Large Observed $v_2$ as a Signature for Deconfinement

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Abstract. We present a new plot for representing $R_{AA}(\phi)$ data that emphasizes the strong correlation between high-$p_\perp$ suppression and its elliptic anisotropy. We demonstrate that existing models cannot reproduce the centrality dependence of this correlation. Modification of a geometric energy loss model to include thermal absorption and stimulated emission can match the trend of the data, but requires $dN_g/dy$ values inconsistent with the observed multiplicity. By including a small, outward-normal directed surface impulse opposing energy loss, $\Delta p_\perp \hat{n}$, one can account for the centrality dependence of the observed Au + Au elliptic quench pattern. We also present predictions for Cu + Cu reactions.

Keywords: Heavy Ion Collisions, Jet Quenching, Deconfinement, RHIC

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1. Introduction

A theoretical model for RHIC mid- to high-$p_\perp$ $R_{AA}(\phi)$ should reproduce both the normalization as well as the azimuthal anisotropy of experimental results; its trend must follow the data on a $v_2$ vs. $R_{AA}$ diagram. This is actually quite difficult due to the anticorrelated nature of $R_{AA}$ and $v_2$; previous models either oversuppressed $R_{AA}$ or underpredicted $v_2$ [1][2][3]. In Fig. (a) and (b), we combine STAR charged hadron $R_{AA}(p_\perp)$ and $v_2(p_\perp)$, PHENIX charged hadron $R_{AA}(p_\perp)$ and $v_2$ centrality, and PHENIX $\pi^0 (p_\perp > 4$ GeV) $R_{AA}(\phi)$ centrality data [4]. We naively averaged the STAR and PHENIX $R_{AA}(p_\perp)$ results to approximately match the $p_\perp$ bins of their corresponding $v_2$ measurements. We report the $R_{AA}$ and $v_2$ modes of the PHENIX $\pi^0 R_{AA}(\phi)$ data. The error bars provided are schematic only.

Hydrodynamics cannot be applied to mid- to high-$p_\perp$ particles due to the lack of equilibrium. Moreover, a naive application would highly oversuppress $R_{AA}$ due to the Boltzmann factors. Parton transport theory attempts to extend hydrody-
namics’ range of applicability to higher transverse momenta. The Mólnar parton
cascade (MPC) succeeded in describing the low- and intermediate-$p_\perp$ $v_2$ results of
RHIC by taking the parton elastic cross sections to be extreme, $\sigma_l \sim 45$ mb \cite{5}. One
sees in Fig. 1 (a) that for the MPC, in this instance run at approximately 30% cen-
trality, no single value of the controlling free parameter, the opacity, $\chi = \int dz \sigma_t \rho_g$,
simultaneously matches the experimental $R_{AA}$ and $v_2$.

pQCD becomes valid for moderate and higher $p_\perp$ partons, and models based
on pQCD calculations of radiative energy loss have had success in reproducing the
experimental $R_{AA}(p_\perp)$ data \cite{6}. These models use a single, representative path-
length; as such, they give $v_2 \equiv 0$. To investigate the $v_2$ generated by including
pathlength fluctuations, we use a purely geometric (neglecting gluon number fluc-
tuations) radiative energy loss model (GREL) based on the first order in opacity
(FOO) radiative energy loss equation \cite{7}; it has been shown that including the
second and third order in opacity terms has little effect on the total energy loss \cite{8}.
The asymptotic approximation of this equation is $\Delta E^{(1)}_{rad}/E \propto (dN_g/dy)L^2 \cite{9}$.
We thus use an energy loss scheme similar to \cite{2}: $\epsilon = \Delta E_{rad}/E = \kappa I$. $\kappa$ is a free
parameter encapsulating the $E$ dependence, etc. of the FOO expression and the pro-
portionality constant between $dN_g/dy$ and $\rho_{part}$. $I$ represents the integral through
the 1D Bjorken expanding medium, taken to be $I = \int_0^\infty dl \int \rho_{part}(\vec{x}_0 + \hat{n}l)$, where
$l_0 = .2$ fm is the formation time. We consider only 1D expansion here because \cite{10}
showed that including the transverse expansion of the medium has a negligible
effect.

The power law spectrum for partonic production allows the use of the momen-
tum Jacobian ($p_\perp^f = (1 - \epsilon)p_\perp^i$) as the survival probability of hard partons. We
distribute partons in the overlap region according to $\rho_{coll} = T_{AA}$ and isotropically in
azimuth; hence $R_{AA}(\phi; b) = \int dx dy T_{AA}(x, y; b)(1 - \epsilon(x, y, \phi; b))^{n_{coll}}$, where $4 \lesssim n \lesssim 5$. The
difference from using $n = 4$ as opposed to $n = 5$ is less than 10%, and in this paper
we will always use the former value. We evaluate $R_{AA}(\phi)$ at 24 values of $\phi$ from 0-2$\pi$
and then find the Fourier modes $R_{AA}$ and $v_2$ of this distribution. Another method
for finding $v_2$, not used here, assumes the final parton distribution is given exactly
by $R_{AA}$ and $v_2$, and then determines $v_2$ from the ratio $R_{AA}(0)/R_{AA}(\pi/2)$; this
systematically enhances $v_2$, especially at large centralities. A hard sphere geometry
is used for all our models, with $R_{HS} = 6.78$ fm ensuring $<r_{LL,W}^2> = <r_{LL,HS}^2>$.

Fig. 1 (a) shows that even with the HS-geometry-enhanced $v_2$, the GREL cannot
recreate both $R_{AA}$ and $v_2$ with a single parameter value.

