Effects of Fluctuations and Inhomogeneities on Jet Quenching in High Energy Nuclear Collisions

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Introduction

Heavy ion collisions at high energies result in a phase transition where matter no longer consists of separate hadrons but as their constituents, quarks and gluons, for about 5 fm/c. This deconfined state, the quark-gluon plasma (QGP), with color degrees of freedom is achieved at critical energy density $\varepsilon_C \approx 1$ GeV/fm^3 and critical temperature $T_C \approx 170$ MeV (10^{12} K).

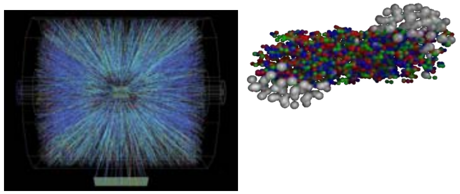

Fig.1 Particle tracks produced in Au-Au collisions at RHIC in Brookhaven National Laboratory at $\sqrt{s_{NN}} = 200$ GeV

The relevant physics that we want to study is a function of the number of binary nucleon-nucleon collisions. This quantity depends on the geometry of the interaction zone and the impact parameter b, in fm:

$$N_{coll}(b) = \sigma_{inel} T_{AB}(b) \quad (1)$$

where σ_{inel} is the inelastic cross section and $T_{AB}(b)$ the thickness function, i.e. the integral of the nuclear densities over the longitudinal direction.

Jet Quenching

Hard scattering is considered to be the dominant process of particle production with $p_T \geq 2$ GeV. Typically, these particles are produced in back-to-back jets and propagate through the dense medium. Partons propagating in colored matter lose energy mostly due to gluon radiation emitted in the medium. Using the GLV formulation for radiative energy loss, a modest reduction in fragmenting parton energy can produce a significant decrease in hadron yield at any given $p_T \geq 3$ GeV [1].

$$\Delta E = C_R \alpha_s L^2 \hat{q} \log\frac{E}{\mu} \quad (2)$$

$C_R \equiv$ color factor
$L \equiv$ distance traveled
$\mu \equiv$ momentum transfer
$\lambda_g \equiv$ mean free path
$\hat{q} \equiv$ transport coefficient

Fluctuations

The medium determines the amount of energy loss via the transport coefficient:

$$\hat{q} = \frac{\mu^2}{\lambda_g} \propto \varepsilon^{3/4} \propto N_{part}^{3/4} \quad (3)$$

where ε is the local energy density and N_{part} the density of participant nucleons. Fluctuations for the number of participants in the medium are calculated through a normal distribution with finite spatial size, λ, in each coordinate and standard deviation, σ, at points within the interaction zone.

Hadronization

Due to color confinement, separated quarks will go through hadron fragmentation, a process in which new quark/anti-quark pairs appear before ever separating further. Through this process, individual quarks lose energy and tight cones of color-neutral particles are created. The fragmentation function $D^{\pi^o}(z,Q^2)$ is the probability for a π^o to carry a fraction $z = p^{\pi^o}/p$ of the momentum of the outgoing parton.

The new hadron spectra can then be calculated as

$$\frac{dN^{\pi^o}}{2\pi p^{\pi^o} dp^{\pi^o}} = \int_{z_{min}}^{1} \frac{dz}{z^2} D^{\pi^o}(z,Q^2) \frac{dN}{2\pi p dp} \quad (4)$$

where the parameter Q^2 is a factorization scale introduced to account for collinear singularities in the structure and fragmentation functions and $dN/(2\pi p dp)$ is the hard scattering cross section.

Rather than looking and the spectra, two observables, v_2 and R_{AA} are introduced.

Elliptic Flow

The dense nuclear overlap at the beginning of a heavy ion collision resembles an ellipsoid due to incomplete overlap of the two colliding nuclei. The spatial anisotropy is converted into momentum anisotropy with any strong scattering. The azimuthal anisotropy of the spectra in the transverse plane can be characterized in terms of the second Fourier coefficient, $v_2(p_T)$, which dominates over the first and higher order coefficients in non-central collisions.

$$\frac{dN}{d\psi p_T dp_T} = \frac{dN}{2\pi p_T dp_T}(1 + 2v_2 \cos 2\psi) \quad (5)$$

with elliptic flow $v_2 = \langle \cos(2\psi) \rangle$ which measures eccentricity in momentum space

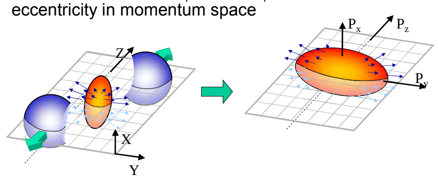

Fig. 2 Semi-peripheral collision seen in momentum space

Nuclear Modification Factor

The nuclear modification factor, R_{AA}, is a useful tool to probe jet suppression, either in the initial or final state. It is a measure of the ratio of number of particles produced in Au+Au collisions to the number of particle produced in p+p collisions, scaled by the average number of collisions.

