$J/\psi$ at small-$x$

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Abstract

It has been suggested that the suppression of $J/\psi$ production in heavy nuclei is a signature of the formation of quark-gluon plasma. We here show that this phenomenon can be understood in terms of conventional physics, i.e. i) perturbative QCD, ii) the parton recombination implementation of shadowing in the initial state, and iii) final state interactions with the hadronic debris of the nuclear target. Unlike previous calculations we include both the direct $J/\psi$ production and its production via radiative $\chi$ decays ($\chi \to J/\psi + \gamma$). We are able to reproduce the experimental data including their small-$x$ behavior. We emphasize the importance of studying the $x_2$-dependence of the ratio $\sigma(bA)/\sigma(bN)$, where $b$ designates the beam and $x_2$ is the momentum fraction of the parton from the nuclear target.
1 Introduction

It has been suggested that the suppression of $J/\psi$ production on heavy nuclei is a signal for the formation of the quark-gluon plasma; however we would like to consider a conventional physics solution to the problem. $J/\psi$ production will be described by conventional perturbative QCD after including the modification of the small-$x$ behavior of the distribution functions for gluons and sea quarks in the nuclear medium [1]. This allows for the continued use of the hard scattering amplitudes and the factorization theorem. This modification, plus a correction for the ‘classical EMC’ effect at intermediate $x$, provides a multiplicative modification of the parton distribution functions, for partons in a nuclear target. Furthermore, because of the hadronic nature of the final state, effects of the interaction of the final state with the hadronic debris of the nuclear target must be included. We will show how such a picture can reproduce in detail a wide range of data on lepto- and hadroproduction of $J/\psi$.

$J/\psi$, $\psi'$ and $\Upsilon$ suppression on nuclear targets [2, 3] provides valuable data for the study of the $A$-dependence at small-$x$ region and/or large $x_F$. Here $x$ is the Bjorken-$x$ variable, the momentum fraction of a parton within a hadron, and $x_F$ is the Feynman-$x$ variable, $x_F = x_1 - x_2$ where $x_1$ and $x_2$ are Bjorken-$x$ variables for the partons from the beam and target, respectively. The experimental energy ranges from 40 to 800 GeV, which spans part of the intermediate $x$ range through the small-$x$ region for $J/\psi$ production.

$J/\psi$ production in Deep Inelastic Scattering (DIS) has been measured by the NMC [3] collaboration for incident muon energies of 200 and 280 GeV. The results are presented as a ratio of cross sections for two different targets: Sn and C.
These data are relevant to the study of the $A$-dependence of the cross-section at small $x$. In fact, $A$-dependence in $J/\psi$ production is already known for hadronic processes and the cross section ratio

$$R = \frac{\sigma^{hA_1}}{\sigma^{hA_2}}$$

(1)

has been studied considering initial and final state nuclear effects. This ratio is for $J/\psi$ production less than unity in the small $x$ region. This result cannot be explained by QCD parton model, which gives the ratio equal to 1.

Nuclear effects have been observed in high energy processes at different momentum transfer, $Q^2$. Those effects can be traced in DIS with neutrinos or charged lepton beams, in Drell-Yan processes, and in hadroproduction of heavy quarks. Only the intensity of the suppression differs, and this is a key aspect. The general behavior is $A_{eff}/A < 1$, where $A_{eff}$ is defined as $\sigma(bA)/\sigma(bN)$, with $b$ designating the beam. Common features include a more pronounced effect for heavier target nuclei, a rapidly diminishing effect with increasing $x$ and very little dependence on $Q^2$. The first result on nuclear dependence were obtained by EMC at intermediate $x$. Since then the experimental results have been extended to smaller $x$ values, and they exhibit the shadowing phenomena. The available data for $J/\psi$ production are presented in Table 1.

2 The model

In DIS as well as in hadroproduction, the gluon fusion process is dominant and the small-$x$ behavior of the target gluon is crucial. In order to understand the heavy meson suppression with nuclear targets, it is critical to understand small-$x$ behavior of the gluon structure function. We here consider a recombination
model to take into account shadowing at the parton level in the initial state of
the process \[\text{[1]}\]. This approach introduces a modification of the parton evolution
equations in order to take into account the superposition probability when the
partons have a large longitudinal size (or large \(1/x\)). This model incorporates the
recombination through ladder diagrams as a perturbative mechanism enabling a
factorized calculation for the cross section ratios \[\text{[1]}\]. This approach successfully
explains both EMC and Drell-Yan small-\(x\) data \[\text{[17]}\].

