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Large transverse momentum suppression of π^0's in Au+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Contents:

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INTRODUCTION:

- Experimental data at RHIC:

$$R_{AA}(b,y,p_T) = \left[\frac{dN^{AA}}{dyd^2p_T}(b)\right] \Big/ \left[n(b)\frac{dN^{pp}}{dyd^2p_T}\right] < 1$$

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 $n(b)$.

Different causes for the yield suppression:

- **At low p_T: Shadowing/saturation**

This suppression is well known in soft collisions when **shadowing** corrections are taken into account.

At very high energies the shadowing effects –nonlinear– lead to **saturation** of the distributions of partons in the colliding nuclei.

These effects are important for the description of inclusive spectra, for particles with $p_T \sim < p_T >$.

With increasing p_T the shadowing corrections decrease and the scaling with $n(b)$ is predicted in perturbative QCD ($R_{AA} \to 1$).

The observed increase is even faster due to initial state interactions, the so-called **Cronin effect** ($R_{AA} > 1$).

• At large p_T:
Final state interactions –jet quenching/jet absorption–.

Final state 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.

A particle scattered at some non zero angle will also loose a fraction of its transverse momentum due to final state interactions with a medium of partonic or prehadronic nature.

The particle with large p_T is shifted to smaller p_T values as a result of the interaction $\Rightarrow$
Small gain of yield at low p_T, suppression at large p_T.

This suppression vanishes at low p_T:
When the p_T of the particle is close to $< p_T >$, 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: 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.

THE MODEL:

• 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:

$$\frac{d\rho_H(x,p_T)}{d^4x} = -\widetilde{\sigma}\ \rho_S \left[\rho_H(x,p_T) - \rho_H(x,p_T+\delta p_T)\right] \quad (1)$$

ρ_S, ρ_H = space-time density of the medium and of large p_T π^0's
$\widetilde{\sigma}$= interaction cross-section, averaged over the momentum distribution of the colliding particles
d^4x=cylindrical space-time variables: longitudinal proper time τ, space-time rapidity y, transverse coordinate s

• Assuming a decrease of densities with proper time $1/\tau$ (isoentropic longitudinal expansion, transverse expansion is neglected):

$$\tau\ \frac{dN_{\pi^0}(b,s,y,p_T)}{d\tau} = \quad (2)$$
$$-\widetilde{\sigma}N(b,s,y)\left[N_{\pi^0}(b,s,y,p_T) - N_{\pi^0}(b,s,y,p_T+\delta p_T)\right]$$

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

• This equation has to be integrated from initial time τ_0 to freeze-out time τ_f:

Using the inverse proportionality between proper time and densities, $\tau_f/\tau_0 = N(b,s,y)/N_{pp}(y)$

$N_{pp}(y)$= density per unit rapidity for minimum bias pp collisions at $\sqrt{s} = 200$ GeV, $N_{pp}(0) = 2.24$ fm^{-2}
$N(b,\,s,\,y)$ = density produced in the primary collisions in DPM

• We obtain the suppression factor $S_{\pi^0}(b,y,p_T)$ of the yield of π^0's at given p_T and at each impact parameter, due to its interaction with the dense medium:

$$S_{\pi^0}(b,y,p_T) = \frac{\int d^2s\ \sigma_{AB}(b)\ n(b,s)\ \widetilde{S}_{\pi^0}(b,s,y,p_T)}{\int d^2s\ \sigma_{AB}(b)\ n(b,s)}\ , \quad (3)$$

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

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

NUMERICAL RESULTS

In order to perform numerical calculations, we need the p_T distribution of the π^0's

• In pp collisions at $\sqrt{s} = 200$ GeV, the shape of the p_T distribution of π^0's can be described as:

$$(1 + p_T/p_0)^{-n}$$

$p_0 = 1.219$ GeV/c and $n = 9.99$.

$< p_T >= 2p_0/(n-3) =$ 0.349 GeV/c = average p_T.

