The Transverse Momentum Dependence of Anomalous $J/\psi$ Suppression

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Abstract:

In proton-nucleus and nucleus-nucleus collisions up to central $S-U$ interactions, the $P_T$-dependence of $J/\psi$ production is determined by initial state parton scattering and pre-resonance nuclear absorption ("normal" $J/\psi$ suppression). The "anomalous" $J/\psi$ suppression in $Pb-Pb$ collisions must reduce the normal $P_T$ broadening, since it occurs mainly in the central part of the interaction region, where also initial state parton scattering and nuclear absorption are strongest. We thus expect for $\langle P_T^2 \rangle$ in $Pb-Pb$ collisions a turn-over and decrease with increasing $E_T$. 
The recently announced “anomalous” $J/\psi$ suppression in $Pb-Pb$ collisions [1] has provided new support for the hope that colour deconfinement can be established at CERN-SPS energy. The estimated energy densities for such collisions do fall into the deconfinement regime predicted by lattice QCD [2], so that there is a theoretical basis for such expectations.

$J/\psi$ suppression was predicted to signal deconfinement [3]. However, all $J/\psi$ production in nuclear collisions up to central $S-U$ interactions shows only pre-resonance absorption in nuclear matter (“normal $J/\psi$ suppression”) [4,5] and hence no evidence for deconfinement. In contrast, $Pb-Pb$ collisions are found to suffer an additional (“anomalous”) suppression, increasing with centrality [1]. So far, this behaviour cannot be consistently accounted for in terms of hadronic comovers [5], in spite of a number of attempts [6–8]. It is compatible with an onset of deconfinement [5][9–11].

Up to now, the experimental studies of anomalous $J/\psi$ suppression have addressed only its centrality dependence. In this note, we want to consider how such suppression should depend on the $J/\psi$ transverse momentum. It is well known that the transverse momenta of secondaries from hadron-nucleus collisions quite generally show a $p_T$-broadening. For secondary hadrons, this is the Cronin effect [12]; a similar behaviour is observed also in Drell-Yan and charmonium production. The natural basis for all such broadening is initial state parton scattering, and it was in fact shown some time ago [13–16] that this describes quite well the $p_T$-dependence observed in $J/\psi$ production from $p-A$ to central $S-U$ collisions.

Consider $J/\psi$ production in $p-A$ collisions, assuming gluon fusion as the dominant process for the creation of a $c\bar{c}$ pair. Parametrizing the intrinsic transverse momentum distribution $f(q_T)$ of a gluon in a nucleon as

$$f(q_T) = \frac{1}{\pi \langle q_T^2 \rangle} \exp \left\{ -\frac{q_T^2}{\langle q_T^2 \rangle} \right\},$$

we obtain by convolution for the transverse momentum distribution $F_{pA}(P_T)$ of the resulting $J/\psi$

$$F_{pA}(P_T) = \frac{1}{\pi \langle P_T^2 \rangle_{pA}} \exp \left\{ -\frac{P_T^2}{\langle P_T^2 \rangle_{pA}} \right\},$$

with

$$\langle P_T^2 \rangle_{pA} = \langle q_T^2 \rangle_A + \langle q_T^2 \rangle_p.$$

The quantity

$$\delta_{pA} \equiv \langle P_T^2 \rangle_{pA} - \langle P_T^2 \rangle_{pp} = \langle q_T^2 \rangle_A - \langle q_T^2 \rangle_p$$

is thus a suitable measure for the observed nuclear broadening.

Assume now that in the passage of the projectile proton through the nuclear target, successive interactions broaden the intrinsic momentum distribution of the corresponding projectile gluon which will eventually fuse with a target gluon to form a $J/\psi$ [13–15].
If the process of $P_T$ broadening during the passage is a random walk, then the relevant parameter of the Gaussian distribution (1) becomes

$$\delta_{pA} = N_c^A \delta_0,$$

(5)

where $N_c^A$ is the average number of collisions the projectile undergoes on its passage through the target up to the fusion point, and $\delta_0$ the average broadening of the intrinsic gluon distribution per collision.

