Probing nuclear matter with jets

Ben-Wei Zhang\textsuperscript{a,b,1}, Yuncun He\textsuperscript{a,b}, R. B. Neufeld\textsuperscript{c}, Ivan Vitev\textsuperscript{c}, Enke Wang\textsuperscript{a,b}

\textsuperscript{a}Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
\textsuperscript{b}Key Laboratory of Quark and Lepton Physics (Central China Normal University), Ministry of Education, China
\textsuperscript{c}Los Alamos National Laboratory, Theoretical Division, MS B238, Los Alamos, NM 87545, U.S.A.

Abstract

Jet physics in relativistic heavy ion collisions, which combines perturbative QCD jet production with quark and gluon energy loss and in-medium parton shower modification, has emerged as a powerful tool to probe the properties of strongly-interacting matter formed in high-energy nuclear reactions. We present selected results for the modification of jet cross sections and related observables in the ambiance of hot and/or dense nuclear medium. We focus on the inclusive jet spectrum and dijets [$O(\alpha_s^3)$], and $Z^0/\gamma^*$ tagged jets [$O(G_F\alpha_s^2)$] in the framework of perturbative QCD.

Keywords: Quark-gluon plasma (QGP), jet production, parton energy loss, perturbative QCD.

1. Introduction

Jets, collimated showers of energetic final-state particles, and the physical observable related to jets are not only most closely related to the perturbative QCD (pQCD) dynamics, but also among the most intensively studied objects in high-energy physics \cite{1,2}. Jet productions in elementary collisions can be accurately calculated and compared to a wealth of experimental data on jet observables, measured in $e^+e^-$, deep inelastic scattering and hadron-hadron reactions. Jets provide not only a laboratory to test and advance pQCD but are also related to important signatures of new physics (beyond the Standard Model).

QCD theory predicts that in relativistic heavy-ion collisions (HIC) a new kind of matter, the quark-gluon plasma (QGP) consisting of deconfined quarks and gluons, may be created. Theoretical studies and experimental measurements have shown that fast partons traversing the QGP medium will undergo multiple scattering and lose energy due to collisional and radiative processes \cite{3}. This parton energy loss and the corresponding suppression of hadron cross sections in nucleus-nucleus ($A+A$) reactions have been dubbed jet quenching. Jet quenching effects in the hot QCD medium will surely alter the production of reconstructed jets, which contain one or several energetic partons prior to hadronization \cite{4}. The concurrent advance in understanding jet production and parton energy loss in hot QCD medium has spawned a new direction of research: the physics of jets in high-energy nucleus-nucleus collisions at RHIC and at the LHC.

In this manuscript we discuss the modification of jet production in relativistic heavy-ion reactions. We include selected results for inclusive jet productions \cite{5,6}, $Z^0/\gamma^*$-tagged jet cross sections \cite{7,8} and the dijet transverse momentum imbalance \cite{9,10} in high-energy nuclear collisions. Our theoretical simulations will be compared with experimental data on jets when available, and predictions for future measurement are also presented.

\textsuperscript{1}Speaker, Email address: bwzhang@iopp.ccnu.edu.cn.
2. Inclusive jet production in HIC

Within the pQCD collinear factorization approach, jet cross sections at \( O(\alpha_s^3) \) in hadron-hadron collisions can generally be expressed as follows [2, 5, 6]:

\[
\frac{d\sigma}{dV_n} = \frac{1}{2!} \int dV_2 \frac{d\sigma(2 \rightarrow 2)}{d\hat{y}_1 d\hat{y}_2 d\hat{E}_T^1 d\hat{E}_T^2} S_2(p_\mu^1, p_\mu^2) + \frac{1}{3!} \int dV_3 \frac{d\sigma(2 \rightarrow 3)}{d\hat{y}_1 d\hat{y}_2 d\hat{y}_3 d\hat{E}_T^1 d\hat{E}_T^2 d\hat{E}_T^3} S_3(p_\mu^1, p_\mu^2, p_\mu^3). \quad (1)
\]

Here, \( V_n = dy_1 \cdots dy_n d\hat{E}_T^1 \cdots d\hat{E}_T^n \) stands for the multi-parton phase space. Up to \( O(\alpha_s^3) \) two contributions should be taken into account: one from \( 2 \rightarrow 2 \) processes at leading order (LO) and the higher-order virtual corrections (given by the first term in above equation). The second one is from \( 2 \rightarrow 3 \) processes, represented by the second term.

In relativistic heavy-ion collisions, energetic partons or jets produced from the hard scattering will pass through the hot/dense QCD medium and the jet-medium interactions will degrade the energy of jets and alter the jet shapes. In our theoretical simulations of jet production in the nuclear environment we utilize the formalism of in-medium parton splitting [12], which in the soft gluon approximation naturally gives the fully differential distribution of the medium-induced energy loss of fast partons in the QCD medium [13].

Fig. 1 illustrates the dependence of the nuclear modification factor for single jet production \( R_{1-jet}^{AA} \) in central Pb+Pb collisions on the jet size \( R \) with an acceptance cut without (\( p_{T,min} = 0 \) GeV) and with (\( p_{T,min} > 0 \) GeV) collisional energy loss [6]. The left panel of Fig. 1 presents \( R_{1-jet}^{AA} \) due to both initial-state and final-state effects for different jet sizes \( R \) and different coupling constant \( g_{med} \). The influence of cold nuclear matter effects is elucidated. The nuclear modification factor \( R_{1-jet}^{AA} \) shows a clear dependence on jet size because for larger \( R \) more medium-induced gluon radiation will be recaptured within the jet [5]. However, our results in Fig. 1 only include radiative energy loss. If collisional energy loss is included, the dependence of \( R_{1-jet}^{AA} \) on the jet size \( R \) will almost disappear [6]. The right panel shows the ratio of jet cross sections at two different jet radii at three sets of jet-medium coupling constant \( g_{med} \). Non-perturbative effects may affect this ratio, as shown in the figure.

