Two particle correlations in jets and triggered distributions in hot and cold matter

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The modification of the correlation between high p_T particles produced in association with trigger particles from jets emanating from a heavy-ion collision is shown to be a valuable probe of the matter produced in such collisions. While the minimal modification on the same side as the trigger is consistent with the picture and parameters of partonic energy loss, the possible observation of Cherenkov like correlations on the away side leads to the possibility of the existence of composite structures in the excited matter.

1. Introduction

Collisions between ultra-relativistic nuclei may lead to the production of excited strongly interacting matter [1]. While the produced matter is demonstratively non-hadronic, the prevalent degrees of freedom are as yet unknown. Very high momentum partons produced in such collisions traverse through the produced matter prior to their escape and conceivably fragment outside the medium [2]. Such high momentum partons and any radiated hard gluons (short wavelength gluons) tend to sample the partonic substructure of the prevalent degrees of freedom. The correlations between such energetic particles are modified by the interaction of the fast partons with the dense medium (referred to as hard-hard correlations). Experimentally, one triggers on a high momentum hadron and correlates it with another in its vicinity [3,4]. Softer gluons radiated from such hard partons, due to their longer wavelengths, are sensitive to the presence of extended composite structures such as colored bound states in the medium. The strong interaction of the soft gluons with such structures modifies the dispersion relation of the gluons [5,6] and may lead to observable consequences on the correlations between a high momentum hadron and a somewhat softer hadron (referred to as hard-soft correlations) [7,8]. The soft gluons are not required to fragment outside the medium for such correlations to exist. In these proceedings we elucidate the two particle correlations emanating from both such sources.

2. Hard-Hard correlations

In this section, the focus will lie on the correlations between two hard particles on the same side. It may be argued that both these particles have their origin in a single jet which is modified by its interaction with the medium. Unlike the away side correlations, such quantities require the introduction of a dihadron fragmentation function [9] (which accounts for the number of pairs of particles fragmenting from a jet). Such two-hadron correlations have been measured both in DIS [10] and high-energy heavy-ion collisions [3,4]. While the two-hadron correlation is found slightly suppressed in DIS off a nucleus versus a nucleon target, it is moderately enhanced or unchanged in central $Au + Au$ collisions relative to that in $p + p$. This is in sharp contrast to the observed strong suppression of single inclusive spectra [11,12] in both DIS and central $A + A$ collisions.

The calculation of the modified dihadron fragmentation function in a nucleus proceeds similarly as that for the modified single hadron fragmentation functions [13]. With no additional parameters, one can predict the nuclear modification of dihadron fragmentation functions within the same kinematics. Since dihadron fragmentation functions are connected to single hadron fragmentation functions via sum rules [9], it is more illustrative to study the modification of the conditional distribution for the second rank hadrons,

$$R_{2h}(z_2) \equiv \int dz_1 D_q^{h_1,h_2}(z_1, z_2) \Big/ \int dz_1 D_q^{h_1}(z_1), \tag{1}$$

where z_1 and $z_2 < z_1$ are the momentum fractions of the triggered (leading) and associated (secondary) hadrons, respectively, and z_1 may be integrated over some appropriate range. Shown in the left panel of Fig. 1 is the predicted ratio of the associated hadron distribution in DIS off a nitrogen ($A = 14$) and a Krypton ($A = 81$) target to that off a proton ($A = 1$), as compared to the HERMES experimental data [10]. The suppression of the associated hadron distribution $R_{2h}(z_2)$ at large z_2 due to multiple scattering and induced gluon bremsstrahlung in a nucleus is quite small compared to the suppression of the single fragmentation functions [11,14]. Since $R_{2h}(z_2)$ is the ratio of double and single hadron fragmentation functions, the effect of induced gluon radiation or quark energy loss is mainly borne by the single spectra of the leading hadrons.

