The Nuclear Modification Factor at Large Rapidities

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RHIC data on high-p_T hadron production display strong suppression in a wide rapidity region, indicating strong induced energy loss for both transversally and longitudinally traveling partons. We investigate the interplay of energy loss and rapidity dependence in a perturbative QCD improved parton model, and estimate the opacity of the produced hot matter in $AuAu$ collisions at energies $\sqrt{s} = 200$ AGeV and 63 AGeV at different rapidity values. Direction-dependent suppression offers the possibility to study the geometry of the hot matter.

1. Introduction

In heavy-ion collisions at RHIC energies we expect the formation of hot and dense matter in the central space-time region of the collision. One can measure the density profile of the color charges in this deconfined region using induced energy loss of partons traversing the dense region in different directions. Data from central rapidity show the transversally propagating partons and their large energy loss (see $AuAu$ data from PHENIX [1] and STAR [2]). At large rapidities strong suppression has been seen by BRAHMS [3,4] in pion and hadron production. This finding offers the possibility to analyze energy loss for different momentum directions.

We apply a perturbative QCD improved parton model to describe hadron production at high p_T [5,6]. The Glauber-Gribov model provides the proper framework to describe hadron production as a superposition of proton-proton results to obtain baseline hadron spectra in heavy-ion collisions. The parton energy loss is calculated by the GLV-method [7], and the opacity of the dense matter is extracted in different rapidity regions, i.e. for different parton momentum directions. We include shadowing and multiscattering, tested in a wide rapidity range in dAu collisions [8,9].

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2. Theoretical Background of the Model

Pion production is calculated in $AuAu$ collisions at RHIC energies using a perturbative QCD improved parton model in leading order (LO) [5,6]. Schematically

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{pA}}{\mathrm{d}^3p} \sim \sum_{abc} T_{AA'}(\mathbf{r},\mathbf{b}) \otimes f_{a/p}(x_a,\mathbf{k}_{Ta},Q^2) \otimes f_{b/A}(x_b,\mathbf{k}_{Tb},Q^2) \otimes \mathrm{d}\hat{\sigma} \otimes D_c^\pi(z_c,\tilde{Q}^2) \ . \quad (1)$$

The collision geometry and the superposition of the nucleon-nucleon collisions is included by the Glauber-Gribov model. In the multidimensional convolution integral (1), $T_{AA'}(\mathbf{r},\mathbf{b}) = t_A(r)t_{A'}(|\mathbf{b}-\mathbf{r}|)$ is the nuclear overlap function for the colliding nuclei. The nuclear thickness function for nucleus A is introduced as $t_A(b) = \int \mathrm{d}z\, \rho_A(b,z)$, normalized as $\int \mathrm{d}^2b\, t_A(b) = A$. We use a Woods−Saxon distribution for Au.

Nuclear PDFs can be constructed from proton and neutron PDFs [5]:

$$f_{a/A}(x,Q^2) = S_{a/A}(x) \left[\frac{Z}{A} f_{a/p}(x,Q^2) + \left(1-\frac{Z}{A}\right) f_{a/n}(x,Q^2) \right] \ . \quad (2)$$

The function $S_{a/A}(x)$ describes 'conventional' nuclear shadowing. Here a b-independent $S_{a/A}(x)$ was taken from the HIJING parametrization [10].

The last term in eq. (1) is the fragmentation function (FF), $D_c^\pi(z_c,\tilde{Q}^2)$. This term gives the probability for parton c to fragment into a pion with momentum fraction z_c at scale $\tilde{Q} = \tilde{\kappa}\, p_T$. We apply the KKP parametrization [11]. The factorization scale (Q) is connected to the momentum of the intermediate jet, $Q = \kappa \cdot p_T/z_c$, which scales together with $\tilde{Q}$ in the FF. We applied $\kappa = \tilde{\kappa} = 2/3$ at RHIC energies.

