Suppression of $\pi^0$ production at large $p_\perp$ in central $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV and quark-gluon plasma

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Abstract

We investigate the suppression of $\pi^0$-spectrum in a wide range of $p_\perp$ up 60 GeV/c which is caused by the energy loss of the gluon and quark jets in quark-gluon plasma. The physical characteristics of initial and mixed phases were found in the effective quasiparticle model by analogy with previous work [5]. The PHENIX data up 10 GeV/c within the limits of precision are described by quasiparticle model with decrease of the thermal gluon mass and effective coupling in the region of phase transition (at $T \rightarrow T_c$ from above). We also take into account the intrinsic transverse momentum $k_\perp$ of partons.

The suppression factor $R_{AA}(p_\perp)$ shows the weak rise with increase of $p_\perp$ above 4 GeV/c, then it reaches smooth maximum at $p_\perp \sim 20$ GeV/c and then decrease at $p_\perp \sim 60$ GeV/c again to value $R_{AA}$ at $p_\perp \simeq 4$ GeV/c. The factor $R_{AA}$ in this range of $p_\perp$ is changing weakly if intrinsic momentum $k_\perp$ is taken into account.

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I. INTRODUCTION

Energy loss of high energy gluon and quark jets in relativistic $A+A$ collisions leads to jet quenching and to suppression of hadron spectra and thus probes the quark-gluon plasma. Recently the considerable suppression of $\pi^0$ spectra was found in central $Au+Au$ collisions at $\sqrt{s}=200$ GeV \[1\].

The energy loss was investigated, for example, in Ref. \[2\] in various orders in opacity $L/\lambda$ (where $L$ is nuclear radius and $\lambda$ is the gluon mean free path). It was shown that opacity expansion is strongly dominated by the first term. It was shown also in Ref \[3\] that the finite kinematic boundaries decrease the energy loss as compared to the asymptotic limits. Recently the suppression of $\pi^0$ spectra in central $Au+Au$ collisions at $\sqrt{s}=130$ GeV was investigated in Ref \[4\] with accounting of dominant first term and of the finite kinematic boundaries. In this work the physical characteristics of initial and mixed plasma phase (i.e. the values $T_0, \tau_0, \tau_c$) were used which have been found in Ref \[5\] on the basis of the quasiparticle model and isentropic expansion. We find that the suppression one can describe by quasiparticle model with decrease of the thermal gluon mass and effective coupling in a region of phase transition (at $T \to T_c$ from above). The possibility of hot glue production at the first stage was also considered in Ref \[4\].

The gluon density was calculated with accounting of plasma expansion and it was shown that plasma is sufficiently thin: the average number of jet scatterings $\bar{n} \simeq 1.3$, so it is possible to use the model of the single hard medium-induced scattering. The physical characteristics of plasma at $\sqrt{s}=200$ GeV was found by analogy with the Ref. \[5\]. We have used the values $T_c=177$ MeV and $\mu_B=29$ MeV for 200 GeV $Au+Au$ central collisions \[6\]. These values are consistent with data for $\bar{p}/p$ ratio and for the number of net protons ($\simeq 5$) at midrapidity \[7\]. Using the formulas (10-18) in Ref. \[4\], we have found for gluons $(dN_g/dy)_{y=0} \simeq 1070$ and for hot glue the temperature $T_g \simeq 373$ MeV. We have obtained also the initial gluon density $n_g(T_g) \simeq 24.77 \, m_\pi^2$. The time which is required to achieve the equilibrium for gluons is:

$$\tau_g = \frac{dN_g}{dy \pi R^2_{Au} n_g} \simeq \frac{0.587}{m_\pi} = 0.834 \, \text{fm}. \ \ (1)$$

The equilibrium temperature $T_0$ for both quarks and gluons and corresponding time $\tau_0$ can be found using the formulas (14-23) in Ref. \[5\]. We have at $\sqrt{s} = 200$ GeV: $T_0 = 224$ MeV, $\tau_0 \simeq 1.585/m_\pi \simeq 2.26$ fm. The corresponding entropy density is $s_0(T_0) = 58.98 \, m_\pi^3$ and total entropy is $S_0 = S_0(T_0)V_0 \simeq 6850$. We have also at $T = T_c = 177$ MeV: $s_c(T_c) \simeq 16.72 \, m_\pi^3$ and
\[ \tau_0 \simeq 4.5/m_q \] (i.e. \( \simeq 6.4 \) fm). In Ref. \([3]\) it was shown, that from conservation of entropy and number of net nucleons follows, that the massive constituent quarks \( (m_q \text{ and } m_s) \) appears with decrease of number of degrees of freedom in the presence of octet of pseudogoldstone states. In addition with the same effective number of degrees of freedom appears hadrons and resonances in hadron part of mixed phase (for SPS and RHIC at \( \sqrt{s} = 130 \) GeV). One can show that it is completely fulfilled for RHIC at \( \sqrt{s} = 200 \) GeV.

