Event-by-Event Jet Quenching and Higher Fourier Moments of Hard Probes

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Abstract
We investigate the effect of event-by-event fluctuations of the fireball created in high energy nuclear collisions on hard probe observables. We show that spatial inhomogeneities lead to changes in the nuclear suppression factor of high momentum hadrons which can be absorbed in the quenching strength \( \hat{q} \). This can increase the theoretical uncertainty on extracted values of \( \hat{q} \) by up to 50%. We also investigate effects on azimuthal asymmetries \( v_2 \) and dihadron correlation functions. The latter show a promising residual signal of event-by-event quenching that might allow us to estimate the size of spatial inhomogeneities in the fireball from experimental data.

Keywords: Quark Gluon Plasma, Heavy Ion Collisions, Energy Loss

High momentum quarks and gluons are a convenient probe of the quark gluon plasma bubble formed in high energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Those hard partons are produced in rare hard processes in nuclear collisions. The process how such quarks and gluons convert into jets of hadrons in the vacuum, e.g. if the they are produced in \( p + p \) collisions, is fairly well documented. On the other hand we are still working to fully understanding how the same process plays out in a medium with which those partons interact. Over the years several ways to compute the energy loss of energetic partons in quark gluon plasma have emerged \cite{1, 2, 3, 4}, using different approximations to master the full complexity of the problem (see \cite{5, 6} for recent reviews).

Calculations based on these models fare well with data from RHIC on nuclear modification factors \( R_{AA} \) for leading hadrons if the overall quenching strength can be adjusted as a parameter. This parameter is often chosen to be \( \hat{q} \), the average momentum square transferred to the high momentum parton per mean free path. However, there are large discrepancies between the extracted values of \( \hat{q} \) even if other details of the calculation, like the simulation of the space-time evolution of the quark gluon bubble are kept identical \cite{7}. Moreover, there is reason to believe that phenomenological details in the calculation, e.g. from fireball evolution or early-time behavior have a significant effect on extracted values of \( \hat{q} \).

We will argue here that inhomogeneities and fluctuations in the transverse spatial distribution of both the medium (the quark gluon plasma) and the hard processes have an effect on \( \hat{q} \) as well. On the other hand, we will show that precision measurements of hard probes can provide valuable experimental constraints on such inhomogeneities \cite{8}.

Let us consider a fast parton emerging from a point \( \vec{r} \) in the transverse plane with zero longitudinal momentum,
traveling at a given azimuthal angle $\psi$ in the transverse plane. For a wide class of jet quenching models the average energy loss for such a parton traveling through a medium with local density $\rho$ is determined by the integral

$$I_\rho(\vec{r},\psi) = \int d\tau d^3\vec{r} \delta(\vec{r} + \tau \vec{e}_\phi)$$

along its trajectory where $\tau$ is the time parameter. The parameter $\beta$ determines the length dependence and would be equal to 1 in order to describe the consequences of the finite formation time known as the LPM effect \cite{5,6}. The impact of energy loss on the parton spectrum as a function of momentum $p_T$ and angle $\psi$ is governed by the integral over all emission points $\vec{r}$ weighted with $n(\vec{r})$, the probability density of jets emerging at point $\vec{r}$,

$$\int d^2r \int d\tau d^3\vec{r} n(\vec{r})\rho(\vec{r} + \tau \vec{e}_\phi)$$

For the case of small energy loss $\Delta p_T \ll p_T$ the correction to the spectrum is directly proportional to this integral. For all other cases the relation might be more complicated, but it is still a monotonous function of the density product $n(\vec{r})\rho(\vec{r} + \tau \vec{e}_\phi)$.

Now let us assume that the densities $n(\vec{r})$ and $\rho(\vec{r})$ fluctuate event-by-event around expectation values $\bar{n}(\vec{r})$ and $\bar{\rho}(\vec{r})$: $n = \bar{n} + \delta n$, $\rho = \bar{\rho} + \delta \rho$. The effect on quenching from the density product, averaged over many events, can then be broken down into two terms

$$(n(\vec{r})\rho(\vec{r} + \tau \vec{e}_\phi)) = \bar{n}(\vec{r})\bar{\rho}(\vec{r} + \tau \vec{e}_\phi) + R(\vec{r}, \vec{r} + \tau \vec{e}_\phi)$$

where the first term corresponds to quenching in a smooth, averaged event, while the deviations from it are described by the correlation function

$$R(\vec{r}_1, \vec{r}_2) = \langle \delta n(\vec{r}_1)\delta \rho(\vec{r}_2) \rangle$$

In other words deviations of quenching when correctly calculated event-by-event and compared to averaged fireballs are sensitive to the correlation between the density of jet emissions and the density of the medium along the path of the jet.