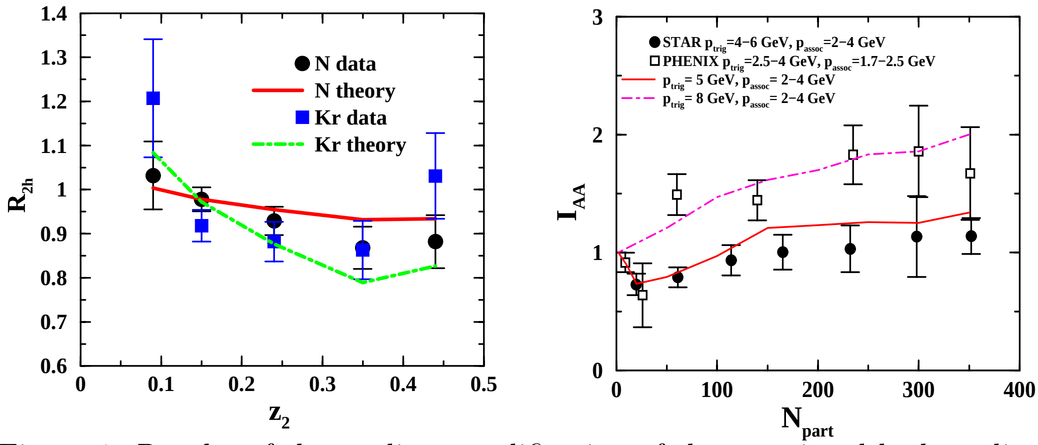

Figure 1. Results of the medium modification of the associated hadron distribution in a cold nuclear medium versus its momentum fraction (left panel) and versus system size in a hot medium (right panel) as compared to experimental data (see text for details).

In high-energy heavy-ion (or $p + p$ and $p + A$) collisions, jets are always produced in back-to-back pairs. Correlations of two high-p_T hadrons in azimuthal angle generally have two Gaussian peaks [3,4]. The integral of the near-side correlation (after background subtraction) over the azimuthal angle can be related to the associated hadron distribution or the ratio of dihadron to single hadron fragmentation functions as in Eq. (1). One has to average over the initial jet energy weighted with the corresponding production cross sections. For a given value of $p_T^{\rm trig}$ of the triggered hadron, one may estimate the average initial jet energy $\langle E_T \rangle$. Because of energy loss in heavy-ion collisions there is a trigger bias effect and $\langle E_T \rangle$ is generally larger than in $p+p$ collisions for a fixed $p_T^{\rm trig}$. We obtain $\langle E_T \rangle$ and its centrality dependence for a given $p_T^{\rm trig}$ from Ref. [15] which in turn determines the average value of $z_1 = p_T^{\rm trig}/\langle E_T \rangle$ and $z_2 = p_T^{\rm assoc}/\langle E_T \rangle$. The ratio of such associated hadron distributions in $Au+Au$ versus $p+p$ collisions, referred to as I_{AA} [3,4], is plotted as the solid line in the right panel of Fig. 1 together with the STAR and PHENIX data, as a function of the number of participant nucleons. In central $Au+Au$ collisions, triggering on a high p_T hadron biases toward a larger initial jet energy and therefore smaller z_1 and z_2. This leads to an enhancement in I_{AA} due to the shape of the dihadron fragmentation functions [16]. This is in contrast to the slight suppression of R_{2h} at large z_2 in DIS off a nucleus (left panel of Fig. 1). The enhancement increases with N_{part} because of increased total energy loss. In the most peripheral collisions, the Cronin effect dominates over energy loss and produces an opposite effect. No doubt, such a schematic estimate does not take into account the distribution of E_T or the dependence of such distribution on the centrality or on $p_T^{\rm trig}$. The inclusion of fluctuations in E_T may result in a revision of the simple picture presented above and is currently in progress.

3. Hard-Soft correlations

For triggered events in central heavy-ion collisions, the gaussian peak associated with the distribution of high p_T associated particles on the away side is almost absent[1]. As the p_T of the associated particle is reduced, curious patterns emerge on the away side. A double humped structure is seen: soft hadrons correlated with a quenched jet have a distribution that is peaked at a finite angle away from the jet [7,8], whereas they peak along the jet direction in vacuum. The variation of the peak with the centrality of the collision indicates that this is not due to the destructive interference of the LPM effect. Such emission pattern can be caused by Cherenkov gluon radiation [17,18], which occurs only when the permitivity for in-medium gluons becomes larger than unity $\epsilon > 1$.

