Jet Conversions in a Quark-Gluon Plasma

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We report our recent work on conversions between gluon and quark jets as they traverse through a quark-gluon plasma (QGP) and their effects on the nuclear modification factors for quark and gluon jets as well as the ratios of p/π^+ and $\bar{p}/\pi^-$ at high transverse momentum in ultra-relativistic heavy ion collisions.

Keywords: Ultra-relativistic heavy ion collisions; Quark-gluon plasma; Jet quenching; Jet conversions

One of the most interesting observations in central heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) is suppressed production of hadrons with large transverse momentum [1]. This phenomenon has been attributed to the radiative energy loss of partonic jets, produced from initial hard scattering of incoming nucleons, as they traverse through the dense partonic matter created during these collisions [2–4]. Recent studies have shown that elastic scattering of jets in the produced quark-gluon plasma (QGP) also leads to an appreciable loss of their energies [5, 6]. Because of its larger color charge, a gluon jet is expected to lose more energy than quark and antiquark jets [7]. Since the ratio of high momentum protons and antiprotons to pions produced from fragmentation of a gluon jet is much larger than that from a quark jet and there are more gluon than quark jets in proton-proton collisions, a larger energy loss of gluon jets than that of quark jets would lead to smaller p/π^+ and $\bar{p}/\pi^-$ ratios at high transverse momentum in central heavy ion collisions than in proton-proton collisions at same energy [8]. This is in contrast to p/π^+ and $\bar{p}/\pi^-$ ratios at intermediate transverse momentum where they are enhanced in central heavy ion collisions due to production via quark coalescence or recombination [9–11]. Experimentally, data from the STAR collaboration have indicated, however, that the p/π^+ and $\bar{p}/\pi^-$ ratios at high transverse momentum in central Au+Au collisions [12] approach those in p+p and d+Au collisions [13], implying that the ratio of final quark and gluon jets at high transverse momentum is similar to that of initial ones. A possible mechanism for reducing the effect due to difference in quark and gluon jet energy losses in QGP is to allow a net conversion of quark jets to gluon jets via both elastic ($q(\bar{q})g \leftrightarrow gq(\bar{q})$) and inelastic ($q\bar{q} \leftrightarrow gg$) scattering with thermal quarks and gluons in the QGP, an idea first considered in Refs.[14] for deeply inelastic scattering. In this talk, we report the results from our recent study [15].

The conversion rate of a quark jet to a gluon jet or vice versa in a QGP is related to its collisional width due to conversion scattering , i.e., given by the thermal average $\Gamma = \langle \overline{\sum_i |M_i|^2} \rangle$ of the sum of squared amplitudes for these scattering processes after averaging over the spins and colors of initial partons and summing over those of final partons. For the two-body processes $q(\bar{q})g \leftrightarrow gq(\bar{q})$ and $q\bar{q} \leftrightarrow gg$, their amplitudes are well-known. To ensure that a quark (gluon) jet is converted to a gluon (quark) jet in elastic scattering, the gluon (quark) in the final state is required to have a larger momentum.

