PHYSICAL REVIEW D VOLUME 49, NUMBER 3 1 FEBRUARY 1994

J/ψ suppression in electro- and hadroproduction: A conventional physics explanation

M. A. Doncheski*
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

M. B. Gay Ducati
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
and Instituto de Física, Universidade Federal do Rio Grande do Sul, C.P. 15051, 91500, Porto Alegre, Rio Grande do Sul, Brazil

F. Halzen
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
(Received 11 February 1993; revised manuscript received 13 October 1993)

Having in mind the importance of the phenomenon for the search for the quark-gluon plasma in the collision of heavy nuclei, we study the suppression of J/ψ production in leptoproduction and hadroproduction on heavy nuclear targets. 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, (iii) the EMC effect, and (iv) final state interactions of the produced J/ψ with the hadronic debris of the nuclear target. Unlike previous calculations we include both the direct J/ψ production and its production via radiative χ decays ($\chi_J \rightarrow J/\psi + \gamma$). 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.

PACS number(s): 14.40.Gx, 12.38.Aw, 24.85.+p

I. INTRODUCTION

The suppression of J/ψ production in the collision of heavy nuclei has been extensively studied as a possible signature for the formation of the quark-gluon plasma. It is therefore important to understand the dynamics of this phenomenon and, with this in mind, here we study the suppression of J/ψ electro- and hadroproduction on heavy nuclear targets. We conclude that the phenomenon can be understood in terms of conventional physics. J/ψ production will be described by 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 European Muon Collaboration (EMC)" effect at intermediate x, requires a multiplicative modification of the 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 J/ψ 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/ψ.

The observed suppression of J/ψ, ψ', and Υ production on nuclear targets [2, 3] represents valuable information for the study of the A dependence at small x 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 the fractional momenta of the partons in 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/ψ production.

J/ψ production in deep inelastic scattering (DIS) has been measured by the New Muon Collaboration (NMC) [3] 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, the A dependence for J/ψ production by hadronic beams [4],

$$R = \sigma^{hA_1}/\sigma^{hA_2}, \qquad (1)$$

has been analyzed considering initial and final state nuclear effects [5, 6]. The ratio is less than unity in the small-x region. This result cannot be explained by QCD, which predicts a ratio equal to 1.

Nuclear effects have been studied for a range of values of the momentum transfer, Q^2, in DIS with neutrino [7] or charged lepton beams [3,8–10], in Drell-Yan processes [11], and in hadroproduction of heavy quarks [4, 2, 12, 13]. Only the intensity of the suppression differs, and this is a key aspect. The general trend is that $A_{\rm eff}/A < 1$, where $A_{\rm eff}$ 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 results on nuclear dependence

*Now at Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada.

were obtained by EMC at intermediate x [14]. Since then the experimental results have been extended to smaller-x values, and they exhibit shadowing phenomena. The available data for J/ψ production are listed in Table I. We concentrate our analysis to $x_2 \leq 0.1$ where the model presented in this paper is appropriate.

II. THE MODEL

In DIS as well as in hadroproduction, the gluon fusion process dominates J/ψ production [15, 16] and therefore the small-x behavior of the target gluon is crucial. In order to accommodate the heavy meson suppression in nuclear targets, it is critical to understand the small-x behavior of the gluon structure function. Here we consider a recombination model which implements shadowing at the parton level in the initial state of the process [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 and, as a perturbative mechanism, still allows for a factorized calculation for the cross section ratios [1]. This approach successfully describes the EMC and Drell-Yan small-x data [17].