3. Tagged jet production in HIC

To investigate jet production in the nuclear environment and infer the properties of the QGP, it is important to place constraints on the magnitude of the parton shower energy in the medium [11]. Electroweak vector bosons, such as \( Z^0, W^\pm \) and \( \gamma \), produced in conjunction with jets can provide such constraints on average [7, 8, 14]. For example, in \( Z^0 \)-tagged jet production at leading-order obeys the relation \( p_{T,\mu} = p_{T,Z^0} \). Next-to-leading order corrections are very
important, as we will see below. Because $Z^0$ and isolated photons do not interact strongly, they can escape from the hot medium undisturbed. By measuring the difference between $p_{T,1}$ and $p_{T,2}$ in the final state, one can deduce the average energy loss of the jet in QCD matter.

Recently the first $O(G_F/\alpha^2_s)$ calculations on $Z^0/\gamma^*$-tagged jet production and event asymmetry in HIC with final-state parton energy loss effect have been done \cite{7,8}. This approach has been extended to study isolated-photon tagged jets in A+A collisions at $O(\alpha_{em}\alpha^2_s)$ \cite{14}. The left panel of Fig. 2 shows $Z^0/\gamma^*$ tagged jet transverse momentum spectra in p+p and Pb+Pb at $\sqrt{s} = 4.0$ TeV. Due to parton energy loss effects, the tagged jet spectra are shifted to smaller $p_{T,jet}$ values. If we plot the ratio of the cross section in Pb+Pb reaction (per binary collision) to the one in p+p, as shown in the insert of the left panel figure, we observe a transition from the enhancement at small momentum to suppression at the large momentum \cite{7}. The right panel of Fig. 2 presents the event asymmetry, where we define $A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$ with $p_{T,1}$ and $p_{T,2}$ being the transverse momenta of the leading and subleading jets. For the case of $Z^0/\gamma^*$ tagged jet production $p_{T,1} = p_{T,Z^0}$ and $p_{T,2} = p_{T,\gamma^*}$. We observe that with jet-medium interaction the tagged jet $A_J$ distributions in Pb+Pb reactions are significantly broader and shifted to $A_J > 0$. The underlying physics mechanism is medium-induced parton splitting: energy is lost due to large-angle radiation out of the jet reconstruction parameter $R$. Consequently, the smaller the jet radius, the larger the width and the average asymmetry of these distributions will be \cite{8}. 

Figure 2: Numerical simulations of $Z^0/\gamma^*$ tagged jet transverse momentum spectra in p+p and Pb+Pb reactions at $\sqrt{s_{NN}} = 4.0$ TeV (left panel). The $Z^0/\gamma^*$ tagged jet transverse momentum asymmetry for p+p and Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV for two different $R = 0.2, 0.4$ (right panel).

Figure 3: Nuclear modification factors for the dijet invariant mass spectra (left panel) and the dijet transverse energy asymmetry distributions (right panel) in Pb+Pb collisions at the LHC with different nPDFs.
4. Dijet asymmetry in high-energy nucleus-nucleus collisions

Recently, the ATLAS and CMS collaborations at the LHC \cite{15,16} published results on the enhancement of the transverse energy imbalance for dijet in Pb+Pb collisions. This was the first evidence for the quenching of reconstructed jets at the LHC. In the framework of pQCD, we investigate dijet productions to O(α^3_s) at RHIC and the LHC by including both initial- and final-state nuclear matter effects \cite{6,9}.

The dijet invariant mass \( M_{JJ} \) is defined as the invariant mass of all particles in the final state, \( [(\sum p_T^2)^{1/2}] \). Cold nuclear matter (CNM) effects on \( M_{JJ} \) and \( A_J \) distributions in Pb+Pb collisions at \( \sqrt{s} = 2.76 \) TeV are displayed in Fig. 3 by implementing four parametrization sets of nuclear parton distributions (nPDFs). The left panel shows dijet invariant mass spectra are enhanced in a wide region of \( M_{JJ} \) due to CNM effects, which is opposite to the suppression resulting from the final-state QGP effects. The right panel of Fig. 3 shows that the dijet asymmetry distribution is insensitive to the CNM effects and, thus, provides a robust observable to probe the final-state effects in the QGP.

The energy fraction \( z = E_{T2}/E_{T1} \), which represents the transverse energy imbalance of dijet production, plays a similar role to the asymmetry \( A_J \). The normalized dijet asymmetry distributions in central Pb+Pb collisions at \( \sqrt{s} = 2.76 \) TeV and imbalance distribution in central Au+Au collisions at \( \sqrt{s} = 200 \) GeV are presented in Fig. 4. We see that in A+A collisions these distributions are enhanced due to the energy loss of jets propagating the QGP. For radiative energy losses, there is distinct dependence on the jet cone radius \( R \). When the collisional energy dissipation of the art on shower is also considered, the dependence of imbalance distributions on jet sizes is very weak, but the sensitivity to the coupling strength of jet to medium is amplified \cite{6}. Furthermore, jet-medium interactions shift the \( z \) distribution to the left and, thus, give smaller averaged \( \langle z \rangle \) in Au+Au collisions \cite{10}, see the right panel of Fig. 4.

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