$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll} \times dN^{pp}/dp_T} \quad (6)$$

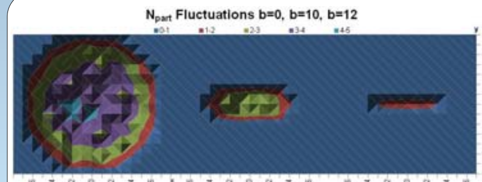

Fig. 3 Bilinear interpolation simulation of random fluctuations in the interaction zone for three impact parameters.
Step size of one fermi and fluctuation size σ=.1 were used.

Methods

We test the consequence of fluctuations present in the energy density ε(x,y) deposited.

A code was developed to implement jet energy loss from (2) as particles travel through the medium and calculate spectra of pions with certain p_T, using KKP fragmentation functions [2]. The color factor and transport coefficient were used as a parameter to make a fit of the p_T spectrum and determine an overall normalization. This parameter was calculated to be .08 to fit experimental data [3].

The goals were to determine the size of the fluctuations required to be observable and if any measurable effects exist.

Results

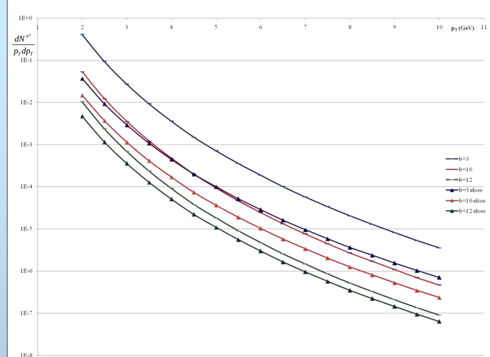

Fig. 4 Calculated π^o spectra with and without energy loss.

Small fluctuations (σ<0.5) and bilinear interpolation did not produce measurable effects on the nuclear modification factor or elliptic flow. Instead, fluctuations were implemented as a checkerboard. At any point in the interaction zone the fluctuation at distance < λ was used to avoid normalization of any possible effect. Fluctuations in R_{AA} were calculated but did not show any dependence, as expected. With large fluctuations of the energy density we find observable effects which are larger for v2 than for RAA and grow from central to peripheral collisions

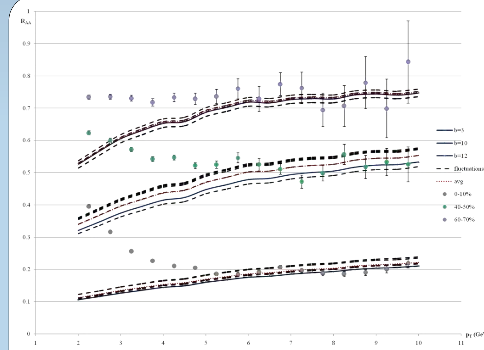

Fig. 5 R_{AA} for pions without fluctuations (solid), 5 random fluctuation events of σ=2(red-dash), and their average(red) compared with PHENIX data at different centrality bins corresponding to their average impact parameter.

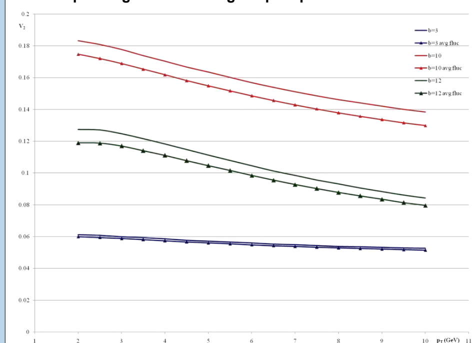

Fig. 6 Plot of the elliptical flow without fluctuations and the average of 20 events.

Conclusions

There was an observed suppression link to centrality but not as expected, which will lead into further investigation.

Future Work

(a) Fluctuations for back-to-back hadron production;
(b) Poisson statistics for N_{part}

References

[1] M. Gyulassy, P. Levai and I.Vitev. Phys. Rev. Lett. 85, 5535 - 5538 (2000).
[2] Bernd A. Kniehl, G. Kramer, B. Potter. Nucl.Phys.B582:514-536 (2000).
[3] PHENIX Collaboration, A. Adare, et al. Phys. Rev. Lett. 101, 232301 (2008).

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