If we were able to measure these deviations we could gain access to the correlation function $R$, and hence estimate the average spatial inhomogeneities in the fireball, despite the fact that high transverse momentum ($p_T$) data at RHIC is averaged over many events. E.g. $R$ would tell us about the average size of the typical granularity in events or the size of so-called hot spots. Fig. 1 shows the distribution $n(\vec{r})$ represented by the number of nucleon-nucleon collisions for a typical Au+Au collision with small impact parameter ($b \approx 3.2$ fm) at RHIC energies together with the average distribution $\bar{n}(\vec{r})$. The distributions were calculated with the Glauber Monte Carlo GLISSANDO \cite{9}. Fig. 2 shows the correlation function $R(\tau) = R(\vec{r}, \vec{r} + \tau \vec{e}_\phi)$ calculated with GLISSANDO events. One can clearly see a region of positive correlation around the emission point (small $\tau$) and a tail of anti-correlation extending to the boundary of the fireball.

This behavior of $R$ confirms the intuitive expectations. The integrals over $\tau$ and $\vec{r}$ will pick up positive and negative contributions to the correlation function and it is hard to argue whether the net effect on the spectra is an enhancement...
or suppression of quenching compared to the case of average fireballs. However, interestingly one can argue that the azimuthal asymmetry $v_2$ should decrease since the anti-correlation tails extend all the way to the boundary of the fireball \cite{8}.

We have run numerical simulations using our PPM package \cite{8} utilizing two different energy loss models: (i) a simple LPM-inspired model (sLPM) with $\Delta E = c_{\text{sLPM}} I_{\text{f}}(\vec{r}, \psi)$ and (ii) the non-deterministic ASW/BDMPS model \cite{2}. In both cases we model the densities $n$ and $\rho$ using the binary nucleon collision densities from GLISSANDO. Note that the parameters $c_{\text{sLPM}}$ and $c_{\text{ASW}}$ can be interpreted as the local quenching strength per density, $\hat{q}/\rho$.

Fig\[2\] shows results for $R_{AA}$ of neutral pions obtained with the ASW model for three different centralities compared to data from PHENIX \cite{10}. First $c_{\text{ASW}}$ is fitted using averaged events without inhomogeneities ("Averaged"), then the same value of $c_{\text{ASW}}$ is used in an event-by-event calculation ("Event-by-Event"). We clearly see a reduction in quenching for all centralities and momenta going from averaged events to realistic, fluctuating events. However, we can adjust $c_{\text{ASW}}$ from 1.6 GeV to 2.8 GeV to refit the $R_{AA}$ data on the same level of accuracy in the event-by-event case ("Refitted"). Calculations using the sLPM energy loss model yield similar results \cite{8}. We conclude that in absence of any knowledge about the spatial inhomogeneities in the fireball this introduces an additional uncertainty on the extracted value of $\hat{q}$ (or any version of this quantity normalized to a density) of at least 50%.

The next interesting question is whether after refitting $R_{AA}$ any observable consequences of spatial inhomogeneities remain. We find that $v_2$ at high $P_T$ is decreased going from averaged events to an event-by-event calculation with the same $\hat{q}$, as predicted above. With the quenching strength used to re-fit $R_{AA}$ the results for $v_2$ are still slightly below the results in averaged events, but the deviations (typically less than 20%) might be too subtle to be useful. On the other hand, triggered two particle correlations might be sensitive enough to put constraints on $\hat{q}$. When going from averaged to event-by-event calculations using the same $\hat{q}$ the decreased suppression almost cancels between hadron pairs and trigger particles, leading to very similar curves. After readjusting $R_{AA}$ we find a rather large suppression of $I_{AA}$ as shown in Fig\[3\].

It is also interesting to ponder the effects that inhomogeneities can have on azimuthal asymmetry coefficients other than $v_2$. We have analyzed a set of engineered events with given spatial anisotropies and have found that the Fourier coefficients $v_n$ scale linearly with the (generalized) spatial eccentricities $e_n$ in both the ASW and the sLPM energy loss models for $n = 2, 3, 4$. Using samples of GLISSANDO events we have indeed found Fourier coefficients up to $n = 6$. However except for $v_2$ and $v_4$ the magnitude of these coefficients is generally below 1%. Further details will be reported in a forthcoming publication \cite{12}.

