We propose a model of suppression of π⁰'s based on two different effects: at low \( p_T \) we take into account the shadowing corrections, which are non-linear and essential for the description of the inclusive spectra, while at large \( p_T \) the suppression is produced through the interaction of the large \( p_T \) pion with the dense medium created in the collision. The main features of the data on \( AuAu \) and \( dAu \) collisions at RHIC energies are reproduced both at mid and at forward rapidities.

Keywords: Shadowing; jet quenching.

1. Introduction

One of the most intriguing results of the heavy ion program at RHIC is the fact that the nuclear modification factor in central \( AuAu \) collisions, \( R_{AA}(b, y, p_T) = \frac{dN_{AA}^{\gamma}(b)}{d^2p_T} / \frac{dN_{pp}^{\pi}(b)}{d^2p_T} \), is smaller than 1 for all \( p_T \). That means that the yield of particles produced in \( AA \) collisions at mid-rapidities and large \( p_T \) increases with centrality much slower than the number of binary collisions \( n(b) \). This phenomenon is particularly interesting since it is not observed in \( dAu \) collisions at RHIC at mid-rapidities.

In order to explain these data, one should take into account two kinds of effects. On one side, we have the effects that are important at low \( p_T \). In most of the models of multiparticle production, two contributions to the multiplicity are considered: one proportional to the number of participant nucleons, \( N_{part} \), and a second one proportional to the number of inelastic nucleon-nucleon collisions, \( n_{part}^{1/3} \), which is the dominant contribution at asymptotic energies. In order to get the right multiplicities at RHIC it is necessary to lower this contribution. Different mechanisms have been proposed, like saturation in high density QCD through the Colour Glass Condensate in the string models. Another possibility is the shadowing through pomeron interaction in the Dual Parton Model. All these mechanisms have in common the modification of a multiple scattering pattern—in the target rest frame— or gluon interaction—in a fast moving frame—. At very high
energies, the shadowing corrections—which are non-linear—lead, as \( s \to \infty \), to a saturation of the distributions of partons in the colliding nuclei. These corrections are important for the description of inclusive spectra, for particles with \( p_T \sim \langle p_T \rangle \). But with increasing \( p_T \) the shadowing corrections decrease and the scaling with \( n(b) \) is predicted in perturbative QCD (\( R_{AA} \to 1 \)).

So in order to explain the data at large \( p_T \), it is necessary to consider that for particles with large momentum transfer, there are in general final state interactions—jet quenching or jet absorption\(^5\). These interactions lead to an energy loss of the large \( p_T \) parton (particle) in the dense medium produced in the collision. Hadrons loose a finite fraction of their longitudinal momentum due to multiple scattering.

From this point of view, it is natural to expect that a particle or a parton scattered at some non-zero angle will also lose a fraction of its transverse momentum due to final state interactions with a medium of partonic or prehadronic nature. The scattered particle does not disappear as a result of the interaction but its \( p_T \) is shifted to smaller values. Due to the steepness of the \( p_T \) distribution, the effect of suppression at large \( p_T \) may be quite large. Moreover, in this case there is also a gain of the yield at small \( p_T \) due to particles produced at larger \( p_T \) which have experienced a \( p_T \) shift due to the interaction with the medium. This suppression vanishes at low \( p_T \): when the \( p_T \) of the particle is close to \( \langle p_T \rangle \), its \( p_T \) can either increase or decrease as a result of the interaction, i.e. in average the \( p_T \) shift tends to zero. Our aim here is to describe the suppression of the yield of pions in a framework based on final state interactions and taking into account shadowing and Cronin effect.

2. The model

Our approach contains dynamical, non-linear shadowing. It is determined in terms of diffractive cross sections and it applies to soft and hard processes. The reduction of multiplicity from shadowing corrections can be expressed by

\[
R_{AB}(b) = \frac{\int d^2 s f_A(s) f_B(b-s)}{T_{AB}(s)}, \quad f_A(b) = \frac{T_A(b)}{1 + AF(s)T_A(b)}
\]

where the function \( F(s) \) represents the integral of the triple Pomeron cross section over the single Pomeron one:

\[
F(s) = 4\pi \int_{y_{min}}^{y_{max}} dy \frac{1}{\sigma^P(s)} \left. \frac{d^2 \sigma^{PPP}}{dy dt} \right|_{t=0} = C[\exp(y_{max}) - \exp(y_{min})].
\]

From this formula one can observe that for a particle produced at \( y = 0 \), with \( y_{max} = \frac{1}{2}\ln(s/m_N^2) \) and \( y_{min} = \ln(R_A m_N/\sqrt{3}) \), the effect of shadowing decreases at large \( p_T \) due to the increase of \( m_T \) in \( y_{max} \).