• In $AuAu$ collisions we assume that the p_T distribution of π^0's at each b is:

$$(1 + p_T/p_0)^{-n}$$

with $n = 9.99$ and changing the scale p_0 into:

$p_0(b) =< p_T >_b (n-3)/2$

$< p_T >_b =$ experimental average p_T at centrality b

In central $AuAu$ collisions ($n_{part} = 350$, $b = 2$):

$< p_T >_{exp}= 0.453$ GeV/c $\Rightarrow p_0 = 1.583$ GeV/c.

n fixed, since at large p_T the shadowing vanishes and the ratio R_{AA} is independent of p_T. Moreover, 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 $\Rightarrow$ R_{AA} **increases with** p_T**.**

To these values we apply the correction due to the suppression factor S_{π^0}:

Neglecting the second term -the shift- in eqs. (1-2) $\Rightarrow$

- **General suppression in R_{AA}, independent of p_T**
- **R_{AA} increases slightly with p_T and agrees with data for $p_T > 5$ GeV/c**
- **At lower p_T the result is significantly lower than the data**

Introducing the second term -shift- in eqs. (1-2):

Assuming that the p_T shift of the π^0, due to its interaction with the medium, is constant (two cases : $\delta p_T = 0.5$ GeV/c and $\delta p_T = 1.5$ GeV/c) $\Rightarrow$

- **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**

Assuming that $\delta p_T \propto (p_T - < p_T >_b) \Rightarrow$

- **The factor S_{π^0} is 1 at $p_T =< p_T >$ as it should be**
- **Slight decrease of R_{AA} at large p_T, consistent with data**
- **Increase of R_{AA} at low p_T, agreement with data**

