Constraints on jet quenching from a multi-stage energy-loss approach

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We present a multi-stage model for jet evolution through a quark-gluon plasma within the JETSCAPE framework. The multi-stage approach in JETSCAPE provides a unified description of distinct phases in jet shower contingent on the virtuality. We demonstrate a simultaneous description of leading hadron and integrated jet observables as well as jet $v_n$ using tuned parameters. Medium response to the jet quenching is implemented based on a weakly-coupled recoil prescription. We also explore the cone-size dependence of jet energy loss inside the plasma.
1. Introduction

Jet evolution through the QGP is characterized by several distinct phases depending on jet virtualities, and different energy loss mechanisms are essential to describe each stage. A multi-stage approach within the JETSCAPE framework provides a unified description of the jet shower, including a high-virtuality gluon-splitting phase and a low-virtuality scattering-dominated phase. In these proceedings, we report a comprehensive study of multi-stage jet evolution by performing a model-to-data comparison to constrain the jet quenching parameter in heavy-ion collisions.

2. Unified approach in JETSCAPE

Throughout this study, a dynamically evolving QGP created in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV is simulated using \((2+1)-D\) VISHNU [1] with fluctuating TRENTo [2] initial conditions, followed by free-streaming and dissipative fluid dynamics. Hard partons produced by PYTHIA [3] with initial state radiation (ISR) and multi-parton interaction (MPI) are initialized in the transverse plane by TRENTo profiles for initial binary collisions. These partons then evolve through the hydrodynamic medium. The multi-stage energy loss formalism consists of MATTER [4, 5] for the high-virtuality stage and LBT [6, 7] for the low-virtuality stage. The phase spaces for the two energy loss models are separated by a switching virtuality \( Q_0 \). The simulation of p+p collisions is performed by MATTER vacuum showers using the JETSCAPE PP19 tune [8].

MATTER is a Monte-Carlo event generator for partons with virtuality \( Q > Q_0 \). Parton splittings are described by a generalized Sudakov form factor, which includes vacuum and medium-modified parton splitting functions. The in-medium contribution, which induces transverse momentum broadening of jets, \( \hat{q} \), in a QGP, is estimated based on the Higher-Twist energy loss model [9–11]. We have used a hard thermal loop technique [12] to formulate \( \hat{q} \).

The time-ordered in-medium shower in LBT for low virtuality partons relies on solving a linearized Boltzmann equation with in-medium kernels. The model contains leading order \( 2 \rightarrow 2 \) elastic and \( 2 \rightarrow 2 + n \) inelastic scatterings, where \( n \) indicates multiple gluon radiation. The Higher-Twist formalism evaluates the average number of emitted gluons from a hard parton, which follows the Poisson distribution.

The switching virtuality \( Q_0 \) is set to 1, 2, and 3 GeV, and a value of \( \alpha_s = 0.25 \) is used for the strong coupling to determine the quenching parameter \( \hat{p} \). Our previous analysis of the single hadron and jet nuclear modification factor \( R_{AA} \) constrained these model parameters [13]. Both the MATTER and the LBT in-medium showers implemented recoil partons based on a weakly-coupled picture to reproduce the medium response to jet quenching. The energies and momenta originating from incoming thermal partons during jet-medium scattering (holes) are subtracted from the jet signals in the final state.

3. Results

The left panel of Fig. 1 shows the jet cross section in p+p collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with two rapidity cuts, normalized by the PYTHIA predictions. The \( p_T \) dependence of the jet cross-section is consistent with data for jet \( p_T > 200 \) GeV at mid-rapidity. The ratio of the jet
Figure 1: Comparison between the results obtained from the JETSCAPE PP19 tune at $\sqrt{s_{NN}} = 5$ TeV and measurements. (Left) Inclusive jet cross-section with $|y_{jet}| < 0.3$ [14], normalized by the PYTHIA predictions. (Right) Ratio of the jet spectra for $R = 0.2$ to 0.8 with respect to $R = 1.0$ [15].

![Figure 1: Comparison between the results obtained from the JETSCAPE PP19 tune at $\sqrt{s_{NN}} = 5$ TeV and measurements.](image)

Figure 2: Inclusive jet $R_{AA}$ in central (top panel) and peripheral (bottom panel) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with various $R$ and $Q_0$ values [15].

![Figure 2: Inclusive jet $R_{AA}$ in central (top panel) and peripheral (bottom panel) Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with various $R$ and $Q_0$ values](image)

cross-section with various $R$ with respect to $R = 1.0$ is displayed in the right panel in Fig. 1. The angular dependence of the jet $R_{AA}$ is well reproduced by the MATTER vacuum shower in JETSCAPE with the PP19 tune.

We present the jet $R_{AA}$ with various $R$ and switching virtualities $Q_0$ in central and peripheral Pb+Pb collisions in Fig. 2. We consistently observe stronger jet quenching with larger values of $Q_0$. The parton shower in the high-virtuality phase (MATTER) is dominated by virtuality splitting, but the low-virtuality phase (LBT) is largely affected by scatterings, which induce jet $p_T$ broadening. This accounts for the jet $R_{AA}$ being more suppressed when the LBT phase starts at higher virtuality $Q_0$. The jet $R_{AA}$ independent to $R$ leads to the $R_{AA}$ ratio with respect to $R = 1.0$ consistent with unity unity as shown in Fig. 3. This monotonic behavior is independent of centrality and jet $p_T$, implying that the jet energy contained within $R < 0.2$ generally dominates the jet $R_{AA}$ value. The steeply falling jet shape function shown in the left panel of Fig. 4 supports this interpretation.
4. Conclusion

We have studied jet modification using a unified approach within the JETSCAPE framework. The results for the jet cross-section in pp collisions using the JETSCAPE PP19 tune show good agreement with data. The multi-stage model with a combination of MATTER and LBT provides a simultaneous description of the integrated and differential jet observables. Our future work will investigate recoils for the detailed jet quenching mechanism at large $R$.

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