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Jet quenching in a multi-stage Monte Carlo approach

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Abstract

We present a jet quenching model within a unified multi-stage framework and demonstrate for the first time a simultaneous description of leading hadrons, inclusive jets, and elliptic flow observables which spans multiple centralities and collision energies. This highlights one of the major successes of the JETSCAPE framework in providing a tool for setting up an effective parton evolution that includes a high-virtuality radiation dominated energy loss phase (MATTER), followed by a low-virtuality scattering dominated (LBT) energy loss phase. Measurements of jet and charged-hadron R_{AA} set strong constraints on the jet quenching model. Jet-medium response is also included through a weakly-coupled transport description.

Keywords: Jet quenching, QGP, heavy-ion physics, QCD, High- p_T jet & hadron R_{AA} , Multi-stage, JETSCAPE

1. Introduction

Ultra-relativistic nucleus-nucleus collisions performed at the Relativistic Heavy-Ion Collider (RHIC) and Large Hadron Collider (LHC) produce an exotic state of deconfined matter that undergoes different stages, namely: initial state hard scattering, expansion of deconfined quark-gluonic matter, jet energy loss in the medium, and hadronization. A unified framework that implements all stages of a heavy-ion collision is required to gain a comprehensive understanding of the QGP and explore new physics. Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope (JETSCAPE) is a state-of-the-art simulation framework with capabilities to accommodate physics of each stage of the heavy-ion collision in a modular form [1–3]. The goal of these proceedings is to demonstrate that a multi-stage jet quenching model gives a simultaneous description of the jet and hadron observables at multiple centralities and collision energies. To see JETSCAPE capabilities in studying intra-jet observables, heavy-quark observables and Bayesian calibration of the soft sector visit Refs. [4–6].

2. Multi-stage jet energy loss with JETSCAPE framework

It has been widely accepted that the evolution of jets through deconfined QCD matter is a multi-scale problem. To incorporate this property within the JETSCAPE framework, we set up an effective parton

evolution in which we incorporated information of the space-time evolution of the medium on parton energy loss during the high-virtuality, radiation dominated portion of the shower using MATTER, followed by a simulation of the low-virtuality, scattering dominated portion with LBT. The switching between stages is performed at a parton-by-parton level depending on local quantities such as local energy density in the medium, off-shellness and energy of the parton.

MATTER [7, 8] is a virtuality-ordered Monte Carlo event generator that simulates the evolution of partons at high energy (E) and high-virtuality (off-shellness) $Q^2 \gg \sqrt{\hat{q}E}$, where $\hat{q}$ is the transport coefficient that controls transverse broadening, and $Q^2 \geq 1 \text{ GeV}^2$. Based on the Higher-Twist formalism, the probability of a parton splitting is computed by sampling the medium modified Sudakov form factor which includes contributions from the vacuum and medium-induced splitting functions. We used a hard thermal loop formulation for $\hat{q}$ [9]. The medium response is included through a weakly-coupled description of the medium in terms of thermal partons, where the propagation of the medium parton kicked out by the jet parton (“recoil”) is described by a kinetic theory-based approach.

LBT [10, 11] is also a Monte Carlo event generator based on the linear Boltzmann equation which simulates in-medium energy loss of high-energy, low-virtuality partons. The model includes both the elastic $2 \rightarrow 2$ scattering processes and inelastic $2 \rightarrow 2+n$ scattering with multiple gluon radiation. The probabilities of these scattering processes are employed to simulate the evolution of the jet shower, recoil partons and radiated gluons due to their scattering with thermal partons in the medium.

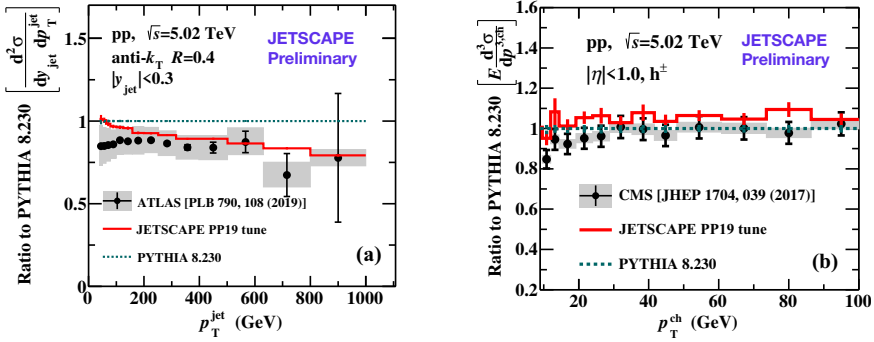


Fig. 1: Comparison of JETSCAPE PP19 tune's results for inclusive jets and charged-hadrons with the experimental data and the default PYTHIA at 5.02 TeV. The ratio is taken w.r.t. to the default PYTHIA result. (a) Ratio of inclusive jet cross-sections as a function of jet p_T for cone size $R = 0.4$. (b) Ratio of charged-hadron yield as a function of charged-hadron p_T .