In nucleus-nucleus collisions, a corresponding broadening occurs for both target and projectile gluon distributions; here, however, measurements at fixed transverse hadronic energy $E_T$ can determine the broadening for collisions at a given centrality. Hence at fixed impact parameter $b$ we have

$$\delta_{AB}(b) = \langle P_T^2 \rangle_{AB}(b) - \langle P_T^2 \rangle_{pp} = N_c^{AB}(b) \delta_0,$$

(6)

with $N_c^{AB}(b)$ denoting the average number of collisions for projectile nucleons in the target and vice versa, at fixed $b$. $N_c^{AB}(b)$ has a maximum at small $b$ and then decreases with increasing $b$; for a hard sphere nuclear model, it would vanish when $b = R_A + R_B$.

In Glauber theory, the quantity $N_c^{AB}(b)/\sigma$ can be calculated parameter-free from the established nuclear distributions [17]; here $\sigma$ denotes the cross section for the interaction of the nucleon on its passage through the target. We shall determine $\sigma\delta_0$ from data, so that $\sigma$ never enters explicitly. Once $\sigma\delta_0$ is fixed, the broadening by initial state parton scattering is given for all $p-A$ and $A-B$ interactions. For Drell-Yan production (with quarks instead of gluons in the partonic interaction), this would be the observed effect, since the final state virtual photon does not undergo any further (strong) interactions. A produced nascent $J/\psi$ will, however, experience pre-resonance nuclear absorption; this suppresses $J/\psi$’s produced early along the path of the projectile, since they traverse more nuclear matter and hence are absorbed more than those produced later. As a net result, this shifts the effective production point to a later stage. In $p-A$ collisions, a Drell-Yan pair will on the average be produced in the center of the target. In contrast, nuclear absorption shifts the average $c\bar{c}$ production point further down-stream. This effectively lengthens the path for initial state parton scattering and hence increases the resulting broadening.

The transverse momentum behaviour of normal $J/\psi$ production in nuclear collisions is thus a combination of initial state parton scattering before the production of the basic $c\bar{c}$ state, and pre-resonance nuclear absorption afterwards; both lead to a broadening of a $P_T$-distribution. A further broadening could arise from elastic random walk scattering of the charmonium state itself in nuclear matter; however, such an effect will be included here if we fit $\sigma\delta_0$ to the data.

The essential task is thus to calculate the number of collisions per cross section, $N_c/\sigma$, for $p-A$ and $A-B$ interactions, taking into account the effect of pre-resonance nuclear absorption.
We begin with $p-A$ collisions. The number of collisions which the projectile nucleon undergoes up to the $c\bar{c}$ formation point $(b, z)$ inside the target is given by

$$N_c(b, z) = A \cdot T_A(b, z) = A \int_{-\infty}^{z} dz' \rho(b, z'),$$

where $b$ denotes the impact parameter. The total effective number of collisions before $c\bar{c}$ formation is obtained by averaging over $z$ with the nuclear density $\rho(b, z)$ and the survival probability $S_A(b, z)$ under nuclear absorption as weights,

$$\frac{N_c(b)}{\sigma} = \frac{A T_A(b, z)}{1 - \exp\{-(A-1)\sigma_{abs} T_A(b)\}} - \frac{A}{(A-1)\sigma_{abs}}.$$  \hspace{1cm} (10)

From Eq. (10) we get

$$\frac{N_c(b)}{\sigma} \bigg|_{\sigma_{abs}=0} = \frac{1}{2} A T_A(b),$$ \hspace{1cm} (11)

and

$$\frac{N_c(b)}{\sigma} \bigg|_{\sigma_{abs}=\infty} = A T_A(b);$$ \hspace{1cm} (12)

for no pre-resonance absorption, the formation thus occurs in the center of the nucleus, for infinite absorption on the far surface, as expected.

