Mach Cones in Quark Gluon Plasma

J Casalderrey-Solana
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 70R0319, Berkeley, CA 94720, USA
E-mail: JCasalderrey-Solana@lbl.gov

Abstract. The experimental azimuthal dihadron distributions at RHIC show a double peak structure in the away side ($\Delta \phi = \pi \pm 1.2$ rad.) for intermediate $p_t$ particles. A variety of models have appeared trying to describe this modification. We will review most of them, with special emphasis in the Conical Flow scenario in which the observed shape is a consequence of the emission of sound by a supersonic high momentum particle propagating in the Quark Gluon Plasma.

1. Introduction

One of the major findings of the relativistic heavy ion program at RHIC is jet quenching [1, 2], the suppression of high momentum particles. This suppression is a consequence of the energy loss of partons when they traverse the hot and dense matter formed in a Au-Au collision. Even though at high energy the loss is dominated by radiative processes [3, 4, 5], at intermediate momentum the microscopic mechanism for this process is not clear and there may be significant contribution from collisional processes as well [6].

From the point of view of the fate of the energy lost by the probe, the different scenarios can be classified in two major categories:

- Those in which the energy is deposited in the medium, such as collisional losses or absorption of the radiated gluons. The good hydrodynamical behavior of the medium leads to collective effects, i.e., the formation of a Mach Cone [7, 8, 9].
- Those in which the energy is transferred to propagating modes that leave the interaction region. These may be gluons with dispersion relation close to the vacuum ones [10, 11], or plasma modes with significantly modified dispersion relations (Cherenkov [12, 13, 14] and Plasmon emission [15]).

The redistribution of the jet energy and momentum is reflected in the correlations of particles associated with the jet. In fact, the experimental dihadron correlation function shows, at intermediate $p_t$, a double peak structure in the away side with the maximum of the correlation at $\Delta \phi \approx \pi \pm 1.2$ rad. [16, 17]. The study of three particle correlations also indicates that the structure responsible for this modification is conical [18, 19].

The experimental situation of these measurements is sketched in Figure 1. The strong quenching biases the observed events to be produced close to the surface of the
interaction region so that the path through matter of the trigger jet (A) is minimal. In turn, the back jet (B) travels a long distance through the medium and loses significant part of (if not all) its energy. Thus, the correlations in the away side are strongly modified, either because of the formation of a Mach like front, or because of the medium induced gluon radiation.

The observed structure of the dihadron distribution may be due, instead, to the deflection of the parent parton [20] or the jet shower [21] due to the medium, as opposed to a redistribution of the energy and momentum of the jet, what leads to a non conical particle distribution.

In what is next we will discuss the different models that attempt to explain the observed large angle correlations.


2.1. Hydrodynamic Description.

Under the assumption that a significant part of the lost energy-momentum is absorbed and thermalized, we can describe its evolution by means of hydrodynamics. The energy-momentum conservation equation is modified as,

$$\partial_{\mu}T^{\mu\nu} = J^{\mu},$$

where the source $J$ codifies the loss process as well as the subsequent relaxation of the initial (non-hydrodynamical) disturbance. Even though the total energy and momentum lost constraints the value of $J$, such constraint is not enough to determine it uniquely.

An accurate description of the backreaction of the medium requires the functional form of $J$. Unfortunately, the lack of knowledge about the interaction and thermalization process of the energy lost prevents us from knowing these details. However, within the context of linearized hydrodynamics in a static medium, a systematic study of the
hydrodynamic fields was performed for a general source [8]. The basic finding is that there are two possible excitation modes

- **Sound**, a propagating mode. The interference of sound waves from a supersonic source leads to the Mach Cone, a conical flow directed at an angle from the jet
  \[
  \cos \theta_M = c_s
  \]  
- **Diffuson**, a non-propagating mode. This disturbance remains in the deposition region and leads to a flow in the direction of the energetic particle.

It was also shown that the production of entropy controls the different excitations [8]. The amplitude of the diffuson mode is proportional to the amount of entropy produced in the particle-fluid interaction and the subsequent thermalization. This motivated the introduction of two types of excitations: **Isentropic excitation**, in which no significant entropy is produced and only sound waves are emitted; **no isentropic excitation**, where significant entropy is produced and the diffuson mode is excited.

The two kinds of excitations have different manifestations in the dihadron correlations [8]. The spectrum of soft particles after the jet passage is given by the Cooper Fry prescription (for the static fluid we have equal time freeze out conditions).

\[
\frac{dN}{d^3p} = \int_V \frac{d^3V}{2\pi^3} e^{-\frac{\delta^2}{T+\delta}}, \quad \delta = \frac{E \delta T}{T} + \frac{pv}{T}.
\]  

The angular distribution of low momentum particles \((p \sim T)\) does not reflect the details of the flow picture due to the large thermal broadening. However, the high momentum ones do reflect the flow and, thus, their angular distribution is different for each excitation mechanism. In the non isentropic case, the particles are mainly produced in the direction of the probe. On the contrary, in the isentropic case the flow moves along the Mach angle and the spectrum reflect this fact.

