The rapidity structure of Mach cones and other large angle correlations in heavy-ion collisions

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Abstract

The pattern of angular correlations of hadrons with a (semi-)hard trigger hadron in heavy-ion collisions has attracted considerable interest. In particular, unexpected large angle structures on the away side (opposite to the trigger) have been found. Several explanations have been brought forward, among them Mach shockwaves and Cherenkov radiation. Most of these scenarios are characterized by radial symmetry around the parton axis, thus angular correlations also determine the rapidity dependence of the correlation. If the observed correlations are remnants of an away side parton after interaction with the medium created in the collision, pQCD allows to calculate the distribution $P(y)$ of the away side partons in rapidity. The measured correlation then arises as a folding of $P(y)$ and the rapidity structure of the correlation taking into account the detector acceptance. This places non-trivial and rather stringent constraints on the underlying scenario. We investigate these dependences and demonstrate that Mach shockwaves survive this folding procedure well whereas Cherenkov radiation scenarios face new challenges.

Key words:

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1 Introduction

Announcements have recently been made by the four detector collaborations at RHIC [1] that a new state of matter, distinct from ordinary hadronic matter
has been created in ultrarelativistic heavy-ion collisions (URHIC). This state of matter has shown a number of unexpected properties already. Recently, measurements of two-particle correlations involving one hard trigger particle have shown a surprising splitting of the away side peak for all centralities but peripheral collisions, qualitatively very different from a broadened away side peak observed in p-p or d-Au collisions [2]. Interpretations in terms of energy lost to propagating colourless [3,4] and coloured [5] sound modes have been suggested for this phenomenon. A comparison with data using a realistic trigger simulation has been performed in [6]. As an alternative mechanism to generate such large angle correlations, Cherenkov radiation from the away side parton has been suggested [7].

In hydrodynamical models for Mach shocks investigated so far [3,9], the simplifying assumption has been made that instead of considering the full three dimensional propagation of the Mach cone through the medium, a boost-invariant 'Mach-wedge' is simulated as an approximation of the situation close to midrapidity. Likewise, in scenarios where large angles arise directly from induced in-medium radiation [7,10], the angular structure is depicted for a single parton. In contrast, in experiment only the rapidity $y_{\text{trig}}$ of the trigger hadron is constrained to be inside the acceptance experimentally. This does however not determine the rapidity $y$ of the away side parton. For this, the conditional probability $P(y)$ given the rapidity and momentum of the parton leading to the trigger hadron can be obtained from pQCD. The measured correlation then results from an integral over all possible $y$ weighted with $P(y)$.

However, most models of jet energy loss would (without considering further interaction of modes excited in the medium) result in a correlation signal that exhibits angular symmetry with respect to the away side parton’s axis. This means that for an away side parton at midrapidity, there is not only a correlation signal at large angle and zero rapidity but also a signal at small angle and large rapidity. Thus, the averaging over $P(y)$ will tend to smear the signal measured at midrapidity out towards smaller angles as compared to a simple midrapidity projection. It follows that the signal before averaging must be at even larger angles than a naive interpretation of the experimental data would suggest.

In the following, we will illustrate this point in greater detail. First, we derive the expression for $P(y)$ for the dominant reaction channels at typical trigger energies from LO pQCD. Then we show how the rapidity structure of the correlation signal arises from the angular information, both for scenarios in which the correlation propagates with the flowing medium and in those where it doesn’t. We demonstrate within the full trigger simulation described in [6] that a Mach shockwave is recovered in the detector acceptance sufficiently undistorted. Since no detailed comparison of a radiative large angle scenario with the data is available, we demonstrate how the large angle correlation
relative to a single away-side jet must move to even larger angles than observed in experiment in such a description.

2 Rapidity distribution of away-side jets

The differential production cross-section of hard partons in A-A collisions can be obtained in leading order pQCD by folding the two particle production cross-sections $d\hat{\sigma}/d\hat{t}$ with the nuclear parton distribution functions $f_{i,j/A}$ (here we use [11]):

$$\frac{d^3\sigma^{AA\rightarrow k+l+X}}{dp_T^2dy_1dy_2} = \sum_{i,j} x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/A}(x_2, Q^2) \frac{d\hat{\sigma}^{ij\rightarrow kl}}{d\hat{t}} .$$  \hspace{1cm} (1)

If the outgoing partons are at rapidities $y_1$ and $y_2$, $x_1$ and $x_2$ are determined by:

$$x_1 = \frac{p_T}{\sqrt{s}} \left[ \exp(y_1) + \exp(y_2) \right] \text{ and } x_2 = \frac{p_T}{\sqrt{s}} \left[ \exp(-y_1) + \exp(-y_2) \right]$$  \hspace{1cm} (2)

Fig. 1. Conditional probability $P(y)$ to find the away side parton at rapidity $y$ if the trigger parton is found at $y_{trig} = 0$ calculated in LO pQCD for the dominant production channels in the low momentum regime as a function of different $p_T$.

