the observed final state anisotropies at high- p_T . Moreover, the color fluctuation model can explain the observed suppression in d - Au collisions without the need of final-state interactions [37].

Heavy ion collisions show clear evidence of jet quenching while small systems do not. Future light-ion collisions such as O - O collisions at the LHC will be important to understand the transition between these two regimes.

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