Scaling patterns of the suppression of $\pi^0$ yields in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV: links to the transport properties of the QGP

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(Dated: October 20, 2009)

Suppression measurements for neutral pions ($\pi^0$) are used to investigate the predicted path length ($L$) and transverse momentum ($p_T$) dependent jet quenching patterns of the hot QCD medium produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The observed scaling patterns show the predicted trends for jet-medium interactions dominated by radiative energy loss. They also allow simple estimates of the transport coefficient $\hat{q}$ and the ratio of viscosity to entropy density $\eta/s$. These estimates indicate that the short mean free path ($\lambda$) in the QCD medium leading to hydrodynamic-like flow with a small value of $\eta/s$, is also responsible for the strong suppression observed.

One of the important discoveries at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), has been the observation that high-$p_T$ hadron yields are suppressed in central and mid-central A+A collisions when compared to the binary-scaled yields from p+p collisions [1]. This observation has been attributed to jet-quenching [2] – the process by which hard scattered partons interact and loose energy in the hot and dense quark gluon plasma (QGP) produced in the collisions. Subsequent to such interactions, the partons which do emerge, then fragment into topologically aligned hadrons (jets) which provide the basis for the $\pi^0$ suppression measurements.

There is considerable current interest in the use of jet quenching as a quantitative tomographic probe of the QGP. Recent theoretical efforts have centered on investigations of the energy loss mechanism for scattered partons which propagate through this medium. Two such mechanisms are; (i) scatterings off thermal partons in binary elastic collisions and (ii) Gluon bremsstrahlung with the Landau-Pomeranchuk-Migdal (LPM) [3] effect. The latter has been investigated via different formalisms [4, 5, 6, 7, 8, 9, 10]. Studies of the relative importance of both jet quenching mechanisms have also been made [11, 12, 13, 14]. To date, a conclusive mechanistic picture is not yet emerged.

Initial quantitative studies with models which incorporate the time evolution of the QGP medium via relativistic ideal (3+1)-dimensional hydrodynamical simulations, are currently underway [15, 16]. However, the value of such studies rests heavily on accurate knowledge of the dominant mechanism/s for jet quenching. Therefore, it is important to pursue validation tests which can lend insight or provide a clear distinction between different energy loss mechanisms.

The experimental probe commonly exploited for jet-quenching studies in AA collisions is the nuclear modification factor ($R_{AA}$):

$$ R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN}{dydpt_T} \frac{T_{AA}}{\sigma_{pp}/dydpt_T}, $$

where $\sigma_{pp}$ is the particle production cross section in p+p collisions and $\langle T_{AA} \rangle$ is the nuclear thickness function averaged over the impact parameter range associated with a given centrality selection

$$ \langle T_{AA} \rangle = \frac{\int T_{AA}(b) \, db}{\int (1 - e^{-\sigma_{pp}^{incl}(T_{AA}(b))}) \, db}. $$

The corresponding average number of nucleon-nucleon collisions, $\langle N_{coll} \rangle$ is routinely obtained via a Monte-Carlo Glauber-based model calculation [18, 19].

In this letter we use $R_{AA}$ measurements to perform validation tests which addresses the question of whether or not medium induced gluon radiation is a dominant mechanism for jet-energy loss.

![Graphs showing nuclear modification factor ($R_{AA}$) for $\pi^0$ production in Au+Au collisions at different centralities and transverse momenta.](image-url)
The measurements employed for these tests are the recently published \( R_{AA}(p_T) \) and \( R_{AA}(\Delta \phi, p_T) \) data for \( \pi^0 \) [17, 20]. Here, \( \Delta \phi \) is the azimuthal angle relative to the reaction plane. A subset of these data is shown as a function of \( p_T \) for several centrality selections in Fig. 1. The minimum bias results in the top left panel indicate that, for \( 2.5 \lesssim p_T \lesssim 5 \text{ GeV/c} \), suppression increases with \( p_T \) to the value \( R_{AA} \sim 0.3 \). By contrast, a much weaker \( p_T \) dependence is observed for \( p_T \gtrsim 5 \text{ GeV/c} \), with a hint that the suppression decreases as \( p_T \) increases. The same trends are evident for all centrality selections spanning central and mid-central collisions, albeit with different absolute magnitudes. These trends provide an important constraint for our tests, as discussed below.