Averaging the number of collisions over the impact parameter $b$ then gives us the required $N_c/\sigma$ for $p-A$ interactions,

$$\frac{N_c}{\sigma} = \int d^2b \frac{N_c(b)}{\sigma} [1 - P_0(b)] \bigg/ \int d^2b [1 - P_0(b)].$$ \hspace{1cm} (13)

Here $P_0(b) = [1 - \sigma T_A(b)]^A$ is the probability for no interaction of the projectile; for a hard sphere nuclear distribution, it would become $\Theta(b - R_A)$.

The formulation of the corresponding expressions for $A-B$ interactions is quite straightforward. The $c\bar{c}$ formation point is now specified by the impact parameter $b$, the positions $(s, z)$ and $(b-s, z')$ in the two nuclei, with $s$ in the transverse plane and $z, z'$ along the beam axis. The number of collisions up to the formation point becomes

$$\frac{N_c(b, s, z, z')}{\sigma} = A \int_{-\infty}^{z} dz_A \rho_A(s, z_A) + B \int_{-\infty}^{z'} dz_B \rho_B(b-s, z_B),$$ \hspace{1cm} (14)

and the corresponding average number of collisions in the presence of pre-resonance absorption is for fixed impact parameter $b$ given by
\[ \frac{N_c(b)}{\sigma} = \int d^2s \int_{-\infty}^{\infty} dz \rho_A(s,z) \int_{-\infty}^{\infty} dz' \rho_B(b-s,z') S_A(s,z) S_B(b-s,z') \frac{N_c(b,s,z,z')}{\sigma} \]

\[ \frac{1}{\int d^2s \int_{-\infty}^{\infty} dz \rho_A(s,z) \int_{-\infty}^{\infty} dz' \rho_B(b-s,z') S_A(s,z) S_B(b-s,z')} \]

From this, we can in turn obtain the corresponding value at fixed transverse energy \( E_T \) in the usual fashion,

\[ \frac{N_c(E_T)}{\sigma} = \int d^2b P(E_T,b) \frac{1 - P_0(b)}{\sigma} \frac{N_c(b)}{\sigma} \int d^2b P(E_T,b) [1 - P_0(b)], \]

by convolution with the \( E_T - b \) correlation function \( P(E_T,b) \) [5]. \( P_0(b) \) here denotes the probability for no interaction in \( A-B \) collisions, a generalisation of the \( p-A \) form used above.

With Eq. (13) for \( p-A \) and Eqs. (15/16) for \( A-B \) collisions, we have the required Glauber results. Ideally, we would now use Eqs. (4/5) and \( p-A \) data to fix \( \sigma \delta_0 \); the broadening for \( A-B \) interactions would then be fully predicted. Unfortunately there are \( p-A \) data only for three values of \( A \) [18,19], and these have rather large errors. We shall therefore instead check if we can obtain a consistent description of all existing \( p-A \) [18,19] and \( A-B \) data [19,20], up to central \( S-U \), in terms of a common \( \sigma \delta_0 \). For \( \langle P^2_T \rangle_{pp} \), NA3 data on \( J/\psi \) production at 200 GeV beam momentum [18] give \( 1.23 \pm 0.05 \) GeV\(^2\); this value is confirmed in an NA38 analysis [19] as well as by a two-parameter fit to all data which we have performed. Using the NA3 proton-proton value, we obtain the best fit to the available \( p-A \), \( O-Cu \), \( O-U \) and \( S-U \) data with \( \sigma \delta_0 = 9.4 \pm 0.7 \); the error corresponds to 95\% c. l., and the minimum \( \chi^2/d.f. \) is 1.1. In the Table, we show the experimental results together with the broadening as obtained from our calculations, using the mentioned \( \sigma_{abs} = 7.3 \pm 0.6 \) mb for the pre-resonance absorption cross section. The behaviour of \( \langle P^2_T \rangle_{SU} \) as function of \( E_T \) is shown in Fig. 1. It is seen that initial state parton scattering and pre-resonance absorption indeed account quite well for the observed \( E_T \) dependence.

