Di-jet correlations in heavy-ion collisions at RHIC energies within the microscopic HSD transport approach

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Abstract. We present a systematic study of correlations in pseudorapidity and azimuthal angle for high-$p_T$ charged hadrons in heavy-ion collisions at the top RHIC energy within the Hadron-String Dynamics (HSD) transport approach. The study shows that a significant part of the high $p_T$ hadron attenuation seen experimentally can be attributed to inelastic interactions of 'leading' pre-hadrons with the dense hadronic environment. It turns out that the 'far-side' correlations are suppressed by up to 60% in central collisions due to the pre-hadronic interactions in line with earlier studies. Since a much larger suppression is observed experimentally in central reactions there should be strong additional partonic interactions in the dense QGP medium created in Au+Au collisions at RHIC. Furthermore, our calculations do not show a 'ridge' on the near-side which also indicates additional non-hadronic correlations.

Partons with high transverse momentum ($p_T$) are informative probes of the high-energy-density matter created in relativistic nucleus-nucleus (A+A) collisions. These partons loose a large fraction of their energy during the early stage of A+A collisions before hadron formation. Such an energy loss is predicted to lead to a phenomenon known as jet quenching [1, 2, 3]. The underlying jet structure for particle production at high-$p_T$ can be probed using di-hadron
correlations, which measure the associated particle distribution in azimuthal angle $\Delta \phi$ and pseudorapidity $\Delta \eta$ with respect to the high-$p_T$ 'trigger' particle. The data on two-particle spectra in the high-$p_T$ region in Au+Au collisions for the c.m.s. energy of the nucleon pair $\sqrt{s_{NN}} = 200$ GeV can be summarized as follows: strong suppression of the away-side hadrons (jet quenching) [4, 5]; specific 'Mach-cone' structure in azimuthal angle $\Delta \phi$ in the region of the away-side jet [5]; long-range pseudorapidity $\Delta \phi$ correlation ('ridge') in the region of the near-side jet [6, 7].

These experimental observations have generated great interest. In particular, various theoretical models are proposed to explain the ridge phenomenon, including (a) longitudinal flow push [8], (b) broadening of quenched jets in turbulent color fields [9], (c) recombination between thermal and shower partons [10], (d) elastic collisions between hard and medium partons (momentum kick) [11], and (e) particle excess due to QCD bremsstrahlung or color-flux-tube fluctuations focused by transverse radial flow [12]. Furthermore, long-range correlations in $\Delta \eta$ might be a consequence of string-like correlation phenomena.

In order to explore especially the latter conjecture of string-like correlations, we use the microscopic HSD transport model [13, 14, 15] for the study of di-jet correlations, which employs dominantly early string formation in elementary reactions and their subsequent decay. We recall, that the HSD model allows to explore systematically the change in the dynamics from elementary nucleon-nucleon to central nucleus-nucleus collisions in a unique way without changing or introducing new model parameters. Inelastic hadron–hadron collisions with energies above $\sqrt{s} \sim 2.6$ GeV are described by the Fritiof model [16] (including Pythia v5.5 with Jetset v7.3 for the production and fragmentation of jets [17]) whereas low energy hadron-hadron collisions are modelled in line with experimental cross sections. We stress that no explicit parton cascading is involved in our present transport calculations.

The di-jet correlations are measured as a function of azimuthal angle $\Delta \phi$ and pseudorapidity $\Delta \eta$ between the trigger and associated particles:

![Figure 1. Near-side and away-side jet correlations from HSD perturbative calculations [18] for p+p (dashed line) and central Au+Au (solid line) collisions at midrapidity for $4 < p_T^{\text{trig}} < 6$ GeV/c and $2 < p_T^{\text{assoc}} < p_T^{\text{trig}}$. The data from Ref. [4] are shown by points. (Adopted from Ref. [18])](image-url)
Figure 2. Angular correlations of associated particles (2 < $p_T^{assoc}$ < 4 GeV/c) with respect to a trigger particle with $p_T^{trig}$ > 4 GeV/c in p+p and in central Au+Au collision events within the HSD transport approach in comparison to the STAR data [4]. The grey area corresponds to the statistical uncertainties of the HSD calculations.

\[ C(\Delta \eta, \Delta \phi) = \frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta \eta d\Delta \phi} \]

where $N_{trig}$ is the number of trigger particles. To obtain the di-jet correlations one has to subtract a background distribution. In our calculations we use the mixed events method which allows to properly subtract the background by taking associated particles for each trigger particle from another randomly chosen event.