The recombination effect is enhanced in the nuclear medium, where the longi-
tudinal size of the parton, \(\Delta z\), can exceed the size of the nucleon at small-\(x\) region.
The quantity measured experimentally is a ratio of structure functions,
\[
R(x, Q^2, A) = \frac{F_2^A(x, Q^2)}{AF_2(x, Q^2)}
\]
and this quantity is found to be approximately \(Q^2\) independent. The \(x\)- and \(A\)-
dependence of this ratio has been parameterized by Berger and Qiu \[\text{[18]}\], and these
authors find that it factors in the DIS case:
\[
R_{EMC}(x, Q^2, A) \approx R_g(x, A)R_a(x, A).
\]
The \(R_g(x, A)\) factor is associated with the partonic shadowing, and it has the
functional form:
\[
R_g(x, A) = \begin{cases}
1 & x_c < x < 1 \\
1 - K_g(A^{1/3} - 1) \left[ \frac{\Delta z - \Delta z_c}{\Delta z_A - \Delta z_c} \right] & x_A < x < x_c \\
1 - K_g(A^{1/3} - 1) & 0 < x < x_A
\end{cases}
\]
where \(K_g\) parameterizes the amount of gluon shadowing, \(\Delta z = 1/(xp)\) is the
wavelength of the gluon, \(\Delta z_c = 1/(x_c p)\) is the longitudinal distance at which
neighboring nucleons begin to interact and \(\Delta z_A = 1/(x_A p)\) is the longitudinal
size of the nucleus. Thus the variables \(x_A\) and \(x_c\) are related to the Bjorken-\(x\)
corresponding to a probe of the nucleus and nucleon, respectively. We assume that \( x_A = x_c/A^{1/3} \), following eq.(9) of Ref. [18]. The remaining factor, \( R_a(x, A) \), parameterizes the classical EMC effect, and it has the approximate form:

\[
R_a(x, A) = \frac{x}{x_1} + K_a(1 - \frac{x}{x_1}) ,
\]

with this parameterization valid for \( 0 \leq x \leq 0.6 \).

The above factors incorporate the ‘classical EMC’ effect and initial state effects. Final state effects are incorporated via a factor, \( R_{ss}(x_F, A) = A^{(\alpha(x_F) - 1)} \), where \( \alpha(x_F) = 0.97 - 0.27x_F^2 \). This expression is suggested by data and also agrees with open charm results. This should be adequate. It is premature to deal with specific final state effects without having a better understanding of the gluon distribution function behavior at small-\( x \). Also, our parameterization of final state effects depends only on a final state variable (\( x_F \)).

Other descriptions of final state interactions have been suggested. The nuclear approach à la Glauber includes rescatterings of the \( Q\bar{Q} \) or heavy meson in the nuclear medium [19]. Other authors also consider specific final state effects (and attempts to make quantitative predictions of them) [20] or Pomeron exchange models [21], or raise the fundamental question of the validity of factorization in this kinematical region [22, 23].

3 \( J/\psi \) in DIS

Deep inelastic photoproduction of \( J/\psi \) is understood to take place by the photon-gluon fusion mechanism \([16]\) \( \gamma + g_1 \rightarrow J/\psi + g_2 \). The extra gluon in the final state is required for the \( c\bar{c} \) to be produced as a color singlet with the correct quantum numbers \( (J^P = 1^-) \) of the \( J/\psi \); color and spin projection techniques were used to
extract the relevant part of the $\gamma + g \rightarrow c\bar{c} + g$ amplitude. It has been shown that in the inelastic region ($z = E_{J/\psi}/E_\gamma < 0.9$) both gluons are hard and it is not very relevant to take care of higher order multiple gluon diagrams.

We combine the color singlet model for leptoproduction (photoproduction) of the $J/\psi$ with the parton recombination model to account for the $A$-dependence of the gluon function. We use the Weizsäcker-Williams approximation for the photon and the Morfin-Tung leading order set of parton distributions [24] for the gluon. An advantage of DIS compared to hadroproduction in that there are no interactions with hadronic components of the beam [20].

The color singlet model for $J/\psi$ production reproduces the rapidity distribution [25]. The color singlet model combined with the Weizsäcker-Williams approximation has been shown to agree with the electroproduction of $J/\psi$ with a 15 GeV electron beam at SLAC [26] and muoproduction with a 280 GeV muon beam at CERN [27, 3], as long as experimental cuts ensure that the $J/\psi$ production is inelastic. We therefore feel confident in applying the method to our study of shadowing in $J/\psi$ muoproduction on nuclear targets. Also, the model has the interesting features of providing a direct measure of the gluon distribution function, in the case $\gamma N \rightarrow J/\psi + X$, or the direct determination of the gluon $A$-dependence by means of Eq. (1).