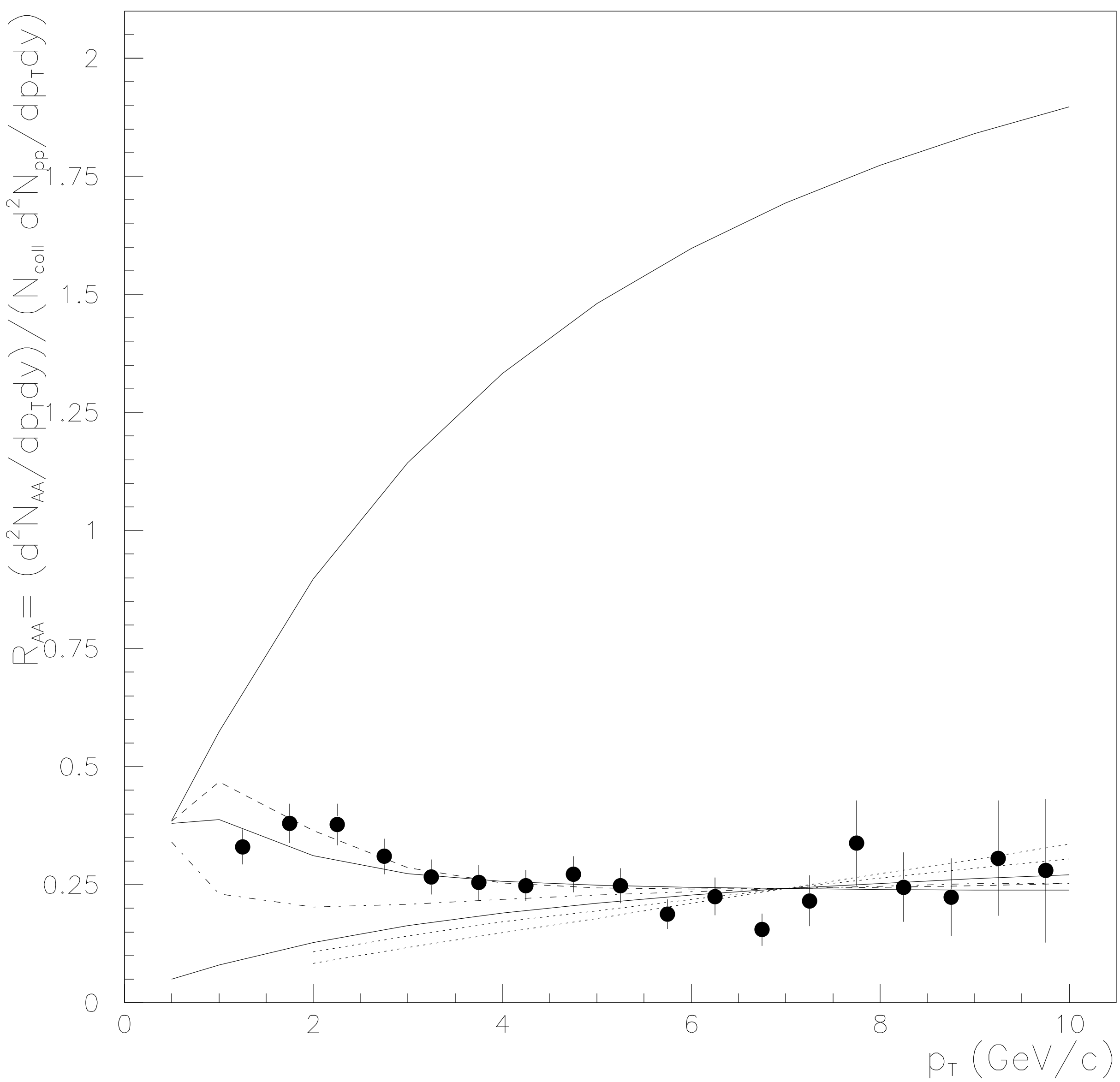


Figure 1: Values of $R^{\pi^0}_{AuAu}(p_T)$ for the 10 % most central collisions at mid-rapidities ($|y^*| < 0.35$) including the case without final state interactions and the ones with interactions -with or without shift–.