The density of the color particles can be measured by the induced energy loss of high-energy quarks and gluons traveling through the hot dense deconfined matter. One can determine the non-abelian radiative energy loss, $\Delta E(E,L)$. This quantity depends on the color charge density through the opacity, $\bar{n} = L/\lambda$, where L is the length of the traversed matter and λ is the mean free path. In "thin plasma" approximation the energy loss is given by the following expression [7]:

$$\Delta E_{GLV} = \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda} \log\left(\frac{E}{\mu}\right) \ . \quad (3)$$

Here C_R is the color Casimir of the jet and $\mu^2/\lambda \sim \alpha_s^2 \rho_{part}$ is a transport coefficient of the medium, which is proportional to the parton density, ρ_{part}. The color Debye screening scale is denoted by μ. $N(E)$ is an energy dependent numerical factor with an asymptotic value 4 at high jet energies.

Jet energy loss influences the final hadron spectra. We can introduce this effect via modifying the momentum fraction of the outgoing parton before the fragmentation. Considering an average energy loss, ΔE, in a static plasma, the argument of the fragmentation functions will be modified as

$$\frac{D_{\pi/c}(z_c,\tilde{Q}^2)}{\pi z_c^2} \quad \longrightarrow \quad \frac{z_c^*}{z_c} \frac{D_{\pi/c}(z_c^*,\tilde{Q}^2)}{\pi z_c^2} \ . \quad (4)$$

Here $z_c^* = z_c/\left(1-\Delta E/p_c\right)$ is the modified momentum fraction.

3. Nuclear modification factor, R^{π}_{AA}, at large rapidities

Fig. 1 displays the calculated nuclear modification factor for pion production in minimum bias dAu (*upper row*) and in central $AuAu$ (*lower row*) collisions at $\sqrt{s} = 200$ AGeV at different rapidities, $\eta = 0$, 1, 3.2. The dAu results indicate the validity of our LO perturbative QCD calculations including multiscattering and shadowing [8,9]. Data on pion and charge hadron production are shown from PHENIX [12] and BRAHMS [13].

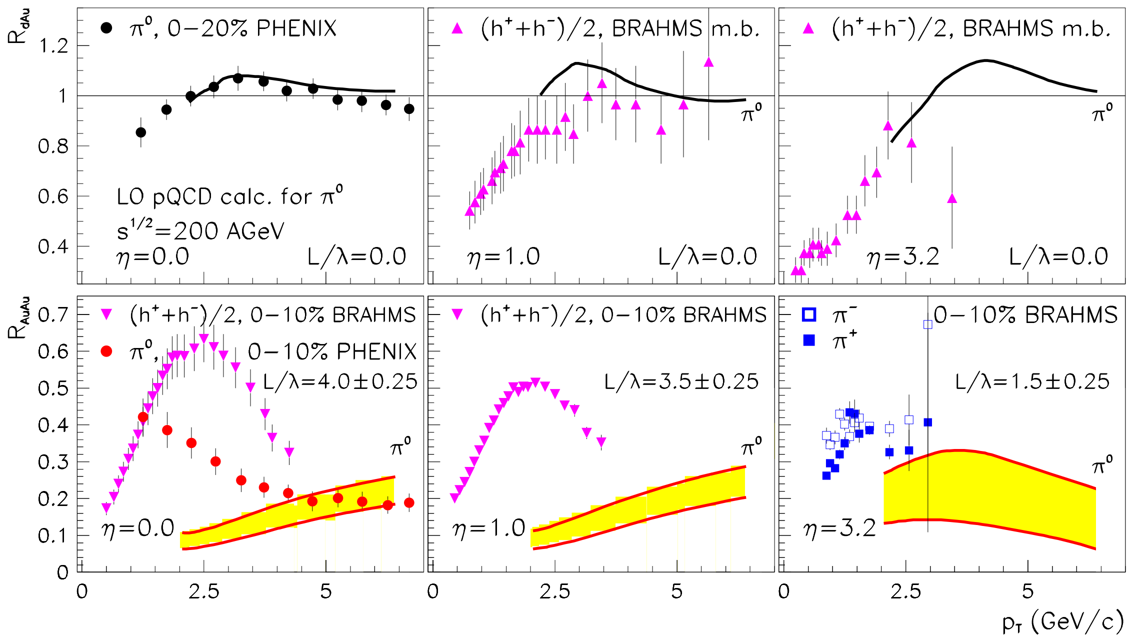

Figure 1. Nuclear modification factors at different rapidities: R^{π}_{dAu} in dAu collisions (*upper row*), R^{π}_{AuAu} in $0 - 10\%$ central $AuAu$ collisions (*lower row*). Data are from PHENIX [1,12] and BRAHMS [3,13] at $\sqrt{s} = 200$ AGeV. Full lines display our pQCD results, the bands indicate the theoretical uncertainties on the value of the opacity.