The simulation of p+p collisions is performed using the JETSCAPE PP19 tune [1]. This tune employs PYTHIA as a hard scattering module with initial state radiation (ISR), multiparton interaction (MPI) flags ON and final state radiation (FSR) flag OFF. MATTER is employed for final state radiation. Simulation of PbPb collision events at 5.02A TeV is done by using fluctuating initial state conditions evolved hydrodynamically within the JETSCAPE framework. TRENTO [12]+PYTHIA is used to simulate the initial state hard scattering. The medium profiles are generated using (2+1)-D VISHNU [13] with fluctuating TRENTO [12] initial conditions. The virtuality-ordered shower is generated using an in-medium MATTER generator which evolves partons to a lower virtuality Q_0 (switching virtuality). Then, these partons are passed to a small-virtuality energy-loss stage, LBT. Finally, the jet partons are hadronized using PYTHIA based string fragmentation.

3. Results

Figure 1 displays a ratio of inclusive jet cross-sections (left) and charged-hadron yields (right). Overall, the JETSCAPE results are compatible with the experimental data (within 10%). Results from PYTHIA tend to be similar to JETSCAPE for the case of the charged-hadron yield but for jets show discrepancies of order $\lesssim 25\%$. Both observables provide a good baseline for their counterparts in nuclear collisions.

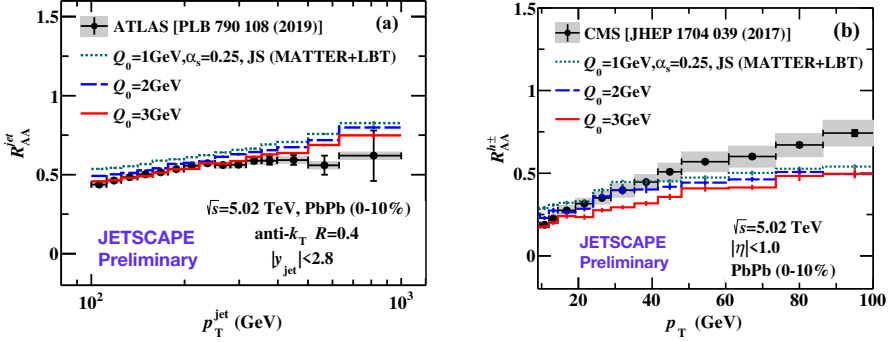


Fig. 2: Comparison of the nuclear modification factor for inclusive jets and charged-hadrons obtained using the multi-stage energy loss approach (MATTER+LBT) within the JETSCAPE framework, with the experimental data for most central 5.02A TeV collisions (0-10%). Results are shown for a switching virtuality parameter $Q_0 = 1, 2$, and 3 GeV. (a) Jet R_{AA} as a function of jet p_T for cone size $R = 0.4$. (b) Charged-hadron R_{AA} as a function of charged-hadron p_T .

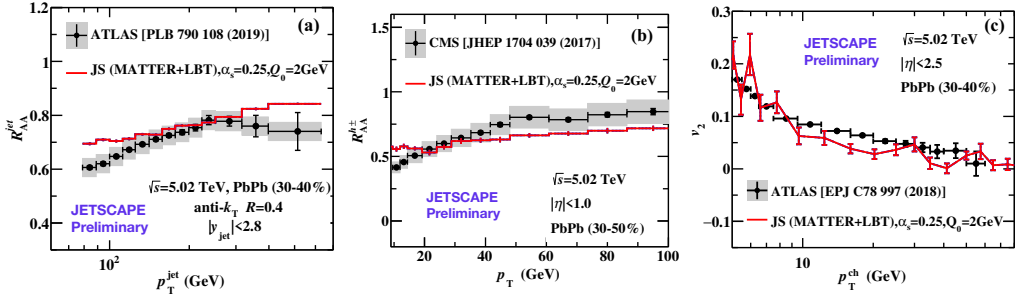


Fig. 3: Comparison of inclusive jet and charged-hadron nuclear modification factor, and azimuthal anisotropy v_2 obtained using the multi-stage energy loss approach (MATTER+LBT) within the JETSCAPE framework, with the experimental data for semi-peripheral 5.02A TeV collisions. The tuning parameters Q_0 and α_s are set by the simultaneous fit of inclusive jet and charged-hadron R_{AA} in the most central 5.02A TeV collisions. (a) Jet R_{AA} as a function of jet p_T for cone size $R = 0.4$. (b) Charged-hadron R_{AA} as a function of charged-hadron p_T . (c) Azimuthal anisotropy v_2 for charged-hadrons as a function of charged-hadron p_T .