In other words, due to coherence conditions, shadowing effects for partons take place at very small \( x \), \( x \ll x_{cr} = 1/m_N R_A \) where \( m_N \) is the nucleon mass and \( R_A \) is the radius of the nucleus. Partons which produce a state with transverse mass \( m_T \) and a given value of Feynman \( x_F \), have \( x = x_\pm = \frac{1}{2}(\sqrt{x_F^2 + 4m_T^2/s} \pm x_F) \).
Our shadowing applies to soft and hard processes. Nevertheless, for large $p_T$ these effects are important only at very high energies, when $x \approx \frac{m}{p_T}$ satisfies the above condition. At fixed initial energy ($s$) the condition for existence of shadowing will not be satisfied at large transverse momenta: In the central rapidity region ($y^* = 0$) at RHIC and for $p_T$ of jets (particles) above 5(2) GeV/c the condition for shadowing is not satisfied and these effects are absent.

So for the large $p_T$ partons it is necessary to include the final state interactions. The interaction of a large $p_T$ particle with the medium is described by the gain and loss differential equations which govern final state interactions:

$$\frac{d\rho_H(x,p_T)}{d^4x} = -\tilde{\sigma} \rho_S [\rho_H(x,p_T) - \rho_H(x,p_T + \delta p_T)]$$

where $\rho_S$ and $\rho_H$ correspond to the space-time density of the medium and of large $p_T\pi^0$'s, $\tilde{\sigma}$ is the interaction cross-section averaged over momenta and $d^4x$ represent the cylindrical space-time variables: longitudinal proper time $\tau$, space-time rapidity $y$, and transverse coordinate $s$.

Assuming a decrease of densities with proper time $1/\tau$ -isentropic longitudinal expansion, transverse expansion is neglected– the above equation transforms into:

$$\tau \frac{dN_{\pi^0}(b,s,y,p_T)}{d\tau} = -\tilde{\sigma} N(b,s,y) [N_{\pi^0}(b,s,y,p_T) - N_{\pi^0}(b,s,y,p_T + \delta p_T)]$$

where $N(b,s,y) \equiv dN/dy d^2s(y,b)$ is the density of the medium per unit rapidity and per unit of transverse area at fixed impact parameter, integrated over $p_T$, and $N_{\pi^0}(b,s,y,p_T)$ is the same quantity for $\pi^0$'s at fixed $p_T$.

If we integrate from initial time $\tau_0$ to freeze-out time $\tau_f$ and taking into account the inverse proportionality between proper time and densities, $\tau_f/\tau_0 = N(b,s,y)/N_{pp}(y)$, where $N(b,s,y)$ is the density produced in the primary collisions in DPM and $N_{pp}(y)$ is the density per unit rapidity for minimum bias $pp$ collisions at $\sqrt{s} = 200$ GeV ≈ 2.24 fm$^{-2}$, we obtain the suppression factor $S_{\pi^0}(b,y,p_T)$ of the yield of $\pi^0$'s at given $p_T$ and at each impact parameter, due to its interaction with the dense medium. We get:

$$S_{\pi^0}(b,y,p_T) = \left[ \int d^2s \sigma_{AB}(b) n(b,s) \frac{S_{\pi^0}(b,s,y,p_T)}{\int d^2s \sigma_{AB}(b) n(b,s)} \right]$$

where the survival probability is given by:

$$S_{\pi^0}(b,s,y,p_T) = \exp \left\{ -\tilde{\sigma} \left[ 1 - \frac{N_{\pi^0}(b,s,y,p_T + \delta p_T)}{N_{\pi^0}(b,s,y,p_T)} \right] N(b,s,y) \ell n \left( \frac{N(b,s,y)}{N_{pp}(y)} \right) \right\}$$

Here $\sigma_{AB}(b) = \{1 - \exp[-\sigma_{pp} AB T_{AB}(b)]\}, T_{AB}(b) = \int d^2sT_A(s)T_B(b-s), T_A(b)$ are the profile functions and $n(b,s) = AB \sigma_{pp} T_A(s) T_B(b-s)/\sigma_{AB}(b)$.