The conditional probability distributions $P(y)$ of producing an away-side parton at rapidity $y$ can then be calculated from the normalized cross-section (Eq. (1)) given the trigger parton at $y_1 = 0$. We show the normalized contributions of the two-dominant channels $gg \rightarrow gg$ and $gq \rightarrow gq$ to those conditional probabilities in Fig. 1 for different $p_T$. There is a significant production probability of away-side partonic jets in the range $\pm 2$ for lower $p_T$. 
which gets somewhat narrower as $p_T$ increases (note that the gluonic contribution dominates over the quark contributions in this momentum regime).

3 Rapidity structure of the correlations

The STAR and PHENIX experiments at RHIC measure the correlation signal averaged over rapidity intervals of $\pm 1$ and $\pm 0.35$, respectively. The measured signal must thus be understood as a superposition of individual two-jet production events in which the trigger condition was fulfilled. The trigger condition largely determines the weighted jet-production vertex distribution from which the near-side and away-side partons emerges. Since the trigger must be inside the acceptance (i.e. close to midrapidity), the away-side partons are be distributed in rapidity according to the conditional probability distributions $P(y)$ derived in section 2. We use a radiative energy loss formalism [12] to determine how much energy is deposited in the medium locally while the near-side and away-side partons traverse it. Characteristic $dE/d\tau$ distributions emerging from the folding of the medium evolution with the jet-energy loss calculation are discussed in [6]. Standard radiative energy loss calculations do not lead to angular structures in the away-side jet’s secondaries that could account for the observed large angle correlation, see e. g. [10].

Several explanation have been brought forward to explain such large angle correlations. It has been argued that those could emerge via the excitation of colorless [3,4] or colorful [5] sound modes by the supersonically traveling away-side jet (excitation of ‘Mach cones’) or by the emission of Cerenkov-like gluon radiation [7] by the superluminally traveling jet in the nuclear medium. Colorful sound modes and Cerenkov-like gluon radiation could only contribute in a QGP phase and are only possible if a space-like longitudinal or transverse dispersion relation is realized. This was pointed out first in [5] and it has been shown in [8] that those could emerge in a plasma if bound states are present. A space-like gluon dispersion relation does not emerge in HTL resummed calculations of the longitudinal and transverse plasma modes which have timelike dispersion relations.

First we focus on the excitations of Mach cones. We only give a brief overview since the details of the calculation employed here have already been discussed in [6]. In addition, the rapidity structure is governed by rather general arguments for which details of the excitation are not relevant. We assume that a fraction $f$ of the locally lost energy of the away-side jet is transferred to a collective colorless mode with a linear dispersion relation $E = c_s p$, where $c_s$ is the speed of sound which is determined by the lattice EoS via $c_s^2 = \partial p/\partial \varepsilon$. The evolution of the shock wave is tracked in the medium and the Mach angle is determined via the averaged speed of sound during the evolution until freeze-
out time as $\bar{c}_s = \int_{\tau_E}^{\tau} d\tau c_s(\tau)/(\tau - \tau_E)$. Finally the additional boost to hadrons due to the Mach shock wave is determined at freeze-out. At momentum scales of 1 GeV, well above typical temperature scales in the medium, considerable contributions to the correlation signal are only expected where transverse flow and the Mach shock are aligned [13]. Freeze-out is then calculated using the Cooper-Frye formula.

It has been pointed out in [14] that since the shock wave travels with $c_s$ in the local rest frame, the spatial position of the shock front has to be determined by solving the characteristic equation:

$$\frac{dz}{dt}\bigg|_{z=z(t)} = \frac{u(z, R, t) + c_s(T(z, R, T))}{1 + u(z, R, t)c_s(T(z, R, T))}\bigg|_{z=z(t)}.$$  (3)

In [14] it has been argued that this could destroy a Mach cone signal. This statement seems to be based on a misinterpretation of the measurement: the observed correlation signal is not a Mach cone in position space but the resulting boost of hadrons in momentum space. Thus the position of the Mach cone at freeze-out is relevant only insofar as the longitudinal flow at $z_{\text{final}}$ determines a longitudinal boost in momentum space. This means that a Mach cone in $\phi, y$-space is elongated significantly in $y$ direction by longitudinal flow. For instance for a Bjorken evolution this amounts to an elongation of a factor of about 1.5 in rapidity. We refer to the effect described in this paragraph in the following as the 'effect of longitudinal flow' on the correlation signal where 'longitudinal' refers to the medium expansion parallel to the beam direction and not along the direction of partonic jets.

In order to compare with experiment, one has to fold the elongated Mach cone structure with the away-side jet distribution $P(y)$ and average the emerging correlation signal over the detector’s rapidity acceptance.

This is very different from scenarios where no hydrodynamical mode is excited (e.g. gluon radiation). Here, there is no reason to assume that the excited mode is moving with given velocity relative to the medium. If the emitted mode is not carried away by the flowing medium, the angular structure should translate directly into the observable signal.

This holds true unless re-interaction with the medium is considered which then needs to be taken into account consistently also for the angular distribution. We emphasize that the initial angular distribution of Cerenkov-like gluon radiation in a static medium faces these problems. The situation could be different if one takes into account how the initial emission structure Cerenkov-like gluons might be altered during the expansion of the medium where a changing index of refraction that depends on the medium evolution and the relative direction between jet and flow could introduce significant changes. We point
out that since a theoretical analysis how this influences the predicted angular

correlation signal in a Cerenkov-like gluon radiation scenario has not yet been

performed, it is not clear that this would eventually predict a considerable

elongation of the cone in $y$ direction.

