Conical Di-jet Correlations from a Chromo-Viscous Neck in AdS/CFT

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Abstract. We show that Mach-like correlations from heavy quark jets in the Gubser et al AdS/CFT string drag model arise not from the expected (weak) hydrodynamical Mach sound wakes zone but from a near “Neck” zone where strong chromo-viscous field effects dominated and lead to a distinctive stress in the plasma of the form $T^\mu\nu_{Neck} \propto \sqrt{\lambda T_0^\mu\nu Y^\mu\nu(x)/x^2}$. We propose that measurement of the jet velocity dependence of moderate $p_T$ hadrons associated with future identified heavy quark jets at RHIC and LHC could be used to look for this novel source of conical correlations which are unrelated to Mach’s law.

Keywords: AdS/CFT, strongly coupled quark-gluon plasma, heavy quark jets, Mach cones.
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1. Introduction

The observation of Mach-like conical correlations reported from the Relativistic Heavy Ion Collider (RHIC) between tagged jets and associated moderate $p_T$ hadrons [1] has been interpreted [2, 3] as providing additional evidence for fast relaxation time and the near perfect fluid property of strongly coupled quark gluon plasmas (sQGP) [4]. This has generated wide interest because if Mach’s law were valid, $\cos \theta_M = c_s/v$, the correlation pattern could provide a direct measurement of of the time averaged speed of sound in this new state of matter.

The question addressed in this talk is whether the perfect fluid hydrodynamic interpretation via Mach’s law is unique or could there be other novel nonequilibrium dynamical mechanisms involved. We do not consider here the possibility that the experimental ZYAM background subtraction method could be partly responsible for the observed away side dip (see [5]). Nor do we consider more conventional
sources correlations such as those due to jets deflected by the strong radial flow in A+A \cite{6}. Rather, we consider the possibility \cite{7,8,9} that di-jet correlations are connected to Anti-de Sitter/Conformal Field Theory (AdS/CFT) \cite{10} models that have been proposed to explain some of the surprising sQGP properties and dynamics. Supergravity models provided a new way of understanding the unexpected $^{3\times SB}$ entropy law \cite{11} that appears to explain numerical lattice QCD data above $T_c$ and the unexpected low viscosity of SQGP \cite{12} determined from collective elliptic flow data. In addition, these models \cite{7,8} offer an alternate to the pQCD’s way \cite{13} of explaining the high opacity of sQGP inferred from heavy quark jet quenching. Therefore, it is of interest to look for further observables to test the developing AdS/CFT phenomenology via high energy nuclear collisions. The recent di-jet correlation data from RHIC and the future data with identified heavy quark jets at RHIC and LHC offer an attractive possibility.

We discuss here results, first presented at WWND08 and reported in \cite{9}, based on a Cooper-Frye freeze-out analysis of the AdS string drag model stress solutions obtained by Gubser, Pufu and Yarom \cite{7}. We show that away trigger side double-shoulder (Mach-like conical) azimuthal correlation arise in this AdS string drag model not from the Mach wake zone but from a novel chromo-viscous “Neck” region close to the quark. We prove that in the supergravity limit, only the singular Neck zone where strong external fields seem to drive an explosive transverse collective flow that can give rise to conical correlations. We propose that this novel mechanism can be tested experimentally by observing a nearly heavy quark jet velocity independence of the conical correlations in contrast to Mach’s law \cite{9}.

The supergravity string drag model \cite{8} based on the AdS/CFT correspondence reveal (as shown in Fig 1) a rather complex pattern of energy-momentum stress, $T^{\mu\nu}(x)$, perturbations in the wake of a supersonic string moving above a blackbrane in an AdS$_5\times$S$_5$ curved background. The idea is that these solutions provide a holographic image of the stress induced by a heavy quark jet in a very strongly coupled conformal supersymmetric Yang-Mills plasma (SYM) cousin of sQGP/QCD. While strings moving in a 10D gedanken curved bulk seem far removed from the real world, experimentalist at RHIC \cite{14} and LHC \cite{15} can soon test or falsify these ideas by measuring identified heavy quark b/c jet quenching \cite{16} and di-jet correlations \cite{9}.