The recombination effect is enhanced in the nuclear medium, where the longitudinal size of the parton, Δz, can exceed the size of the nucleon in the small-x region. The quantity measured experimentally is a ratio of structure functions,

$$R(x, Q^2, A) = \frac{F_2^A(x, Q^2)}{AF_2(x, Q^2)}, \tag{2}$$

which is found to be approximately Q^2 independent. The x and A dependences of this ratio has been parametrized by Berger and Qiu [18]. For DIS,

$$R_{\rm EMC}(x, Q^2, A) \approx R_g(x, A) R_a(x, A). \tag{3}$$

The $R_g(x, A)$ factor is associated with the partonic shadowing, it has the functional form

$$R_g(x, A) = \begin{cases} 1, & x_c < x < 1, \\ 1 - K_g(A^{1/3} - 1)\left[\frac{\Delta z - \Delta z_c}{\Delta z_A - \Delta z_c}\right], & x_A < x < x_c, \\ 1 - K_g(A^{1/3} - 1), & 0 < x < x_A, \end{cases} \tag{4}$$

where K_g parametrizes the gluon shadowing, $\Delta z = 1/(xp)$ is the wavelength of the gluon, $\Delta z_c = 1/(x_c p)$ is the longitudinal distance for which neighboring nucleons begin to interact, and $\Delta z_A = 1/(x_A p)$ is the longitudinal size of the nucleus. Thus x_A and x_c are related to the Bjorken-x variable and define the resolution for probing the nucleus and nucleon, respectively. We assume that $x_A = x_c/A^{1/3}$, following Eq.(9) of Ref. [18]. The remaining factor, $R_a(x, A)$, parametrizes the classical EMC effect. It has the approximate form

$$R_a(x, A) = \frac{x}{x_1} + K_a\left(1 - \frac{x}{x_1}\right), \tag{5}$$

which is valid for $0 \leq x \leq 0.6$.

In summary, the factors R_g and R_a incorporate initial state screening and the "classical EMC" effect. We finally have to account for the final state interactions of the J/ψ in the final state. Final state effects are poorly understood. As our goal is only to demonstrate that J/ψ production can be understood in terms of conventional physics we decided to parametrize these cor-

TABLE I. Summary of experimental results on J/ψ production on nuclear targets. The values of x_2 were derived using $\tau = M^2_{J/\psi}/s$.

Experiment	Beam energy (GeV)	Beam type	Target	x_2 range	x_F range	Reference
NA3	43	π^-	Be, Cu, W	0.1–0.3	0–0.95	[31]
NA3	39.5	π^-	H, W	0.11–0.34	0–0.85	[32]
NA3	150	π^-	H, Pt	0.03–0.17	0.01–0.9	[13]
	200	π^-, p	H, Pt	0.0225–0.15	0.01–0.8	
	280	π^-	H, Pt	0.016–0.127	0.01–0.9	
E537	125	$\bar{p}$, π^-	W, Cu, Be	0.04–0.20	0.02–0.75	[4]
E672	530	π^-	C, Al, Cu, Pb	0.013–0.124	0.1–0.8	[33]
E772	800	p	D, C, Ca, Fe, W	0.01–0.4	0.15–0.65	[2] (J/ψ, ψ')
E772	800	p	D, C, Ca, Fe, W	0.1–0.35	0–0.7	[34] (Υ)
E705	300	p, $\bar{p}$, π^+, π^-	Li	0.015–0.122	0–0.45	[35]
NMC	280	μ	H, D	0.02–0.3	NA	[25]
NMC NA37	200 280	μ	C, Sn	0.02–0.2	NA	[3]

rections in terms of the experimental data [5]. They can be conveniently incorporated via yet another factor $R_{ss}(x_F, A) = A^{[\alpha(x_F)-1]}$, where $\alpha(x_F) = 0.97 - 0.27x_F^2$ [5]. This expression is suggested by data on J/ψ [4] and also agrees with open charm results. For ψ', our best description (using the same shadowing parameters as in the J/ψ case) is obtained with $\alpha(x_F) = 0.95 - 0.47x_F^2$, since more suppression is expected. To make this fit, we kept the form of the final state effect suppression as suggested by experiment, but allowed for different numerical values for the parameters.