To perform validation tests on the data for medium induced gluon radiation, we use the “pocket formula” of Dokshitzer and Kharzeev (DK) [8]. This formula gives the quenching of the transverse momentum spectrum for jets produced from scattered light partons [8] as:

\[
R_{AA}(p_T, L) \simeq \exp \left[ -\frac{2 \alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}}{p_T}} \right],
\]

where \( \alpha_s \) is the strong interaction coupling strength, \( C_F \) is the color factor, \( L \) is the path length [of the medium] that the parton traverses and \( \hat{q} \) is the transport coefficient which reflects the squared average transverse momentum exchange per unit path length, between the medium and the parton.

Here, there are two essential points. First, Eq. 1 is derived with an explicit assumption that the mechanism for energy loss is medium induced gluon radiation [21]. Second, this equation gives specific testable predictions for the dependence of \( R_{AA}(p_T, L) \) on \( L \) and \( p_T \) for \( p_T > 5 \text{ GeV/c} \). That is, \( \ln[R_{AA}(p_T, L)] \) should scale as \( L \) and \( 1/\sqrt{p_T} \) respectively (i.e. \( \ln[R_{AA}(p_T, L)] \) should show a linear dependence on both \( L \) and \( 1/\sqrt{p_T} \) if medium induced gluon radiation is indeed the dominant energy loss mechanism).

To study the \( L \) dependence, the transverse size of the system \( \hat{R} \) was used as an estimate for the angle averaged path length \( L \), as well as to determine its value in- \( (L_x) \) and out- \( (L_y) \) of the reaction plane. For each centrality selection, the number of participant nucleons \( N_{\text{part}} \), was estimated via a Monte-Carlo Glauber-based model [18, 19]. The corresponding transverse size \( \hat{R} \) was then determined from the distribution of these nucleons in the transverse \( (x, y) \) plane via the same Monte-Carlo Glauber model:

\[
\frac{1}{\hat{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)},
\]

where \( \sigma_x \) and \( \sigma_y \) are the respective root-mean-square widths of the density distributions; here, averaging is performed over configurations. For these calculations, the initial entropy profile in the transverse plane was assumed to be proportional to a linear combination of the number density of participants and binary collisions [22, 23]. The latter assures that the entropy density weighting is constrained by hadron multiplicity measurements.

The results from our validation tests for medium-induced gluon radiation are summarized in Figs. 2 – 4. Figs. 2 (a) and (b) show plots of \( \ln[R_{AA}(p_T, L)] \) vs. \( 1/\sqrt{p_T} \) for \( p_T > 5 \text{ GeV/c} \) and centrality selections of 0-5\% (L=1.90 fm) and 20-30\% (L=1.45 fm) respectively. The dot-dashed curve in each panel is a fit to the data (see text).
ments in- and out of the reaction plane for $\pi^0$s detected in- and out of the reaction plane. The data are taken from Ref. 24 for the selection 5 $< p_T < 8$ GeV/c. Error bars are statistical only. (b) ln $[R_{AA}(p_T,L)]$ vs. $L_{xy}$, the path length in- and out of the reaction plane. The systematic errors for both (a) and (b) are similar to those of Fig. 3. The dashed curve is a linear fit to the data.

Further evidence for this linear dependence is also evident in Fig. 3 where we show results for $R_{AA}$ measurements in- and out of the reaction plane for $\pi^0$s with 5 $< p_T < 8$ GeV/c 24. Panel (a) shows that, for the same number of participants, $\pi^0$ suppression is larger out-of-plane than it is in-plane. However, panel (b) shows that, when plotted as ln $[R_{AA}(p_T,L_{x,y})]$ vs. $L_x$ and $L_y$, the in-plane and out-of-plane data show a single linear dependence on $L_{x,y}$. This same dependence is found for all other reaction plane orientations for $p_T > 5$ GeV/c. This confirms that the azimuthal anisotropy of particle yields (at high $p_T$) stem from the path-length dependence of jet quenching. The dashed curve (fit to the data) in the figure reinforces the predicted linear dependence of these data on the path length (cf. Eq. 1).

