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Jet Tomography Studies in $AuAu$ Collisions at RHIC Energies

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Abstract. Recent RHIC results on pion production in $AuAu$ collision at $\sqrt{s} = 130$ and 200 AGeV display a strong suppression effect at high p_T. This suppression can be connected to final state effects, namely jet energy loss induced by the produced dense colored matter. Applying our pQCD-based parton model we perform a quantitative analysis of the measured suppression pattern and determine the opacity of the produced deconfined matter.

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1 Introduction

The experimental data on high-p_T π^0 production in central $AuAu$ collisions at mid-rapidity at $\sqrt{s} = 130$ and 200 AGeV have shown a strong suppression compared to binary scaled pp data [1,2]. This suppression vanishes with increasing centrality and no effect appears in peripheral $AuAu$ collisions. Thus a detailed quantitative analysis of the suppression pattern (*"jet tomography"* [3]) yields information about the properties of the produced dense matter and the impact parameter dependence of the formation of deconfined matter in $AuAu$ collisions. Recent data on dAu collisions [4,5] validate our effort: since no suppression was found at mid-rapidity in the dAu reaction, initial state effects (e.g. a strong modification in the internal parton structure of the accelerated Au nuclei) can not be responsible for the measured suppression in $AuAu$ collisions. Thus, induced jet-energy loss in the final state becomes a strong candidate to explain the missing pion yield. Jet energy loss can be calculated in a perturbative quantum chromodynamics (pQCD) frame [6,7].

We investigate jet energy loss in a pQCD improved parton model. In Sect. 2 we introduce the basis of our model, especially a phenomenological intrinsic transverse momentum distribution (intrinsic k_T) for the colliding nucleons, which is necessary to reach a better agreement between data and calculations in pp collisions [8,9,10,11]. For nucleus-nucleus (AA) collisions, initial state effects are considered, e.g. nuclear multiple scattering, saturation in the number of semihard collisions, and a weak shadowing effect inside the nucleus [9,10]. In Sect. 3 we summarize the description of induced gluon radiation in thin non-Abelian matter and include the GLV-description [7] of energy loss into the pQCD improved parton model. This way our model becomes capable to extract the opacity values of the produced colored matter at different centralities. In Sect. 4 we discuss the obtained results.

2 Initial State Effects in $AuAu$ Collisions

The invariant cross section of pion production in an AA' collision can be described in a pQCD-improved parton model developed for pp collision and extended by a Glauber-type collision geometry and initial state nuclear effects for AA' collisions as [13,14,12]:

$$
\begin{aligned}
E_\pi \frac{\mathrm{d}\sigma_\pi^{AA'}}{\mathrm{d}^3 p} &= \int \mathrm{d}^2 b\, \mathrm{d}^2 r\; t_A(r)\; t_{A'}(|\mathbf{b}-\mathbf{r}|)\; \frac{1}{s} \sum_{abc} \times \\
&\times \int_{vw/z_c}^{1-(1-v)/z_c} \frac{\mathrm{d}\hat{v}}{\hat{v}(1-\hat{v})} \int_{vw/\hat{v}z_c}^{1} \frac{\mathrm{d}\hat{w}}{\hat{w}} \int^{1} \mathrm{d}z_c \times \\
&\times \int \mathrm{d}^2\mathbf{k}_{Ta} \int \mathrm{d}^2\mathbf{k}_{Tb}\; f_{a/A}(x_a, \mathbf{k}_{Ta}, Q^2)\; f_{b/A'}(x_b, \mathbf{k}_{Tb}, Q^2) \\
&\times \left[\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{v}} \delta(1-\hat{w}) + \frac{\alpha_s(Q_r)}{\pi} K_{ab,c}(\hat{s}, \hat{v}, \hat{w}, Q, Q_r, \tilde{Q}) \right] \times \\
&\times \frac{D_c^\pi(z_c, \tilde{Q}^2)}{\pi z_c^2} \, . \qquad (1)
\end{aligned}
$$

Here $t_A(b) = \int \mathrm{d}z\, \rho_A(b,z)$ is the nuclear thickness function normalized as $\int \mathrm{d}^2 b\, t_A(b) = A$. For small nuclei we use a sharp sphere approximation, while for larger nuclei the Wood-Saxon formula is applied.

