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.

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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. 1(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 hydro-
moments' range of applicability to higher transverse momenta. The Mőlár 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, $\sigma_1 \sim 45$ mb [8]. One sees in Fig. 1(a) that for the MPC, in this instance run at approximately 30% centrality, 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 [9]. 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 fluctuations) radiative energy loss model (GREL) based on the first order in opacity (FOO) radiative energy loss equation [10]; it has been shown that including the second and third order in opacity terms has little effect on the total energy loss [8]. The asymptotic approximation of this equation is $\Delta E^{(1)}_{\text{rad}}/E \propto (dN_g/dy)L^2$ [10]. We thus use an energy loss scheme similar to [2]: $\epsilon = \Delta E_{\text{rad}}/E = \kappa I$. $\kappa$ is a free parameter encapsulating the $E$ dependence, etc. of the FOO expression and the proportionality constant between $dN_g/dy$ and $\rho_{\text{part}}$. $I$ represents the integral through the 1D Bjorken expanding medium, taken to be $I = \int_0^{\infty} dl l \frac{dN_g}{dy} \rho_{\text{part}}(x_0 + nl)$, where $l_0 = .2$ fm is the formation time. We consider only 1D expansion here because [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 momentum Jacobian ($p_{f,\perp} = (1 - c)p_{i,\perp}$) as the survival probability of hard partons. We distribute partons in the overlap region according to $\rho_{\text{coll}} = T_{AA}$ and isotropically in azimuth; hence $R_{AA}(\phi; b) = \frac{\int dxdy T_{AA}(x_0,y_0;b)(1 - c(x_0,y_0;b))^n}{\int dxdy T_{AA}(x_0,y_0;b)\rho_{\text{coll}}}$, 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 $<r_{1,WS}^2> = <r_{1,HS}^2>$. 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 [9], Wang and Wang derived the first order in opacity formula for stimulated emission and thermal absorption associated with the multiple scattering of a propagating parton, and found $\Delta E^{(1)}_{\text{abs}}/E \propto (dN_g/dy)L$. To model this we use $\epsilon = \frac{\Delta E_{\text{rad}}}{E} - \frac{\Delta E_{\text{abs}}}{E} = \kappa I - k I_2$, where $\kappa I$ is the same as in the GREL model, $k$ is a free parameter encapsulating the proportionality constants in the absorp-
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...tion formula, and $I_2$ represents an integral through the 1D expanding medium: $I_2 = \int_0^\infty dl \frac{\rho_{\text{part}}(\vec{x} + \hat{n}l)}{\rho_{\text{part}}(\vec{x})}$. $I_2$ 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 $dN^{\text{rad}}_g/dy \sim \kappa \frac{4E_c}{9\pi C_B \alpha_s^2 \bar{v}_1} \frac{dL}{dL_{\text{part}}}$, and $dN^{\text{abs}}_g/dy \sim k \frac{4E_c^2}{9\pi C_B \alpha_s^2 \bar{v}_2} \frac{dL}{dL_{\text{part}}}$, where $\bar{v}_1$ and $\bar{v}_2$ correspond to the bracketed terms in the energy loss and energy gain approximations of [9]. For our fitted values of $\kappa$ and $k$, the choice of $E = 6$ GeV, $L = 5$ fm, and $\alpha_s = .4$ gives $dN^{\text{rad}}_g/dy \sim 1000$ and $dN^{\text{abs}}_g/dy \sim 3000$ for most central collisions. For $E = 10$ GeV, $dN^{\text{rad}}_g/dy \sim 1000$ and $dN^{\text{abs}}_g/dy \sim 9000$. The huge increase of $dN^{\text{abs}}_g/dy$ 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 $dN^{\text{abs}}_g/dy \sim 1000$ 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](image)

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 $dN^{\text{abs}}_g/dy$. (c) $C_u + C_d$ 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 ($\sim 1$ 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. 1(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 discounted 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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References