This behavior of the correlation function can be observed in Figure 2. In Figure 2a) the correlation function for non isentropic excitations is plotted and, as a consequence of the diffuson mode, the correlation is concentrated along the jet direction. Similar findings were obtained in [22, 23] where non linear hydrodynamics was solved. In Figure 2b) the correlation function for the isentropic case is studied at different \(p_t\) intervals. As explained above, the low momentum part does not reflect the Mach cone, but as the associate momentum is increased the angle of maximum correlation is shifted off \(\pi\) and saturates at a value given by the Mach angle. However, in order to get significant correlation strength at realistic values of the associate \(p_t\) in this static approximation, very large values of the energy loss (and jet energy) are required.

This large value of the energy loss is an artifact of the static approximation. In a dynamic medium, since the density of the fluid where the perturbation propagates decreases, the effective amplitude of the sound waves increases and one can get larger correlation strength for realistic values of the jet energy loss [24]. The expansion also affects the direction of propagation of the shock. As the RHIC fireball cools down the speed of sound of matter changes from \(c_s^2 = 1/3\) in the QGP phase to \(c_s \approx 0\) in the
Figure 2. Two particle correlation for the different hydrodynamical medium excitations. Left: non-isentropic excitations, with $10 < p^{assoc}_t/T < 25$ and $dE/dx = 63T^2$ (solid) and $dE/dx = 10T^2$ (dashed). Right: isentropic excitations for $dE/dx = 63T^2$ for $1 < p^{assoc}_t/T < 5$ (solid), $5 < p^{assoc}_t/T < 10$ (dashed), $10 < p^{assoc}_t/T < 15$ (dotted), $15 < p^{assoc}_t/T < 20$ (dash-dotted). The quoted value of $dE/dx$ corresponds to $T = 200$ MeV [8].

Since the sound waves move with the speed of sound in the fluid rest frame and due to the strong transverse flow of the RHIC fireball, one expects a broadening in the typical direction of the fluid with respect to $\theta_M$ [29]. The strong longitudinal flow also leads to a $\eta$ broadening of the signal.

These issues were addressed in [30, 31]. In this work, the authors do not solve hydrodynamics but introduced a simplified model that captures the main physics of the hydrodynamical solution. A fraction of energy $f = 0.75$ is transferred into the sound mode, which propagates at the Mach angle. The remaining energy $1 - f$ propagates in the jet direction. The advantage of this approach is that the dynamics of the medium are correctly taken into account, as well as the geometry of production of the jet pairs. The energy loss is computed via the BDMPS [5] approach. The speed of sound is evaluated locally and the effect of the different flows is taken into account. The smearing of the back jet is also considered. The results of this computation can be seen in Figure 3.

Finally, in [32] it was shown that energetic probes propagating through a strongly coupled $\mathcal{N} = 4$ super Yang Mills plasma emit sound waves. These calculations, based on the AdS/CFT correspondence, do not assume thermalization and, even though $\mathcal{N} = 4$ SYM is not QCD, it is important to understand how this happens in this dynamical gauge theory because it may shed light on the jet-medium coupling at RHIC.
2.2. Transport description

Without the assumption of thermalization, the backreaction of the medium can be addressed via a transport model. Such a study was performed in [33, 34], where the two and three particle correlations of the AMPT model were analyzed. This model is a $2 \leftrightarrow 2$ parton cascade in which the hadronization is performed via coalescence. The partonic cross sections are tuned to reproduce the observed elliptic flow. What it is found is that the two particle correlations show a large angle structure similar to what is expected from the Mach Cone. The structure also has a conical shape. The large angle signal grows with the cross section and with the system size. All these observations are consistent with the formation of sound waves in the transport calculations.

3. Transfer of Energy to Propagating Modes

3.1. Large Angle Gluon Radiation

The standard mechanism of energy loss, the medium induced gluon radiation, transfers the energy of the jet into gluons which propagate with the vacuum dispersion relations out of the interaction region and fragment. The multiple scattering with the medium constituents leads to the LPM effect which suppresses the zero angle emission and, thus, the angular distribution of inclusive gluons around the jet axis peaks at an angle off zero [10, 11]. For small enough frequency, this angle can be large.

In this case, the delocalization in rapidity of the back jet plays a crucial role in the manifestation of this angular distribution in the two particle correlations. It was noted in [10] that the angular dependence of the inclusive distribution is washed out as a consequence of the smearing. However, in the experimental measurements in which the large angle correlations are observed, the trigger and associate particles are close in momentum. The tight kinematic window means that the fragmentation into several...
Mach Cones in Quark Gluon Plasma

6

gluons is suppressed. This point was noted in [11], where the authors suggested that only the exclusive fragmentation into one gluon is relevant for the experimental kinematic region. As a consequence of this, a Sudakov form factor is introduced which leads to a much stronger angular dependence of the single gluon radiation probability. This strong dependence survives the smearing and the final single gluon distribution peaks at large angles similar to those of the experimental correlations. The centrality dependence of the peak position is also reproduced.