One can estimate which amount of the effect takes place in the partonic phase and which one happens in the hadronic phase. We can divide our suppression factor in two parts:

Partonic, from initial density $N(b,s,y) = \frac{dN}{dy} \pi_{RA}^0 \sim \frac{1000}{\pi RA} \approx \frac{300}{\pi RA}$, or equivalently from $\tau_0 = 1$ fm to $\tau_p = 3.36$ fm, and hadronic, from partonic density
\[
\frac{dN}{dy} \sim 300 \pi R_A^2 \quad \text{to} \quad N_{pp}(y) = \frac{dN}{dy} \pi R_p^2 = 2.24 \text{fm}^{-2}, \quad \text{or equivalently from} \quad \tau_p = 3.36 \text{fm} \quad \text{to} \quad \tau_f = 5 - 7 \text{fm}. \quad \text{We find that} \quad 75\% \quad \text{of the effect takes place in the partonic phase while only} \quad 25\% \quad \text{of the effect takes place in the hadronic phase.}
\]

3. Numerical results

In order to perform numerical calculations, we need \(\tilde{\sigma}\) – our free parameter, \(\tilde{\sigma} \sim 1 \text{mb}\) – and the \(p_T\) distribution of the \(\pi^0\)'s. We have proceeded as follows:

In \(pp\) collisions at \(\sqrt{s} = 200 \text{ GeV}\), the shape of the \(p_T\) distribution of \(\pi^0\)'s can be described as \((1 + p_T/p_0)^{-n}\) with \(n = 9.99\) and \(p_0 = 1.219 \text{ GeV/c}\). The corresponding average \(p_T\) is \(< p_T > = 2p_0/(n - 3) = 0.349 \text{ GeV/c}\). In \(AuAu\) collisions we assume that the \(p_T\) distribution of \(\pi^0\)'s at each \(b\) is given by the same shape, \((1 + p_T/p_0)^{-n}\), with \(n = 9.99\) and changing the scale \(p_0\) into \(p_0(b) = < p_T >_b (n - 3)/2\), where \(< p_T >_b\) is the average value of \(p_T\) measured experimentally at the corresponding centrality. For central \(AuAu\) collisions \((n_{part} = 350, b = 2)\), \(< p_T >_{exp} = 0.453 \text{ GeV/c}\) resulting in a \(p_0\) of 1.583 GeV/c.

We take \(n\) as fixed, since at large \(p_T\) the shadowing vanishes and the ratio \(R_{AA}\) is independent of \(p_T\). Also, the experimental value of \(n\) in \(dAu\) is the same as in \(pp\) within errors.

We can thus compute the ratio \(R_{AA}\) in the absence of final state interaction (column I, Table 1). In this case \(R_{AA}\) increases with \(p_T\), there is shadowing are low \(p_T\) and we have a Cronin effect that does not decrease at large \(p_T\).

To these values we apply the correction due to the suppression factor \(S_{\pi^0}\):

First, we neglect the second term -the gain- in eqs. (3-4) (column II, Table 1). We find a general suppression in \(R_{AA}\) independent of \(p_T\). Also, the experimental value of \(n\) in \(dAu\) is the same as in \(pp\) within errors.