In Sec. II we calculate the energy loss \( \Delta E \) of the high energy gluon and quark jets with energy \( E \) in expanding quark-gluon plasma (at \( Au + Au \) collisions at \( \sqrt{s} = 200 \) GeV) in the dominant first order of opacity expansion (by analogy with the Ref. \([4]\)) We use here the characteristics of expanding plasma which are found in effective quasiparticle model (with accounting of the hot glue production at first stage).

In Sec. III we calculate the suppression of \( \pi^0 \) spectra in central \( Au + Au \) collisions at \( \sqrt{s} = 200 \) GeV in wide range of \( p_\perp \) \( (4 \leq p_\perp \leq 60 \) GeV). In this Sec. we do not take into account the intrinsic transverse momentum \( k_{\perp,i} \) of partons.

In Sec. IV we calculate the suppression of \( \pi_0 \) spectra taking into account the intrinsic transverse momentum of partons. We use here a Monte-Carlo method for calculation of invariant cross section of hadron production. We show, that if take into consider the physical restrictions, then the parton cross section does not have the divergence at too large \( k_{\perp,i} \), which are considered in other works (for example, in Ref. \([8]\)). Therefore there is no necessity to introduce a regulator \( \mu^2 \) in the denominators of the parton-parton cross sections. We show that this model reproduces the data for \( \pi_0 \) spectra at high \( p_\perp \) in pp-collisions at \( \sqrt{s} = 200 \) GeV without introduction of \( K \)-factor \( ( \text{ at } < k^2_{\perp} > \simeq 1.8 \) GeV\(^2\)\). We show also, that suppression factor \( R_{AA}(p_\perp) \) is changes weakly in above-mentioned range of \( p_\perp \), if intrinsic momentum \( k_{\perp,i} \) is taken into account.

In Sec. V - Conclusion.

II. ENERGY LOSS OF HIGH ENERGY GLUON AND QUARK JETS

In previous section the physical characteristics of the plasma stage for RHIC at \( \sqrt{s} = 200 \) GeV were found. The production of hot glue at the first stage is caused by relatively large \( gg \) cross section in comparison with \( qg \) and \( qq \) cross section. We use these characteristics for investigation of energy loss of the high energy parton jets. The dominant first order
radiation intensity distribution \( \frac{dI}{dx} \) for expanding plasma is given in Ref. [3] and correspond to formula (3) in Ref. [4], which have the form:

\[
\frac{dI}{dx} = \frac{9C_R E}{\pi^2} \int_{z_0}^{\infty} dz \rho(z) \int |k|_{\text{max}} |k|_{\text{min}} d^2k \alpha_s \\
\int_0^{q_{\text{max}}} d^2q \frac{\alpha_s^2}{|q^2 + \mu^2(z)|^2} \frac{kq}{k^2(k-q)^2} \left[ 1 - \cos \left( \frac{(k-q)^2(z-z_0)}{2x(1-x)E} \right) \right],
\]

(2)

In this formula the value \( E \) is the jet energy and \( C_R \) is the color factor of jet: \( C_R \) is \( N_c \) for gluon and \( \frac{4}{9}N_c \) for quark jet. It is assumed that quark-gluon plasma can be modeled by the well separated color-screened Yukawa potentials. In Ref. [4] was shown, that this condition is well realized for partons scattering on gluon potential, but this is not realized for partons scattering on the quark Yukawa potential. Therefore the estimation of parton energy loss \( \Delta E \) on the gluon Yukawa potential is the most real in this model. In formula (2) we have \( |q|_{\text{max}} = \sqrt{3\mu(\tau)E} \), where \( \mu^2(\tau) = 4\pi\alpha_s T^2(\tau) \). and the kinematic bounds are \( k^2_{\text{max}} = \min \{ 4E^2x^2, 4^2x(1-x) \} \) and \( k^2_{\text{min}} = \mu^2(\tau) \) for gluons with the light cone momentum fraction \( x \). The value \( z = \tau \) is limited in fact by duration of the plasma phase \( \tau_g \leq \tau \leq \tau_c \) (and \( \tau_c \leq R_{Au} \)). The value \( \rho(\tau) \) is gluon density \( n_g \) at time \( \tau \) along the jet path, which is calculated in effective quasiparticle model. The energy loss \( \Delta E_g \) of gluon jet is determined by integration of \( dI/dx \) in (2) over \( x \). The corresponding integral \( I_0(E, \tau) \) (look a formula (22) in Ref. [4]) is calculated in above-mentioned finite kinematic bounds by Monte Carlo method for values \( \tau(T) \) from \( \tau_g \) to \( \tau_c \) and for of \( E \) up to 60 – 70 GeV. The energy loss \( \Delta E_g \) is determined by formula:

\[
\Delta E_g(E) = \frac{9C_R E}{\pi^2} \int_{\tau_g}^{\tau_c} \frac{d\tau}{\mu^2(\tau)} I_0(E, \tau)n_g(\tau).
\]

(3)

