Transverse Momentum Dependence of Anomalous $J/\psi$ Suppression in Pb-Pb Collisions

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Abstract

The recently published data for $\langle p_t^2 \rangle$ for $J/\psi$ production in Pb-Pb collisions at 158 A GeV are analyzed. For low values of transverse energy $E_t$, where normal suppression dominates, $\langle p_t^2 \rangle(E_t)$ scales with the path length of the gluons which fuse to make the $J/\psi$. In the $E_t$ domain of anomalous suppression $\langle p_t^2 \rangle(E_t)$ is found to rise linearly with the relative amount of anomalous suppression. This empirical law is reproduced within an analytically solvable transport model which allows high $p_t J/\psi$’s to escape anomalous suppression. Interpreted in this way, the data for $\langle p_t^2 \rangle(E_t)$ lead to an estimate of $t_A \sim 4$ fm/c for the duration of anomalous suppression.

New data mean new surprises. This has been a recurrent phenomenon in the study of charmonium suppression in high energy nuclear collisions during the last decade of research. It also holds for the recently released data of transverse momentum distributions for charmonia taken in Pb-Pb collisions at 158 A GeV [1]. In particular for central collisions where anomalously large suppression has been observed, the new data display interesting features: the mean values $\langle p_t^2 \rangle$ of transverse momentum $p_t$ increase slowly with transverse energy $E_t$ and turn steeply upward where the $J/\psi$ yield drops (see Fig. 1). Can this behavior tell us something new about the nature of anomalous $J/\psi$ suppression?

The previous data for the transverse momentum dependence of $J/\psi$ production in nuclear pA and AB collisions and their interpretation are presented in two reviews [2, 3]. Basically, two mechanisms are proposed:

(i) Rescattering of gluons in the initial state [4, 5]: In a pA collision, the gluon of the projectile proton scatters from target nucleons before it fuses with a gluon from the target to form the $J/\psi$. Gluon rescattering in the initial state is treated as a random walk in transverse momentum and the observed $\langle p_t^2 \rangle$ is predicted to increase linearly with the mean length $\ell_g$ of the path of the incident gluon. In an AB collision both gluons which fuse to the $J/\psi$ are affected by the rescattering. This effect in the initial state has been clearly identified in the data, also for AB collisions [4]. For central AB collisions it had
Figure 1: Data for the mean transverse momentum $\langle p_t^2 \rangle$ of $J/\psi$'s produced in $Pb - Pb$ collisions at 158 A GeV as a function of transverse energy $E_t$ together with the data for the relative $J/\psi$ production cross section $S = \sigma(Pb + Pb \rightarrow J/\psi + X)/\sigma(Pb + Pb \rightarrow DY + X)$ in the same experiment[1]. The range of $E_t$ values is divided into the domains of normal suppression (“N”) ($E_t < 50$ GeV) and anomalous suppression (“A”) ($E_t > 50$ GeV). Within the domain “A”, the subdomain “fl” with $E_t > 100$ GeV indicates events of high $E_t$ which rise from fluctuations. The solid line $S_N(E_t)$ is calculated for normal nuclear suppression “N”[13], while $S_{ob}$ denotes the observed values.
been predicted \cite{7,8} that initial state rescattering together with anomalously strong $J/\psi$ absorption in the final state may lead to a saturation or even a decrease of $\ell_g$ and therefore of $\langle p_t^2 \rangle$ for the very large values of $E_t$. The new data for Pb-Pb collisions contradict this prediction.

(ii) Escape of high $p_t$ $J/\psi$’s in the final state \cite{9,10,11}: Within the scenario of the quark-gluon plasma (QGP) anomalous charmonium suppression occurs in a limited space-time region during final state interaction. Only, $J/\psi$’s with sufficiently high transverse momenta $p_t$ have a chance to escape the “deadly” region. Therefore anomalous suppression acts preferentially on low $p_t$ $J/\psi$’s and the surviving charmonia should show higher values of $\langle p_t^2 \rangle$ with increasing amount of anomalous suppression. This is what indeed is seen in the new data. Do the data then confirm this mechanism?