2. String Drag Stress Zones

The energy-momentum stress induced by a heavy quark moving at velocity $v$ through a supersymmetric Yang-Mills plasma (SYM) can be decomposed into terms that dominate in different spatial regions or zones. In the supergravity $N_c \gg 1, g_{YM}^2 \ll 1, \lambda = g_{YM}^2 N_c \gg 1$ limit the AdS Minkowski boundary stress can be written as

$$T^{\mu\nu}(x) = T_0^{\mu\nu} + \delta T_{Mach}^{\mu\nu} + \delta T_{Neck}^{\mu\nu} + \delta T_{Coul}^{\mu\nu}. \quad (1)$$

We choose coordinates $x_1 = z - vt$ along the direction, $n^{\mu} = (0, -1, 0, 0)$, of the away side jet, and $x_\perp$ as the cylindrical transverse cylindrical radial coordinate.
Conical Di-jet Correlations in AdS/CFT

perpendicular to the jet axis. In this system the beam direction is \((0,0,0,1)\) and the trigger jet is in direction \((-\mathbf{n}\)µ\). The far zone “Mach” part of the stress can be expressed in terms the local temperature and fluid (Landau) flow velocity fields \((T(x_1,x_\perp), U^\alpha(x_1,x_\perp))\) through the Navier-Stokes stress form

\[
\delta T_{\text{Mach}}(x_1,x_\perp) = \frac{3}{4} K \left\{ T^4 \left( \frac{4}{3} U^\mu U^\nu - \frac{1}{3} g^\mu\nu + \frac{\eta}{sT} \partial(\mu U^{\nu}) \right) - T_0^\mu\nu \right\} \theta(1 - 3Kn)
\]

where in the supergravity limit \(\eta/s = 1/4\pi\) \([12]\), \(\partial(\mu U^{\nu})\) is the symmetrized traceless shear flow velocity gradient, and \(Kn\) is the local Knudsen number defined below.

Currently only drag solutions in a static, uniform \(T = T_0\) SYM have been tabulated \([7]\). The background \(N = 4\) infinitely coupled SYM plasma (in the strict \(\lambda = \infty\) limit) is characterized by the remarkably simple equation of state “3/4” of the ideal conformal Stefan-Boltzmann form: \(T_0^{\mu\nu} = P_0 \text{diag}(3,1,1,1)\), with \(P_0 = \epsilon_{\text{SYM}}/3\) and \(\epsilon_{\text{SYM}} = \frac{3}{4} KT_0^0\). The Stefan Boltzmann constant is \(K = (N_c^2 - 1)\pi^2/2\) for this imaginary world of \(N_c^2 \to \infty\) massless adjoint color vector fields, fermions, and bosonic degrees of freedom. This make believe gedanken world offers great theoretical calculational advantages due to its very high \(SO(4,2)\) isometry constraints corresponding to conformal as well as Poincare invariance on the gauge theory side.

No one should be squirmish about jumping into the imaginary \(\text{AdS}_5\) black hole - after all, quarks and gluons, the sQGP, imaginary time partition functions, lattice QCD, pomeron cuts in the complex angular momentum plane, \(x = 0\) CGC and all other “standard model” concepts are simply symbols for specific calculational algorithms invented to reduce data to as few parameters as possible and to predict new falsifiable phenomena. AdS/CFT thus viewed is just a novel set of algorithmic tools with new calculus tricks that have been mostly developed thus far to try to predict strongly coupled non-Abelian gauge dynamics phenomena. Identified heavy quark dijet tomography, among other observables such as direct photons, leptons and hyperons produced in \(A + A\) at RHIC and LHC, will test which algorithm most efficiently captures the experimental constraints: either the downward extrapolation \(3 \sim N_c \ll \infty\), \(\alpha_c \sim \lambda/12\pi \ll \infty\) of the AdS supergravity calculus or the upward extrapolation \(0 \ll \alpha_M = \lambda/12\pi \to \alpha_c\) of the pQCD calculus. Here, \(\alpha_c \approx 0.5\) is Gribov’s critical strong QCD coupling \([17]\) proposed to explain the mystery of confinement. Recent progress to solve numerically radiative pQCD transport theory \([18]\) showed that \(\eta/s\) apparently saturates the AdS/CFT KSS bound \([12]\) when \(\alpha_s\) is extrapolated near \(\alpha_c\).