In our next-to-leading order (NLO) calculation [12], $\mathrm{d}\widehat{\sigma}/\mathrm{d}\hat{v}$ represents the Born cross section of the partonic subprocess and $K_{ab,c}(\hat{s},\hat{v},\hat{w},Q,Q_r,\tilde{Q})$ is the corresponding higher order correction term, see Ref.s [12,13,14]. We fix the factorization and renormalization scales and connect them to the momentum of the intermediate jet, $Q = Q_r = (4/3)p_q$ (where $p_q = p_T/z_c$), reproducing pp data with high precision at high p_T [15].

The approximate form of the 3-dimensional parton distribution function (PDF) is the following:

$$f_{a/p}(x_a,\mathbf{k}_{Ta},Q^2) \;\; = \;\; f_{a/p}(x_a,Q^2)\cdot g_{a/p}(\mathbf{k}_{Ta}) \; . \qquad (2)$$

Here, the function $f_{a/p}(x_a,Q^2)$ represents the standard longitudinal NLO PDF as a function of momentum fraction of the incoming parton, x_a at scale Q (in the present calculations we use the MRST(cg)[16] PDFs). The partonic transverse-momentum distribution in 2 dimensions, $g_{a/p}(\mathbf{k}_T)$, is characterized by an "intrinsic k_T" parameter as in Ref.s [10,12]. In our phenomenological approach this component is described by a Gaussian function [10,11].

Nuclear multiscattering is accounted for through broadening of the incoming parton's transverse momentum distribution function, namely an increase in the width of the Gaussian:

$$\langle k_T^2\rangle_{pA} = \langle k_T^2\rangle_{pp} + C\cdot h_{pA}(b) \; . \qquad (3)$$

Here, $\langle k_T^2\rangle_{pp} = 2.5$ GeV^2 is the width of the transverse momentum distribution of partons in pp collisions [10,15], $h_{pA}(b)$ describes the number of *effective* NN collisions at impact parameter b, which impart an average transverse momentum squared C. The effectivity function $h_{pA}(b)$ can be written in terms of the number of collisions suffered by the incoming proton in the target nucleus. In Ref. [10] we have found a limited number of semihard collisions, $\nu_m = 4$ and the value $C = 0.4$ GeV^2.

We take into account the isospin asymmetry by using a linear combination of p and n PDFs. The applied PDFs are also modified inside nuclei by the "shadowing" effect[17].

The last term in the convolution of eq. (1) is the fragmentation function (FF), $D_c^{\pi}(z_c,\tilde{Q}^2)$. This gives the probability for parton c to fragment into a pion with momentum fraction z_c at fragmentation scale $\tilde{Q} = (4/3)p_T$. We apply the KKP parametrization [18].

3 Jet-Quenching as a Final State Effect

The energy loss of high-energy quark and gluon jets traveling through dense colored matter is able to give information on the density of gluons [3]. This non-Abelian radiative energy loss $\Delta E(E,L)$ can be described as a function of gluon density: $\bar{n} = L/\lambda_g$, the mean number of jet scatterings, where L is the length traversed by the jet and λ_g is the mean free path in non-Abelian dense matter. In "thin plasma" approximation energy loss in first order is

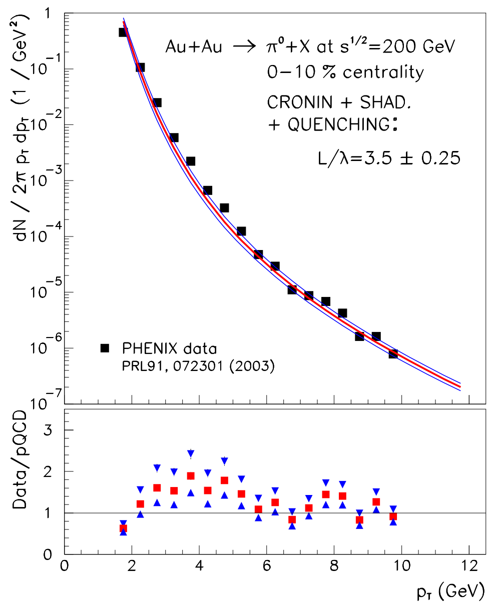

Fig. 1. Pion production in central $AuAu$ collision with the calculated opacities $\bar{n} = 3.5 \pm 0.25$ (upper panel). Data are from PHENIX Collaboration [1]. The lower panel displays a comparison between the data and the calculations.

