$J/\psi$ suppression in Pb+Pb collisions and $p_T$ broadening

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We have analysed the NA50 data, on the centrality dependence of $p_T$ broadening of $J/\psi$'s, in Pb+Pb collisions, at the CERN-SPS. The data were analysed in a QCD based model, where $J/\psi$'s are suppressed in 'nuclear' medium. Without any free parameter, the model could explain the NA50 $p_T$ broadening data. The data were also analysed in a QGP based threshold model, where $J/\psi$ suppression is 100\% above a critical density. The QGP based model could not explain the broadening of $J/\psi$'s in Pb+Pb collisions. The QCD based nuclear absorption model, predict $p_T$ broadening at RHIC energy. Both the models, the QGP based threshold model and the QCD based nuclear absorption model, predict $p_T$ broadening very close to each other.

Since the prediction by Matsui and Satz [1] that binding of a $c\bar{c}$ pair into a $J/\psi$ meson will be hindered in quark-gluon plasma (QGP), $J/\psi$ suppression is recognized as an important tool for the identification of the possible phase transition from confined to deconfined matter. NA50 collaboration measured centrality dependence of $J/\psi$ suppression in 158 A GeV Pb+Pb collisions [2]. They observed suppression well beyond the standard nuclear absorption model. Initially the data were interpreted in terms of successive melting of charmonium states in QGP [2]. However, later, it was realized that the data could be explained in a variety of models with or without QGP [3–7]. What it more intriguing is that the predicted centrality dependence of $J/\psi$ at RHIC energy in a model without QGP, matches with the model prediction with QGP [6]. It appears that the $J/\psi$ suppression may not be a good signal for the deconfining phase transition.

Apart from the centrality dependence of $J/\psi$ suppression, NA50 collaboration also presented data on the transverse energy (centrality) dependence of $p_T$ broadening of $J/\psi$'s [8], which did not receive much attention. Kharzeev et al [9] suggested that $p_T$ broadening of $J/\psi$ can distinguish between QGP and nuclear matter. They argued that in a nuclear matter, $p_T$ broadening will saturate at large $E_T$. In contrast, in a QGP, $p_T$ broadening will visibly decrease. They used conventional Glauber model of nuclear absorption, which we know, could not explain the NA50 data on the centrality dependence of $J/\psi$ over Drell-Yan ratio. The centrality dependence of $J/\psi$ suppression is well explained in the 'unconventional' QCD based nuclear absorption model [6]. In the present letter we have analysed the NA50 $p_T$ broadening data in the model. Without any free parameter, the model could explain the data. For comparison purpose, we have analysed the data also in the QGP based threshold model [3]. The model fails to fit the data. We have also predicted $p_T$ broadening at RHIC energy. Interestingly, both the models predict very similar $p_T$ broadening at RHIC. It seems that, like the $J/\psi$ suppression, centrality dependence of $p_T$ broadening of $J/\psi$ may not be a good signal for the deconfining phase transition.

It is well known that in pA and AA collisions, the secondary hadrons generally shows a $p_T$ broadening. The natural basis for this broadening is the initial state parton scatterings. For $J/\psi$'s, gluon fusion being the dominant mechanism for $c\bar{c}$ production, initial state scattering of the projectile/target gluons with the target/projectile nucleons causes the intrinsic momentum broadening of the gluons, which is reflected in the $p_T$ distribution of the resulting $J/\psi$'s. Parametrizing the intrinsic transverse momentum of a gluon, inside a nucleon as,

$$f(q_T) \sim \exp(-q_T^2/\langle q_T^2 \rangle)$$

momentum distribution of the resulting $J/\psi$ in NN collision is obtained by convoluting two such distributions,

$$f_{NN}^{J/\psi}(p_T) \sim \exp(-p_T^2/\langle p_T^2 \rangle_{NN})$$

where $\langle p_T^2 \rangle_{NN} = <q_T^2> + <q_T^2>$. In nucleus-nucleus collisions at impact parameter $b$, if before fusion, a gluon undergo random walk and suffer $N$ number of subcollisions, its square momentum will increase to $q_T^2 \rightarrow q_T^2 + N\delta_0$, $\delta_0$ being the average broadening in each subcollision. Square momentum of $J/\psi$ then easily obtained as,

$$<p_T^2>_{AB}^{J/\psi}(b) = <p_T^2>_{NN} + \delta_0 N_{AB}(b)$$

where $N_{AB}(b)$ is the number of subcollisions suffered by the projectile and target gluons with the target and projectile nucleons respectively.