The values \( I_0(\tau) \) and \( n_g(\tau) \) for expanding plasma at \( \sqrt{s} = 200 \) GeV and the values of energy loss for gluon jet we show in Table I for example at \( E = 10 \) GeV. The complete energy loss \( \Delta E \) is calculated by numeral integration over \( \tau \). We have \( \Delta E = 3.6 \) GeV at \( E = 10 \) GeV, i.e. not great increase in comparison with \( \sqrt{s} = 130 \) GeV. The complete energy loss \( \Delta E_g(E) \) of gluon jet is shown in Figure 1 and the relative energy loss \( \Delta E_g/E \) in Figure 2. For energy loss of quark jet we have \( \Delta E_q/E = \frac{4}{9} \Delta E_g(E) \). That is important non-Abelian feature of parton energy loss.
Figure 1: The energy loss of gluon jet in quark-gluon plasma at RHIC energy \( \sqrt{s} = 200 \text{ GeV} \)

It should be noted, that these energy loss correspond to the model of phase transition with decrease of effective coupling strength \( G(T) \) and gluon mass \( m_g(T) \) for \( T \to T_c \) from above. In Ref. \[5\] we already noted, that model with increase of \( G(T) \) for \( T \to T_c \) agrees with new lattice data and provides description of baryon and meson spectra, but it give too large suppression of hadrons with large \( p_\perp \) which disagrees with data.

III. SUPPRESSION OF PIONS WITH LARGE \( P_\perp \) AT \( \sqrt{S} = 200 \text{ GEV/C} \) WITHOUT ACCOUNTING OF INTRINSIC MOMENTA \( K_\perp \) OF PARTONS.

The energy loss reduces the jet energy before fragmentation, where the jet transverse momentum is shifted on the value \( \Delta E(E) \). If this effect is taken into account, we should
Table I: The physical values for expanding plasma at $\sqrt{s} = 200$ GeV and energy loss $\Delta E_g$ at $E = 10$ GeV

| $T$ (MeV) | $\tau$ ($m^{-1}$) | $\alpha_s$ | $\mu^2$ ($m_\pi^2$) | $n_g$ ($m_\pi^3$) | $I_0$ | $\Delta E$ (GeV) |
|-----------|------------------|------------|-----------------|-------------|------|-----------------|
| 373       | 0.587            | 0.269      | 24.34           | 24.77       | 0.097| 2.64            |
| 350       | 0.64             | 0.268      | 21.35           | 20.12       | 0.095| 2.61            |
| 325       | 0.713            | 0.266      | 18.27           | 15.75       | 0.092| 2.36            |
| 300       | 0.808            | 0.263      | 15.39           | 12.035      | 0.089| 1.905           |
| 275       | 0.935            | 0.259      | 12.74           | 8.92        | 0.084| 1.62            |
| 250       | 1.116            | 0.254      | 10.32           | 6.34        | 0.081| 1.34            |
| 224       | 1.585            | 0.246      | 8.024           | 3.87        | 0.080| 1.065           |
| 210       | 1.935            | 0.239      | 6.85            | 2.99        | 0.078| 0.96            |
| 200       | 2.293            | 0.231      | 6.01            | 2.428       | 0.076| 0.84            |
| 190       | 2.838            | 0.22       | 5.16            | 1.886       | 0.075| 0.7             |
| 185       | 3.267            | 0.21       | 4.67            | 1.612       | 0.063| 0.59            |
| 180       | 3.98             | 0.19       | 4.025           | 1.32        | 0.05 | 0.448           |
| 177       | 4.5              | 0.057      | 1.16            | 1.39        | 0.0063 | 0.0204 |

replace the vacuum fragmentation function by the effective one $\frac{z^*_c}{z_c} D_{h/c}(z^*_c, Q^*)$ [10] where

$$z^*_c = \frac{z_c}{1 - \frac{\Delta E}{E}}.$$  \hspace{1cm} (4)

The invariant cross section of hadron production in central $A + A$ collisions is given by

$$E_h \frac{d^2 \sigma_{AA}}{dp^2} = \int_0^{b_{max}} d^2 b \ d^2 r \ t_A(r) t_A(|b - r|) \sum_{abcd} \int dx_a dx_b d^2 k_{\perp,a} d^2 k_{\perp,b} \times$$

$$\times g_A(k_{\perp,a}, Q^2, r) g_A(k_{\perp,b}, Q^2, |b - r|) f_{a/A}(x_a, Q^2, r) f_{b/A}(x_b, Q^2, |b - r|) \times$$

$$\times \frac{d\sigma}{dt} \frac{z^*_c}{z_c} D_{h/c}(z^*_c, \hat{Q}^2) \pi z_c.$$  \hspace{1cm} (5)

Here $t_A$ is the nuclear thickness function, the $k_{\perp,a}$ and $k_{\perp,b}$ are the intrinsic transverse momenta of partons, the values $f_{a/A}$ and $f_{b/A}$ are the partons structure function. It is usually assumed that distribution $g_A(k_{\perp})$ has a Gaussian form. It should be noted, that intrinsic $k_{\perp}$ are more important for final hadron spectra for SPS energies. With the increase of energy the spectra become flatter and intrinsic momenta are less important [8]. At higher
energy the intrinsic momenta $k_\perp$ are included in order to account for phenomenologically the next -to- leading order correction \[11\] (instead of K-factor). The accounting of $k_\perp$ change weakly the factor $R_{AA}$. We will take into account the intrinsic momenta of partons in the next Section.