given by the following form [7]:

$$\Delta E^{(1)}_{GLV} = \frac{2C_R\alpha_s}{\pi}\frac{EL}{\lambda_g}\int_0^1 \mathrm{d}x \int_0^{k^2_{max}} \frac{\mathrm{d}\mathbf{k}_T^2}{\mathbf{k}_T^2} \times$$
$$\times \int_0^{q^2_{max}} \frac{\mathrm{d}^2\mathbf{q}_T\mu^2_{eff}}{\pi\left(\mathbf{q}_T^2+\mu^2\right)^2}\cdot\frac{2\mathbf{k}_T\cdot\mathbf{q}_T\,(\mathbf{k}-\mathbf{q})_T^2\,L^2}{16\,x^2\,E^2+(\mathbf{k}-\mathbf{q})_T^4\,L^2}$$
$$= \frac{C_R\alpha_s}{N(E)}\frac{L^2\mu^2}{\lambda_g}\log\left(\frac{E}{\mu}\right) \quad , \qquad (4)$$

where C_R is the color Casimir of the jet, $\mu/\lambda_g \sim \alpha_s^2\rho_{part}$ is a transport coefficient of the medium, proportional to the parton density, ρ_{part}. The color Debye screening scale is μ, and λ_g is the radiated gluon mean free path. $N(E)$ is an energy dependent factor with asymptotic value 4.

Considering a time-averaged, static plasma, the average energy loss, ΔE, will modify the argument of the FFs:

$$\frac{D_{\pi/c}(z_c,\tilde{Q}^2)}{\pi z_c^2} \longrightarrow \frac{z_c^*}{z_c}\,\frac{D_{\pi/c}(z_c^*,\tilde{Q}^2)}{\pi z_c^2}. \qquad (5)$$

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

In Fig. 1 we present our result on pion production in most central $(0-10\%)$ $AuAu$ collisions at $\sqrt{s} = 200$ AGeV. We included all initial and final state effects discussed above and used the opacity value $\bar{n} = 3.5 \pm 0.25$ to reproduce the experimental data.

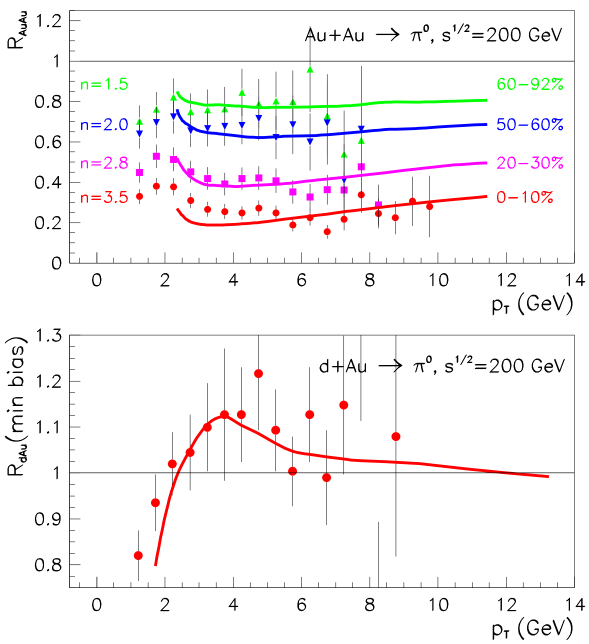

Fig. 2. Upper panel displays the pion production in $AuAu$ collision in different centrality bins with the calculated opacities. Data are from PHENIX Collaboration [1]. Lower panel shows the pion production in dAu collision [4] and the result of our calculation [15].

4 Centrality Dependence in $AuAu$ collisions

In the top panel of Fig. 2 we display the nuclear modification factor

$$R_{AA'}(p_T, b) = \frac{1}{N_{bin}} \cdot \frac{E_\pi \mathrm{d}\sigma_\pi^{AA'}(b)/\mathrm{d}^3 p_T}{E_\pi \mathrm{d}\sigma_\pi^{pp}/\mathrm{d}^3 p_T}, \qquad (6)$$

(where N_{bin} is the number of binary collisions), as a function of p_T at different impact parameter ranges. The measured suppression is reproduced in the most central collisions with opacity $\bar{n} = 3.5 \pm 0.25$ as it was shown in Fig. 1. Curves with lower values of opacities are shown for comparison to the more peripheral data. Since the centrality $60 - 92\%$ includes non-peripheral events, the obtained $\bar{n} = 1.5$ seems to be a reasonable opacity value for this bin. In the very peripheral case the opacity should be reduced to a small value [19], however $\pm 20\%$ error on the nuclear modification factor does not allow more detailed investigation. A more quantitative analysis can be performed, when data will be available with smaller error bars. At higher precision, the geometry of the hot overlap zone can be included and a more detailed analysis of the impact parameter dependence can be accomplished. In this case the properties of the produced hot matter will be studied in a more quantitative way.