Average number of collisions $N_{AB}(b)$ can be obtained in a Glauber model. At impact parameter $b$, the positions $(s, z)$ and $(b - s, z')$ specifies the formation point of $c\bar{c}$ in the two nuclei, with $s$ in the transverse plane and $z, z'$ along the beam axis. The number of collisions, prior to $c\bar{c}$ pair formation, can be written as,

$$N(b, s, z, z') = \sigma_{gN} \int_{-\infty}^{z} dz_A \rho_A(s, z)$$

$$+ \sigma_{gN} \int_{-\infty}^{z'} dz_B \rho_B(b - s, z')$$

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arXiv:nucl-th/0209012v5 10 Apr 2003.
where \( \sigma_{\gamma N} \) is the gluon-nucleon cross section. Above expression should be averaged over all positions of \( \bar{c}c \) formation with a weight given by the product of nuclear densities and survival probabilities \( S \),

\[
N_{AB}(b) = \int d^2 s \int_{-\infty}^{\infty} dz \rho_A(s, z) \int_{-\infty}^{\infty} dz' \rho_B(b - s, z') \times \tag{5}
\]

\[
S(b, s, z, z') N(b, s, z, z')/ \int d^2 s \int_{-\infty}^{\infty} dz \rho_A(s, z) \times
\int_{-\infty}^{\infty} dz' \rho_B(b - s, z') S(b, s, z, z')
\]

Finally, corresponding quantity at fixed transverse energy \( E_T \) is obtained as,

\[
N_{AB}(E_T) = \int d^2 b P(b, E_T) \sigma_{AB} N_{AB}(b)/ \int d^2 b P(b, E_T) \sigma_{AB}
\tag{6}
\]

where \( \sigma_{AB} \) is the inelastic cross section for AB collisions. \( P(b, E_T) \) is the \( E_T - b \) correlation function. We have used the Gaussian form for the \( E_T - b \) correlation,

\[
P(b, E_T) \propto \exp(-(E_T - q N_p(b))^2/2 q^2 a N_p(b)) \tag{7}
\]

where \( N_p(b) \) is the number of participant nucleons at impact parameter \( b \). \( a \) and \( q \) are parameters related to dispersion and average transverse energy. For Pb+Pb collisions the parameters are, \( a=1.27 \) and \( q=0.274 \) GeV [3].

Survival probability \( S(b, s, z, z') \) in Eq.5 is model dependent. We have calculated it using our QCD based 'unconventional' nuclear absorption model [6,10]. Briefly, \( J/\psi \) production is assumed to be a two step process, (a) formation of a \( c\bar{c} \) pair, which is accurately calculable in QCD and (b) formation of a \( J/\psi \) meson from the \( c\bar{c} \) pair, which is conveniently parameterized. The \( J/\psi \) cross section in AB collisions, at center of mass energy \( \sqrt{s} \) was then written as,

\[
\sigma^{J/\psi}(s) = K \sum_{a,b} \int dq^2 \frac{(\bar{\sigma}_{ab\to cc})}{Q^2} \int dx_F \phi_{a/A}(x_a, Q^2)
\tag{8}
\]

\[
\phi_{b/B}(x_b, Q^2) \frac{x_a x_b}{x_a + x_b} \times F_{c\bar{c}\to J/\psi}(q^2),
\]

where \( \sum_{a,b} \) runs over all parton flavors, and \( Q^2 = q^2 + 4 m_c^2 \). The \( K \) factor takes into account the higher order corrections. The incoming parton momentum fractions are fixed by kinematics and are \( x_a = (\sqrt{x_F^2 + 4Q^2/s} + x_F)/2 \) and \( x_b = (\sqrt{x_F^2 + 4Q^2/s} - x_F)/2 \). \( \bar{\sigma}_{ab\to cc} \) are the subprocess cross section and are given in [11].