This concludes the description of the framework which we will confront with the experimental data. Other descriptions of final state interactions have been suggested. The nuclear approach in the manner of Glauber includes rescattering of the $Q\bar{Q}$ or heavy meson in the nuclear medium [19]. Other authors have considered specific final state effects [20] or Pomeron exchange models [21]. Others have raised the question of the validity of QCD factorization in this kinematical region [22, 23].

III. J/ψ IN DIS

Deep inelastic photoproduction of J/ψ is understood to take place by the photon-gluon fusion mechanism [16] $\gamma + g_1 \to J/\psi + g_2$. 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/ψ; color and spin projection techniques were used to extract the relevant part of the $\gamma + g \to c\bar{c} + g$ 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 necessary to take care of higher-order multiple gluon diagrams.

We combine the color singlet model for leptoproduction (photoproduction) of the J/ψ with the parton recombination model to account for the A dependence of the gluon structure 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 is that there are no interactions with hadronic components of the beam [20].

The color singlet model for J/ψ production reproduces the rapidity distribution [25]. Combined with the Weizsäcker-Williams approximation it agrees with the data on electroproduction of J/ψ 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/ψ production is inelastic. We therefore are confident in applying the framework to our study of shadowing in J/ψ muon production on nuclear targets.

We assume that there is no EMC effect in the light carbon target and for tin, the parameters K_a and x_1 are 1.20 and 0.25, respectively. We choose the value of x_c for carbon given by Eq. (9) in Ref. [18] which for $A = 12$ yields $x_c = 0.10$. For tin, we allow x_c and K_g to be free parameters, and fit to the existing data. We choose the ranges $0 \le x_c \le 0.25$ and $0 \le K_g \le 0.50$. We subsequently calculate the ratio of the cross sections at the x values of the NMC data points, and perform a χ^2 analysis.

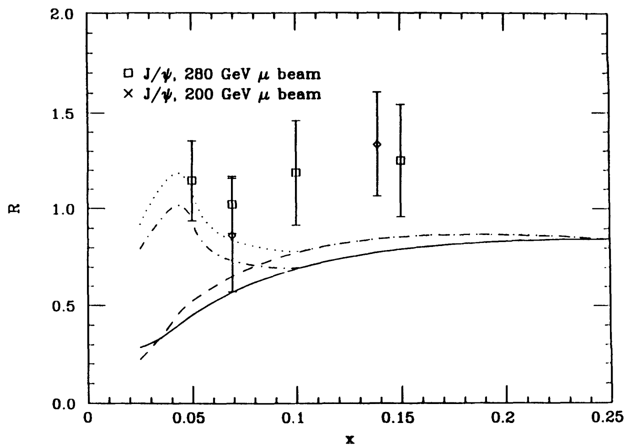

FIG. 1. Production of J/ψ for a μ beam of energy 280 GeV on tin (Sn) and carbon (C) targets (experimental data from Ref. [3]). The curves correspond to shadowing ($x_c = 0.03$ and $K_g = 0.50$), EMC effect and strong screening (dotted), shadowing ($x_c = 0.10$ and $K_g = 0.20$ for comparison), EMC effect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

It is interesting that the A dependence on DIS and hadroproduction of J/ψ (ψ') can be understood in this unified treatment. The DIS data are, however, rather sparse. Our results are presented in Fig. 1 and it is clear that more statistics is needed to enable a more critical analysis of this model. As a result of 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, Eq. (2).