The upper limit for the impact parameter is $b_{\text{max}} \simeq 0.632 R_{Au}$ for 10% central $Au + Au$ collisions. Since the energy of collisions is very high, we will consider for simplicity the collisions of flat disks. In that case the integral of overlapping is $T_{AA}(b) = \frac{A^2}{\pi R_A^2} \simeq 262 \text{ fm}^{-2}$. The parton shadowing factor $S_A$ for flat disks also should be taken into account. We used the shadowing functions $S_A(x, Q^2)$ from EKS98 parameterization \[12\]. These shadowing functions affected weakly on suppression factor $R_{AA}$, especially at large $p_\perp$ (at least at $p_\perp < 20 \text{ GeV/c}$). It was shown also in Ref. \[17\]. At more of $p_\perp$ it is possible the additional decrease of $R_{AA}$ due to EMC modification of nuclear structure function. We use the parton distribution from Ref. \[13\] and fragmentation function $D_g$ and $D_q$ from Ref. \[14\] both in LO parametrization.

We will use the equation (5) in another aspect, in order to compare the energy loss with other works, for example with Ref. \[15\] and \[16\]. Let us consider at first the hadrons production at parton collisions in the absence of the medium. A parton produced initially with transverse momentum $p_\perp + u$ fragmentire into hadron with momentum $p_\perp$. We have $z = \frac{p_\perp + u}{p_\perp}$, and we use the factorization scale $Q = \frac{p_\perp + u}{2z}$, that is $Q(u) = \frac{p_\perp + u}{2}$. We have here $u_{\text{min}} = 0$ and $u_{\text{max}} = \frac{\sqrt{s}}{2} - p_\perp$. The invariant cross section for $\pi^0$ production in $pp$ collisions for example gluon jet is (without accounting of partons intrinsic momentum):

$$E_\pi \frac{d\sigma^{pp}}{d^3p} = \frac{9}{2} \int_0^{\frac{\sqrt{s}}{2}-p_\perp} du \frac{a_s^2(u)}{p_\perp (p_\perp + u)^4} D(z(u), Q^2(u)) \times$$

$$\int_{k(u)}^{1} d\xi f_{gg}(\xi) x_1 G_g(x_1, Q) x_2 G_g(x_2, Q),$$

(6)

where $k(u) = \frac{p_\perp + u}{\sqrt{s}}$. We introduce here the new variable $x_1 = \frac{(p_\perp + u)\xi}{\sqrt{s}}$, $x_2 = \frac{(p_\perp + u)\xi}{\sqrt{s}(\xi - 1)}$. We describe the contribution of the different elementary sections in variable $\xi$:

$$f_{gg}(\xi) = \frac{3(\xi - 1)}{\xi^4} - \frac{(\xi - 1)^2}{\xi^6} + \frac{1}{(\xi - 1)^3} + \frac{(\xi - 1)^2}{\xi^3},$$

(7)
\[ f_{qq}(\xi) = \frac{4}{9} \left( \frac{1}{\xi^2} + \frac{1}{\xi^3} - \frac{1}{\xi^4} \right) + \frac{\xi^2 + 1}{\xi^4(\xi - 1)} + \frac{\xi - 1}{\xi^2} + \frac{(\xi - 1)^3}{\xi^4}. \]  

(8)

For corresponding contributions into quark-quark cross section for identical \( f_{qq}^{id} \) and for different \( f_{qq}^{dif} \) quarks we have:

\[ f_{qq}^{id} = \frac{4}{9} \left( \frac{\xi^2 + 1}{\xi^4(\xi - 1)} + \frac{\xi - 1}{\xi^2} \right) - \frac{8}{27} \frac{1}{\xi^2}, \]  

(9)

\[ f_{qq}^{dif} = f_{qq}^{id} + \frac{8}{27} \frac{1}{\xi^2}. \]  

(10)

In the presence of medium the parton loses the additional energy \( \Delta E \) and we have from (4):

\[ z^*(u, \Delta E) = \frac{p_\perp}{p_\perp + u - \Delta E}. \]  

(11)

and also:

\[ Q^*(u) = \frac{p_\perp}{2z^*} = \frac{p_\perp + u - \Delta E}{2}. \]  

(12)

The value \( z^g_{max} \) for gluons (i.e. and \( u^g_{min} \)) in the presence of medium we find from relation (4):

\[ z^g_{max} = \frac{p_\perp}{E - \Delta E^g} = 1 \]  

for every value of \( p_\perp \) (Ref. [4]). The value \( z^q_{max} \) for quarks is fined by substitution of \( (\Delta E)^q \) instead of \( (\Delta E)^g \). The value \( E_{min} \) which correspond to gluon jet for given \( p_\perp \) can be found from Figure 1 (in large scale). In the range \( E_{min} \leq E \leq \sqrt{s} \) we construct the dependence \( (\Delta E/E)^g(z) \) using Figure 2. For analogous function for quarks \( (\Delta E/E)^q(z) \) we use the relation \( (\Delta E)_{q} = \frac{4}{9}(\Delta E)_{g} \). From these relations we find the values \( (\Delta E)_{g,q}(u) \). For example, we find for gluons at \( p_\perp = 8 \text{ GeV} \) (with (3 − 5)% precise):

\[ \left( \frac{\Delta E}{E} \right)^g(z) = 0.42z + 0.05 + 0.35(z - 0.08)(0.665 - z). \]  

