Conical Correlations, Bragg Peaks, and Transverse Flow Deflections in Jet Tomography

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Abstract
We use (3+1)-dimensional ideal hydrodynamics to describe a variety of different jet energy loss scenarios for a jet propagating through an opaque medium. The conical correlations obtained for fully stopped jets, revealing a Bragg peak, are discussed as well as results from pQCD and AdS/CFT. Moreover, we investigate transverse flow deflection. It is demonstrated that a double-peaked away-side structure can be formed due to the different contributions of several possible jet trajectories through an expanding medium.

1. Introduction

The observation of a double-peaked structure in azimuthal di-hadron correlations\cite{1} arose a lot of recent interest, since it was suggested\cite{2} that this structure could be related to the emission angles of Mach cones that are via Mach's law ($\cos \phi_M = c_s/v_{jet}$) directly related to the Equation of State (EoS). In general, energetic back-to-back jets produced in the early stages of a heavy-ion collision propagate through the medium, depositing energy and momentum along their path. Certainly, the properties of this deposition depends on the physics of the jet-medium interactions. Recently, different mechanisms of jet energy loss were analyzed, ranging from weak\cite{3} to strong coupling\cite{4,5}. While the static background offers the possibility to compare to results obtained from AdS/CFT, the expansion of a system formed in a heavy-ion collision will certainly influence any kind of jet deposition scenario\cite{6}. We demonstrate that taking into account various possible trajectories of jets propagating through the plasma\cite{7} lead to a double-peaked structure on the away-side of the final particle correlations. Here, the medium is investigated using Glauber initial conditions, corresponding to a gold nucleus with $r = 6.4$ fm and a maximum temperature of $T_{max} = 200$ MeV. We focus on radial flow only and consider most central collisions, thus neglecting any elliptic flow contribution. For simplicity, the medium is always considered as an ideal gas of massless SU(3) gluons. In our system of coordinates, the beam axis is pointing into the $z$ direction and the associated jet moves along the $x$ direction.

2. A Hydrodynamical Prescription of Jets

Assuming that the energy lost by the jet thermalizes quickly\cite{8}, we solve the ideal hydrodynamical equations using a (3+1)-dimensional SHASTA algorithm\cite{9}

$$\partial_\mu T^{\mu \nu} = S^\nu.$$  \hspace{1cm} (1)
Figure 1: Temperature pattern and flow velocity profile (arrows) after a hydrodynamical evolution of $t = 4.5$ fm for a jet that decelerates according to the Bethe–Bloch formula and stops after $\Delta x = 4.5$ fm. The jet’s initial velocity is $v_{\text{jet}} = 0.999$. In the left panel a vanishing momentum loss rate is assumed while in the right panel energy and momentum loss are considered according to the Bethe–Bloch formalism.

The source term for the decelerating jet is given by

$$S^\nu = \int_{\tau_i}^{\tau_f} \frac{dM' \delta(4)}{d\tau} \left[ x'^\mu - x_{\text{jet}}^\mu (\tau) \right],$$

(2)

where $\tau_f - \tau_i$ denotes the proper time interval associated with the jet evolution and $dM'/d\tau = (dE/d\tau, d\vec{M}/d\tau)$ is the energy and momentum loss along the trajectory of the jet $x'^\mu (\tau) = x_0^\mu + u_{\text{jet}}^\mu \tau$. We assume that $dE(t)/dt = a/v_{\text{jet}}(t)$, according to the Bethe–Bloch formalism \[10\], leading to a Bragg peak as demonstrated in Ref. \[11\]. For a jet starting at $v_{\text{jet}} = 0.999$, the initial energy loss rate can be determined by imposing that the jet stops after $\Delta x = 4.5$ fm, resulting in $a \approx -1.3607$ GeV/fm \[11\]. Fig. 1 displays the temperature and flow velocity profiles of a jet with an energy loss as determined above and vanishing momentum deposition (left panel) as well as an energy and momentum deposition (right panel). In the latter case, the creation of a diffusion wake behind the jet is clearly visible, which leads to an away-side peak in the associated jet direction \[11\] after performing a Cooper–Frye (CF) \[12\] freeze-out. Considering vanishing momentum deposition, the away-side peak is replaced by a conical (double azimuthal peak) distribution at the expected Mach cone angle \[11\].