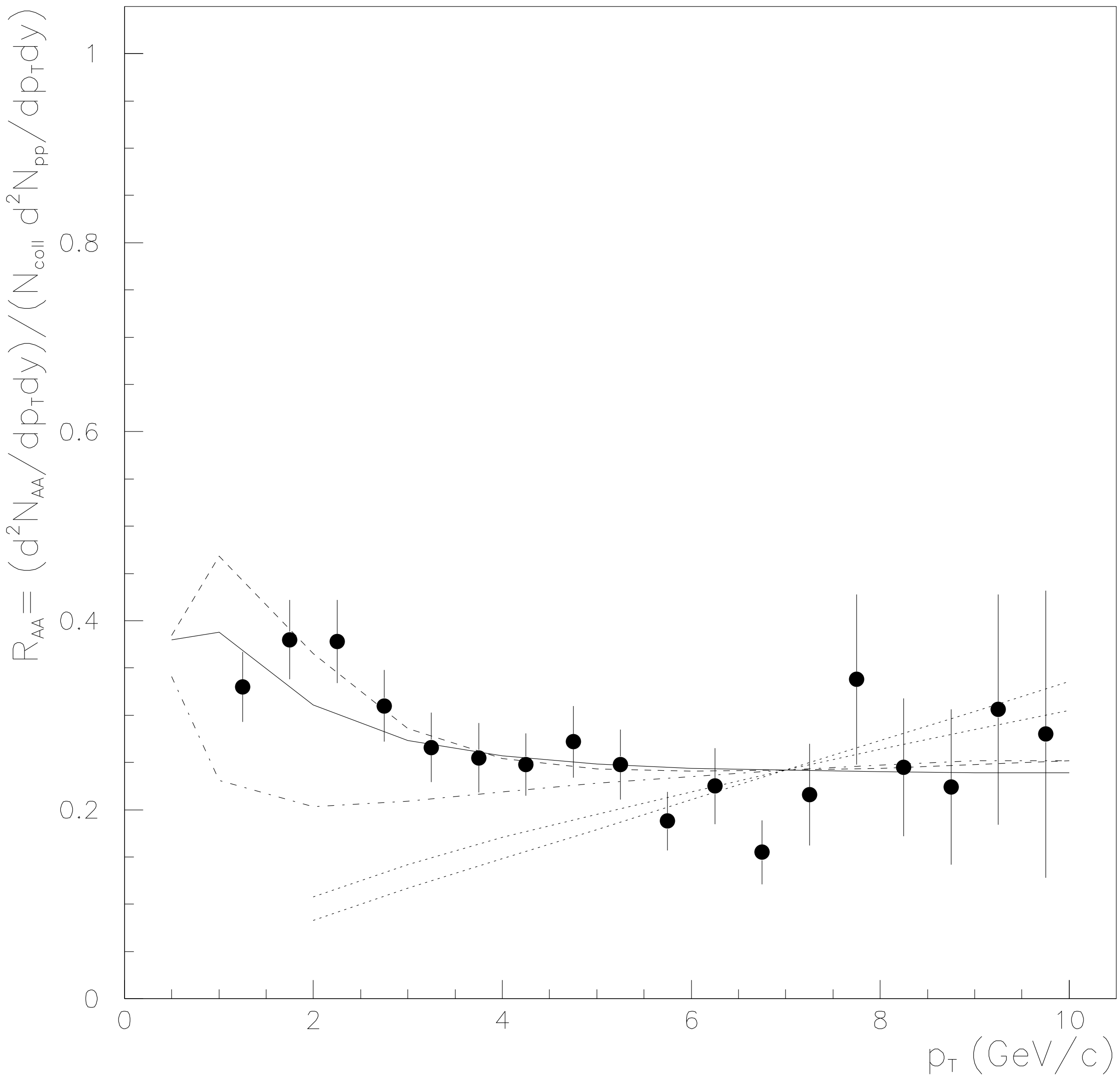


Figure 2: Values of $R^{\pi^0}_{AuAu}(p_T)$ for the 10 % most central collisions at mid-rapidities ($|y^*| < 0.35$), using the p_T shift as
$\delta p_T = (p_T - < p_T >_b)^{1.5}/20$ (solid line),
$\delta p_T = (p_T - < p_T >_b)/20$ (dashed-dotted line),
$\delta p_T = (p_T - < p_T >_b)^2/20$ (dashed line),
$\delta p_T =$ constant (dotted lines).