The apparent complementarity of both approaches when extrapolated near to the critical coupling scale suggests that

\[
\lim_{\alpha_s \to \alpha_c} pQCD \approx sQGP \approx \lim_{\alpha_c \to \lambda/12\pi} \lim_{3^+ \to N_c} \text{AdS/CFT}.
\]

It is generally believed that static equilibrium properties of sQGP are reliably pre-
dicted by lattice QCD and at best AdS/CFT can only provide analytic insight into what went on during $10^{18}$ flosps in the computer. Eq.\(^3\) is however proposed to be relevant to nonequilibrium real time dynamical processes as well for which LQCD provides no information (see, however, the recent results \([19]\)). Future experiments at RHIC and LHC are needed to answer how large a domain of observables and in which corners of phase space Eq. \(3\) may hold. On the theory side, further advances in both pQCD radiative transport theory and in the AdS phenomenology will also be essential to improve and quantify the level of adequacy denoted by $\approx$ symbol.

The theta function, $\theta(1 - 3Kn)$, defines a far “Mach” zone where the equilibration rate is large enough compared to the stress gradient scales that Navier-Stokes dissipative hydrodynamics provides an adequate description of the evolution. Numerical transport theory results indicate that local equilibrium is achieved when the effective number of collisions $1/Kn$ exceeds about 3. Operationally, we define \([20]\) the Knudsen number field $Kn(x) = \frac{\Gamma_s |\nabla \cdot \vec{S}|}{|S|}$ in terms of the $S_i = T_0^0 P_{i0}$ Poynting vector field, and the sound attenuation length $\Gamma_s \equiv 4\eta/3Ts \geq 1/3\pi T_0$ that is bounded from below in ultra-relativistic systems by the uncertainty principle \([21]\). In the conformal supergravity limit $\Gamma_s$ saturates the KSS bound \([12]\) $1/3\pi T_0$. We note that the “Mach” zone of the AdS solution contains not only the minimally diffused conical “Mach” sound wake, but also a near axis trailing diffusion plume \([3, 9]\).

The far zone excludes a compact Neck zone (see Fig.1 insert) close to the heavy quark jet where the local Knudsen number is large and the Navier-Stokes form of the stress is not applicable. In the Neck the effective number of collisions over the scale of stress variation, $1/Kn(x) < 3$, and even uncertainty bounded equilibration rates are too small to maintain local equilibrium. As shown in \([20, 22]\) the non-equilibrium zone is characterized by a stress of the form

$$\delta T_{Neck}(x_1, x_\perp) \approx \theta(3Kn(x) - 1)\frac{\sqrt{\lambda T_0^2}}{x_1^2 + \gamma^2 x_\perp^2} Y^\mu\nu(x_1, x_\perp)$$

where $Y^\mu\nu$ is a dimensionless “angular” tensor field. At very small distances from the jet, $Y^\mu\nu$ reduces to the analytic analytic Yarom stress tensor, $(x_\perp^2 + \gamma^2 x_1^2) T^\mu\nu_{Y}(x_1, x_\perp)$ \([22, 23]\). Fig.2 shows $T_{Y}^{00}/\epsilon_{SYM}$ and its Knudsen field. Note that the $Kn(x) = 1/3$ and the $T_{Y}^{00}/\epsilon_{SYM} = 1/3$ contours are similar for this velocity. They are also similar in the range $c_s < v < 0.9$, where we expect the Mach angle to vary the most. For $v \to 1$, where the Mach angle saturates at $\theta_M = acos(1/\sqrt{3}) = 0.955$ rad, the $Kn$ distribution acquires an additional distinct Lorentz contracted pancake component between the two lobes shown for $v = 0.9$ in Fig.2.

Within the Neck zone, there is also an inner “Head” region where the stress becomes dominated by the contracted Coulomb self field stress of the quark shown in Fig.3. The Head zone can formally be defined as in Ref. \([24]\) by equating the analytic Coulomb energy density \([7, 25]\), $\varepsilon_{C}(x_1, x_\perp)$, to the analytic near zone Yarom energy density \([22]\), $\varepsilon_{Y}(x_1, x_\perp)$. The Head zone is a Lorentz contracted pancake with longitudinal thickness $\Delta x_{1,C} \pi T_0 \sim 1/\gamma^{3/2}$ and an effective transverse
radius $\Delta x_{1,C} \pi T_0 \sim 1/\gamma^{1/2}$, which is in agreement with the general considerations in Ref. [24]. However, the numerical results reported in [20] show that for $v = 0.99$ jets, the Knudsen Neck has a two lobe structure also seen in Fig 2 for $v = 0.9$. The lobes are nearly independent of $v$ and the lobe region thickness is $\Delta x_{1,Kn} \sim 1/\pi T_0 \gg \Delta x_{1,C}$. The second thin pancake component of the $Kn$ that develops for large $\gamma$ (not shown) is similar to the shape of the Head zone. The relative independence of the two lobe component of the Red Neck zone on $v$ is in agreement with the parametric dependence $\Delta x_{1,N} \propto 2/\pi T_0 \sim 6\Gamma_s$ expected from relativistic uncertainty principle bounded dissipation rates [12, 21].