In $AuAu$ collisions strong final state interaction (induced jet energy loss) appears and data display suppression at high p_T [1]. At midrapidity, our pQCD result with average opacity of $L/\lambda = 4.0 \pm 0.25$ is consistent with data at $p_T \geq 4$ GeV/c, where the high-p_T region sets in (see Fig. 1). Recent BRAHMS data [3,4] may indicate rapidity independent suppression for pion production in the intermediate-p_T region ($p_T < 3.5$ GeV/c). Assuming that this finding is also valid for the high-p_T region, we wish to achieve a similar high-p_T suppression at large rapidities. A smaller opacity, $L/\lambda = 3.5 \pm 0.25$ at $\eta = 1$, and $L/\lambda = 1.5 \pm 0.25$ at $\eta = 3.2$ is needed to do this. (Note the difference between charge hadron and pion suppression.) This result indicates that longitudinally traveling partons see less colored matter then those traveling in the transverse direction.

Fig. 2 displays available data and our pQCD results for $AuAu$ collisions at $\sqrt{s} = 62.4$ AGeV for different η values. Due to the smaller Bjorken energy density [3,14], $\varepsilon^{62.4}_{Bj} < \varepsilon^{200}_{Bj}$, we have used reduced opacity parameters, namely $L/\lambda = 3.25 \pm 0.25$ at mid-rapidity, $L/\lambda = 2.75 \pm 0.25$ at $\eta = 1.$ and $L/\lambda = 0.75 \pm 0.25$ at $\eta = 3.2$. Extended bands indicate the size of the theoretical uncertainties on the induced energy loss.

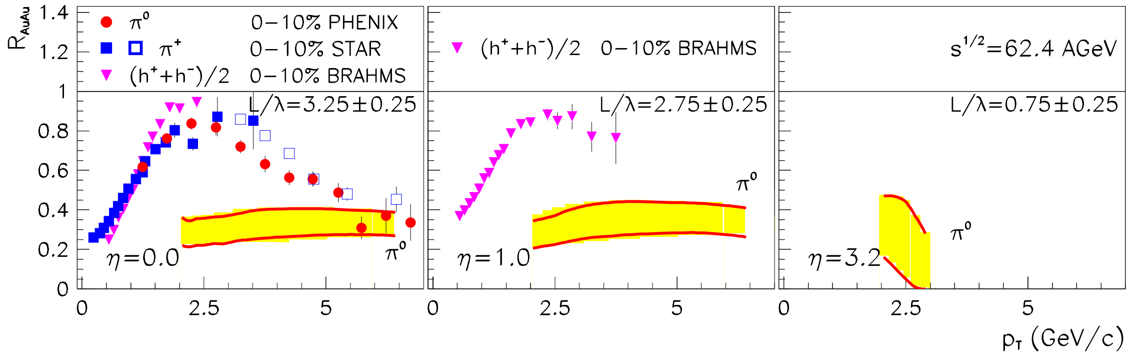

Figure 2. Nuclear modification factor, R^{π}_{AuAu}, at $\eta = 0$, 1 and 3.2 in $0-10\%$ central $AuAu$ collisions at RHIC energy, $\sqrt{s} = 62.4$ AGeV. Our pQCD results with varying opacities (full lines and bands) are compared to PHENIX [1], STAR [2], and BRAHMS [3] data.

Comparing R^{π}_{AuAu} results of Fig. 1 and Fig. 2, the decreasing tendency of the opacity parameter is clearly seen as η is increasing. At large forward rapidities the interplay between stronger shadowing and weaker quenching effects maintains a rapidity independent nuclear modification factor (no data are available at $\eta = 3.2$ for $\sqrt{s} = 62.4$ AGeV $AuAu$).

Whether π suppression is approximately rapidity independent will of course be decided by the data. The present hint of this behavior motivated us in this study to examine the interplay of rapidity dependence and jet energy loss. One particle quark tomography combined with jet-jet correlation results provides information on the geometry of the hot region. Energy dependence and $CuCu$ results may be used to verify our conclusions.

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