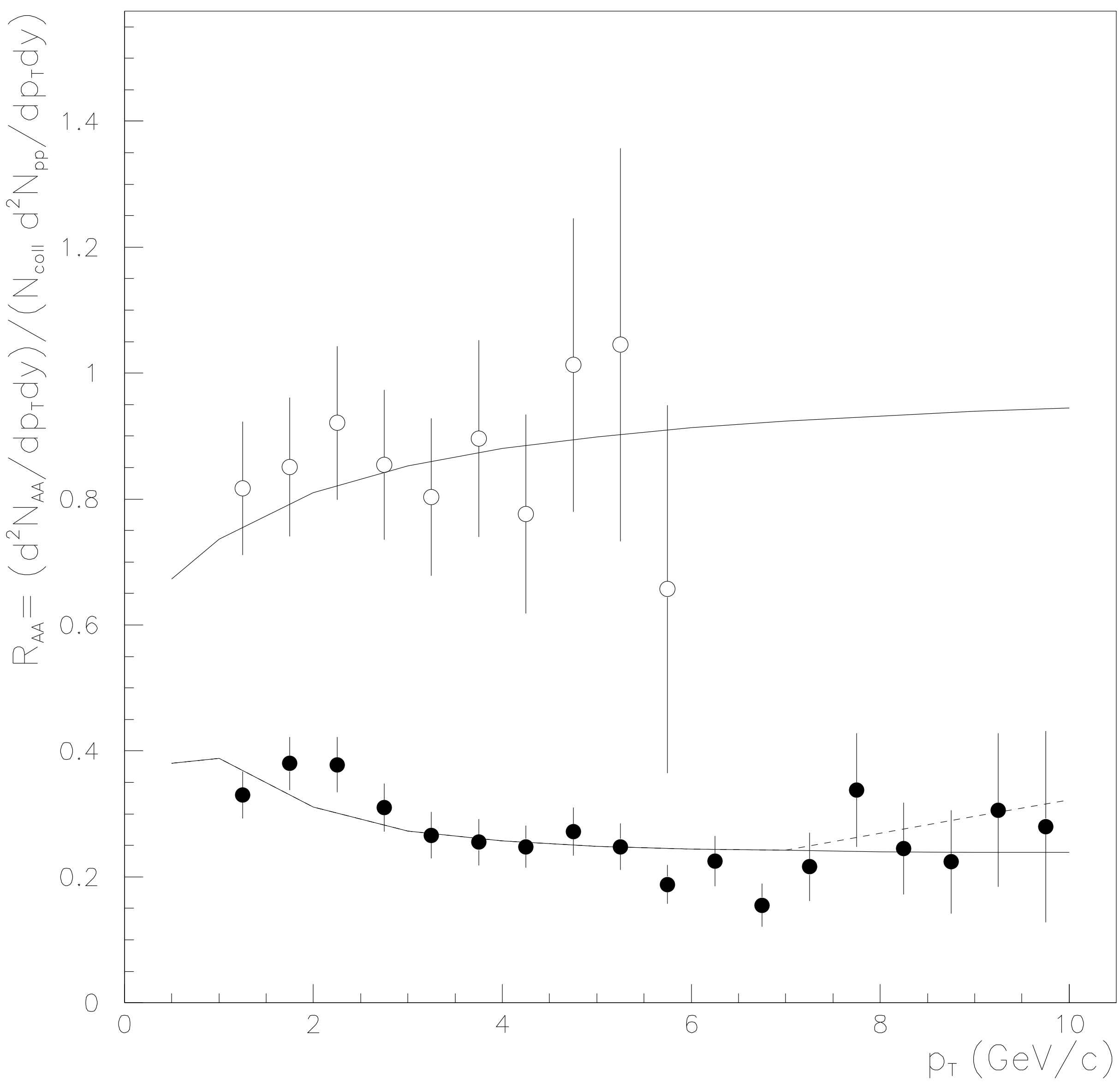


Figure 3: Values of $R^{\pi^0}_{AuAu}(p_T)$ for the 10 % most central collisions (lower line) and for peripheral (80-92 %) collisions (upper line) at mid-rapidities ($|y^*| < 0.35$), using the p_T shift as $\delta p_T = (p_T - < p_T >_b)^{1.5}/20$, (solid line). The dashed line is obtained using $\delta p_T = (p_T - < p_T >_b)^{1.5}/20$ for $p_T \leq 7$ GeV/c and $p_T =$ constant for $p_T \geq 7$ GeV/c. The data are from PHENIX