\[ F_{c\bar{c}\to J/\psi}(q^2) \] are the transition probability that a \( c\bar{c} \) pair with relative momentum square \( q^2 \) evolve into a physical \( J/\psi \) meson. It is parameterized as,

\[
F_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi} \theta(q^2) \theta(4m^2_c - 4m^2_c - q^2) \tag{9}
\]

\[
(1 - \frac{q^2}{4m^2_c - 4m^2_c})^\alpha_F.
\]

In a nucleon-nucleus/nucleus-nucleus collision, the produced \( c\bar{c} \) pairs interact with nuclear medium before they exit. It is argued that the interaction of a \( c\bar{c} \) pair with nuclear environment increases the square of the relative momentum between the \( c\bar{c} \) pair. As a result, some of the \( c\bar{c} \) pairs can gain enough relative square momentum to cross the threshold to become an open charm meson. Consequently, the cross section for \( J/\psi \) production is reduced in comparison with nucleon-nucleon cross section. If the \( J/\psi \) meson travel a distance \( L \), \( q^2 \) in the transition probability is replaced to \( q^2 \rightarrow q^2 + \epsilon \sqrt{2L} \), \( \epsilon \) being the relative square momentum gain per unit length. Parameters of the model were fixed from experimental data on total \( J/\psi \) cross section in pA/AA collisions. It is thus essentially a parameter free calculation for Pb+Pb collisions.

Fluctuations of \( E_T \) at a fixed impact parameter plays an important role in \( J/\psi \) suppression in Pb+Pb collisions. The 2nd drop in the \( J/\psi \) over Drell-Yan ratio at 100 GeV is due these fluctuations only. Fluctuations of \( E_T \) at a fixed impact parameter also affect the average number of collisions \( N_{AB}(E_T) \). As will be shown later, it plays an important role in explaining the NA50 \( p_T \) broadening data. We have taken into account the \( E_T \) fluctuations by the replacement,

\[
N_{AB}(b) \rightarrow E_T/ <E_T> (b)N_{AB}(b). \tag{10}
\]

![FIG. 1. (a) NA38 data on \( E_T \) dependence of \( J/\psi \) suppression in S+U collisions. The solid line is a fit obtained in the 'unconventional' nuclear absorption model. (b) NA38 data on \( p_T \) broadening in S+U along with the fit obtained in the 'unconventional' nuclear absorption model.](image-url)
and (ii) the product of the gluon-nucleon cross section and the average parton momentum broadening per collision, \( \sigma_{gN}\delta_0 \). Since gluons are not free, the second quantity is essentially non measurable. We obtain \( \sigma_{gN}\delta_0 \) from a fit to the NA38 \( p_T \) broadening data [12] in S+U collisions at 200 GeV/c. \( \langle p_T^2 \rangle_{NN} \) at corresponding energy is known from NA3 experiment, \( \langle p_T^2 \rangle_{NN} = 1.23 \pm 0.05 \) [13]. The \( E_T - b \) correlation parameters, \( a \) and \( q \) for S+U collisions are, \( a=3.2 \) and \( q=0.74 \) GeV [14]. To show that the present 'unconventional' nuclear absorption model also reproduces the centrality dependence of \( J/\psi \) over Drell-Yan ratio in S+U collisions, in Fig.1a, we have compared our results with the experimental data. We have neglected the effect of \( E_T \) fluctuations in S+U collisions. The agreement between data and theory is good. In Fig.1b, NA38 experimental data on the \( E_T \) dependence of \( p_T \) broadening are shown. The solid line is a fit to the data, obtained with \( \langle p_T^2 \rangle_{NN} = 1.23 \) (fixed) and \( \sigma_{gN}\delta_0 = 0.442 \pm 0.056 \). Value of \( \sigma_{gN}\delta_0 \) agrees closely with the value obtained by Kharzeev et al [9] in the conventional nuclear absorption model and also with the value obtained in the comover model [15].

Experimental data being limited to 60 GeV only, extrapolation to RHIC energy is unreliable.