IV. J/ψ IN $hP(A)$

The hadroproduction of J/ψ can proceed through a number of parton level processes. The leading order diagram for J/ψ production in hadron-hadron collisions is gluon-gluon fusion ($g + g \to J/\psi + g$) [28, 29], although it is actually not the dominant contribution to the cross section. The combination of a lower order (in α_s) and large branching fraction makes χ_J production, followed by radiative decay ($\chi_J \to J/\psi + \gamma$), the dominant source of J/ψ (hereafter referred to as radiative production). The leading contribution to χ_J production is the low p_T process $g + g \to \chi_{0,2}$. Additional contributions of the same order in α_s as direct production come from $g + g \to \chi_{0,1,2} + g$, $q + g \to \chi_{0,2} + q$ and $q\bar{q} \to \chi_{0,2} + g$. All the required parton level cross sections can be found, e.g., in Refs. [28, 29]. 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. As we are attempting to perform a more careful calculation of J/ψ 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.[1] We then include the factors $R_{\rm EMC}$ and R_{ss} in the calculation of the various cross sections for production on the heavy nuclear target. The J/ψ cross section and x_2 distribution can be constructed from the direct and radiative χ_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 fit to 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 χ^2 analysis.

We consider data from p and π 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/ψ [Fig. 2(a)] and ψ' [Fig. 2(b)]. As the quarkonia are formed after the production of the heavy quark pair we use the same parameters for both resonances. Since the ψ' is a spatially bigger resonance than J/ψ we allowed, however, for a difference in the ψ''s final state effects. We obtain very good agreement for 800 GeV for both cases. Also for a 200 GeV p beam the agreement is good; the results are shown in Fig. 3. For π we reproduce the general trend of the 280 and 200 GeV data as shown in Figs. 4 and 5, respectively, but for smaller-x values our result is below the data. It is likely that the pion distribution function used is not suitable for this kinematical region.

It is well known that the data on J/ψ production scale in the variable x_F. Our model, in principle, does not as it depends explicitly on x_2. We checked that the violation is unobservably small except in the region x_F above 0.97.

As an overall result, considering that higher statistics are still needed to clarify this convoluted 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

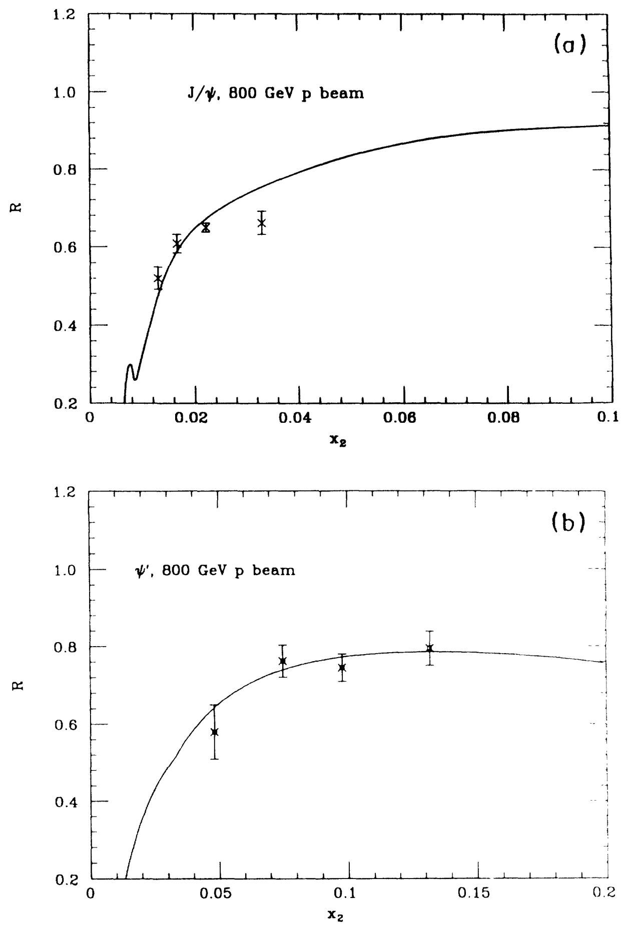

FIG. 2. Production of (a) J/ψ and (b) ψ' for a proton beam of energy 800 GeV on tungsten (W) and hydrogen (H_2) targets (experimental data from Ref. [2]). In (a), the best fit requires the shadowing parameters $x_c = 0.185$ and $K_g = 0.04$, while in (b), we require the same shadowing parameters for ψ' as for J/ψ, and the best fit uses a different parametrization of final state effects as discussed in the text.