In this letter we analyze the new data for $\langle p_t^2 \rangle$ of $J/\psi$ production in Pb-Pb collisions and identify two empirical laws: (a) In the domain of normal $J/\psi$ suppression the values for $\langle p_t^2 \rangle$ depend linearly on the path lengths of the gluons. (b) A linear correlation between the values of $\langle p_t^2 \rangle$ and the relative amount of anomalous suppression is discovered in the $E_t$ range where anomalous suppression has been identified. To our knowledge the second empirical law has not been noticed before. We discuss various explanations and then present an analytically solvable transport model based on mechanism (ii), i.e. escape of high $p_t$ $J/\psi$’s from the region of anomalous suppression. A more detailed analysis of all the data from \cite{1} in the light of both mechanisms (i) and (ii) is in preparation.

Fig. 1 shows the data of ref. \cite{1} for $\langle p_t^2 \rangle(E_t)$ of $J/\psi$’s as a function of transverse energy $E_t$ together with the previously published data on $J/\psi$ suppression in the form of the ratio $S(E_t) = \sigma(Pb + Pb \rightarrow J/\psi + X)/\sigma(Pb + Pb \rightarrow DY + X)$. We divide the $E_t$ region into three domains: (a) Small transverse energy ($E_t < 50$ GeV), where there is no anomalous suppression and the yield is well described by the Glauber approach with an effective $J/\psi$ nucleon absorption cross section (which correctly describes pA and S-U collisions). We denote quantities in this domain by the index “N” (for “normal”). (b) For values $E_t > 50$ GeV one observes anomalous suppression, i.e. the data $S_{\text{ob}}(E_t)$ deviate from the the predictions of the Glauber approach. We denote all quantities in this $E_t$ region by the index “A” (for “anomalous”). (c) Within the anomalous region the data at very high values, $E_t > 100$ GeV, show a particular behavior: the suppression drops while the data for $\langle p_t^2 \rangle$ rise. These high values of $E_t$ correspond to the most central collisions and are interpreted \cite{12,13} to arise from fluctuations in the transverse energy. We have indicated this origin by the symbol “fl” at the appropriate places.

We begin our analysis of the data by investigating to which degree (for which values of $E_t$) the mechanism (i), gluon rescattering in the initial state, explains the data. This mechanism
leads to a dependence

$$\langle p_t^2 \rangle^{AB} (E_t) = \langle p_t^2 \rangle^{NN} + \frac{\langle p_t^2 \rangle^g}{\lambda_g N} \ell_g^{AB} (E_t),$$  \hspace{1cm} (1)$$

where $\langle p_t^2 \rangle^{NN}$ is the contribution already present in $J/\psi$ production in the elementary $NN$ event, while the second term is linear in the mean length $\ell_g (E_t)$, which the two gluons travel in nuclear matter before they fuse. The constant in front of $\ell_g$ depends on $\langle p_t^2 \rangle^g$, the mean transverse momentum acquired in a gluon-nucleon collision, and $\lambda_g N$, the mean free path of a gluon in nuclear matter. This constant is taken as an adjustable parameter, while $\ell_g (E_t)$ is calculated. Then the observed values of $\langle p_t^2 \rangle^{AB} (E_t)$ are plotted versus the calculated values of $\ell_g^{AB} (E_t)$. If a linear relation appears, one takes it as support for the gluon rescattering mechanism. This analysis has already been done in ref. [1] for the Pb-Pb data. However, $\ell_g^{AB} (E_t)$ is calculated neglecting absorption of the $J/\psi$ in the final state. We therefore repeat their analysis with absorption. Of course, the results depend on the employed absorption model.