2. Exclusion of Detailed Balance and Success of the Punch

In \cite{9}, Wang and Wang derived the first order in opacity formula for stimu-
lated emission and thermal absorption associated with the multiple scattering of
a propagating parton, and found $\Delta E^{(1)}_{abs}/E \propto (dN_g/dy)L$. To model this we use
$\epsilon = \Delta E^{(1)}_{rad}/E - \Delta E^{(1)}_{abs}/E = \kappa I - kI_2$, where $\kappa I$ is the same as in the GREL model,
k is a free parameter encapsulating the proportionality constants in the absorp-
tion formula, and \( I_2 \) represents an integral through the 1D expanding medium: 
\[ I_2 = \int_0^\infty dl \frac{1}{\cosh^2 p_{\text{part}}(\vec{x}_0 + \hat{n}l)}. \]
\( I_2 \) has one less power of \( l \) in the integrand; this permits a unique determination of the two free parameters, \( \kappa = .5 \) and \( k = .25 \) fits the 20-30% centrality PHENIX \( \pi^0 \) \( R_{AA}(\phi) \) data point, and allows the model to duplicate the data as seen in Fig. 1 (b). Taking the \( \Delta E/E \) equations seriously, we invert them and solve for \( dN_g/dy; \) thus 
\[ dN_g^{\text{rad}}/dy \sim \kappa \frac{4E}{9\pi C_R \alpha_s^2 \hat{v}_1 l_0 + L} N_{\text{part}}, \]
and 
\[ dN_g^{\text{abs}}/dy \sim k \frac{4E^2}{9\pi C_R \alpha_s^2 \hat{v}_2 l_0 + L} N_{\text{part}}, \]
where \( \hat{v}_1 \) and \( \hat{v}_2 \) correspond to the bracketed terms in the energy loss and energy gain approximations of [2]. For our fitted values of \( \kappa \) and \( k, \) the choice of \( E = 6 \) GeV, \( L = 5 \) fm, and \( \alpha_s = 4 \) gives \( dN_g^{\text{rad}}/dy \sim 1000 \) and \( dN_g^{\text{abs}}/dy \sim 3000 \) for most central collisions. For \( E = 10 \) GeV, \( dN_g^{\text{rad}}/dy \sim 1000 \) and \( dN_g^{\text{abs}}/dy \sim 9000. \) The huge increase of \( dN_g^{\text{abs}}/dy \) to values too large to fit the RHIC entropy data reflects the \( E^2 \) dependence of the Detailed Balance absorption. It seems the only way to have a large enough energy gain while maintaining \( dN_g^{\text{abs}}/dy \sim 1000 \) is to increase \( \alpha_s \) above 1. Note that these calculations were performed using a hard sphere nuclear geometry profile, which naturally enhances the produced \( v_2 \) [2].

Fig. 1. (a) STAR \( h^\pm \) data for 0-5%, 10-20%, 20-30%,... , and 40-60%, PHENIX \( h^\pm \) data for 0-20%, 20-40%, and 40-60%, and PHENIX \( \pi^0 \) data for 10-20%, 20-30%,... , 50-60% centralities. Inability of previous models to fit the data. (b) Addition of thermal absorption or momentum punch to GREL; both fit the data, but absorption requires entropy-violatingly large \( dN_g^{\text{abs}}/dy. \) (c) \( Cu + Cu \) predictions for the three models.

Building on the success of radiative energy loss in reproducing \( R_{AA}(p_T), \) and supposing that latent heat, the bag constant, the screening mass, or other deconfinement effects might provide a small (~ 1 GeV) momentum boost to partons in the direction normal to the surface of emission, we created a new model based on the GREL model that includes a momentum “punch,” \( \Delta p_{\perp}. \) After propagating to the edge of the medium with GREL, the parton’s final, “punched-up” momentum and angle of emission are recomputed, giving a new probability of escape. Fitting to a single \( (R_{AA}, v_2) \) point provides a unique specification of \( \kappa \) and punch magnitude. The results are astounding: one sees from Fig. 1 (b) that a tiny, .5 GeV, punch on a 10 GeV parton reproduces the data quite well over all centralities. Fitting the PHENIX 20-30% \( \pi^0 \) data sets \( \kappa = .18 \) and the aforementioned \( \Delta p_{\perp} = 5 \) GeV. The size of the representative parton’s initial momentum is on the high side for the displayed RHIC data; however, the important quantity is the ratio \( \Delta p_{\perp}/E. \) Moreover, although the geometry used naturally enhances the \( v_2, \) we feel confident that when this model is implemented for a Woods-Saxon geometry, the necessarily larger final punch magnitude will still be relatively small. We expect the magnitude
of this deconfinement-caused momentum boost to be independent of the parton’s
momentum; hence \( v_2(p_\perp) \) will decrease like \( 1/p_\perp \). Moreover, since \( \epsilon \) is larger out
of plane than in, a fixed \( \Delta p_\perp \) enhances \( R_{AA}(\pi/2) \) more than \( R_{AA}(0) \). These are
precisely the preliminary trends shown by PHENIX at QM2005. Keeping the same
values for \( \kappa, k, \Delta p_\perp \), etc. as for \( Au+Au \), we show in Fig. 11(c) the centrality-binned
\( R_{AA} \) and \( v_2 \) results for \( Cu+Cu \) in the three geometric energy loss models.

3. Conclusions

By failing to simultaneously match the \( R_{AA} \) and \( v_2 \) values seen at RHIC we dis-
counted the MPC and pure GREL models. We showed that while including medium-
induced absorption reproduces the \( R_{AA}(\phi) \) phenomena, it does so at the expense
of inconsistent and huge \( dN_g/dy \). But the addition of a mere 5% punch created a
RHIC-following trend. This impulse is small enough to be caused by deconfinement
effects and future calculations should follow the \( p_\perp \) dependence of \( R_{AA}(\phi; p_\perp) \).

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