We now turn to \( Pb-Pb \) collisions; the corresponding “normal” transverse momentum behaviour is shown in Fig. 2.* Its basic feature remains the monotonic increase of \( \langle P^2_T \rangle \) with \( E_T \), even though the collision geometry makes this slightly weaker for \( Pb-Pb \) than for \( S-U \) interactions [21].

The onset of anomalous suppression results in a striking modification of this pattern. If the \( J/\psi \)'s in the hot interior of the medium produced in the collision are suppressed, then this will reduce their contribution from the part of phase space leading

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* A similar form was recently obtained from initial state parton scattering only, neglecting pre-resonance absorption [21]. Since such absorption can be simulated by choosing a somewhat larger \( \delta_0 \), the overall pattern remains comparable.
to the most broadening. To illustrate the effect, we assume suppression by deconfinement; in this case the result is readily calculable [5,9,16]. To be specific, we assume deconfinement to start once the interaction measure [5]

$$\kappa(b, s) \equiv \frac{N_c(b, s)}{N_w(b, s)}$$ (17)

passes a certain critical value $\kappa_c$; $N_c$ and $N_w$ are the number of collisions and of wounded nucleons, respectively, as obtained from Glauber theory. To calculate the effect of such a melting in the hot center, the integrations in Eq. (15) just have to be constrained to the cool outer region by introduction of $\Theta(\kappa_c - \kappa(b, s))$. In Fig. 2 we have included the resulting patterns for several value of $\kappa_c$; the change of behaviour due to anomalous $J/\psi$ suppression is qualitatively evident.

To obtain a quantitative prediction for the forthcoming $Pb–Pb$ results, we take into account the mixed (40%/60%) origin of the observed $J/\psi$’s from intermediate $\chi_c$’s and direct $\psi$ production. In this case, the overall anomalous suppression had been found [5] to be quite well reproduced with $\kappa_c^\chi \simeq 2.3$ and $\kappa_c^\psi \simeq 2.9$. Using these values and the mentioned $\chi/\psi$ composition, we compare in Fig. 3 the anomalous $E_T$-dependence of $\langle P_T^2 \rangle$ to the normal form. Deconfinement should thus lead to an onset of anomalous behaviour in the $P_T$-dependence of $J/\psi$ production just as it occurs in the integrated production rates. – In contrast, the $P_T$ broadening observed for Drell-Yan production in $p–A$ and $A–B$ collisions [18–20] should continue in its “normal” fashion also for $Pb–Pb$ interactions.

The observation of such anomalous transverse momentum behaviour for $J/\psi$ suppression would thus constitute another piece of evidence for the onset of new physics in $Pb–Pb$ collisions. In particular, its occurrence in $Pb–Pb$ collisions, with a normal $P_T$-dependence in $S–U$ interactions, would again rule out a hadronic explanation of anomalous $J/\psi$ suppression: any absorption by hadronic comovers must be present in continuously varying degrees in all nucleus-nucleus collisions. On the other hand, as we have seen here, such anomalous $P_T$-behaviour would arise naturally in case of deconfinement. It should disappear only for $P_T$ values so high that gluon fragmentation replaces gluon fusion as dominant $J/\psi$ production mechanism or when the relative $J/\psi$-gluon momentum becomes too large for an effective $J/\psi$ dissociation (for $P_T \geq 5–10$ GeV) [22].
Table Caption

Experimental and theoretical values of $\langle P_T^2 \rangle$ for $p-A$ and $A-B$ interactions. Data for $p-p$ and $p-Pt$: NA3 [18]; the other from NA38 [19,20].

Figure Captions

Fig. 1: $P_T$ broadening in $S-U$ collisions; diamonds from [19], stars from [20].

Fig. 2: Normal and anomalous $P_T$ behaviour for $Pb-Pb$ collisions; the anomalous behaviour is calculated for deconfinement at the given critical values of the interaction measure $\kappa_c$.