We choose the one of ref. [13], which correctly reproduces the data for $J/\psi$ suppression even in the domain of fluctuations. Then

$$\ell_g^{AB} (E_t) = \frac{\int d^2b \, d^2s \, dz_A \, dz_B \left( \ell_g^A (\vec{s}, z_A) + \ell_g^B (\vec{b} - \vec{s}, z_B) \right) K (\vec{b}, \vec{s}, z_A, z_B, E_t)}{\int d^2b \, d^2s \, dz_A \, dz_B \, K (\vec{b}, \vec{s}, z_A, z_B, E_t)},$$  \hspace{1cm} (2)$$

where

$$\ell_g^A (\vec{s}, z_A) = \int_{-\infty}^{z_A} dz \, \rho_A (\vec{s}, z)/\rho_0,$$

$$\ell_g^B (\vec{b} - \vec{s}, z_B) = \int_{z_B}^{\infty} dz \, \rho_B (\vec{b} - \vec{s}, z)/\rho_0$$  \hspace{1cm} (3)$$

are the geometric lengths which the two gluons travel through the nuclear density along the $z$-direction with impact parameter $b$, and $\rho (\vec{r})$ is the density of nuclear matter. To simplify the numerical calculations, we use in the following the uniform distribution. The expression for the kernel $K$ in eq. (2) is taken from ref. [13]:

$$K (\vec{b}, \vec{s}, z_A, z_B, E_t) = \rho_A (\vec{s}, z_A) \rho_B (\vec{b} - \vec{s}, z_B) \cdot \exp \left( -\sigma_{abs}^{J/\psi} \left[ \int_{z_A}^{\infty} dz \, \rho_A (\vec{s}, z) + \int_{z_B}^{\infty} dz \, \rho_B (\vec{b} - \vec{s}, z) \right] \right) \cdot \Theta \left( n_c - \frac{E_t}{\langle E_t \rangle (b)} \cdot n_p (\vec{b}, \vec{s}) \right) \cdot P (E_t | \vec{b}).$$  \hspace{1cm} (4)$$

Here, the final state absorption for the $J/\psi$ is contained in the exponential ("normal" absorption by nucleons with an absorption cross section $\sigma_{abs}^{J/\psi}$) and in the Theta function ("anomalous" suppression suddenly setting in, when the density of produced matter exceeds a threshold density $n_c$). The function $P (E_t | b)$ describes the distribution of transverse energy in events at a
Figure 2: The observed values \(\langle p_t^2 \rangle(E_t)\) for \(J/\psi\)'s from \(Pb-Pb\) collisions [1] plotted versus \(\ell_g(E_t)\), the mean path of the gluons before they fuse to the \(J/\psi\). The values \(\ell_g(E_t)\) are calculated within the model [13] which contains normal and anomalous nuclear suppression and which is able to reproduce the cross section data in Fig.1. As defined in Fig.1 we have divided the \(E_t\) range into domains “N”, “A” and “fl”: Only the five data points on the straight line belong to the domain of normal suppression, while all data on the backward branch belong to anomalous suppression.

given impact parameter \(b\). We have followed ref. [13] in the notation and the numerical values for the constants and therefore refer the reader who is interested in more details, to this paper.

Fig.2 shows a plot of the experimental values of \(\langle p_t^2 \rangle(E_t)\) versus the calculated values of \(\ell_g^{AB}(E_t)\). The qualitative picture is rather different from the one given in ref. [1]: Only those values of \(E_t\), which correspond to the domain of normal (“N”) suppression in Fig. 1, show a linear relation. We fit it by a straight line and find a value for the slope constant

\[
a_{gN} = \frac{\langle p_t^2 \rangle_{gN}}{\lambda_{gN}} = (0.102 \pm 0.006) (GeV/c)^2/fm,
\]

which differs from the value \((0.081 \pm 0.003) (GeV/c)^2/fm\) given in ref. [1], since we use a different prescription for the calculation of \(\ell_g^{AB}\). In the \(E_t\) domain where anomalous suppression (“A”) sets in, the plot shows an anticorrelation: With increasing values of \(E_t\), the calculated values of \(\ell_g(E_t)\) decrease, while the experimental values for \(\langle p_t^2 \rangle(E_t)\) increase. This behavior in the anomalous domain hides some physics other than gluon rescattering and will be studied in the following.

