Jet-fluid string formation and decay in high-energy heavy-ion collisions

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We propose a new hadronization mechanism, jet-fluid string (JFS) formation and decay, to understand observables in intermediate to high-p_T regions comprehensively. In the JFS model, hard partons produced in jet lose their energy in traversing the QGP fluid, which is described by fully three-dimensional hydrodynamic simulations. When a jet parton escapes from the QGP fluid, it picks up a partner parton from a fluid and forms a color singlet string, then it decays to hadrons. We find that high-p_T v_2 values in JFS are about two times larger than in the independent fragmentation model.

1. Introduction

Models based on the color strings have been highly successful to describe high energy hadronic collisions. A hadron-string cascade picture in high energy heavy-ion collisions works well at AGS[1] and SPS[2] energies, and it also describes some low-p_T observables such as p_T-distribution and η-distribution[3,4] at RHIC energies. However, hadron-string cascade models underestimate the elliptic flow v_2 at RHIC energies, therefore we need partonic pressure in the early stage.

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There are several observations explained as a signal of quark-gluon plasma (QGP) formation at RHIC. A large elliptic flow of bulk matter, suppression of hadron yield at high-p_T, and quark number scaling of elliptic flow at intermediate-p_T, are explained as consequences of hydrodynamical evolution in the early stage,[5] parton energy loss in deconfined matter,[6] and parton recombination,[7] respectively. All of these explanations support the formation of a QGP. While these three pictures — hydrodynamics, fragmentation, recombination — have succeeded in explaining many data at RHIC, there are some problems left unsolved. One of the problems is that elliptic flow generated by radiative energy loss is always smaller than observed data, when we fit the nuclear modification factor.

In this proceeding, we consider jet-fluid string (JFS) formation and its decay processes, where a propagating jet parton picks up a partner parton from the fluid to form a string. If we take account of JFS formation at the end of QGP evolution, JFSs would have a large momentum anisotropy coming from both of the hydro-dynamically evolved fluid parton and the jet parton which suffers the energy loss. Furthermore, we can take account of both quarks and gluons on the same footing in JFS formation. We show the basic concept of the JFS model in Fig.1. We find that JFS decay is an efficient process to produce high-p_T hadrons, and a large energy loss is required to describe the high-p_T hadron spectra. As a result of this large energy loss, high-p_T hadron elliptic flow becomes larger than in the independent fragmentation (IF) picture, while we slightly underestimate the observed v_2 of pions at high-p_T.

There are several attempts to include hadron formation processes from jet (or shower) and fluid (or soft/thermal) partons. Recombination processes of thermal-thermal (TT), thermal-shower (TS), and shower-shower (SS) partons have been considered to form hadrons, which are considered to dominate in a wide range of p_T in
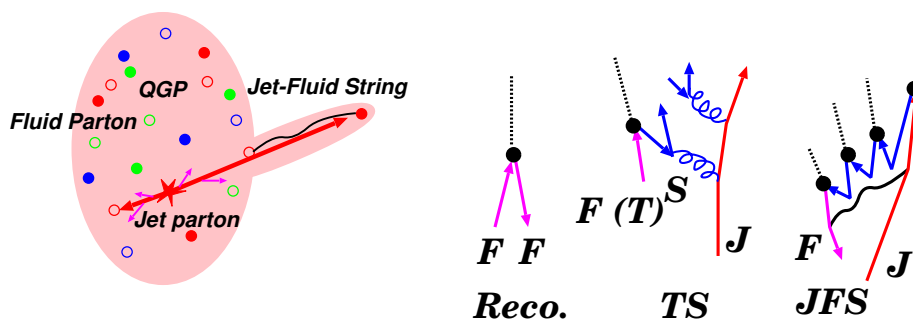

Fig. 1. Left panel: A sketch of JFS model. Produced jet parton traverses in the evolving fluid with energy loss. When it reaches to the QGP phase boundary, it picks up a fluid parton and forms a string and decays into hadrons. Right panel: Schematic view of simple Recombination,[7] Thermal-Shower recombination,[8] and JFS fragmentation (See text).

Ref.[8]. In the quark coalescence model,[9] coalescence of a soft parton and a quenched jet parton (soft-hard coalescence) is found to be important in intermediate-p_T ($3 < p_T < 6$ GeV/c) hadron production. In a recombination model,[10] several processes to combine soft and hard partons are investigated. In these models, quarks are considered to form hadrons (including resonances) directly. On the other hand, we consider *gluons* as well as quarks can form *strings*, which decay into several hadrons in this work.