(13)

The corresponding equation for quarks is (with accounting that \( z^q_{max} \neq z^g_{max} \)):

\[ \left( \frac{\Delta E}{E} \right)^q(z) = \frac{4}{9} \left( 0.4z + 0.049 + 0.3(z - 0.08)(0.835 - z) \right). \]  

(14)

At increase of \( p_\perp \) the dependence \( (\Delta E)/E \) become linear. For example, at \( p_\perp = 20 \text{ GeV} \) we have:

\[ \left( \frac{\Delta E}{E} \right)^g(z) = 0.227z + 0.036 \]  

(with 0.2 ≤ \( z \leq 0.786 \)),

\[ \left( \frac{\Delta E}{E} \right)^q(z) = \frac{4}{9} \left( \frac{\Delta E}{E} \right)^g \]  

(with 0.2 ≤ \( z \leq 0.893 \)).  

(15)
We have here in variable u:

\[(\Delta E)^g(u) = 5.26 + 0.036u \text{ (with } 5.4 \leq u \leq 80 \text{ (GeV)})\] (16)

The fragmentation scale is now:

\[Q_g(u) = \frac{p_\perp + u - \Delta E^g(u)}{2}, \quad Q_q(u) = \frac{p_\perp + u - \Delta E^q(u)}{2}.\] (17)

Let us write down the formula of type (6) in AA collisions for \(\pi^0\) production in gluon jet with accounting of energy loss in medium:

\[
E_\pi \frac{d\sigma_{AA}}{d^3p} = \frac{9}{2} \frac{\mathcal{A}^2}{\pi R_A^2} \int_{\frac{k(u)}{u_{\min}(p_\perp)}}^{\frac{\sqrt{2}p_\perp}{p_\perp}} du \frac{\alpha_s^2(Q(u))}{p_\perp(p_\perp + u)^4} \frac{D_g(z^*(u), Q_g(u))}{1 - \frac{\Delta E^g(u)}{p_\perp + u}} \int_1^{1/k(u)} d\xi f_{gg}(\xi) x_1 G_g(x_1, Q(u)) x_2 G_g(x_2, Q(u)).\] (18)

For calculation of complete energy loss we must take into account also quark-gluon and quark-quark collisions with corresponding structure function and elementary cross section \((7-10)\) and the energy losses \((\Delta E)^g,q(u)\). We take into account also the gluon collisions with sea quarks.

The suppression factor \(R_{AA}(p_\perp)\) is the ratio of the sum of invariant cross section of type (18) to the sum cross section of binary NN collisions of type (6) without accounting of nuclear effects - jet quenching and shadowing. We have calculated the factor \(R_{AA}(p_\perp)\) in wide range of \(p_\perp\) from 4 up 60 GeV/c. In order to avoid too small values at calculation for great \(p_\perp\), we multiply the numerator and denominator in this ratio on value \(p_\perp^4\).

It should be noted, that energy loss in medium can not be expressed by simple manner through vacuum cross section \(\frac{d\sigma}{dp_\perp^2 + \Delta E}\) (as for example in [15], [16]). The situation have more complex character.

We show in Table II the results for suppression factor \(R_{AA}(p_\perp)\) for flat disks with accounting of nuclear shadowing function \(S_A(x, Q^2)\) from EKS98 parameterization [12]. We take into account in this Table also the intrinsic transverse momentum of partons (look at formula (24) in [15]. The contribution of nuclear shadowing effects in \(R_{AA}(p_\perp)\) is small (less
Table II: The suppression $R_{Au,Au}(p_\perp)$ of neutral pions at $\sqrt{s} = 200$ GeV. The $u_{\text{min}}$ and $z_{\text{max}}$ are shown only for gluon jet.

| $p_\perp$ | $u_{\text{min}}^g$ | $z_{\text{max}}^g$ | $R_{AA}$ |
|----------|----------------|----------------|--------|
| 4        | 3              | 0.572          | 0.22   |
| 6        | 3.5            | 0.632          | 0.27   |
| 8        | 4              | 0.667          | 0.34   |
| 10       | 4.3            | 0.7            | 0.38   |
| 14       | 4.8            | 0.745          | 0.42   |
| 20       | 5.4            | 0.786          | 0.44   |
| 30       | 6              | 0.833          | 0.42   |
| 40       | 6.2            | 0.866          | 0.38   |
| 50       | 6.5            | 0.885          | 0.32   |
| 60       | 6.8            | 0.898          | 0.25   |
| 70       | 7.2            | 0.907          | 0.22   |

than 10%). It was noted also in the work [17]. At large $p_\perp > 20$ GeV this contribution increase up to $\sim 20\%$ and that gives decrease of $R_{AA}$ due to EMC effect.