We assume that all \(J/\psi\)’s which are suppressed by an anomalous mechanism have still another source influencing the transverse momentum distribution above the one from gluon rescattering in the initial state. If we decompose the observed cross section \(S_{ob}(E_t)\) for \(J/\psi\)-
production (relative to \(DY\)-production) into its two contributions

\[
S_{ob}(E_t) = S_N(E_t) - S_A(E_t),
\]

where the contribution \(S_N(E_t)\) from normal absorption is a theoretical quantity and is calculated by using the kernel \(K\) from eq. (4), \textit{without} the Theta function and is shown in Fig. 1 by the solid line. The anomalous suppression, \(S_A(E_t)\), is defined as the difference between observed, \(S_{ob}(E_t)\), and calculated values, \(S_N(E_t)\). We associate different values, \(\langle p_t^2 \rangle_N(E_t)\) and \(\langle p_t^2 \rangle_A(E_t)\), with the normal and anomalous contributions, respectively. Then the observed value \(\langle p_t^2 \rangle_{ob}(E_t)\) can be written as

\[
\langle p_t^2 \rangle_{ob}(E_t) = \frac{S_N(E_t)\langle p_t^2 \rangle_N(E_t) - S_A(E_t)\langle p_t^2 \rangle_A(E_t)}{S_{ob}(E_t)}
\]

\[
= \langle p_t^2 \rangle_N(E_t) + \frac{S_A(E_t)}{S_{ob}(E_t)} \delta p_t^2(E_t),
\]

where

\[
\delta p_t^2(E_t) = \langle p_t^2 \rangle_N(E_t) - \langle p_t^2 \rangle_A(E_t).
\]

Eq. (8) should be valid in the full \(E_t\) domain comprising anomalous suppression and normal one (where \(S_A(E_t) = 0\), by definition). For normal suppression, the \(E_t\) dependence of the observed values \(\langle p_t^2 \rangle_{ob}(E_t)\) is solely carried by values \(\langle p_t^2 \rangle_N(E_t)\) calculated from eqs. (2-4) without the \(\Theta\)-function and displayed in Fig. 2. The calculation of \(\langle p_t^2 \rangle_N(E_t)\) can also be extended into the domain of anomalous suppression \((E_t > 50 \text{ GeV})\). We find that \(\langle p_t^2 \rangle_N(E_t)\) changes by maximally 3% over the whole domain \(0.25 \leq S_A/S_{ob} \leq 1.25\), where data exist and are displayed in Fig. 3. Therefore, in the domain of anomalous suppression, the \(E_t\) dependence of \(\langle p_t^2 \rangle_{ob}(E_t)\) is predominantly carried by the second term in eq. (8). In order to disentangle the \(E_t\) dependence residing in \(S_A/S_{ob}\) from the one in \(\delta p_t^2(E_t)\), we plot the observed values of \(\langle p_t^2 \rangle_{ob}(E_t)\) versus the ratio \(S_A(E_t)/S_{ob}(E_t)\). The result is displayed in Fig. 3. To a very good accuracy all points lie on a straight line with a slope

\[
\delta p_t^2 = (0.132 \pm 0.007)(\text{GeV}/c)^2.
\]

The result indicates that the \(E_t\) dependence of \(\langle p_t^2 \rangle_{ob}(E_t)\) in the domain of anomalous suppression arises predominantly from the ratio \(S_A(E_t)/S_{ob}(E_t)\). We also draw the attention to the \(E_t\) region “fl”, where fluctuations dominate: While a sudden drop in the \(J/\psi\) suppression and a sudden rise in \(\langle p_t^2 \rangle\) occur (Fig. 1), the empirical regularity shown in Fig. 3 continues into the domain “fl” without any noticeable change in character indicating that no new physics appears in this domain of \(E_t\). The empirical correlation displayed in Fig. 3 is the first new result of this paper.
Figure 3: The observed values $\langle p_t^2 \rangle (E_t)$ (in the “A” domain, $E_t > 50$ GeV) for $J/\psi$’s from $Pb-Pb$ collisions plotted against the relative amount of anomalous suppression $S_A(E_t)/S_{ob}(E_t)$. Here, $S_A(E_t)$ is the difference between the calculated value $S_N(E_t)$ and the observed values $S_{ob}(E_t)$ in Fig.1. (The data in the “N” domain, not shown, would all be found at $S_A/S_{ob} = 0$).