The fits to the data in Fig. 3 (for the two $p_T$ cuts) indicate an intercept $L \approx 0.6$ fm, which suggests a minimum path length requirement for the initiation of $\pi^0$ suppression. Such a requirement is akin to the plasma formation or cooling times proposed in Refs. 24, 22.

The corresponding slopes (for $p_T > 5$ and $p_T > 10$ GeV/c) indicate similar magnitudes with a hint of a small decrease in slope with increasing $p_T$. This relatively weak $p_T$ dependence (which is also reflected in Fig. 3) could be an indication that $\hat{q}$ has a dependence on $p_T$, eg. $\hat{q} = \hat{q}_0 \left( \frac{p_T}{T} \right)^\lambda$ where $\lambda$ is a small fractional power 26.

To obtain an estimate of the magnitude of $\hat{q}$, we use Eq. 1 in conjunction with the slope, $-1.26 \pm 0.06$ fm$^{-1}$, extracted from Fig. 3 for $p_T > 10$ GeV/c. This gives the value $\hat{q} \approx 0.75$ GeV$^2$/fm for the values $\alpha_s = 0.3$ 16, $C_F = 9/4$ 27 and $\hat{L} = n = 8.1 \pm 0.05$ 20. This estimate of $\hat{q}$, which can be interpreted as a space-time average, is comparable to the recent estimates of $\sim 1-2$ GeV$^2$/fm obtained from fits to hadron suppression data (for the most central Au+Au collisions) within the framework of the higher twist (HT) expansion 28, 29 and the Gyulassy-Levi-Vitev (GLV) scheme 30, 31. It is, however, much less than the value recently extracted via the approach of Arnold, Moore and Yaffe (AMY) 16, 32 and that of Armesto Salgado and Wiedemann (ASW) 16, 33.

The ratio of the shear viscosity ($\eta$) to the entropy density ($s$) can also be estimated as 33:

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

where $T$ is the temperature. This estimate can be compared to the value of $4\pi \hat{q}^2 \approx 1.3 \pm 0.3$ extracted from flow data 23 for $T \sim 220$ MeV 35. It is noteworthy
that if we use this same temperature in conjunction with our extracted value for $\hat{q}$ (in the above equation), we obtain a strikingly similar estimate for $\eta/s$. We conclude therefore, that the relatively short mean free path in the plasma which drives hydrodynamic-like flow with small shear viscosity, is also responsible for the strong jet quenching observed.

In summary, we have performed validation tests of the scaling properties of jet quenching to investigate the dominant mechanism for jet-energy loss. Our tests confirm the weak $1/\sqrt{p_T}$ dependence, as well as the linear dependence on path length ($L$ and $L_{x,y}$) predicted by Dokshitzer and Kharzeev, for jet suppression dominated by the mechanism of medium-induced gluon radiation in a hot and dense QGP. The quenching patterns indicate a minimum path length requirement for the initiation of $\pi^0$ suppression (corona), suggests a possible $p_T$ dependence for $\hat{q}$ and gives the estimate $\hat{q} \sim 1$ GeV/$\text{fm}$ which is comparable to that obtained within the framework of the HT and GLV models. This estimate also indicates a small value of $\eta/s$ which is in good agreement with that obtained via flow measurements. The present study will have to be extended to the heavy quark systems to arrive at an even more definitive conclusion about the role of a perturbative radiative energy loss mechanism. Nonetheless, these results will undoubtedly provide important model constraints in future attempts to use jet-quenching as a quantitative tomographic probe of the QGP.

Acknowledgments

We thank D.E. Kharzeev for crucial and interesting discussions. This work was supported by the US DOE under contract DE-FG02-87ER40331.A008.

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