In the bottom panel of Fig. 2 the dAu data are compared to our calculation [15] to demonstrate the validity of our description for the initial nuclear effects.

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References

1. G. David *et al.* (PHENIX Coll.), Nucl. Phys. **A698**, (2002) 227; D. d'Enterria *et al.* (PHENIX Coll.), Nucl. Phys. **A715**, (2003) 749; S.S. Adler *et al.* (PHENIX Coll.), Phys. Rev. Lett. **91**, (2003) 072301; (`nucl-ex/0308006`).
2. J.C. Dunlop *et al.* (STAR Coll.), Nucl. Phys. **A698**, (2002) 515; J.L. Klay *et al.* (STAR Coll.), Nucl. Phys. **A715**, (2003) 733; J. Adams *et al.* (STAR Coll.), Phys. Rev. Lett. **91**, (2003) 172302; (`nucl-ex/0308023`).
3. E. Wang, X.N. Wang, Phys. Rev. Lett. **89**, (2002) 162301; I. Vitev, M. Gyulassy, Phys. Rev. Lett. **89**, (2002) 252301; M. Gyulassy, P. Lévai, I. Vitev, Phys. Lett. **B538**, (2002) 282; M. Gyulassy, I. Vitev, X.N. Wang, B.W. Zhang, `nucl-th/0302077`.
4. S.S. Adler *et al.* (PHENIX Coll.), Phys. Rev. Lett. **91**, (2003) 072303.
5. J. Adams *et al.* (STAR Coll.), Phys. Rev. Lett. **91**, (2003) 072304.
6. M. Gyulassy and M. Plümer, Phys. Lett. **B243**, (1990) 432; M. Gyulassy, M. Plümer, M.H. Thoma and X.-N. Wang, Nucl. Phys. **A538**, (1992) 37c.
7. M. Gyulassy, P. Lévai and I. Vitev, Phys. Rev. Lett. **85**, (2000) 5535; Nucl. Phys. **B571**, (2000) 197; *ibid.* **B594**, (2001) 371.
8. C.Y. Wong and H. Wang, Phys. Rev. **C58**, (1998) 376.
9. X.N. Wang, Phys. Rev. **C61**, (2001) 064910.
10. Y. Zhang, G. Fai, G. Papp, G.G. Barnaföldi, and P. Lévai, Phys. Rev. **C65**, (2002) 034903.
11. G.G. Barnaföldi, P. Lévai, G. Papp, G. Fai, and Y. Zhang, APH NS Heavy Ion Phys. **18**, (2003) 79, `nucl-th/0206006`.
12. G. Papp, G.G. Barnaföldi, P. Lévai, and G. Fai, `hep-ph/0212249`.
13. F. Aversa, P. Chiappetta, M. Greco, and J.Ph. Guillet, Nucl. Phys. **B327**, (1989) 105.
14. P. Aurenche, M. Fontannaz, J.Ph. Guillet, B. Kniehl, E. Pilon, and M. Werlen, Eur. Phys. J. **C9**, (1999) 109; P. Aurenche, M. Fontannaz, J.Ph. Guillet, B. Kniehl, and M. Werlen, Eur. Phys. J. **C13**, (2001) 347.
15. P. Lévai, G. Papp, G.G. Barnaföldi and G. Fai, `nucl-th/0306019`.
16. A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. **C23**, (2002) 73.
17. S.J. Li and X.N. Wang, Phys. Lett. **B527**, (2002) 85.
18. B.A. Kniehl, G. Kramer and B. Pötter, Nucl. Phys. **B597**, (2001) 337, `hep-ph/0011155`.
19. G.G. Barnaföldi, P. Lévai, G. Papp, G. Fai, and Y. Zhang, *Proc. of XXXII. Int. Symposium on Multiparticle Dynamics*, (World Sci. Singapore 2003), `nucl-th/0212111`.