We assume that there is no EMC effect in the carbon target, since it is light and for tin, the parameters $K_a$ and $x_1$ are 1.20 and 0.25 respectively. We also choose a fixed value of $x_c$ for carbon, given by Eq. (9) in Ref. [18], which for $A = 12$ gives $x_c = 0.10$. For tin, we allow $x_c$ and $K_g$ to be free parameters, and try to fit the existing data. We choose the ranges $0 \leq x_c \leq 0.25$ and $0 \leq K_g \leq 0.50$. We then calculate the ratio of the cross sections at the $x$ values of the NMC data points,
and perform a $\chi^2$ analysis. We now describe our results for $A$-dependence on DIS and hadroproduction of $J/\psi$ ($\psi$).

The DIS data is still not abundant but it is extremely useful for comparison with the hadronic case. Our results are presented in Fig. 1 and it is clear that more statistics are needed to enable a more critical analysis of this model. Due to the large error bars it is difficult to constrain the parameters. Also an extension to lower $x$ is important to provide a better definition of the $x$ behavior of the ratio, Eqn. (2).

4 $J/\psi$ in $hp(A)$

The hadroproduction of $J/\psi$ can proceed through a number of parton level processes. The leading order source of $J/\psi$ in hadron-hadron collisions is due to gluon-gluon fusion ($g + g \rightarrow J/\psi + g$) [28, 29], although it is not the most important contribution. The combination of a lower order (in $\alpha_s$) and large branching fraction makes $\chi_J$ production, followed by radiative decay ($\chi_J \rightarrow J/\psi + \gamma$), the dominant source of $J/\psi$ (hereafter referred to as radiative production). The leading contribution to $\chi_J$ production is the low $p_T$ process $g + g \rightarrow \chi_{0,2}$. Additional contributions of the same order in $\alpha_s$ as direct production come from $g + g \rightarrow \chi_{0,1,2} + g$, $q + g \rightarrow \chi_{0,2} + q$ and $q\bar{q} \rightarrow \chi_{0,2} + g$. All the required parton level cross sections can be found, e.g., in Refs. [28, 29]. Furthermore, we use the Morfin-Tung leading order parton distribution functions [24] for partons from the target or from the proton beam, and Owens pion set 1 [30] for partons from the pion beam. We are attempting to perform a more careful calculation of $J/\psi$ production on heavy nuclear targets than previous analyses, and so the cross sections we use are those in which the correct color singlet structure, the correct angular
momentum quantum numbers and small relative momenta are projected out. We then include the factors $R_{EMC}$ and $R_{ss}$ in the calculation of the various cross sections for production on the heavy nuclear target. The $J/\psi$ cross section and $x_2$ distribution can be constructed from the direct and radiative $\chi_J$ components, with the inclusion of branching ratios where appropriate.

As in the DIS case, we allow $x_c$ and $K_g$ to be free parameters, and try to fit the existing data. We choose the ranges $0 \leq x_c \leq 0.25$ and $0 \leq K_g \leq 0.50$. We then compare the experimental data points on $R(x_2)$ (where $x_2$ is the parton momentum fraction of the gluon from the target nucleus) to our calculations, and perform a $\chi^2$ analysis.

We consider data from $p$ and $\pi$ beams with energies from 200 to 800 GeV, focusing on higher mass nuclear targets where the effect of a heavy nucleus is more pronounced. In Fig. 2 the results are presented for $J/\psi$ (Fig. 2a) and $\psi'$ (Fig. 2b). The best agreement requires different parameters for each case. This should not be surprising since the $\psi'$ is a spatially bigger resonance than $J/\psi$. A more refined version of this calculation should include this fact in the final state effects.

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1Because of the existence of $g + g \rightarrow \chi_{0,2}$, the higher order (non-zero $p_T$) processes involving $\chi_{0,2}$ diverge at low $p_T$. This is merely an artifact of an incomplete calculation. If one performs a full calculation of $\chi_{0,2}$ ($g + g \rightarrow \chi_{0,2}$ including all 1 loop graphs) production, and cancels the low $p_T$ divergences against virtual infrared divergences and then absorbs the remaining collinear divergences into the running of the parton distribution functions, the cross section is indeed finite. We adopt a less rigorous approach to this problem. It is known that at low $p_T$, $d\sigma/dp_T^2 \propto e^{-6M_T}$ where $M_T$ is the transverse mass of the charmonium state. Also, the divergences in $|A(gg \rightarrow \chi_{0,2}g)|^2$ and $|A(qg \rightarrow \chi_{0,2}q)|^2$ are $1/t$, which gives $1/p_T^2$ at low $p_T$. Therefore we regularize these squared amplitudes with a factor