The rich and non-intuitive structure of the near zone $O(\sqrt{\lambda T^2/x^2})$ stress is presumably associated with the non-trivial way in which the Coulomb self field of the jet couples to the viscous but also conductive SYM fluid. Whether the AdS large chromo-viscous dynamics in the Neck/Head region is a nonperturbative generalization of QCD chromo-viscous-hydrodynamics [26, 27] is an interesting open question.

3. Cooper-Fryed AdS Holograms

We now turn to the observable consequences of the AdS string drag stress model by assuming a Cooper-Frye (CF) hadronization scheme [28] as in [3, 29, 30]. This is an strong model assumption on top of the AdS calculus and will need much closer scrutiny in the future. We present it as a first attempt to try to map the AdS boundary stress (the hologram) into hadronic observables.

The axial symmetry with respect to the trigger jet axis allows us to write $U_{\mu}(x_1, x_\perp) = (U_0, U_1, U_\perp \cos \phi, U_\perp \sin \phi)$. The CF associated away side azimuthal distribution of massless ($\sim$ pions) at midrapidity, $f(\phi) = dN/(2\pi p_T^2)dp_Tdyd\phi|_{y=0}$, with respect to the nuclear beam axis is given by [9]

$$f(\phi; V) = \int_V dx_1 dx_\perp x_\perp \left( e^{-p_T/(U_0 - U_1 \cos(\pi - \phi))}I_0(a_\perp) - e^{-p_T/T_0} \right)$$

where $V$ is a particular (Mach, Neck, or Head) zone volume of interest and $a_\perp = p_\perp U_\perp \sin(\pi - \phi)/T$ and $I_0$ is the modified Bessel function.

In the supergravity approximation $a_\perp \sim O(\sqrt{\lambda/N^2}) \ll 1$ and, thus, we can expand the Bessel function to get the approximate equation for the distribution

$$f(\phi) \simeq e^{-p_T/T_0} \frac{p_T}{T_0} \left[ \frac{\langle \Delta T \rangle}{T_0} + \langle U_1 \rangle \cos(\pi - \phi) \right]$$

where deviations from isotropy are then controlled by the following global moments $\langle \Delta T \rangle = \int_V dx_1 dx_\perp x_\perp \Delta T$ and $\langle U_1 \rangle = \int_V dx_1 dx_\perp x_\perp U_1$. Therefore, in the strict supergravity $N_c \rightarrow \infty$ limit, $\Delta T/T_0 \ll 1$ and $\vec{p} \cdot \vec{U}/T \ll 1$ with tiny corrections $O(\lambda/N^2)$ and formally for any fixed $p_T/T_0$ associated hadron the away side distribution is a trivial broad peak about $\phi = \pi$ regardless of the nice Mach wake evident
in Fig. 1. This simple theorem holds independent of the strength of the diffusion wake and holds for any $\Delta T(x)$ and $U(x)$ fields as long as they are small.

The only way that a nontrivial angular correlation can arise in the AdS/CFT string drag model is if we relax the formal $N_c, \lambda \rightarrow \infty$ but $\sqrt{\lambda/N_c^2} \rightarrow 0$ condition used to derive the stress and boldly extrapolate, in the sense of Eq.(3), toward more “physical” parameters to make contact with our QCD world.

4. Numerical Results

We computed $f(\phi; V)$ with $N_c = 3, \lambda = 5.5$ [32] for $v = 0.58, 0.75, 0.90$, in a static uniform background from the tables of $T^{00}$ and $T^{0i}$ provided by Gubser et al [7]. Our total CF volume is defined by $-14 < X_1 (\pi T_0) < 1, 0 < X_\perp (\pi T_0) < 14$, and $\phi \in [0, 2\pi]$. Here we define the head of the jet as the volume where $\xi > 0.3$, which roughly corresponds to the region between $-1 < X_1 (\pi T_0) < 1$ and $0 < X_\perp (\pi T_0) < 2$. We show results for the azimuthal angular correlations in Fig. 4.