FIG. 3. (a) NA50 data on the centrality dependence of the ratio, \( J/\psi \) over Drell-Yan, is compared with the ‘unconventional’ QCD based nuclear absorption model (solid line) and QGP based threshold model (dashed line). (b) NA50 data on \( p_T \) broadening of \( J/\psi \)’s in Pb+Pb collisions. The solid and dashed lines are the prediction in the ‘unconventional’ nuclear absorption model, with and without the effect of \( E_T \) fluctuations on \( N_{AB} \). The prediction in the QGP based threshold model [3], with and without the \( E_T \) fluctuations are shown as the dash-dot and dash-dot-dot lines.

For completeness purpose, in Fig.3a, we have shown the NA50 data [2] on the centrality dependence of the ratio, \( J/\psi \) over Drell-Yan. The solid line is the fit obtained to the data in the ‘unconventional’ QCD based nuclear absorption model. The data are well explained in the model. In Fig.3a, we have also shown the \( J/\psi \) suppression obtained in the QGP base threshold model [3]. In the threshold model, in addition to the conventional nuclear absorption, an anomalous suppression is included such that all the \( J/\psi \)’s are suppressed above a critical density \( n_c \). The dashed line is obtained in the threshold model with \( n_c=3.7\, fm^{-2} \) [3]. It also gives satisfactory description to the data. Centrality dependence of \( J/\psi \) suppression could not distinguish different natures of absorption.

In Fig.3b, we have compared the centrality dependence of \( p_T \) broadening in the model with the NA50 experiment [8]. We have used \( \langle p_T^2 \rangle_{NN}=1.15 \, GeV^2 \) and \( \sigma_{gN}\delta_0=0.442 \). The solid and dashed lines are the \( p_T \) broadening with and without the effect of \( E_T \) fluctua-
tions on $N_{AB}(b)$. When the effect of $E_T$ fluctuations is not taken into account, the $p_T$ broadening continues to increase with $E_T$ till 100 GeV (the knee of the $E_T$ distribution). Thereafter, $p_T$ broadening decreases. The behavior is unlike the $p_T$ broadening in the 'conventional' nuclear absorption model, rather more like the behavior in a QGP [9]. In the conventional nuclear absorption model, at large $E_T$, $p_T$ broadening saturates while in a QGP it decreases. Indeed, the different centrality dependence of $p_T$ broadening in nuclear and in QGP medium led Kharzeev et al [9] to suggest 'decreasing $p_T$ broadening at large $E_T$' as a signal of QGP. We find that 'unconventional' nuclear absorption model also produces a 'decreasing $p_T$ broadening at large $E_T$'. At large $E_T$, $J/\psi$'s are largely suppressed and $<p_T^2>$ decreases. Decrease of $<p_T^2>$ at large $E_T$ cannot be considered as a signal of deconfinement phase transition.

Centrality dependence of $<p_T^2>$ at large $E_T$ is changed when the effect of $E_T$ fluctuations, on average number of gluon-nucleon collisions, is taken into account. The decreasing trend of $<p_T^2>$ beyond 100 GeV is changed to an increasing trend (the solid line). Effect of $E_T$ fluctuations essentially increases the average number of gluon-nucleon collisions at a fixed impact parameter and is counter balance the large suppression effect beyond the knee of the $E_T$ distribution. NA50 data also shows an increasing trend beyond 100 GeV. The model reproduces the data very well (within 2%).

We have also analysed the data in the QGP based threshold model [3]. Hufner et al [20] calculated $p_T$ broadening in the threshold model (Fig.2 in ref [20]) and found that the NA50 data could not be fitted in the model. They did not take into account the effect of $E_T$ fluctuations on the average number of gluon-nucleon collisions, which we have seen, is important for explaining the data. In Fig.3b, the dash-dot-dot line is the $p_T$ broadening in the threshold model, without the effect of $E_T$ fluctuations on $N_{AB}$. As in [20] the model can not explain the data. However, at low $E_T$, the $p_T$ broadening in close agreement with the 'unconventional' QCD based nuclear absorption model. It is expected, as in peripheral collisions (low $E_T$) QGP is not produced and $J/\psi$'s are suppressed in nuclear medium only. When the effect of $E_T$ fluctuations on $N_{AB}(b)$ is taken into account (the dash-dot line), even though the difference between the theory and experiment is lessened, the model still fails to explain the data. At large $E_T$ the model predict 4% less $p_T$ broadening, also the upward trend beyond 100 GeV is not reproduced. However, we note that the $p_T$ broadening in the threshold model and in the nuclear absorption model are very close to each other, the difference is less than within 3% or so. Since the NA50 data are very accurate, it can distinguish the small difference between the two models. We may mention that NA50 $p_T$ broadening data were analysed by Armesto et al [15], in the comover model. The comover model also gives very good fit to the data, only the increasing trend after $E_T=100$ GeV, could not be reproduced. They also neglected the effect of $E_T$ fluctuations on the average number of gluon-nucleon collisions, which give that tendency.