2. JFS Model

In the JFS model, we have four ingredients to describe high-p_T hadron distribution; mini-jet production, jet parton evolution in the QGP fluid, jet-fluid string formation, and its decay. First, mini-jet partons are generated in the pQCD framework by using the PYTHIA program (version 6.4).[11] We have tuned PYTHIA parameters, K-factor ($K \sim 1.85$) and minimum p_T of jet partons ($p_{T0} \sim 2$ GeV), to reproduce the high-p_T pion spectrum in $p + p$ collisions at RHIC.[12] Secondly, the energy loss of generated jet partons in the QGP fluid is evaluated by using the first order Gyulassy-Lévai-Vitev (GLV) energy loss formula[6] with simplification[13]:

$$\Delta E = C \times 3\pi\alpha_s^3 F_{\text{color}} \int_{\tau_0}^{\infty} d\tau \, \rho(\tau, \boldsymbol{x}(\tau)) \cdot (\tau - \tau_0) \log\left(\frac{2E_0}{\mu^2 L}\right), \tag{1}$$

where F_{color} is a color factor (1 and 9/4 for $q(\bar{q})$ and g), E_0 is the initial energy, $\alpha_s = 0.3$, $\mu = 0.5$ GeV, and $L = 3$ fm. We utilize the fluid evolution obtained by the 3D hydrodynamical model calculation[13,14] with the Glauber type initial condition[15] to evaluate parton density $\rho(\tau, \boldsymbol{x})$, which can be obtained on the web.[16] The overall energy loss factor C is regarded as an adjustable parameter to reproduce R_{AA}, and fixed as $C \sim 6$ by fitting pion p_T-spectrum in mid-central Au+Au collisions as discussed later. Low-p_T ($p_T < 2$ GeV/c) partons are considered to be absorbed in the QGP fluid. Next, a jet parton is assumed to pick up a fluid parton at the boundary of QCD phase transition to form a color singlet string. We here only consider a string formation ($\bar{q}q$ or gg) whose mass is larger than 2 GeV. Fluid parton momenta are obtained from Lorentz-boosted Fermi (Bose) distribution for q or $\bar{q}$ (g). Light flavored (u, d and s) fluid quarks are regarded as massless and the flavor is chosen with the same probability of 1/3. Effects of hadronic resonance formations for a mass smaller than 2 GeV will be reported in the future. Finally, the decay of these strings producing multi-hadrons are evaluated in the Lund string fragmentation model PYTHIA. We also show the results in the independent fragmentation (IF) for comparison.

3. Results and Discussions

In the left panel of Fig. 2, we show the calculated p_T-spectrum of charged pions in mid-central Au+Au collisions at RHIC. The energy loss factor of $C \sim 6$ is found to fit the high-p_T part of the spectrum. When JFS results are combined
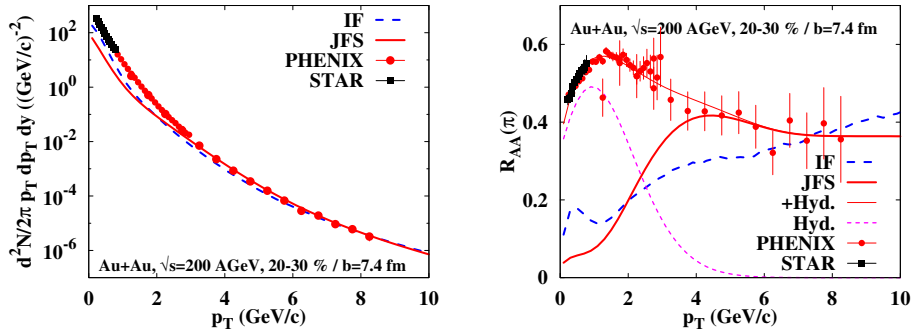
Fig. 2. Left panel: Charged pion p_T-spectrum in mid-central ($b = 7.4$ fm) Au+Au collisions. We show JFS results and those combined with hydrodynamic exponential component. Experimental data of $\pi^{\pm}$ are taken from STAR[18] and PHENIX[20], and π^0 multiplied by two are taken from PHENIX[19] data, with corresponding centrality 20-30%. Right panel: Two types of fragmentation scheme, JFS and IF, are compared in R_{AA} for mid-central collisions. We see saturating behavior at high-p_T in JFS, and agrees with the data well.

with the low momentum hydro dominant part parametrized in the exponential form $Ed^3N_{\mathrm{Hydro}}/dp^3 = A_1 \exp(-p_T/T_1) + A_2 \exp(-p_T/T_2)$, the calculated spectrum agrees with experimental data from STAR[18] and PHENIX.[19,20]

It would be instructive to compare the JFS results with those in a standard picture, in which high-p_T hadrons are formed through the IF of jet partons.[13] In the right panel of Fig. 2, we compare the nuclear modification factor R_{AA} in different hadronization schemes (JFS and IF) by using the same fluid evolution profile. Experimental values are pion p_T-spectrum of Au+Au [18,19,20] normalized by that of $p + p$[12] and N_{coll}. The latter model (IF) is similar to the Hydro+Jet model by Hirano and Nara[13] at high-p_T, but we have not taken care of the Cronin and shadowing effects, which enhance the intermediate-p_T hadrons.