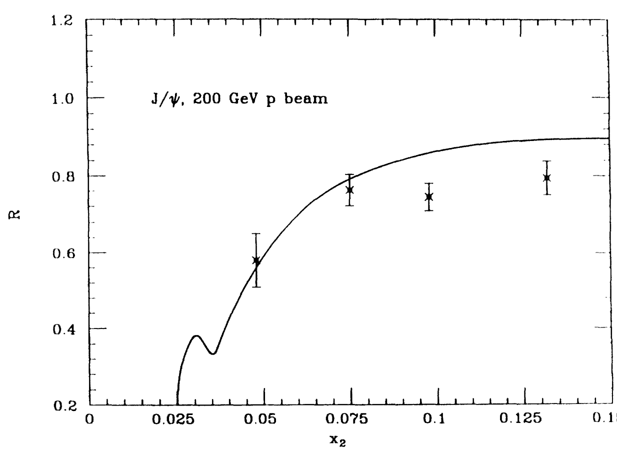

FIG. 3. Production of J/ψ for a proton beam of energy 200 GeV on platinum (Pt) and H_2 targets (experimental data from Ref. [13]). The curve shown includes only final state effects and the "classical EMC" effect.

[1]Because of the existence of $g + g \to \chi_{0,2}$, the higher-order (nonzero 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 $\chi_{0,2}$ ($g + g \to \chi_{0,2}$ including all one-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 $|A(gg \to \chi_{0,2}g)|^2$ and $|A(qg \to \chi_{0,2}q)|^2$ are $1/t$, which gives $1/p_T^2$ at low p_T. Therefore we regularize these squared amplitudes with a factor $(p_T/p_{T0})^3 e^{-6(M_T - M_{T0})}$, for $p_T < p_{T0}$, 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 $g + g \to \chi_{0,2}$ subprocesses and vary p_{T0} until the integration of the regularized $|A|^2$ yields the correct value.

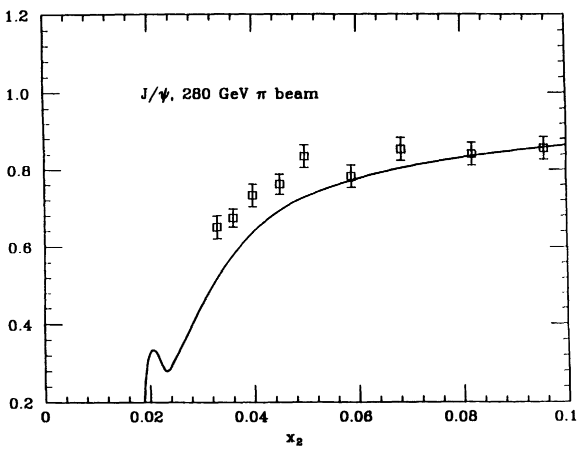

FIG. 4. Production of J/ψ for a π^- beam of energy 280 GeV on Pt and H_2 targets (experimental data from Ref. [13]). The best fit is achieved by including only final state effects and the "classical EMC" effect.

behavior of the gluon distribution function is needed, and in this the DESY ep collider HERA and photoproduction experiments can play an important role.

V. 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/ψ production. If this is the case, it is apparent that a fixed c.m. 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 $\tau = M^2_{J/\psi}/s$ 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/ψ mass, and so the kinematical relations must be modified somewhat. In Fig. 6, we show the invariant mass distribution for J/ψ and Υ. The average invariant mass in J/ψ production is over 1 GeV above the J/ψ mass (when we include only the $g + g \to J/\psi + g$ subprocess), but the difference is relatively smaller in the Υ case, so use of the correct kinematical expressions for x_1 and x_2 is in order. The inclusion of radiative χ_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 laboratory frame, and x_F. The expression can be simply derived starting from Eq. (3.2) in Ref. [16]:

$$\hat{s} = \frac{M^2}{z} + \frac{p_T^2}{z(1-z)}, \tag{6}$$

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

$$x_{1,2} = \frac{1}{2}\left\{ \left[(x_F + z_{\text{obs}}) + \frac{M_T^2}{s z_{\text{obs}}}\right] \pm \sqrt{(x_F + z_{\text{obs}})^2 + \left[\frac{M_T^2}{s z_{\text{obs}}}\right]^2 - \frac{2[x_F M_T^2 - z_{\text{obs}}(p_T^2 - M^2)]}{s z_{\text{obs}}}} \right\}, \tag{7}$$