The existance of coloured bound states in a deconfined plasma [19] along with the assumption that these bound states have excitations which may be induced by the soft gluon radiated from a jet allows for a large index of refraction. If the energy of the gluon is smaller than that of the first excited state, the scattering amplitude is attractive leading to an attractive optical potential for such a gluon. As a consequence, the gluon dispersion relation in this regime becomes space-like ($\epsilon > 1$) and Cherenkov radiation will occur. This may be very simply demonstrated in a Φ^3 theory at finite temperature with three fields: ϕ a massless field representing the gluon and two massive fields Φ_1 and Φ_2 with masses m_1 and m_2 in a medium with a temperature T (see Ref.[5] for details). The resulting dispersion relations of the ϕ field for different choices of masses of Φ_1, Φ_2 are shown in Fig. 2 along with the corresponding Cherenkov angles of the radiation in the right panels. We obtain a space-like dispersion relation at low momentum which approaches the light-cone as the momentum of the gluon (p^0, p) is increased. The variation of the corresponding

[1] As shown for the first time at this conference, this away side peak reappears at very high p_T.

angles may be actually detectable in current experiments. Even though we have studied a simple scalar theory, the attraction leading to Cherenkov-like bremsstrahlung has its origin in resonant scattering. Thus, the result is genuine and only depends on the masses of the bound states and their excitations.

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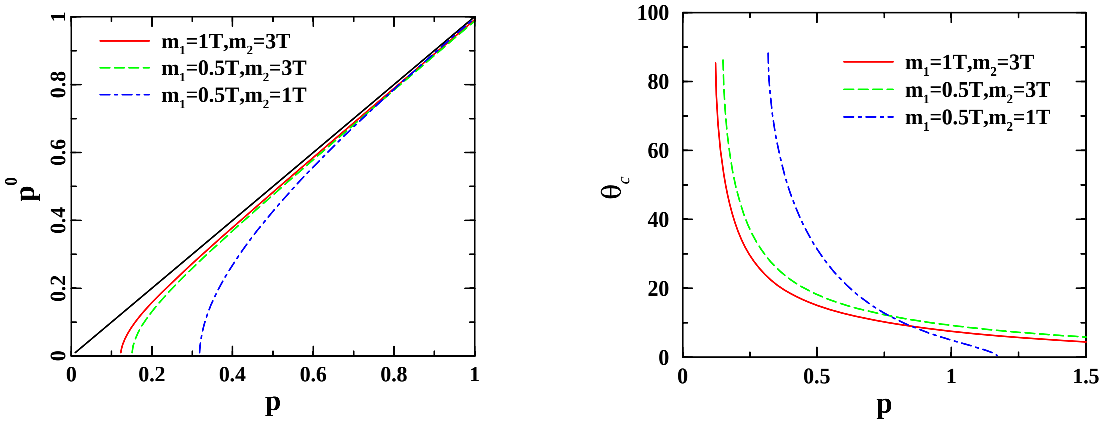

Figure 2. The left panel shows the dispersion relation of ϕ in a thermal medium with transitional coupling to two massive particle. The right panel shows the corresponding Cherenkov angles versus the three momentum of the gluon.

REFERENCES

1. P. Jacobs and X. N. Wang, Prog. Part. Nucl. Phys. **54** (2005) 443.
2. M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077.
3. C. Adler *et al.*, Phys. Rev. Lett. **90** (2003) 082302.
4. S. S. Adler *et al.*, Phys. Rev. C **71** (2005) 051902.
5. V. Koch, A. Majumder and X. N. Wang, arXiv:nucl-th/0507063.
6. A. Majumder and X. N. Wang, arXiv:nucl-th/0507062.
7. J. Adams *et al.*, arXiv:nucl-ex/0501016.
8. S. S. Adler *et al.*, arXiv:nucl-ex/0507004.
9. A. Majumder and X. N. Wang, Phys. Rev. D **70** (2004) 014007; **72** (2005) 034007.
10. P. Di Nezza, J. Phys. G **30**, S783 (2004).
11. A. Airapetian *et al.*, Eur. Phys. J. C **20**, 479 (2001); Phys. Lett. B **577**, 37 (2003).
12. K. Adcox *et al.*, Phys. Rev. Lett. **88**, 022301 (2002); C. Adler *et al.*, Phys. Rev. Lett. **89**, 202301 (2002).
13. X. F. Guo and X. N. Wang, Phys. Rev. Lett. **85**, 3591 (2000); X. N. Wang and X. F. Guo, Nucl. Phys. A **696**, 788 (2001).
14. E. Wang and X. N. Wang, Phys. Rev. Lett. **89**, 162301 (2002).
15. X. N. Wang, Phys. Lett. B **595**, 165 (2004).
16. A. Majumder, E. Wang and X. N. Wang, arXiv:nucl-th/0412061.
17. J. Ruppert and B. Muller, Phys. Lett. B **618**, 123 (2005).
18. I. M. Dremin, JETP Lett. **30**, 140 (1979); I. M. Dremin, arXiv:hep-ph/0507167.
19. E. V. Shuryak and I. Zahed, Phys. Rev. D **70** (2004) 054507