In JFS and IF models, different values of energy loss factor C are needed to fit high-p_T spectrum, $C_{\mathrm{JFS}} \sim 6$ and $C_{\mathrm{IF}} \sim 2$. This is because high-p_T hadron production is easier in JFS decay; when a high-p_T jet parton picks up an approximately collinear low-p_T fluid parton, a light mass string is formed and decays into a fewer hadrons. It is also due to the fragmentation scheme itself.[17] We also find a different p_T dependence of R_{AA}. While R_{AA} saturates at around $p_T \sim 6$ GeV/c in JFS, it slowly grows in the IF model. The latter dependence may be compensated at intermediate-p_T by the Cronin and shadowing effects, but the high-p_T dependence would remain.

Next, we evaluate the elliptic flow v_2 in the JFS model. In the left panel of Fig. 3, we show the calculated p_T dependence of charged pion v_2 in comparison with the experimental data of charged pions.[21,22] We find that the JFS results are around two times larger than IF results, and are close to the data at high-p_T; the
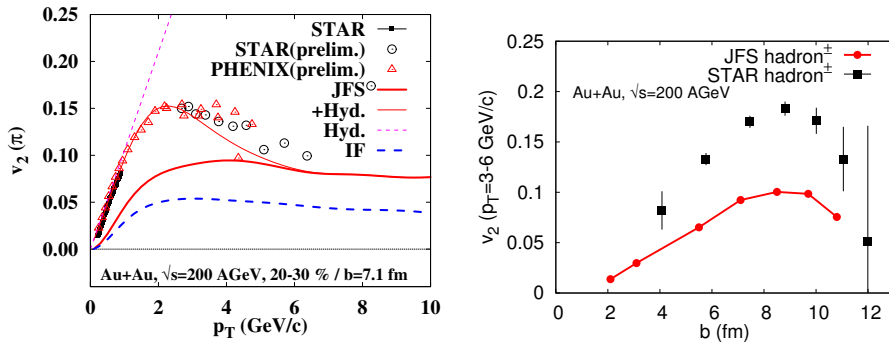
Fig. 3. Left panel: Charged pion v_2 as a function of p_T. We compare JFS results with STAR data[23] of corresponding centrality 20-30%, and PHENIX and STAR preliminary data[22] of minimum-bias events. Right panel: Integrated v_2 of charged hadrons in the range of $3 < p_T < 6$ GeV/c versus impact parameter b. We compare JFS results are compared with STAR data[23].

data may be around 0.10, and JFS gives ~ 0.08 at $p_T > 6$ GeV/c. The difference between JFS and IF mainly comes from the energy loss strength (parameter C in Eq. (1)), and the picked fluid parton v_2 also contributes to enhance the hadron v_2 by around 0.01. The high-p_T v_2 values in JFS is comparable with the results in the Recombination+Fragmentation model[7] ($v_2 \sim 0.10$ at $p_T \sim 5 - 10$ GeV/c), and Hydro+Jet model[13] ($v_2 \sim 0.10$ at $p_T \sim 3$ GeV/c). In the former, the parton energy loss is parameterized by the angle dependent path length, then a sharp edge density distribution is implicitly assumed. In the latter, v_2 decreases and underestimates the data at higher p_T ($p_T > 5$ GeV/c). We also show the combined results of JFS and the Hydro component, whose relative weight is already fixed from the p_T-spectrum fit. Combined results well explain v_2 data up to around 2 GeV/c with Hydro component having $v_2 \propto p_T$. We clearly find that we underestimate the data at intermediate-p_T ($3 - 6$ GeV/c), where recombination processes would be important.

In the right panel of Fig.3, we plot the impact parameter dependence of charged hadron v_2 integrated in the range of $3 < p_T < 6$ GeV/c in comparison with STAR data[23] obtained by four-particle cumulant method. We note that the calculated v_2 values are only around half of the data. However, we would like to point out that the present v_2 values are two times larger than those in a simple simulation with Woods-Saxon density distribution[23] and comparable to those in a simple calculation with hard-sphere density profile (maximum $v_2 \sim 0.10$),[23] while we simulate the parton dynamics with time-evolving 3D hydrodynamics.

4. Summary

We have proposed a Jet-Fluid String (JFS) model as a mechanism to produce high-p_T hadrons. In the JFS model, following components are combined; mini-jet

production in pQCD, energy loss with simplified GLV formula, 3D hydrodynamic simulations, and Lund string decay. JFS decay is found to produce high-p_T hadrons effectively, and we can utilize the 3D hydrodynamical expansion. After fitting high-p_T spectrum in Au+Au collisions, we find that the calculated v_2 values roughly reproduce the data at high-p_T. At intermediate-p_T, JFS results of v_2 are about two times larger than in the independent fragmentation, but still they are around half of the data. This underestimate may be due to the lack of lower mass (< 2 GeV) string or resonance, or the Fluid-Fluid String formation. From these results, we conclude that JFS would be a plausible fragmentation scheme to produce high-p_T hadrons in relativistic heavy-ion collisions.

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