Then we introduce the second term -the gain- in eqs. (3-4) in two ways:

Assuming that the \(p_T\) shift of the \(\pi^0\), due to its interaction with the medium, is constant (two cases: \(\delta p_T = 0.5 \text{ GeV/c}\) and \(\delta p_T = 1.5 \text{ GeV/c}\)) (columns III and IV), we obtain a slight increase of \(R_{AA}\) at large \(p_T\), rather insensitive to the value of the shift, consistent with data. The problem at small \(p_T\) remains.

| \(p_T\) | I  | II | III | IV | V  | VI |
|--------|----|----|-----|----|----|----|
| 0.5    | 0.38 | 0.05 | 0.08 | 0.11 | 0.20 | 0.34 | 0.38 |
| 2      | 0.90 | 0.13 | 0.18 | 0.21 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| 5      | 1.48 | 0.21 | 0.18 | 0.24 | 0.24 | 0.24 | 0.25 | 0.25 | 0.25 |
| 7      | 1.69 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| 10     | 1.84 | 0.27 | 0.34 | 0.30 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |

Table 1. Values of \(R_{AuAu}^{\pi^0}(p_T)\) for the 10% most central collisions \(AuAu\) collisions at mid-rapidities \(|y| < 0.35\). Column I is the result obtained with no final state interaction. The other columns include final state interaction with several ansatzs for the \(p_T\) shift.
If we assume that \( \delta p_T \propto (p_T - \langle p_T \rangle_b) \) (columns V and VI), in such a way that the factor \( S_{\pi^0} \) is 1 at \( p_T = \langle p_T \rangle_b \) as it should be –no suppression at low \( p_T \)–, we obtain a slight decrease of \( R_{AA} \) at large \( p_T \), consistent with data and an increase of \( R_{AA} \) at low \( p_T \)–due to the shift of large \( p_T \) particles– resulting in an agreement with data.

We turn next to minimum-bias \( dAu \) collisions at central rapidity. Here \( < p_T > = 0.39 \text{ GeV}/c \). With the same value of \( n \) as above \( (n = 9.99) \), this corresponds to \( p_0 = 1.346 \). Calculating the ratio \( dAu \) to \( pp \) we obtain the result of Fig. 1. At forward rapidity, \( R_{dAu} \) decreases as \( y \) increases due two effects:

The first effect is basically due to energy-momentum conservation. It has been known for a long time in hadron-nucleus collisions at SPS energies –low \( p_T \) “triangle”–. Its extreme form occurs in the hadron fragmentation region, where the yield of secondaries in collisions off a heavy nucleus is smaller than the corresponding yield in hadron-proton. This phenomenon is known as nuclear attenuation. It turns out, that, at RHIC energies, this effect produces a decrease of \( R_{dAu} \) of about 30 % between \( \eta^* = 0 \) and \( \eta^* = 3.2 \).

The second effect is the increase of the shadowing corrections in \( dAu \) with increasing \( y^* \). This produces a decrease of \( R_{dAu}(p_T) \) between \( \eta^* = 0 \) and \( \eta^* = 3.2 \) of about 30 % for pions produced in minimum bias collisions. Therefore, we expect a suppression factor of about 1.7 between \( R_{dAu}(p_T) \) at \( \eta^* = 0 \) and at \( \eta^* = 3.2 \), practically independent of \( p_T \). This is consistent with the BRAHMS results.
Finally, there are some importants remarks to be done:

- We use jet absorption, which is equivalent to jet quenching. It points to the existence of a dense system.
- Our final interaction takes place at very short times—with a medium of partonic or prehadronic nature—. This is not a rescattering of fully formed hadrons.
- We have studied the different possibilities of \( \delta p_T \). This is equivalent to a test on whether the mean energy loss \( \langle p_T \rangle \) being \( E \) at \( y = 0 \) is constant with energy—which is the BDMPS\(^5\) result for large enough energies—.
- Our results for \( p_T > 5 \text{ GeV}/c \) depend little on the form of \( \delta p_T \). The increase of the ratio with increasing \( p_T \) for a constant \( \delta p_T \) coincides with jet quenching results when reasonable kinematical constraints are imposed\(^9\).
- In perturbative QCD, \( R_{AA} \) should tend to unity at large \( p_T \). However, this may occur at much larger values of \( p_T \) than the present ones. The BDMPS energy loss result being energy independent applies for parton energies larger than those available at RHIC.
- We use Cronin effect in an effective way. Our Cronin does not die at large \( p_T \), and it does not increase with \( y \) either.
- For the region in which \( x \) is small enough, we use shadowing. It would lead to saturation at very small \( x \). So our shadowing provides a transition between saturation at very small \( x \) and no shadowing at large \( x \sim 0.1 \).

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