Figure 2 shows inclusive jet R_{AA} (left) and charged-hadron R_{AA} (right) in most central 5.02A TeV PbPb collisions (0-10%) for switching virtualities $Q_0 = 1, 2, 3$ GeV and the jet-medium coupling parameter $\alpha_s = 0.25$. Increasing Q_0 from 1 to 3 GeV increases the effective length of LBT based energy-loss. Since the partons in the LBT stage are close to on-shell ($Q_0 \sim [1, 3]$ GeV, $E \sim p_T$), the partons at low- p_T see significant energy loss effects. Our results are consistent with this concept. Increasing Q_0 from 1 to 3 GeV suppresses the low- p_T region of the charged-hadron R_{AA} spectrum. This leads to suppression of the jet R_{AA} at all jet p_T 's. The parameter set $Q_0 = 2$ GeV and $\alpha_s = 0.25$ provides the best simultaneous description of the jet and hadron R_{AA} data. We observe a $\sim 20\%$ deviation at high p_T in the charged-hadron R_{AA} that could be due to the absence of any scale dependence (hard parton's off-shellness) in $\hat{q}$ [14].

Figure 3 shows inclusive jet R_{AA} (left), charged-hadron R_{AA} (center) and azimuthal anisotropy coefficient v_2 (right) in semi-peripheral 5.02A TeV PbPb collisions for the parameter set (Q_0 and α_s) extracted from fits to the most central 5.02A collisions inclusive jet R_{AA} and charged-hadron R_{AA} data. The agreement with the experimental measurement for hadron- R_{AA} and v_2 are within 10%, but the jet R_{AA} shows a deviation of $\sim 20\%$. A similar attempt to explain the hadron- R_{AA} and v_2 can be found in Ref. [15], whereas the hadron- R_{AA} and the jet R_{AA} can be found in Ref. [16].

Figure 4 shows inclusive jet R_{AA} (left) and charged-hadron R_{AA} (right) in the most central 2.76A TeV PbPb collisions for the parameter set (Q_0 and α_s) extracted from fits to the most central collision inclusive jet R_{AA} and charged-hadron R_{AA} data at 5.02A TeV. Results are consistent with the experimental measurements.

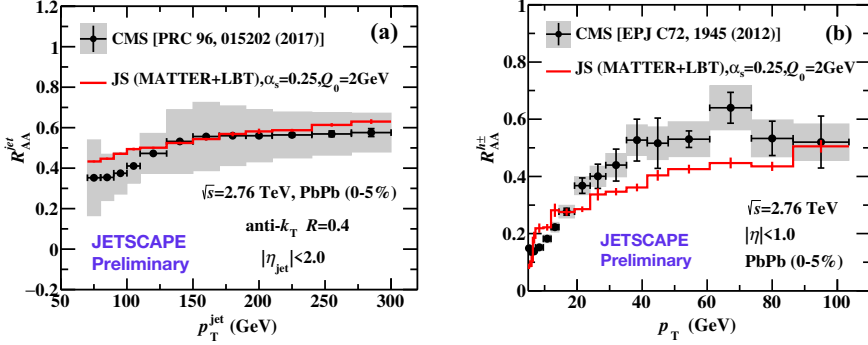


Fig. 4: Comparison of the nuclear modification factor for inclusive jets and charged-hadrons obtained using multi-stage energy loss approach (MATTER+LBT) within the JETSCAPE framework with the experimental data for most-central 2.76 TeV collisions. The tuning parameters Q_0 and α_s are set by the simultaneous fit of the inclusive jet and charged-hadron R_{AA} in the most central 5.02 A TeV collisions. (a) Jet R_{AA} as a function of jet p_T for cone size $R = 0.4$. (b) Charged-hadron R_{AA} as a function of charged-hadron p_T .

4. Conclusion

A multi-stage energy-loss based jet quenching model is presented. This unified approach effectively captures the physics of multi-scale jet quenching in QCD plasma. The free parameters in pp collisions are fixed by the JETSCAPE PP19 tune. A simultaneous fit of the jet R_{AA} and charged-hadron R_{AA} in the most central 5.02 A TeV collisions has been carried out to constrain the jet quenching model. The extracted parameters qualitatively describe the charged-hadron and jet R_{AA} , and the elliptic flow coefficient v_2 in semi-peripheral collisions at multiple collision energies, but quantitative differences remain. The differences are significant and represent physics that is missing in the model.

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