$$\left(\frac{p_T}{p_{T0}}\right)^3 e^{-6(M_T-M_{T0})}$$  \hspace{1cm} (6)

where $p_{T0}$ is a free parameter. At low $p_T$, $|A|^2$ should be (a slowly varying function of $p_T$)/$p_T^2$, and so our regularization should reproduce the observed $p_T^2$ distribution. To find a value for $p_{T0}$, we first calculate the total $\chi_{0,2}$ cross section from the $g + g \rightarrow \chi_{0,2}$ subprocesses and vary $p_{T0}$ until the integration of the regularized $|A|^2$ yields the correct value.
obtain very good agreement for 800 GeV for the $J/\psi$ case. It is interesting to note that for the $\psi'$ case, the value of $x_c$ required for the best fit is rather large (the largest we allow in our analysis). A reasonable fit to the data can be obtained, in this case, in a range of parameter space as demonstrated by the dashed line in Fig. 2b.

Also for 200 GeV and $p$ beam the agreement is good and the results are shown in Fig. 3. However for $\pi$ we reproduce quite well the general behavior at 280 and 200 GeV, as shown in Figs. 4 and 5, respectively, but for smaller $x$ our result is below the data. It is likely that the pion distribution function used is not suitable for this kinematical region.

As an overall result, considering that higher statistics are still needed to clarify this complicated problem, we believe that a conventional model as the one presented here is able to accommodate the data. However, it should be emphasized that a better understanding of the small-$x$ behavior of the gluon distribution function is needed, and in this HERA and photoproduction experiments can play an important role.

5 Discussion

The inclusion of the finite $p_T$ contributions modifies the kinematics of the problem somewhat. Previous analyses have assumed that a $2 \to 1$ subprocess dominates the $J/\psi$ production. If this is the case, it is apparent that a fixed cm energy ($\sqrt{s}$) and a fixed invariant mass ($M^2$), implies a fixed $\tau = M^2/s$. But since $\tau = x_1 x_2$, the relations between the kinematical variables is given by $x_1 = (\sqrt{4\tau + x_F^2} + x_F)/2$, $x_2 = (\sqrt{4\tau + x_F^2} - x_F)/2$. Simply putting $\tau = M_{J/\psi}^2/s$ and measuring $x_F$, one can extract the parton momentum fractions. Now, however, with the possible
addition of more final state partons, the invariant mass of the produced state is no longer the $J/\psi$ mass, and so the kinematical relations must be modified somewhat. In Fig. 6, we show the invariant mass distribution for $J/\psi$ and $\Upsilon$. The average invariant mass in $J/\psi$ production is over 1 GeV above the $J/\psi$ mass (when we include only the $g + g \to J/\psi + g$ subprocess), but the difference is relatively smaller in the $\Upsilon$ case, so use of the correct kinematical expressions for $x_1$ and $x_2$ is in order. The inclusion of radiative $\chi_J$ decays will not significantly alter the preceding argument. The correct expressions for $x_1$ and $x_2$ depend on the mass of the produced charmonium state, its $p_T$ and energy measured in the lab frame, and $x_F$. The expression can be simply derived starting from equation (3.2) in Ref. [16]

$$\hat{s} = \frac{M^2}{z} + \frac{p_T^2}{z(1-z)}$$

where $z = E_{onia}/E_{g_1}$ with the energies measured in the lab frame and $g_1$ is the gluon from the beam. Replace $z$ with $z_{obs}/x_1$ ($z_{obs} = E_{onia}/E_{beam}$) and $\hat{s}$ with $x_1 x_2 s$ and solve for $x_1$ and $x_2$ in terms of experimentally measurable quantities.

$$x_{1,2} = \frac{1}{2} \left\{ \left[ (x_F + z_{obs}) + \frac{M_T^2}{s z_{obs}} \right] \right\}$$

$$\pm \sqrt{(x_F + z_{obs})^2 + \left[ \frac{M_T^2}{s z_{obs}} \right]^2 - \frac{2 (x_F M_T^2 - z_{obs} (p_T^2 - M^2))}{s z_{obs}}}$$

where $M_T = \sqrt{p_T^2 + M^2}$ is the transverse mass of the charmonium state produced. It is important to note that the values for $x_1$ and $x_2$ assuming fixed $\tau$ are not even correct at $p_T = 0$, since it is possible for the final state parton to be collinear with the charmonia state without being soft.