Can we understand this relation? Are we able to calculate the constant $\delta p_t^2$? We will discuss two possible explanations, intermediate $\chi$ production and escape of high $p_t$ charmonia in the final state and start with the $\chi$.

The observed intensity of $J/\psi$’s produced in nuclear collisions has two contributions, directly produced $J/\psi$’s and those arising from produced $\psi'$’s and $\chi$’s which decay into $J/\psi$ long after the collision but before detection. The indirect contributions amount to about 40% [2, 3]. Since $\psi'$’s and $\chi$’s are less bound than the $J/\psi$, it has been argued [3] that anomalous suppression should act predominantly on the $\chi$’s and $\psi'$’s rather than on the directly produced $J/\psi$’s. The $\chi$’s may have a smaller value of $\langle p_t^2 \rangle_\chi$ than the $J/\psi$ and $\psi'$, since the $\chi$’s can be produced directly by fusion of two gluons. $J/\psi$ and $\psi'$ production involves three gluons, where the third one is presumably radiated off from a color octet intermediate state and generates additional $\langle p_t^2 \rangle$. If anomalous suppression acts predominantly on the $\chi$, the linear relation eq. (7) seems plausible with

$$\delta p_t^2 \sim \left( \langle p_t^2 \rangle _{J/\psi} - \langle p_t^2 \rangle _\chi \right).$$

Un fortunately, we have no calculations for the difference in eq. (10). Furthermore, the emission of a gamma ($\chi \rightarrow J/\psi + \gamma$) reduces the difference by about 0.1$(GeV/c)^2$ and may even change the sign of $\delta p_t^2$. If the mechanism of intermediate $\chi$ production was the dominant explanation for the observed value of $\delta p_t^2$, the values of $\langle p_t^2 \rangle$ observed in the production of $\psi'$’s should have no anomalous values. However, the contrary is true according to the data in Pb-Pb collisions [1]. Therefore the contribution of $\chi$ to the observed $J/\psi$ does not seem a compelling explanation.
for the behaviour of $\langle p^2_t \rangle$ in the anomalous region.

We come to the second explanation: Only high $p_t$ charmonia escape anomalous suppression. This argument is not new\cite{4, 5, 6}. In this paper we start from this idea and propose a solvable transport model, in order to see whether the empirical relation Fig. 3 and the value $\delta p^2_t$, eq. (3), can be understood.

We introduce the phase space distribution $n(\vec{r}, \vec{p}, t)$ for $J/\psi$’s produced in a Pb-Pb collision with a definite value of $E_t$. In a system where the $J/\psi$’s have zero longitudinal momentum, the values of $\vec{r}$ and $\vec{p}$ denote the transverse position and momentum of the $J/\psi$’s, respectively. We denote by $t = 0$ the time, when all collisions involving nucleons (production $N + N \rightarrow J/\psi + X$ and suppression $J/\psi + N \rightarrow$ no $J/\psi$) have ceased. Then at $t = 0$ we have what we call normal suppression and therefore have

$$S_N = \int d^2 \vec{r} d^2 \vec{p} n(\vec{r}, \vec{p}, 0), \quad (11)$$

$$\langle p^2_t \rangle_N = \int d^2 \vec{r} d^2 \vec{p} p^2 n(\vec{r}, \vec{p}, 0)/S_N \quad (12)$$

for the intensity $S_N$ and $\langle p^2_t \rangle_N$ of the $J/\psi$, respectively. Here and in the following we consider one particular impact parameter (one value of $E_t$). For $t > 0$ the phase space distribution $n(\vec{r}, \vec{p}, t)$ evolves under the influence of anomalous suppression. In order to obtain analytical results, we have to introduce three simplifying assumptions: (a) Instead of the absorption process happening continuously for $t > 0$ until all charmonia are “eaten up”, we let anomalous suppression happen at one particular time $t = t_A$, while for $0 < t < t_A$, the phase space distribution evolves freely, i.e.