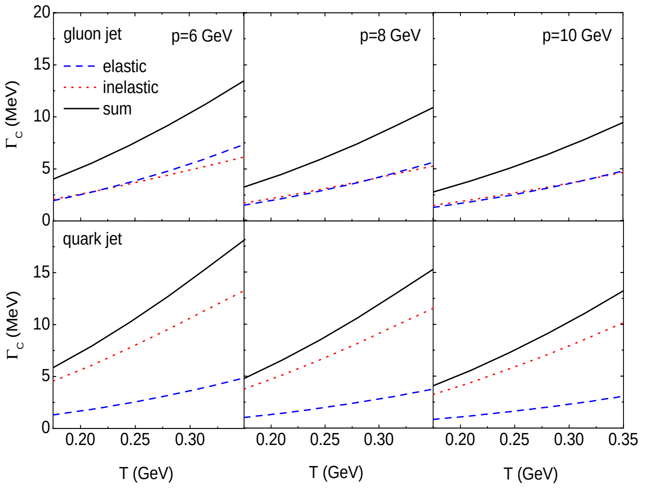

FIG. 1: (Color online) Collisional widths for gluon to quark jet (upper panels) and quark to gluon jet (lower panels) conversions in QGP due to elastic scattering $q(\bar{q})g \leftrightarrow gq(\bar{q})$ (dashed lines) and inelastic scattering $q\bar{q} \leftrightarrow gg$ (dotted lines) as well as their sum (solid lines) as functions of temperature for different quark and gluon momenta of 6 (left panels), 8 (middle panels), and 10 (right panels) GeV/*c*.

To take into account medium effects, we include the thermal masses $m_q = m_g/\sqrt{3} = gT/\sqrt{6}$ [16] of quarks and gluons in the QGP at temperature T, where g is the QCD coupling constant. With $\alpha_s = g^2/4\pi = 0.3$, appropriate for energy scales considered here, calculated collisional widths for gluon to quark jet (upper panels) and quark to gluon jet (lower panels) conversions in a chemically equilibrated QGP are shown in Fig. 1 for different jet momenta. Because of larger (about a factor of two) quark than gluon densities in the chemically equilibrated QGP with thermal quark and gluon masses, contributions from elastic (dashed lines) and inelastic (dotted lines) scattering to the conversion of gluon jets to quark jets are comparable, while inelastic scattering is more important than elastic scattering for quark to gluon jet conversion. Adding both contributions leads to a larger total conversion rate for a quark jet than for a gluon jet, particularly at high transverse momentum, as shown by solid lines in Fig. 1.

The rate of energy loss for quark and gluon jets in QGP is determined by their drag coefficients, which are given by av-

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*On leave from Institute of Particle Physics, Huazhong Normal University, Wuhan 430079, China erages similar to that for the collisional width, i.e., $\gamma(|\mathbf{p}|,T) = \sum_i\langle\overline{|M_i|^2}\rangle - \sum\langle\overline{|M_i|^2}\mathbf{p}\cdot\mathbf{p}'\rangle/|\mathbf{p}|^2$, with $\mathbf{p}$ and $\mathbf{p}'$ denoting the momentum of a jet before and after a collision, respectively. Since we are mainly concerned with conversions between gluon and quark jets in the QGP, we have only considered explicitly the contribution of two-body scattering to their energy losses and mimic the effect due to more important radiative energy loss by introducing a phenomenological multiplication factor K_E.

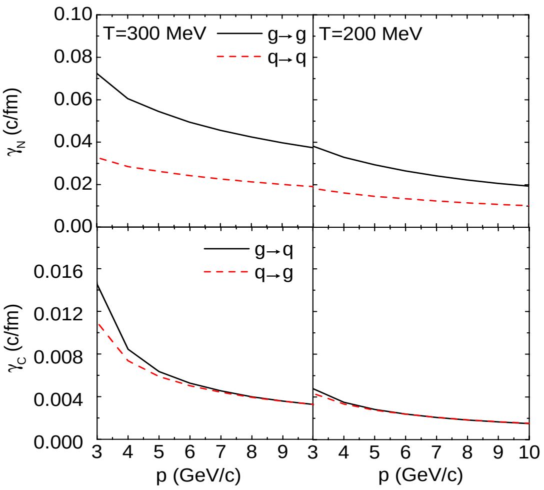

FIG. 2: (Color online) Drag coefficients of gluon and quark jets due to non-conversion (upper panels) and conversion (lower panels) two-body scattering as functions of their momentum in QGP at temperature $T = 300$ MeV (left panels) and $T = 200$ MeV (right panels).