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 τ 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.

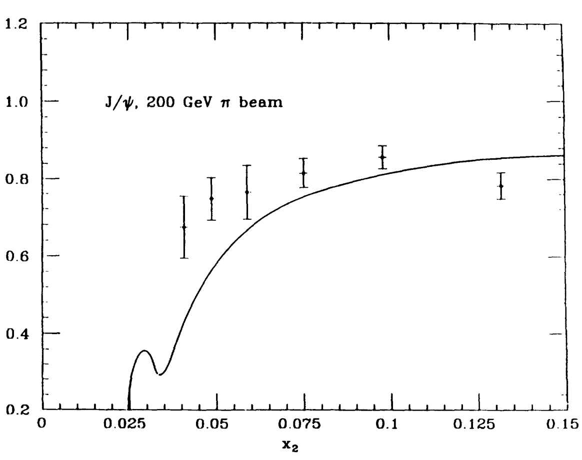

FIG. 5. Production of J/ψ for a π^- beam of energy 200 GeV on Pt and H_2 targets (experimental data from Ref. [13]). The best fit is achieved by including only final state effects and the "classical EMC" effect.

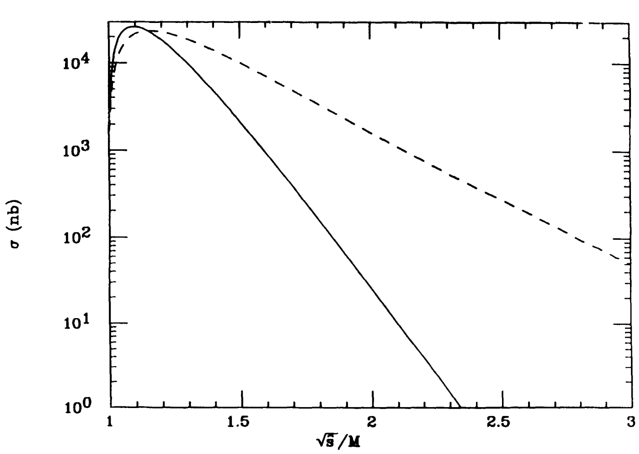

FIG. 6. The cross section vs scaled invariant mass ($\sqrt{\hat{s}}/M$) for the subprocesses $g + g \to J/\psi + g$ (dotted) $g + g \to \Upsilon + g$ (solid), assuming a proton beam of energy 800 GeV on a H_2 target.

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.

ACKNOWLEDGMENTS

One of the authors (M.B.G.D.) acknowledges the hospitality of the Institute for Elementary Particle Physics Research at the University of Wisconsin and the support by CAPES (Brazil). This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, in part by the Texas National Research Laboratory Commission under Grant Nos. RGFY9173 and RGFY9273, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

[1] A. H. Mueller and J. Qiu, Nucl. Phys. **B268**, 427 (1986); J. Qiu, *ibid.* **B291**, 746 (1987).

[2] D. M. Alde *et al.*, Phys. Rev. Lett. **66**, 133 (1991).

[3] P. Amaudruz *et al.*, Nucl. Phys. **B371**, 533 (1992).

[4] S. Katsanevas *et al.*, Phys. Rev. Lett. **60**, 2121 (1988).

[5] L. N. Epele, C. A. Garcia Canal, and M. B. Gay Ducati, Phys. Lett. B **226**, 167 (1989).