4 Results

We calculate shockwave excitation in the dynamical evolution model frame-

work as outlined above and compare with the $1 < p_T < 2.5$ GeV two-particle
correlation signal for central collisions given a $2.5 < p_T < 4$ GeV trigger aver-
eraged over the PHENIX detector’s rapidity $|\eta| < 0.35$ window. Since the

fraction of the jet’s lost energy that is transferred to the collective sound mode

$f$ cannot yet be calculated from first principles, we treat $f$ as a parameter [6].

![Fig. 2. Calculated 2-particle correlation on the away side for $|y| < 0.35$ and

$1.0 < p_T < 2.5$ GeV. Indicated are also the partial contributions originating from

away side partons going into different rapidity intervals given a trigger parton at

midrapidity.](image.png)

In Fig. 2 we show a comparison of our calculation with the PHENIX two-
particle correlation data [2] on the away-side for $f = 0.75$. Note that zero
degrees is chosen such that it is opposite to the trigger, i.e. at the expected av-
erage position of the away side parton. We also show the relative contribution
to this signal from Mach cones excited by away-side partons from different ra-
pidity intervals. Contributions emerging from Mach cones from away-side jets
produced at $|y| > 2$ are suppressed since only part of the cone contributes in
the detector’s rapidity window $|y| < 0.35$. The maximum of the $\phi$ distribution

\footnote{This value of $f$ differs somewhat from that one previously determined in [6] were

we used to make somewhat more simplistic assumptions about the rapidity structure

of the source.}
is shifted to lower angles $\phi \ll \phi_{\text{max}}$, where $\phi_{\text{max}}$ is the maximum of the calculated correlation signal for all $y$. Contributions emerging from Mach cones from away-side jets produced at $0.5 < |y| < 2$ contribute significantly at angle $\phi \sim \phi_{\text{max}}$. The contribution at low angles $\phi < 40$ degrees is dominated by contributions from the bow shock (i.e. the $(1 - f)$ contribution to the deposited energy) emerging from away-side jets at $|y| < 0.5$. Contributions of away side jets at $|y| < 0.5$ are also important for the correlation signal around $\phi \sim 0$.

This bow shock contribution falls almost completely out of the acceptance of the detector for away-side jets with $|y| > 0.5$ as it is always very close to the rapidity of the away side parton.

Fig. 3 also illustrates that the shift of the maximum of the correlation signal to lower angles $\phi < \phi_{\text{max},\delta(y)}$ is more pronounced, if the elongation of the

![Graph](image-url)
Mach cone in momentum space due to longitudinal flow would not have been taken into account. In addition the width of the two-particle correlation would increase. Such a correlation signal would no longer be in agreement with the PHENIX data. This argument can also be turned around: if no elongation would be present, the maximum of the emission angle from a single away-side jet at fixed $y$ has to be larger than $\phi_{\text{max}}$ and the width considerably smaller than in the measured correlation signal. This is a strong constraint for gluon radiation scenarios, if the angular emission pattern of the radiated gluons is assumed to be directly translated in a two-particle hadronic correlation signal.

5 Conclusions

In this paper we have investigated the rapidity structure of two-particle correlation signals involving one hard trigger particle. We have shown that the rapidity structure of the correlation signal arises because of two different reasons: the away-side jets have a specific distribution in rapidity $P(y)$ that can be determined by pQCD since the near-side jet is almost centered at midrapidity and the Mach shock fronts induced by those away-side jets in the medium are elongated along the rapidity axes by a longitudinal boost in momentum space due to longitudinal flow.

We have demonstrated that Mach cones as excited modes of the nuclear medium lead to the explanation of a correlation signal on the away-side that is in good agreement with the PHENIX data if we employ the dynamical evolution framework developed in [6]. The most significant contribution to the correlation signal at small angles away from the away-side jet’s axis stems from a bow-shock contribution emerging from away-side jets centered around midrapidity ($|y| < 0.5$) whereas the large angle correlation is induced mainly by away-side jets from a wider range of rapidities ($|y| < 2$). We also discussed how the rapidity structure would appear if the medium would not lead to an elongation of the Mach cone along the rapidity axes due to the longitudinal boost in momentum space. The correlation signal would in this case be considerably widened and the maximum of the correlation signal would be shifted to significantly smaller angles. This is what would appear to have to be realized in scenarios in which no hydrodynamical mode is excited (e.g. gluon radiation). Therefore in general scenarios in which the signal does not couple strongly to the longitudinal flow face new challenges.

Our findings hence indicate that medium effects on the signal structure along

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2 We mention that we checked that even if the near-side partonic jet is slightly (e.g. ± 0.3 units in rapidity) off mid-rapidity the shape of the correlation signal (black line in Fig.2) remains essentially unaltered and no additional spread is introduced.
the beam axis are essential in order to explain the observed correlation.

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