The away-side diffusion peak in the particle correlation also prevails when considering the Neufeld pQCD source term \[3, 13\], because it involves a large momentum deposition (see Fig. 2). The freeze-out results of the AdS/CFT solution, however, show a double-peaked structure in spite of the diffusion plume due to a novel nonequilibrium strong coupling effect in the “Neck” region as shown in Ref. \[5\].

For the expanding medium, we choose the following ansatz for the energy and momentum deposition of the jet, scaling with the temperature of the dynamical background

$$S^\nu = \int_{\tau_i}^{\tau_f} \frac{dM' \delta(4)}{d\tau} \left[ T(t, \vec{x}) \frac{1}{T_{\text{max}}} \right]^3 \delta(4) \left[ x'^\mu - x_{\text{jet}}^\mu (\tau) \right],$$

(3)

where $dE/dt_0 = 1$ GeV/fm and $dM/dt_0 = 1/vdE/dt_0$. Since deceleration does not alter the freeze-out results significantly \[11\], we do not include this effect in the present study for the
expanding medium. Below, we consider a 5 GeV trigger parton which corresponds to trigger-$p_T$ of $p_T^{\text{trig}} = 3.5$ GeV assuming that a fragmenting jet creates particles with $\sim 70\%$ of its energy.

Experiments can only trigger on the jet direction, thus one has to consider different starting points for the jet which is done according to $x = r \cos \phi, y = r \sin \phi$, where $r = 5$ fm is chosen to model surface emission. We incorporate $\phi = 90, 120, 150, 180, 210, 240, 270$ degrees. To model the experimental situation, the CF freeze-out results are convoluted by a Gaussian representing the near-side jet, leading to a background subtracted, normalized, and jet-averaged CF signal for $b = 0$ fm

$$\langle CF(\phi) \rangle = \frac{1}{\int_{0}^{2\pi} \langle N_{\text{back}}(\phi) \rangle d\phi} \left[ \frac{d\langle N_{\text{con}}(\phi) \rangle}{p_T dp_T dy d\phi} - \frac{d\langle N_{\text{back}}(\phi) \rangle}{p_T dp_T dy d\phi} \right]. \quad (4)$$

This CF signal (see solid lines in the upper panels of Fig. 3) displays a broad away-side peak for $p_T^{\text{assoc}} = 1$ GeV, while a double-peaked structure occurs for $p_T^{\text{assoc}} = 2$ GeV. The reason is that the contribution of the different paths (for $\phi = 90, 180$ degrees see lower panels of Fig. 3) add up to two peaks in the left and in the right part of the away-side (dashed lines in the upper panel of Fig. 3).

It is important to notice that the main contributions to the peaks in the left and right part of the away-side come from non-central jets (see lower panel of Fig. 3).

Thus, we have shown, using a full $(3+1)$-dimensional ideal hydrodynamical prescription, that a double-peaked away-side structure can be formed due to the different contributions of several possible jet trajectories through an expanding medium [3, 7]. Therefore, it seems natural to conclude that this shape, interpreted as a conical signal, does not result from a “true” Mach cone, but is actually generated by the averaging of distorted wakes. Clearly, the emission angle of such a structure is not connected to the EoS. However, these results do not imply that Mach cones are not formed in heavy-ion collision. The effects of longitudinal expansion, finite impact parameter, and different freeze-out prescriptions (like coalescence [14]) remain to be considered.
Figure 3: The normalized, background-subtracted, and path-averaged azimuthal two-particle correlation after performing an isochronous CF freeze-out (solid lines in the upper panels) for 5 GeV jets depositing energy and momentum for a $p_T^{assoc} = 1$ GeV (left panel) and a $p_T^{assoc} = 2$ GeV (right panel). The dashed lines in the upper panels represent the averaged contributions from the different jet paths. The lower panel displays the contribution from the different jet trajectories with $\phi = 90...180$ degrees.

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