The previous HSD analysis of high-$p_T$ spectra in Ref. [18] includes all model details and discusses the nuclear modification factor $R_{AA}(p_T)$ as the function of $p_T$ and centrality. In the earlier studies jets were considered perturbatively and no back-coupling to the medium has been incorporated. Thus possible acceleration of medium particles due to interactions with jets was not taken into account. The HSD perturbative result for angular correlations of di-jets with 4 < $p_T^{trig}$ < 6 GeV/c and 2 < $p_T^{assoc}$ < $p_T^{trig}$ for p+p and central Au+Au collisions at midrapidity is shown in Fig. 1. In extension of the previous investigations we include the full evolution of jets in the transport approach including the response of the medium [19], which is important as the ‘Mach-cone’ and ‘ridge’ structures are attributed to medium evolution effects due to jet-medium interactions.

Angular correlations of associated particles in p+p and central Au+Au collisions with different cuts for $p_T^{trig}$ and $p_T^{assoc}$ are shown in Figs. 2 and 3. There are two maxima: the ‘near-side’ and ‘away-side’ peaks at $\Delta \phi = 0$ and $\Delta \phi = \pi$, correspondingly. Fig. 2 provides a comparison to the data from the STAR Collaboration with the cuts for $p_T^{trig}$ and $p_T^{assoc}$ similar to those in the previous HSD calculations shown in Fig. 1. We find a good agreement between the earlier perturbative [18] and current non-perturbative HSD results [19]. Thus, one may conclude that a medium modification in this kinematic region of $p_T^{trig}$ and $p_T^{assoc}$ is of order few percent in HSD. We mention that the HSD results reasonably reproduce the data for p+p collisions (within error bars). For Au+Au central collisions HSD shows clearly an insufficient suppression of the ‘away-side’ peak at $\Delta \Phi/\pi = 1$. Note also that for the most central collisions the experimentally observed suppression of single-particle spectra at high-$p_T$ can not fully be described by HSD.
Figure 3. Angular correlations of associated particles with different cuts for $p_T^{\text{trig}}$ and $p_T^{\text{assoc}}$ in p+p and in central Au+Au collisions within the HSD transport approach in comparison to the PHENIX data [5]. The grey areas correspond to the statistical uncertainties of the HSD calculations.
$R_{AA}^{HSD}(p_T) = 0.35 \pm 0.4$ whereas $R_{AA}^{exp}(p_T) = 0.2 \pm 0.25$ at $p_T > 4$ GeV/c. Our first conclusion is that the hadron-string medium is too transparent for high-$p_T$ particles (as already pointed out in [18]).

Fig. 3 corresponds to the data of the PHENIX Collaboration with different cuts for $p_T^{trig}$ and $p_T^{assoc}$. For the top panel these cuts are $p_T^{trig} = 2 \div 3$ GeV/c and $p_T^{assoc} = 0.4 \div 1$ GeV/c. This is the kinematic region where one expects a strong medium response to the jet energy loss. The experimental data show the presence of a 'Mach-cone' structure in azimuthal angle $\Delta \phi$ for the 'away-side' jet. This structure does not appear in the HSD simulations.

In Fig. 4 we present the HSD results for p+p and Au+Au collisions for the associated differential particle ($\Delta \eta$, $\Delta \phi$) distribution (1). We use the same cuts as the STAR Collaboration, $4 < p_T^{trig} < 6$ GeV/c and $2 < p_T^{assoc} < 4$ GeV/c [6], and for the PHOBOS Collaboration, $p_T^{trig} > 2.5$ GeV and $p_T^{assoc} > 0.02$ GeV/c [7]. In the HSD transport calculations we obtain on average 0.5 and 5 trigger particles in an event for the STAR and PHOBOS set of cuts, correspondingly. The di-jet correlations obtained in the HSD transport simulations of Au+Au collisions (Fig. 4, bottom panels) do not show a ridge structure in the pseudorapidity for the near-side jet as in the data [6, 7].

Figure 4. The associated particle ($\Delta \eta$, $\Delta \phi$) distribution (1) for p+p (top panels) and central Au+Au (b=0, bottom panels) collisions for the trigger hadron with $4 > p_T^{trig} > 6$ GeV/c (left) and $p_T^{trig} > 2.5$ GeV/c (right) within the HSD transport approach.
In summary, we conclude that the HSD hadron-string medium does not show enough suppression for the away-side jet-associated particles. For the first time the medium response on the interactions has been taken into account in the present non-perturbative HSD calculations in extension to previous perturbative studies [18]. The non-perturbative calculations, however, do not reproduce the experimentally observed ‘Mach-cone’ structure in $\Delta \phi$ for the away-side jet and the long-range rapidity correlations (the ‘ridge’) for the near-side jet while supporting the results from perturbative investigations. It is interesting to check in future whether the recently proposed parton-HSD model (PHSD) [20] – incorporating explicit partonic degrees of freedom and dynamical hadronization – will be able to improve an agreement with the data and reproduce the structures observed by the PHENIX, PHOBOS and STAR Collaborations.

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