The small-$x$ region represents one of the last frontiers of perturbative QCD [22]. For this reason as well as for the very important study of gluon shadowing more
data, both at lower $x$ and with higher statistics, are needed.

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| Experiment | Beam energy (GeV) | Beam type | Target       | $x_2$ range | $x_F$ range | Reference |
|------------|------------------|-----------|--------------|-------------|-------------|-----------|
| NA3        | 43               | $\pi^-$   | Be, Cu, W    | 0.1 - 0.3   | 0 - 0.95    | [31]      |
| NA3        | 39.5             | $\pi^-$   | H, W         | 0.11 - 0.34 | 0 - 0.85    | [32]      |
| NA3        | 150              | $\pi^-$   | H, Pt        | 0.03 - 0.17 | 0.01 - 0.9  | [33]      |
|            | 200              | $\pi^-, p$| H, Pt        | 0.0225 - 0.15 | 0.01 - 0.8 | [34]      |
|            | 280              | $\pi^-$   | H, Pt        | 0.016 - 0.127 | 0.01 - 0.9 | [35]      |
| E537       | 125              | $\bar{p}, \pi^-$| W, Cu, Be | 0.04 - 0.20 | 0.02 - 0.75 | [36]      |
| E672       | 530              | $\pi^-$   | C, Al, Cu, Pb| 0.013 - 0.124 | 0.1 - 0.8 | [37]      |
| E772       | 800              | $p$       | D, C, Ca, Fe, W | 0.01 - 0.4 | 0.15 - 0.65 | (J/ψ, ψ') |
|            | 800              | $p$       | D, C, Ca, Fe, W | 0.1 - 0.35 | 0 - 0.7 | (Υ) |
| E705       | 300              | $p, \bar{p}, \pi^+, \pi^-$ | Li | 0.015 - 0.122 | 0 - 0.45 | [38] |
| NMC        | 280              | $\mu$    | H, D         | 0.02 - 0.3 | NA         | [25]      |
| NMC        | 200              | $\mu$    | C, Sn        | 0.02 - 0.2 | NA         | [3]       |
| NA37       | 280              | $\mu$    | H, D         | 0.02 - 0.3 | NA         | [25]      |

Table 1: Summary of experimental results on $J/\psi$ production on nuclear targets. The values of $x_2$ were derived using $\tau = M_{J/\psi}^2/s$. 


Figure Captions

Figure 1 - Production of $J/\psi$ for a $\mu$ beam of energy 280 GeV on tin ($Sn$) and carbon ($C$) targets (experimental data from Ref. [3]). The curves correspond to shadowing ($x_c = 0.03$ and $K_g = 0.50$), EMC effect and strong screening (dotted), shadowing ($x_c = 0.10$ and $K_g = 0.20$ for comparison), EMC effect and strong screening (dashed), shadowing ($x_c = 0.03$ and $K_g = 0.50$) and strong screening (dotdashed) and strong screening alone (solid).

Figure 2 - Production of $J/\psi$ (a) and $\psi'$ (b) for a proton beam of energy 800 GeV on tungsten ($W$) and hydrogen ($H_2$) targets (experimental data from Ref. [2]). In Figure 2a, the best fit requires the shadowing parameters $x_c = 0.185$ and $K_g = 0.04$, while in Figure 2b, the best fit requires $x_c = 0.25$ and $K_g = 0.10$ (solid line). Also shown Figure 2b is the fit for $x_c = 0.20$ and $K_g = 0.135$ (dashed line).

Figure 3 - Production of $J/\psi$ for a proton beam of energy 200 GeV on platinum ($Pt$) and $H_2$ targets (experimental data from Ref. [13]). The curve shown includes only final state effects and the ‘classical EMC’ effect.

Figure 4 - Production of $J/\psi$ for a $\pi^-$ beam of energy 280 GeV on $Pt$ and $H_2$ targets (experimental data from Ref. [13]). The best fit is achieved by including only final state effects and the ‘classical EMC’ effect.

Figure 5 - Production of $J/\psi$ for a $\pi^-$ beam of energy 200 GeV on $Pt$ and $H_2$ targets (experimental data from Ref. [13]). The best fit is achieved by including only final state effects and the ‘classical EMC’ effect.

Figure 6 - The cross section vs. invariant mass ($\sqrt{s}$) for the subprocess $g+g \rightarrow J/\psi + g$, assuming a proton beam of energy 800 GeV on a $H_2$ target.
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