We now give prediction for $p_T$ broadening at RHIC energy. For RHIC energy, parameters $a$ and $q$ in the $E_T-b$ correlation are taken as; $a=1.97$ and $q=0.46$ GeV [7]. They were obtained by fitting rescaled $E_T$ distribution data in Pb+Pb collisions at CERN SPS. At RHIC energy, the so called hard component, which is proportional to the number of binary collisions, appear. Model dependent calculations indicate that the hard component grows from 22% to 37% as the energy changes from 56 GeV to 130 GeV [21]. In our calculation, we have used 37% hard scattering component. In Fig.4a, the predicted centrality dependence of the ratio of $J/\psi$ over Drell-Yan ratio is shown. The QCD based nuclear absorption model and the QGP based threshold model, both predict nearly the same $J/\psi$ suppression. Different nature suppression is not distinguished.

FIG. 4. (a) Predicted centrality dependence of $J/\psi$ over Drell-Yan ratio at RHIC. The solid and dashed lines are the prediction in the QCD based nuclear absorption model and the QGP based threshold model. (b) Predicted centrality dependence of $p_T$ broadening of $J/\psi$'s.

In Fig.4b, the predicted $p_T$ broadening at RHIC are shown. We have used $<p_T^2>_{NN}$=2.45 (GeV$^2$) and $\sigma_{NN}=0.442$. We again warn that these numbers are approximate only. The solid and the dashed lines are the predicted $p_T$ broadening obtained in the 'unconventional' nuclear absorption model and in the QGP based threshold model, both with the effect of $E_T$ fluctuations on $N_{AB}$ included. Both the models give similar centrality dependence for the $p_T$ broadening. After the initial rise
with $E_T$, large suppression forces the $p_T$ broadening to decrease, till 180 GeV (the knee of the $E_T$ distribution). Beyond the knee, large suppression is counter balanced by the effect of $E_T$ fluctuations on the average number of gluon-nucleon collisions and $p_T$ broadening nearly saturates. The predictions in two models closely agree (within 1.5%) with each other. Given the uncertainty in $<p_T^2>_{NN}$ and $\sigma_{N\delta_0}$, such small difference may not be distinguished experimentally. The results suggest that at RHIC energy, centrality dependence of $p_T$ broadening of $J/\psi$, like the centrality dependence of $J/\psi$, may not be able to distinguish a deconfinement phase transition.

To summarize, we have analysed the NA50 data on $p_T$ broadening of $J/\psi$'s. The data were analysed in the QCD based, 'unconventional' nuclear absorption model \cite{6} and in the QGP based threshold model \cite{3}. It was shown that the $E_T$ fluctuations at a fixed impact parameter plays an important role in explaining the $p_T$ broadening data. If the effect is not incorporated, both the models predict a decreasing $p_T$ broadening at large $E_T$, contrary to the experiment. When the effect is included, the 'unconventional' nuclear absorption model could explains the data without any free parameter. The QGP based threshold model could not explain the data. At large $E_T$, it produces 4% less $p_T$ broadening, also the increasing trend beyond 100 GeV is not reproduced. The analysis also indicate that, the 'visibly decreasing $p_T$ broadening at large $E_T$', can not be considered as a probe of the deconfinement phase transition. "Unconventional" nuclear absorption also produces a decreasing $p_T$ broadening at large $E_T$. We have also obtained prediction for centrality dependence of $p_T$ broadening at RHIC energy. At RHIC, both the models predict very similar $p_T$ broadening. We conclude that $p_T$ broadening of $J/\psi$'s can not probe the deconfinement transition at RHIC energy also.

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