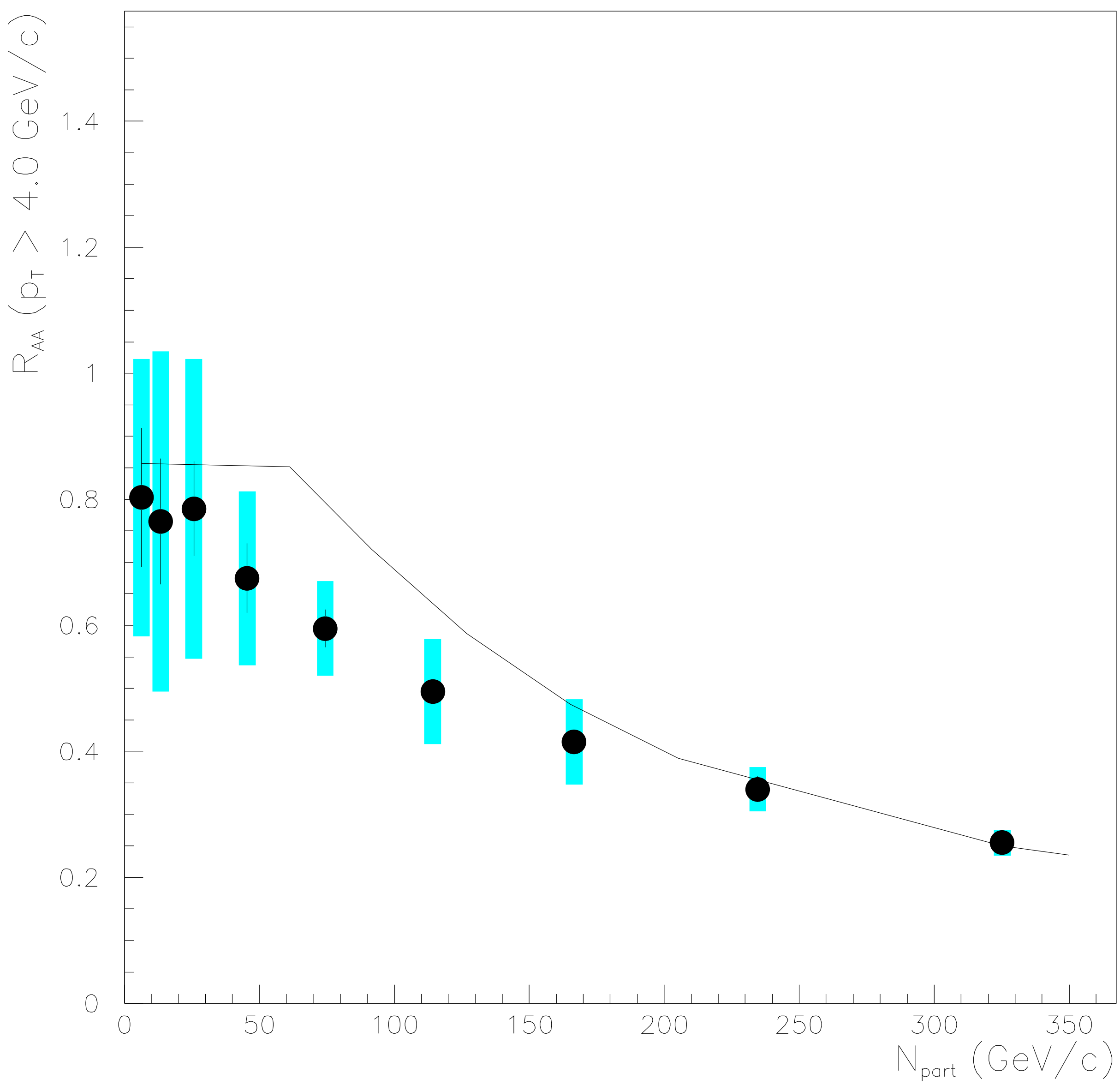
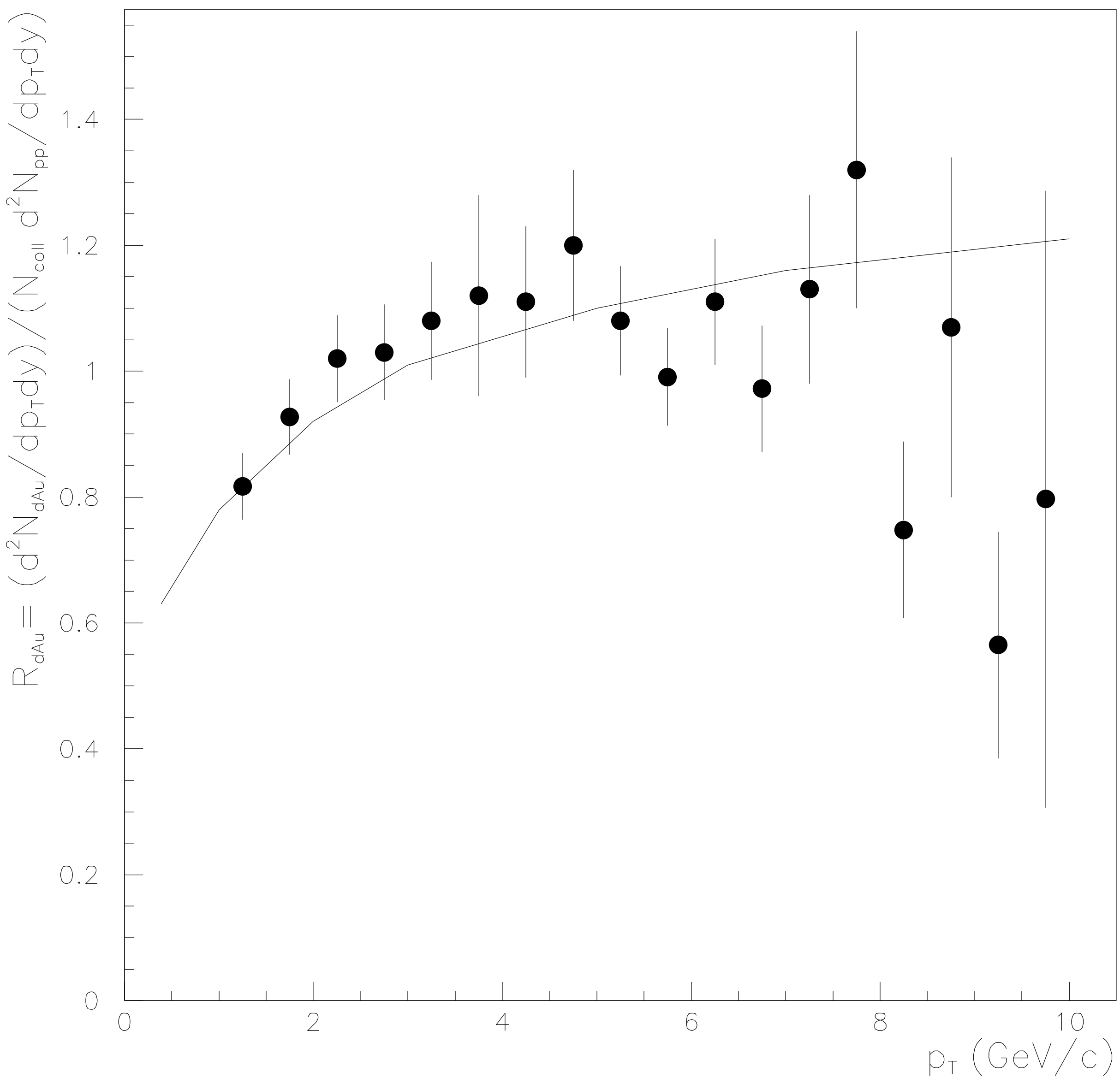