[6] F. E. Close, J. Qiu, and R. G. Roberts, Phys. Rev. D **40**, 2820 (1989).

[7] BEBC WA59 Collaboration, P. P. Allport *et al.*, in *Proceedings of the XIXth International Symposium on Multiparticle Dynamics*, Arles, France, 1988, edited by D. Schiff and J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, 1988).

[8] M. Arneodo, in *Quest for Links to New Physics,* Proceedings of the 15th International Warsaw Meeting on Elementary Particle Physics, Kazimierz, Poland, 1992, edited by Z. Ajduk, S. Pokorski, and A. K. Wroblewski (World Scientific, Singapore, 1993).

[9] P. Amaudruz *et al.*, Z. Phys. C **53**, 73 (1992); E665 Collaboration, Phys. Rev. Lett. **68**, 3266 (1992); P. Amaudruz *et al.*, Z. Phys. C **51**, 387 (1991).

[10] M. Arneodo *et al.*, Nucl. Phys. **B333**, 1 (1990); M. Arneodo *et al.*, Phys. Lett. B **211**, 493 (1988).

[11] D. M. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).

[12] M. E. Duffy *et al.*, Phys. Rev. Lett. **55**, 1816 (1985).

[13] J. Badier *et al.*, Z. Phys. C **20**, 101 (1983).

[14] J. J. Aubert *et al.*, Phys. Lett. **105B**, 215 (1983).

[15] R. K. Ellis, in *Physics at the 100 GeV Mass Scale,* Proceedings of the 17th SLAC Summer Institute on Particle Physics, Stanford, California, 1989, edited by E. C. Brennan (SLAC Report No. 361, Stanford, California, 1990).

[16] E. L. Berger and D. Jones, Phys. Rev. D **23**, 1521 (1981).

[17] A. L. Ayala *et al.*, University of Wisconsin Report No. MAD/PH/707, 1992 (unpublished).

[18] E. L. Berger and J. Qiu, in *Nuclear Chromodynamics*, Proceedings of Topical Conference, Argonne, Illinois, 1988, edited by J. Qiu and D. Sivers (World Scientific, Singapore, 1988).

[19] A. Capella *et al.*, Phys. Lett. B **243**, 144 (1990).

[20] R. Vogt, S. J. Brodsky, and P. Hoyer, Nucl. Phys. **B360**, 67 (1990).

[21] P. Castorina and A. Donnachie, Z. Phys. C **45**, 141 (1989).

[22] J. C. Collins and P. V. Landshoff, Phys. Lett. B **276**, 196 (1992).

[23] P. Hoyer, M. Vanttinen, and U. Sukhatme, Phys. Lett. B **246**, 217 (1990).

[24] J. G. Morfin and W.-K. Tung, Z. Phys. C **52**, 13 (1991).

[25] D. Allasia *et al.*, Phys. Lett. B **258**, 493 (1991).

[26] U. Camerini *et al.*, Phys. Rev. Lett. **35**, 483 (1975).

[27] J. J. Aubert *et al.*, Nucl. Phys. **B213**, 1 (1983).

[28] R. Baier and R. Rückl, Z. Phys. C **19**, 251 (1983).

[29] R. Gastmans, W. Troost, and T. T. Wu, Phys. Lett. B **184**, 257 (1987); Nucl. Phys. **B291**, 731 (1987).

[30] J. F. Owens, Phys. Rev. D **30**, 943 (1984).

[31] Y. M. Antipov *et al.*, Phys. Lett. **76B**, 235 (1978).

[32] M. J. Corden *et al.*, Phys. Lett. **110B**, 415 (1982).

[33] S. Kartik *et al.*, Phys. Rev. D **41**, 1 (1990).

[34] D. M. Alde *et al.*, Phys. Rev. Lett. **66**, 2285 (1991).

[35] L. Antoniazzi *et al.*, Phys. Rev. D **46**, 4828 (1992).