The blue curves exclude the chromo-viscous Neck zone from the CF volume. On the other hand, the red Neck curves only include the Neck zone approximated here by $\delta T^{00}(x) > 0.3 \epsilon_{SYM}$. Only the red Neck curves display the double-peak structure, while the “Mach” zone is too weak even in the $N_c = 3$ extrapolation of AdS to produce a dip at $\phi = \pi$. For $v = 0.9$ the two peaks from the Neck zone appear at angles accidentally similar to the putative Mach cone angle. However, the surprising result shown for $v = 0.58$ and $v = 0.75$ indicates that unlike hydrodynamic Mach cones, the double peaks are relatively independent of $v$, in violation Mach’s law indicated by the small arrows. We propose that looking for deviations from Mach’s law for supersonic but not ultrarelativistic identified heavy quark jets could test this novel prediction of the AdS/CFT drag model.

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Conical Di-jet Correlations in AdS/CFT

Fig. 1. The relative energy density perturbation $\Delta \epsilon(z - vt, r)/\epsilon_{SYM}$ due to a heavy supersonic quark jet with $v/c = 0.9$ top and $v = 0.58 > 1/\sqrt{3}$. The numerical results are from Gubser et al [7] for using the AdS/CFT string drag calculus for a $\mathcal{N} = 4$ SYM plasma for $N_c = 3, \lambda = g_{YM}^2, N_c = 5.5$. Left panels show the far zone (amplified by a factor of 100). The Mach wake zone is above the dashed Mach cone line, $\cos \phi_M = 1/(\sqrt{3}v)$, while the Diffusion plume zone lies below that line. The normalized momentum flux flow directions are indicated by arrows. The insert shows the nonequilibrium AdS Neck zone (with Coulomb stress subtracted for clarity). The Neck here is defined approximately by $\Delta \epsilon/\epsilon_{SYM} > 0.3$. Strong transverse energy flow is generated near the jet.
Fig. 2. The Neck zone fractional energy density perturbation $\Delta \epsilon(Yarom)/\epsilon_{SYM}$ for $v/c = 0.9$ using the analytic near field stress from Ref. [22]. The higher temperature (red) $z > vt$ Neck zone with positive $\Delta \epsilon > 0$ contributes more to the correlation signature than the cooler (blue) $z < vt$ Neck zone. The local Knudsen number field for the near zone Yarom stress is shown on right panel. Note that the $3Kn > 1$ region defining the Knudsen Neck Zone is similar to the region defined by large energy density perturbation $\Delta \epsilon/\epsilon_{SYM} > 0.3$.

Fig. 3. The logarithmic contours of the fractional energy density $\Delta \epsilon_{Coul}/\epsilon_{SYM}$ of the Coulomb Head are compared for $v = 0.58, 0.90, 0.99$ cases. Ohm’s law generates a chromo current through the plasma mostly transverse to the jet as $v \rightarrow 1$ and leads via Joule heating to high temperatures/pressures that produce plasma flow transverse to the jet. This observed conical correlation is thus unrelated to Mach’s law in the AdS model.
Fig. 4. Midrapidity azimuthal away side associated angular distribution (scaled in arbitrary units, a.u.) from the Cooper-Frye freezeout of the AdS/CFT string drag model $(T(x), \vec{U}(x))$ fields from [7]. Three cases for various heavy quark jet velocity and associated hadron transverse momentum ranges, 1 : $(v/c = 0.9, p_T/\pi T_0 = 4-5)$, 2 : $(v/c = 0.75, p_T/\pi T_0 = 5-6)$, and 3 : $(v/c = 0.58, p_T/\pi T_0 = 6-7)$, are compared. The short arrows show the expected Mach angles. The red curves showing the double shoulder away side dip (conical) correlations are from the Neck region defined here as where $\Delta \epsilon/\epsilon_{SYM} > 0.3$ (see fig 1). The blue curves result from integrating only in the far Mach zone outside the Neck region and show no sign of the weak Mach wake seen in Fig.1 because of the NO-GO freezeout theorem Eq.(6) remains in force even for our $N_c = 3, \lambda = 5.5$ downward extrapolation from the supergravity limit. The sum total correlation exhibits a double shoulder correlation for $v < 0.9$ arising from the chromo-viscous near zone that is however unrelated to the Mach wakes seen in Fig.1.