It should be noted, that at large $p_\perp$ the value $R_{AA}(p_\perp)$ is determined quantitatively in the main by quark jets — the contribution of gluons into numerator of ratio $R_{AA}$ become small ($\sim 10\%$ already at $p_\perp = 10$ GeV).

The dependence $R_{AA}(p_\perp)$ is shown in Figure 3. This function have the weak rise above $p_\perp = 4$ Gev/c and broad maximum in the range $p_\perp \sim 15 - 30$ Gev/c. The PHENIX data there are only up 10 GeV/c [1]. It is possible to describe these data by effective quasiparticle model with decrease of effective coupling at $T \rightarrow T_c$ from above (look at Table 1) without additional free parameters. The following decrease of $R_{AA}$ at $p_\perp > 20$ GeV is caused by some factors — in particular, by increase of $u_{\text{min}}$ with increase of $p_\perp$.

It is interesting to note, that dependence $R_{AA}(p_\perp)$ in Figure 3 disagrees with monotonous increase at sufficiently large of $p_\perp$, which was considered for example in the paper [21]. This question have interest and for LHC, where also the continuous rise of suppression $R_{AA}$ with $p_\perp$ was found [19]. We will investigate this question in the forthcoming work. But of course the calculation for large $p_\perp$ may be questionable in very near region to boundary of phase.
Figure 3: a: The suppression factor $R_{AA}(p_\perp)$ for $\pi^0$ in central Au + Au at $\sqrt{s} = 200$ GeV in the range of $p_\perp$ to 15 GeV/c and PHENIX data. b: The suppression factor $R_{AA}$ which was calculated in the range of $p_\perp$ to 60 GeV/c.

space ($p_\perp \approx \sqrt{s}/2$), where overall energy and momentum conservation may be important.

IV. THE CALCULATIONS WITH ACCOUNTING OF INTRINSIC TRANSVERSE MOMENTA OF PARTONS

The invariant cross section of hadron production in central $A + A$ collisions with accounting of intrinsic transverse momenta is given by formula [5]. We already have mentioned, that we will consider for simplicity the collisions of flat disks. In this case the integral of overlapping for $Au + Au$ collisions is $\bar{T}_{AA}(b) = \frac{A^2}{\pi R_A^2} \simeq 262$ fm$^{-2}$. We describe the Mandelstam variables for elementary parton-parton scattering in term of light-cone variables $x_1$, $x_2$. 

\[ x_1, x_2, x_3, x_4, ..., x_n \]
In equation (5) one should restrict the initial transverse momentum
\[ k_{\perp 1} \leq x g x t \text{hadrons} \]. We introduce the new variables
\[ f \].

Here \( p_{\perp} \) and \( y \) are the transverse momentum and rapidity of produced particles,
\[ \cos(\gamma_1) = \frac{k_{\perp 1} p_{\perp}}{k_{\perp 1} p_{\perp}} \], \( \cos(\gamma_2) = \frac{k_{\perp 2} p_{\perp}}{k_{\perp 2} p_{\perp}} \). It is usually assumed that initial \( k_{\perp} \) distribution
\[ g_N(k_{\perp}, Q^2) \] has a Gaussian form:
\[ g_N(k_{\perp}, Q^2) = \frac{e^{-k_{\perp}^2}}{\pi < k_{\perp}^2 >_N} \].

In equation (5) one should restrict the initial transverse momentum \( k_{\perp 1} < x_1 \sqrt{s} \) and
\( k_{\perp 2} < x_2 \sqrt{s} \) such that longitudinal momenta of partons have the same signs as their parent hadrons. We introduce the new variables \( t_1 \) and \( t_2 \): \( k_{\perp 1} = t_1 x_1 \sqrt{s} \), \( k_{\perp 2} = t_2 x_2 \sqrt{s} \), where
\( 0 \leq t_i \leq t_{\text{max}} \) and \( t_{\text{max}} < 1 \). The variables (19) one can describe in the following form:
\[ \begin{align*}
\hat{s} &= s x_1 x_2 \Psi(t_1, t_2, \gamma_1, \gamma_2), \\
\hat{t} &= -s x_1 x_2 \phi_1(t_1, \gamma_1), \\
\hat{u} &= -s x_1 x_2 \phi_2(t_2, \gamma_2),
\end{align*} \]
where
\[ x_1^\perp = \frac{2p_{\perp}^\perp}{\sqrt{s}} \].