In Fig. 2, we show gluon and quark drag coefficients γ_N due to non-conversion (upper panels) and γ_C due to conversion (lower panels) scattering as functions of their momentum in a QGP at temperatures $T = 300$ MeV (left panels) and $T = 200$ MeV (right panels). It is seen that the drag coefficients due to non-conversion scattering are much larger than those due to conversion scattering. While the drag coefficient for a gluon jet is about a factor of two large than that for a quark jet in non-conversion scattering, they are similar in conversion scattering. Enhancing above calculated drag coefficients due to two-body scattering by a factor $K_E = 4$, we have found that both their values and momentum dependence are similar to those extracted from the energy loss formula derived in Ref. [3] for quark and gluon jet radiative energy losses in a quark-gluon plasma, leading thus to a satisfactory description of the observed quenching of high transverse momentum pions at RHIC.

We have considered central Au+Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV. The initial transverse momentum spectra of quarks, anti-quarks, and gluons at mid-rapidity are obtained from multiplying the quark and gluon transverse momentum spectra from PYTHIA for p+p collisions at same energy by the number of binary collisions (~ 960) in central Au+Au collisions. For the dynamics of formed QGP, we follow that of Ref. [17] by assuming that it evolves boost invariantly in the longitudinal direction but with an accelerated transverse expansion. Specifically, its volume expands in the proper time τ according to $V(\tau) = \pi R(\tau)^2\tau c$, where $R(\tau) = R_0 + a(\tau-\tau_0)^2/2$ is the transverse radius with an initial value R_0=7 fm, τ_0=0.6 fm/c is the QGP formation time, and $a = 0.1c^2$/fm is the transverse acceleration. Starting with an initial temperature $T_i = 350$ MeV, time dependence of the temperature is obtained from entropy conservation, leading to the critical temperature $T_c = 175$ MeV at proper time $\tau_c = 5$ fm/c. For a quark or gluon jet moving through the QGP, the rate for the change of its mean transverse momentum $\langle p_T\rangle$ is then given by $d\langle p_T\rangle/d\tau = -\langle\gamma(p_T,T)p_T\rangle \approx \gamma(\langle p_T\rangle,T)\langle p_T\rangle$ [18]. Because of conversion scattering, the quark or gluon jet can be converted to a gluon or quark jet with a rate given by corresponding collisional width.

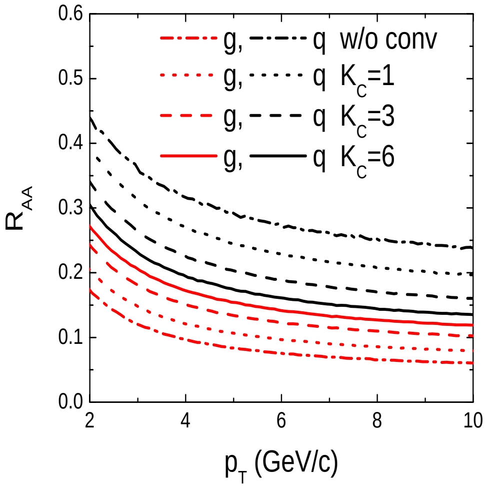

FIG. 3: (Color online) Nuclear modification factors for quark (upper lines) and gluon (lower lines) jets in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as functions of transverse momentum without (dash-dotted lines) and with different enhancement factors $K_C = 1$ (dotted lines), $K_C = 3$ (dashed lines), and $K_C = 6$ (solid lines) for conversion scattering.

The ratio of final quark or gluon jet spectrum to its initial spectrum, defined as its nuclear modification factor R_{AA}, is shown in Fig. 3. Upper and lower dash-dotted lines are those for the quark and gluon jets due to energy loss only. The R_{AA} for gluons is much smaller than that for quarks as a result of larger energy loss for gluon jets than for quark jets. Including conversions between quark and gluon jets through conversion scattering reduces the difference between the quark and gluon R_{AA} as shown by upper and lower dotted lines in the figure.

To obtain proton, antiproton and pion spectra at high transverse momentum from those of quark and gluon jets, we have used the AKK fragmentation functions [19]. While protons and antiprotons are equally produced from gluon fragmentation, fragmentation of quark and antiquark jets is known to produce mainly protons and antiprotons, respectively [12, 13, 20]. We have therefore assumed that no antiprotons are produced from the quark jet and no protons are produced from the antiquark jet as in Ref. [13], where it has been shown that measured charged pion, proton, and antiproton spectra at high transverse momentum from p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV can be reasonably described.