$$n(\vec{r}, \vec{p}, t) = n((\vec{r} + \vec{v}t), \vec{p}, 0), \quad (13)$$

where $\vec{v} = \vec{p}/M$ is the velocity of a $J/\psi$ with momentum $\vec{p}$ within a non-relativistic approximation. (b) Anomalous suppression happens in such a way that all $J/\psi$’s, whose position $r$ is smaller than a given radius $r_A$ are suppressed (where $r_A$ depends on $E_t$, $r_A(E_t)$). This assumption corresponds to the $\Theta$ function, eq. (4), introduced in ref. [3]. Then

$$S_{ob}(E_t) = \int_{r < r_A(E_t)} d^2 \vec{r} d^2 \vec{p} n(\vec{r}, \vec{p}, t_A) \quad (14)$$

$$\langle p^2_t \rangle_{ob}(E_t) = \int_{r < r_A(E_t)} d^2 \vec{r} d^2 \vec{p} p^2 n(\vec{r}, \vec{p}, t_A)/S_{ob}(E_t) \quad (15)$$

for the observed intensity $S_{ob}(E_t)$ and the observed $\langle p^2_t \rangle_{ob}(E_t)$, respectively. With the further assumption (c) of a Gaussian for the initial phase space distribution

$$n(\vec{r}, \vec{p}, t = 0) = c_0 \exp \left( -\frac{r^2}{R^2} - \frac{p^2}{\langle p^2_t \rangle_N} \right) \quad (16)$$
all integrals in eqs. (11-15) can be evaluated explicitly and after some algebra one arrives at

\[ \langle p_t^2 \rangle_{ob}(E_t) = \langle p_t^2 \rangle_N + \ln \left( 1 + \frac{S_A(E_t)}{S_{ob}(E_t)} \right) \cdot \delta p_t^2, \]  

(17)

\[ \delta p_t^2 = \frac{\langle p_t^2 \rangle_N R^2}{M^2} \cdot \frac{\langle p_t^2 \rangle_N}{t_A^2 R^2}. \]  

(18)

Eq. (17) for the mean squared transverse momentum \( \langle p_t^2 \rangle_{ob}(E_t) \) in the domain of anomalous suppression is the second new result of our paper. It shows the dependence of this quantity on the degree of anomalous suppression \( S_A = S_N - S_{ob} \), and one recovers the empirical law, eq. (7) after expanding the logarithm for small values of \( S_A/S_{ob} \) (the logarithmic dependence seems to be an artifact of the Gaussian shape for the phase space distribution eq. (16)). Furthermore, eq. (18) gives an analytical expression for the value \( \delta p_t^2 \). It involves the mean squared transverse velocity of the produced \( J/\psi \), the mean squared transverse radius \( R \) of the overlap zone of the two colliding nuclei (for central collisions, \( R \) is related to the mean squared radius of the Pb nucleus) and the time \( t_A \), when anomalous suppression happens. Using the empirical values for \( \delta p_t^2 = 0.132(GeV/c)^2 \), eq. (11), \( \langle p_t^2 \rangle_N = 1.77(GeV/c)^2 \) and \( R^2 = \frac{2}{5} \langle r^2 \rangle_{Pb} \), one finds \( t_A = 4 \text{ fm/c} \). This value is not unreasonable in view of values of \( 5 - 7 \text{ fm/c} \) discussed in the literature[14] for the lifetime of the fireball in central Pb-Pb collisions. We expect our value for \( t_A \) to change somewhat, if some of the above assumptions (a-c) are relaxed. However, the basic dependence of \( \delta p_t^2 \) on the quantities \( R, \langle p_t^2 \rangle_N \) and \( t_A \) should remain (also for dimensional reasons).

In summary, we have been able to show, that normal nuclear suppression goes along with values of \( \langle p_t^2 \rangle \) which depend linearly on the path lengths \( \ell_A^{AB} \) of the gluons which fuse to form the \( J/\psi \), Fig. 2. In the domain of anomalous suppression, the data show a linear dependence on the relative amount of anomalous suppression \( S_A/S_{ob} \). This relation also holds for the domain of fluctuations in \( E_t \) and supports the interpretation that no qualitatively new mechanism begins for these very high values of \( E_t \). The empirical relation in the domain of anomalous suppression is consistent within the geometric picture “high \( p_t \) J/\psi’s escape anomalous suppression”, which has been proposed [9, 10] and worked out [11] long ago.

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