Here we use designation:
\[ \Psi(t_1, t_2, \gamma_1, \gamma_2) = 1 + t_1^2 t_2^2 - 2t_1 t_2 \cos(\gamma_1 - \gamma_2), \\
\phi_1(t_1, \gamma_1) = 1 + t_1^2 - 2t_1 \cos(\gamma_1), \\
\phi_2(t_2, \gamma_2) = 1 + t_2^2 - 2t_2 \cos(\gamma_2). \]

Now for example instead of \( f_{gg}(\xi) \) (7) we have:
\[ f_{gg}(\xi, t_1, t_2, \gamma_1, \gamma_2) = \frac{3(\Psi \xi - \phi_2)}{\Psi^2 \phi_1^4} - \frac{\phi_1 \phi_2 (\Psi \xi - \phi_2)^2}{\Psi^4 \phi_1^4 \phi_2^4} + \frac{\phi_2 (\Psi \xi - \phi_2)}{\Psi \phi_2^2 \phi_1^4} + \frac{\phi_2^2 (\Psi \xi - \phi_2)^2}{\Psi \phi_2^2 \phi_1^4 \xi^3}. \]

We have analogous modification and for other elementary cross section (8-10).

In the structure function \( G_g(x_1)G_g(x_2) \) we have the modification: \( x_1 = \frac{x_{\text{max}} \xi}{2z_c} \) and
\[ x_2 = \frac{x_1 \phi_1}{2z_c (\Psi \xi - \phi_2)}. \]
The invariant cross section for hadron production (for example in gluon jet) in central \( Au + Au \) collisions with accounting of partons initial momenta \( k_\perp \) have the form:

\[
E \frac{d\sigma^{AA}}{d^3p} = \frac{9A^2}{\pi R_A^2} \int_{x_\perp^1}^{x_\perp^2} d^2z \frac{z^2\alpha_s^2(Q(z))D_{h/f}(z_c^*, Q^2)}{p_\perp^4(1 - \frac{\Delta E}{E}(z))} \int_0^{t_{max}(z)} dt_1 \int_0^{t_{max}(z)} dt_2 \times
\]

\[
\frac{2\pi}{2\pi} \int_0^{d\gamma_1} d\gamma_1 \int_0^{d\gamma_2} d\gamma_2 \int_{\frac{2\pi}{2\pi}}^{2\pi} d\xi g_1(t_1, \xi, z)g_2(t_1, t_2, \gamma_1, \gamma_2, \xi, z) \times
\]

\[
f_{gg}(\xi, t_1, t_2, \gamma_1, \gamma_2)x_1^2x_2^2s^2\Psi(t_1, t_2, \gamma_1\gamma_2)x_1G_g(x_1, Q^2)x_2G_g(x_2, Q^2).
\]

The value \( z_{\max}^g(p_\perp) \) can be found from condition \( z_{\max}^g = \frac{p_\perp}{p_\perp + u_{\min}^g(p_\perp)} \), where the values \( u_{\min}^g(p_\perp) \) (and also \( z_{\max}^g \) which can be found independently) there are in Table III.

In this work we neglect of the transverse momentum smearing from the jet fragmentation.

The Gaussians \( g_1 \) and \( g_2 \) in (24) have the form:

\[
g_1(t_1, \xi, z) = \frac{\exp \left( - \frac{t_1^2 \left( \frac{2\pi}{2\pi} \xi^2 \right)}{<k_\perp^2>} \right)}{\pi <k_\perp^2>},
\]

\[
g_2(t_1, t_2, \gamma_1, \gamma_2, \xi, z) = \frac{\exp \left( - \frac{t_2^2 \left( \frac{2\pi}{2\pi} \xi^2 \right)}{<k_\perp^2>} \right)}{\pi <k_\perp^2>}. \tag{25}
\]

With accounting of nuclear shadowing the parton distribution \( G_g(x, Q^2) \) must be modified: \( G_g(x, Q^2)S_A(x, Q^2) \).

In order to find the restriction \( t_{max}(z) \), one should take into account, that lower limit of integral on \( \xi \) must be \( > 0 \) at any values of \( t \) and \( \gamma \). That correspond to condition: \( 2\Psi_{\min} > \phi_{1max}x_\perp^\pi \). But the value \( \Psi \) have minimum at \( \gamma_1 = \pi \), therefore we have the condition: \( 2z(1 + t)^2(1 - t)^2 > x_\perp^\pi(1 + t)^2 \), i.e. \( t < 1 - \frac{x_\perp^\pi}{2z} \). At mentioned values of angles \( \gamma \) the lower limit of \( \xi \) is: \( \xi(z, t) = \frac{2z(1 + t)^2}{2z(1 - t)^2 - x_\perp^\pi} \), and we have \( t \leq t_{max} \), where \( t_{max}(z) \) correspond to \( \xi(z, t_{max}) = \xi_{max} = \frac{2z}{x_\perp^\pi} \). For set of values of \( p_\perp \) we calculate by numeral way the function \( t_{max}(z) \).
For example, for $p_{\perp} = 8$ GeV/c we find:

$$t_{\text{max}}(z) = 1 - \sqrt{\frac{0.04}{z}} - 0.2929 \exp\left(\sqrt{z - 0.08}\right)(0.0618 - 10.9786z + 27.8446z^2 - 29.0236z^3 + 10.78z^4)$$

(26)
and for $p_{\perp} = 20$ GeV/c we find correspondingly

$$t_{\text{max}}(z) = 1 - \sqrt{\frac{0.1}{z}} - 0.2929 \exp\left(\sqrt{z - 0.2}\right)(0.6808 - 8.0412z + 15.8356z^2 - 14.1458z^3 + 4.744z^4).$$

(27)

At calculation of the invariant cross section by formula (24) we use Monte-Carlo method. We use here the factorization scale $Q = \frac{p_{\perp}}{2z c}$ and fragmentation scale $Q^* = \frac{p_{\perp}}{2z c}$. In absence of nuclear effects — jet quenching and shadowing the equation (24) describes the collection of binary NN collisions. We have in this case $\Delta E = 0$ and $z_{\text{max}}^q = 1$. For binary collisions we use the value $< k_{\perp}^2 >_{pp} \simeq 1.8$ GeV$^2$ [18]-[19].