3.2. Plasma Modes

As opposed to the previous case, for gluons of frequency not much larger than the medium scale ($T \approx 300MeV$) one may expect that the color waves emitted by the high energy particle do not have the vacuum dispersion relations.

In [12] the authors argued that if the quark gluon plasma at temperatures right above the phase transition is formed by bound states [35] (as opposed to free quarks and gluons) the dispersion relation of the gluons in the medium becomes space like as a consequence of the excitation of different levels of those bound states. The frequencies at which this phenomenon happens are of the order of the interlevel spacing.

The fact that the dispersion relations become space-like means that there is spontaneous gluon emission from the probe. In this frequency region, the in-medium speed of the gluons is smaller than 1 and ultrarelativistic particles lead to Cherenkov radiation [12, 14] which has analogous consequences to the Mach Cone for particle correlations. Unfortunately, a concrete model for the structure of the bound states able to explain the experimental correlations was not provided.

A similar mechanism of conical emission has been advocated in [15], where it is the plasmon (longitudinal mode) the one that becomes space like.

4. Deflected Jets

All the previous scenarios are characterized by conical emission of particles in the final state around the jet axis. However some authors have proposed mechanisms in which the large angle structure observed in the dihadron correlations is due to a shift of the entire shower of particles coming from the jet to a finite angle off the jet axis.

In [21] it was argued that the strong flow of matter at RHIC modifies the gluon emission distributions making them non symmetric around the jet axis. This is a consequence of the increase with the fluid velocity of the mean transferred momentum to the jet. This idea was originally proposed to explain the rapidity elongation of the jets, but the strong radial flow can lead to a similar effect in the transverse plane.

Another possibility explored in [20] is that intermediate momentum particles receive large kicks from the particles in the bath as they propagate out the medium. These kicks lead to deflection of the direction of propagation of the parton, which in [20] was treated as a Markovian process. The cooling of the medium, which leads to a reduction of the
typical momentum transfer with time, ensures that the final distribution of particles peaks at certain angle with respect to the jet axis. Estimates of the necessary typical angular deviation of the jet after this kicks leads to very large values.

5. Conclusions

The measured dihadron azimuthal distributions at RHIC have inspired several models that attempt to explain the observed data.

The good hydrodynamical behavior of the matter formed in AuAu collisions implies that the medium reacts collectively to the jet passage, leading to the formation of a Mach shock from sound emission \[7, 8, 9\]. Unfortunately, the freedom in the coupling of the high energy partons and the hydro fields does not allow to make a clean prediction of the observed magnitude of the correlations. Under the assumption that the medium excitation is isentropic, only sound is produced and the particle production associated to the jet passage is peaked at the Mach angle, only dictated by the speed of sound in the medium, \(\Delta \phi = \pi \pm 1.2\) rad. which agrees with the experimental observation. For a fixed trigger \(p_t\), the large angle structure disappears for low \(p_t\) associate particles. As the trigger \(p_t\) increases, the contribution of the jets that go through the medium fills up the dip at \(\Delta \phi = \pi\), but the medium contribution remains the same for soft particles, in particular it does not change its width. These two effects have been also observed \[36\]. Finally, the particle emission is conical, which is consistent with the current three particle correlation analysis \[18, 19\].

The exclusive medium induced one gluon emission distribution also shows features similar to the experimental dihadron distributions \[11\]. In this case the opening angle is solely dependent of the jet energy and the path length traveled. The centrality dependence of the peak is reproduced. Even though there is not explicit calculation yet, the splitting angle should decrease with the associate \(p_t\) for a fixed trigger \(p_t\) since the kinematic window is larger and the process becomes more exclusive. A similar effect leads to fill up of the dip at \(\pi\). Finally, only for the configuration in which the gluon and the parton deflect by a similar angle, this mechanism leads to a conical signal in the 3 particle correlations. Even though it is plausible that is the dominant one, an estimate of the magnitude of this configuration with respect to others has not yet been done.

The emission of plasma modes with space like dispersion relations \[12, 13, 14\], different from what is obtained by usual perturbative techniques, has been also advocated. In this case, the space like character is postulated in order to support the formation of Mach like structures. A physical mechanism based on the presence of multi level bound states right above the phase transition was presented in \[12\], which leads to such dispersion relation. However, in order to accommodate the experimental observations, heavy bound states \((M \sim 1 - 2\) GeV\) are needed. Even though the statement depends on the detailed bound state structure, one expects that the opening angle decreases with the associate \(p_t\), in contradiction with the experimental findings.

Finally, the scenarios based on jet deflection \[20, 21\] seem disfavored by the recent
results on three particle correlations [18, 19].

Acknowledgments

Some of the results presented in this talk were worked out with E. Shuryak and D. Teaney. Discussion with V. Koch, A. Majumder, T. Renk, J. Ruppert, C. Salgado and X. N. Wang were very helpful in preparing this talk.

References

[18] Zhang C (PHENIX Collaboration), these proceedings.
[19] Pruneau C A (STAR Collaboration), these proceedings.