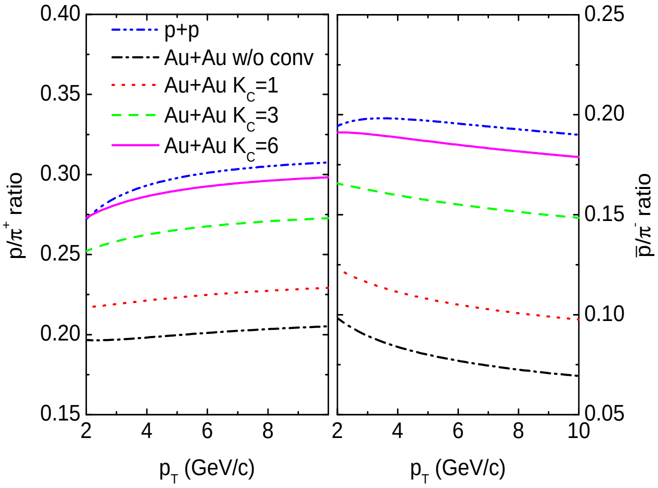

FIG. 4: (Color online) Same as Fig. 3 for p/π^+ (left panel) and $\bar{p}/\pi^-$ (right panel) ratios from quark and gluon jet fragmentation. Dash-dot-dotted lines correspond to p+p collisions at same energy.

Results for p/π^+ and $\bar{p}/\pi^-$ ratios are shown in the left and right panels Fig. 4, respectively. Dash-dotted lines are for the case without conversions between quark and gluon jets, and they are significantly smaller than those in p+p collisions shown by dash-dot-dotted lines. Including conversions between quark and gluon jets increases p/π^+ and $\bar{p}/\pi^-$ ratios, as shown by dotted lines, but are still below those from p+p collisions. To further increase p/π^+ and $\bar{p}/\pi^-$ ratios or reduce the difference between the quark and gluon R_{AA}, we have multiplied the conversion widths shown in Fig. 1 by an enhancement factor K_C. Results using $K_C = 3$ and 6 are shown in Figs. 3 and 4 by dashed and solid lines, respectively. It is seen that for $K_C = 6$ the quark and gluon nuclear modification factors R_{AA} become very close and final p/π^+ and $\bar{p}/\pi^-$ ratios are also similar to those in p+p collisions.

We have assumed in the above that the QGP produced at RHIC is in chemical equilibrium with about twice many quarks and antiquarks than gluons. If the produced partonic matter is a pure gluon or quark matter, resulting p/π^+ and $\bar{p}/\pi^-$ ratios turn out to be slightly smaller or larger than those from a chemically equilibrated QGP. As in the latter case, none of these two scenarios is able to increase the p/π^+ and $\bar{p}/\pi^-$ ratios at high transverse momentum in central Au+Au collisions to approach those in p+p collisions at same energy without requiring a large enhancement factor for the net quark to gluon jet conversion rate.

The observed similarity in the p/π^+ and $\bar{p}/\pi^-$ ratios in central Au+Au and p+p collisions at $\sqrt{s} = 200$ GeV by the STAR collaboration at RHIC thus implies that the net quark to gluon jet conversion rate in these collisions is much larger than that given by the lowest order QCD. This result may not be surprising as previous studies using the multi-phase transport (AMPT) model [21], that includes only two-body scattering among partons, have also shown that a much larger parton scattering cross section than that given by the lowest order QCD is needed to describe many of the experimental observations at RHIC [22]. The large enhancement factor over the lowest order QCD results can be considered as an effective parameter to take into account effects not considered in present study such as higher-order contributions and multi-body effects. Our results could also be another indication that the QGP produced at RHIC is a strongly coupled one [23].

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