Figure 4: Centrality dependence of $R^{\pi^0}_{AuAu}$ for $p_T > 4$ GeV/c using the p_T shift $\delta p_T = (p_T - < p_T >_b)^{1.5}/20$. The data are from PHENIX.

• In minimum bias dAu collisions at central rapidity: $< p_T >_{exp} = 0.39$ GeV/c $\Rightarrow p_0 = 1.346$ GeV/c; $n = 9.99$.



• In dAu collisions at forward rapidity: $\Rightarrow R_{dAu}$ decreases as y increases due to:

• Energy-momentum conservation:

It happens also for hadron-nucleus collisions at SPS: **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: **Nuclear attenuation**

At RHIC energies, this effect produces a decrease of R_{dAu} of about 30 % between $\eta = 0$ and $\eta = 3.2$.

• Increase of the shadowing corrections in dAu with increasing y:

Decrease of $R_{dAu}(p_T)$ between $\eta = 0$ and $\eta = 3.2$ of about 30 % for pions produced in minimum bias collisions

The situation is different in $AuAu$. Here the shadowing decreases with increasing η, but the variation is smaller than in dAu

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

SOME REMARKS

We use jet absorption $\sim$ jet quenching $\Rightarrow$ 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 study the different possibilities of δp_T:

Our results for $p_T > 5$ GeV/c depend little on the form of δp_T.