In the presence of medium we use the estimation in Ref. [18]:

$$< k_{\perp}^2 >_{AA} = < k_{\perp}^2 >_{pp} + C(\nu_m - 1),$$

(28)

where $C \simeq 0.4$, $\nu_m \simeq 4$, i.e. we have the estimation $< k_{\perp}^2 >_{AA} \simeq 3$. At calculation we use also the estimation $< k_{\perp}^2 >_{AA} \simeq 4$. This have a weak influence on the value of suppression $R_{AA}(p_{\perp})$.

We use now the formula (24) for calculation of the spectrum of high $p_{\perp}$ neutral pions in $pp$ collisions at $\sqrt{s} = 200$ GeV. We take into account the sum of elementary parton - parton cross section [7]-[10] with accounting their modification of type (23). We have not the divergence at calculation and therefore we do not introduce a regulator $\mu^2$ in the denominators of elementary cross section. We do not introduce also the K-factor. In Figure 4 we show our calculation for the spectrum of high $p_{\perp}$ neutral pions in $pp$ collisions and PHENIX data [20] up to $p_{\perp} \simeq 14$ GeV/c One can see that calculation by formula of type (24) for $pp$ collisions reproduces the data in the region $p_{\perp} > 4$ GeV/c.

It should be noted, that we calculated also the factor $R_{AA}^{e0}(p_{\perp})$ at $\sqrt{s} = 200$ GeV by formula (24) with Cronin effect and shadowing, but without the energy loss (for flat discs) using the value $< k_{\perp}^2 >_{AA}$ in the presence of medium (27). We find the values $R_{AA} = 1.56$ at $p_{\perp} = 4$ GeV/c and $R_{AA} = 1.1$ at $p_{\perp} = 8$ GeV/c. That agrees with results of paper [19]. We
use also the formula (24) for calculation of suppression $R_{AA}$ for great $p_{\perp}$ with accounting of intrinsic momentum $k_{\perp,i}$. They give the small increase of factor $R_{AA}$ - less than 10%. The results are shown in Table II and in Figure 3.

It should be noted, that formula of type (24) can be used also for investigation of the Cronin enhancement at SPS energy ($\sqrt{s} = 17$ GeV).

V. CONCLUSION

In this work we use the physical characteristics of initial and mixed plasma phases which were found in the effective quasiparticle model for investigation of suppression of neutral pion spectra in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV. The specific feature of this model consist in decrease of thermal gluon mass and effective coupling in a region of phase transition. We use also the hypothesis of hot glue production at the first stage of plasma expansion. We describe the following evolution of plasma in isentropic model. The energy loss of the high energy gluon and quark jets in plasma leads to suppression of hadron spectra. For calculation of energy loss we use opacity expansion [3], which is dominated by first term. At calculation we take into account the finite kinematic boundaries, which often
do not accounted for. We calculate the gluon density in plasma and show that plasma is sufficiently thin. This to some extent justify the model of the single hard medium-induced scattering.

We show that suppression factor $R_{AA}(p_{\perp})$ has no continuous rise with increase of $p_{\perp}$ - one has the weak rise, then smooth maximum at $P_{\perp} \sim 20$ GeV/c and then it decrease with further increase of $p_{\perp}$. This question is interesting for LHC, where the calculations [19, 21] show continuous rise. We will consider this question in the forthcoming work. It is interesting to investigate also the hard photon suppression - apparently it is much smaller than for hadrons [17, 21].

We use in this work the simplified model of collisions of flat discs at $\sqrt{s} = 200$ GeV. We are planning to use the more complex model of nuclear geometry in the forthcoming work. It should be noted, that model of collisions with transverse expansion and Woods-Saxon nuclear distribution with some parametrization of energy loss was used in the work [9]. There was found also slight increase of nuclear modification factor $R_{AA}$ with increase of $p_{\perp}$ at 200 GeV (at accounting of both gluon and quark jets). In recent work we used the parameters which were found in effective quasiparticle model and nuclear modification of structure function from [12]. We take into account also the intrinsic transverse momentum of partons $k_{\perp,i}$. We show, that one can avoid of divergence at large $k_{\perp,i}$, if we take into account the physical restrictions on initial transverse momentum. Therefore there is no necessity to introduce a regulator $\mu^2$ in parton-parton cross-section. It can have the meaning at more low SPS energies, for example at investigation of Cronin effect, where the suppression factor $R_{AA}$ can be much larger than 1.

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