Let us summarize. Inhomogeneities in the space-time structure of a quark gluon fireball have a potentially large effect on hard probes. One can define a correlation function $R$ which encodes valuable information on the granularity and average magnitude of these fluctuations and which can potentially be extracted even in event-averaged measurements in heavy ion collisions. We have studied the function $R$ within the GLISSANDO Glauber model and have investigated the effect of event-by-event quenching for two different energy loss models. We find that $R_{AA}$ increases and $v_2$ decreases event-by-event compared to averaged events if the same quenching strength $\hat{q}$ per density is used. However, we can not use this effect to constrain $R$ since a simple redefinition of $\hat{q}$ can fit RHIC data quite well.
Figure 3: Left panel: Nuclear modification factor $R_{AA}$ for neutral pions in Au+Au collisions in three different centrality bins. Data from PHENIX [10] is compared to calculations using averaged events with $\hat{q}$ fitted (dotted lines), event-by-event calculations with the same $\hat{q}$ (dashed lines), and event-by-event calculations with $\hat{q}$ refitted to the data (solid lines). Right panel: Triggered $\pi^0$-$\pi^0$ correlation $I_{AA}$ for central Au+Au collisions as a function of associated particle momentum $p_T$. The trigger particle momentum lies between 7 and 9 GeV. Data from the PHENIX Collaboration [11] is compared to our calculations for the averaged event (dotted line), the event-by-event calculations with unchanged $\hat{q}$ (solid line) and the event-by-event calculation with $\hat{q}$ refitted to describe $R_{AA}$.

However, in turn this means that there is a roughly 50% additional uncertainty on the extracted values of $\hat{q}$ which comes from our lack of knowledge about $R$. On the other hand we observe that two particle correlations like $I_{AA}$ carry residual signatures of the correlation function $R$. If all other uncertainties were under control they could be used to experimentally constrain $R$ and gain tomographic insight into the spatial structure of the fireball. We have also found a linear scaling of $v_n$ with $\epsilon_n$ at large momentum and we find higher order Fourier coefficients in event-by-event jet quenching calculations which might be accessible in future measurements.

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References

[1] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, D. Schiff, Radiative energy loss and p(T)-broadening of high energy partons in nuclei, Nucl. Phys. B484 (1997) 265–282. arXiv:hep-ph/9608322, doi:10.1016/S0550-3213(96)00581-0.

[2] U. A. Wiedemann, Jet quenching versus jet enhancement: A quantitative study of the BDMP-Z gluon radiation spectrum, Nucl. Phys. A690 (2001) 731–751. arXiv:hep-ph/0008241, doi:10.1016/S0375-9474(01)00362-1.

[3] M. Gyulassy, P. Levai, I. Vitev, Reaction operator approach to non-Abelian energy loss, Nucl. Phys. B594 (2001) 371–419. arXiv:nucl-th/0006010, doi:10.1016/S0550-3213(00)00662-0.

[4] P. B. Arnold, G. D. Moore, L. G. Yaffe, Photon and Gluon Emission in Relativistic Plasmas, JHEP 06 (2002) 030. arXiv:hep-ph/0204343.

[5] A. Majumder, M. Van Leeuwen, The theory and phenomenology of perturbative QCD based jet quenching arXiv:1002.2206.

[6] R. J. Fries, C. Nonaka, Evaluating Results from the Relativistic Heavy Ion Collider with Perturbative QCD and Hydrodynamics arXiv:1012.1881.

[7] S. A. Bass, et al., Systematic Comparison of Jet Energy-Loss Schemes in a realistic hydrodynamic medium, Phys. Rev. C79 (2009) 024901. arXiv:0808.0908, doi:10.1103/PhysRevC.79.024901.

[8] R. Rodriguez, R. J. Fries, E. Ramírez, Event-by-Event Jet Quenching, Phys. Lett. B693 (2010) 108–113. arXiv:1005.3567, doi:10.1016/j.physletb.2010.08.023.

[9] W. Broniowski, M. Kryszczynski, P. Bozek, GLISSANDO: GLauber Initial-State Simulation AND mOre., Comput. Phys. Commun. 180 (2009) 69–83. arXiv:0719.5731, doi:10.1016/j.cpc.2008.07.016.

[10] A. Adare, et al., Suppression pattern of neutral pions at high transverse momentum in Au+Au collisions at $t(sNN) = 200$ GeV and constraints on medium transport coefficients, Phys. Rev. Lett. 101 (2008) 232301. arXiv:0801.4020, doi:10.1103/PhysRevLett.101.232301.

[11] A. Adare, et al., Trends in Yield and Azimuthal Shape Modification in Dihadron Correlations in Relativistic Heavy Ion Collisions, Phys. Rev. Lett. 104 (2010) 252301. arXiv:1002.1077, doi:10.1103/PhysRevLett.104.252301.

[12] R. J. Fries, R. Rodriguez, in preparation.