Fig. 3: The $P_T$ behaviour for deconfinement in $Pb-Pb$ collisions for a 40%/60% $\chi/\psi$ origin of the observed $J/\psi$’s, compared to normal behaviour.

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Fig. 1.

\[ \langle P_T^2 \rangle (\text{GeV}^2/c^2) \]

\[ E_T \ (\text{GeV}) \]

S-U
Fig. 2

Pb-Pb

$<P_T^2>$ (GeV$^2$/c$^2$)

$E_T$ (GeV)

$\kappa_c = 2.9$

$\kappa_c = 2.7$

$\kappa_c = 2.5$

$\kappa_c = 2.3$

normal
Fig. 3

Pb-Pb

\[ \langle P_T^2 \rangle \text{ (GeV}^2/c^2) \]

\[ E_T \text{ (GeV)} \]

normal

decof.

Fig. 3
| A-B   | \(E_T^0\) (GeV) | \(\langle P_T^2 \rangle_{exp}\) (GeV²/\(c^2\)) | \(\langle P_T^2 \rangle_{th}\) (GeV²/\(c^2\)) |
|-------|-----------------|---------------------------------|---------------------------------|
| p-p   |                 |                                 |                                 |
| p-Pt  |                 |                                 |                                 |
| p-Cu  |                 |                                 |                                 |
| p-U   |                 |                                 |                                 |
|       | All \(E_T^0\)  | 1.23 ± 0.05                     | 1.23 ± 0.05                     |
|       |                 | 1.57 ± 0.03                     | 1.47 ± 0.05                     |
|       |                 | 1.41 ± 0.04                     | 1.38 ± 0.05                     |
|       |                 | 1.49 ± 0.05                     | 1.50 ± 0.05                     |
|       | p-Cu            |                                 |                                 |
|       | 13 – 21         | 1.38 ± 0.06                     | 1.42 ± 0.05                     |
|       | 21 – 30         | 1.47 ± 0.07                     | 1.49 ± 0.05                     |
|       | 29 ± 30         | 1.70 ± 0.08                     | 1.53 ± 0.05                     |
|       | ≥ 30            | 1.52 ± 0.08                     | 1.56 ± 0.06                     |
|       | O-U             |                                 |                                 |
|       | 20 – 30         | 1.62 ± 0.07                     | 1.60 ± 0.06                     |
|       | 31 – 39         | 1.65 ± 0.07                     | 1.67 ± 0.06                     |
|       | 39 – 45         | 1.75 ± 0.09                     | 1.72 ± 0.06                     |
|       | 45 – 52         | 1.82 ± 0.10                     | 1.76 ± 0.06                     |
|       | ≥ 5             | 1.85 ± 0.12                     | 1.78 ± 0.06                     |
|       | S-U             |                                 |                                 |
|       | 15 – 30         | 1.57 ± 0.04                     | 1.58 ± 0.06                     |
|       | 34 – 49         | 1.75 ± 0.06                     | 1.66 ± 0.06                     |
|       | 49 – 62         | 1.71 ± 0.06                     | 1.71 ± 0.06                     |
|       | 62 – 71         | 1.77 ± 0.07                     | 1.76 ± 0.06                     |
|       | 71 – 78         | 1.83 ± 0.09                     | 1.78 ± 0.06                     |
|       | ≥ 78            | 1.74 ± 0.08                     | 1.80 ± 0.07                     |
|       | S-U (M)         |                                 |                                 |
|       | 15 – 39         | 1.60 ± 0.04                     | 1.59 ± 0.06                     |
|       | 39 – 56         | 1.66 ± 0.03                     | 1.68 ± 0.06                     |
|       | 56 – 70         | 1.76 ± 0.04                     | 1.74 ± 0.06                     |
|       | 70 – 82         | 1.72 ± 0.04                     | 1.79 ± 0.06                     |
|       | 82 – 94         | 1.77 ± 0.04                     | 1.81 ± 0.07                     |
|       | ≥ 94            | 1.79 ± 0.04                     | 1.82 ± 0.07                     |