The increase of the ratio with increasing p_T for a constant δp_T coincides with jet quenching results when reasonable kinematical constraints are imposed (Salgado and Wiedemann).

In perturbative QCD, $R_{AA} \rightarrow 1$ at large p_T. However, this may occur at much larger values of p_T than present ones.

We use Cronin effect in an effective way.

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 $x \sim 0.1$.

OPEN QUESTIONS

What is the correct treatment of the energy loss? Should we use the perturbative approach or nonperturbative processes with small momentum transfer are dominant?

Should the suppression effect decrease as p_T increases? Note that these secondary reinteractions violate QCD factorization theorem.

What is the correct transition from coherent (shadowing) to non-coherent region?

Is the formula for interaction with comovers than we are using reasonable for large p_T?

Where are the effects of suppression due to nuclear absorption? At large p_T, nuclear absorption is expected to be present both in dAu and $AuAu$ collisions. The dAu data at large p_T are consistent with the presence of nuclear absorption. However, the error bars are too large in order to perform a quantitative study of this question – and determine the value of σ_{abs}. Introducing nuclear absorption in $AuAu$ collisions would result in a smaller value of $\widetilde{\sigma}$.

DETAILS

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 $x = x_{\pm} = 1/2(\sqrt{x_F^2 + 4m_T^2/s} \pm x_F)$

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.

We assume longitudinal boost invariance. Therefore, the above picture is not valid in the fragmentation regions.

We assume that the dilution in time of the densities is only due to longitudinal motion: Transverse expansion is neglected. The fact that HBT radii are similar at SPS and RHIC and of the order of magnitude of the nuclear radii, seems to indicate that this expansion is not large. The effect of a small transverse expansion can presumably be taken into account by a small change of the final state interaction cross-section.

The logarithmic factor in Eq. 3 is the result of an integration in the proper time τ from the initial time to freeze-out time. (One assumes a decrease of densities with proper time in $1/\tau$.) A large contribution to this integral comes from the few first fm/c after the collision – where the system is in a pre-hadronic stage. Actually, Brodsky and Mueller introduced the comover interaction as a coalescence phenomenon at the partonic level.

At RHIC $N_{pp}(0) = 2.24$ fm^{-2}. This density is about 90 % larger than at SPS energies. Since the corresponding increase in the AA density is comparable, the average duration time of the interaction will be approximately the same at CERN-SPS and RHIC, about 5 to 7 fm.

p_T	I	II	III	IV	V	VI	VII
0.5	0.38	0.05			0.34	0.38	0.38
2	0.90	0.13	0.08	0.11	0.20	0.31	0.31
5	1.48	0.21	0.18	0.19	0.23	0.25	0.25
7	1.69	0.24	0.24	0.24	0.24	0.24	0.24
10	1.84	0.27	0.34	0.30	0.25	0.24	0.32

Values of $R^{\pi^0}_{AuAu}(p_T)$ for the 10 % most central $AuAu$ collisions at $\sqrt{\mathbf{s}_{NN}} =$ 200 GeV and at mid-rapidities ($|y^*| < 0.35$).

Column I is the result obtained with no final state interaction.

Column II is the result obtained with final state interaction neglecting the shift.

Column III and IV is the result obtained with final state interaction introducing the shift as $\delta p_T = 0.5$ GeV/c and $\delta p_T = 1.5$ GeV/c.

Column V is the result obtained with final state interaction introducing the shift as $\delta p_T = (p_T - < p_T >_b)/20$.

Column VI is the result obtained with final state interaction introducing the shift as $\delta p_T = (p_T - < p_T >_b)^{1.5}/20$.

Column VII is the result obtained with final state interaction introducing the shift as $\delta p_T = (p_T - < p_T >_b)^{1.5}/20$ for $p_T < 7$ GeV/c and $\delta p_T = (7 - < p_T >_b)/20$ for $p > 7$ GeV/c.