A dependence of hadron-nucleus massive lepton pair production

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(Received 25 May 1993; revised manuscript received 9 August 1993)

Nuclear effects in the small x region of hadron-nucleus Drell-Yan processes at 800 GeV are analyzed. We employ the parton recombination model to describe the suppression in the $R_{\mathrm{DY}}^{pA}(x_2)$ ratio and we compare it with $R_{\mathrm{EMC}}(x)$, in the same kinematical region. Our results show that shadowing effects in Drell-Yan and deep inelastic scattering processes admit a description based on this model in both cases but with different characteristic parameters. Good agreement with experimental results is obtained.

PACS number(s): 25.40.Ve, 13.85.Qk, 24.85.+p, 25.30.−c

I. INTRODUCTION

Massive lepton pair hadroproduction has been the subject of continuous study in the last two decades, contributing largely to the understanding of hadronic structure [1–5]. In such processes, the hadron-hadron interaction gives rise to a highly virtual timelike photon, whose experimental signature is the decay into a massive lepton pair. It is also well established that quantum chromodynamics provides the theoretical basis for the description of the physical mechanism involved [6].

Recent very high-energy hadron-nucleus Drell-Yan (DY) experiments have shown an A (mass number) dependence of the normalized cross sections at small values of x (x_2), the Bjorken variable related to the target [7,8]. This fact, once analyzed in terms of structure functions, immediately suggests that a parton in a nucleus behaves differently than it does in an isolated nucleon. This experimental evidence for DY is aligned with a similar one observed in deep inelastic scattering (DIS) [9] and heavy quark hadroproduction [10–13] in the equivalent kinematical region.

In previous work, the A dependence of π^- and $\bar{p}$ J/ψ at 125 GeV was analyzed [14]. There, the parton recombination model for shadowing [15–17] together with a further suppression due to final-state interactions [18–20] were used to account for the observed effects.

Good results obtained there lead us to undertake a detailed analysis of DY processes on nuclei in order to disentangle initial state from final-state effects. In other words, we try to distinguish parton shadowing from the so-called hadron shadowing [21]. Our purpose is to investigate comparatively the parton recombination contribution in DIS off nuclei and in hadron-nucleus DY processes. This comparison is possible if we assume the validity of the usual hypothesis of factorization of the hadronic cross section in the kinematical region of interest. In this case, nuclear effects will be present only in the initial parton interaction because the final produced particles, a pair of muons, do not see the nuclear medium. This is not the case for the J/ψ production which involves gluon distribution functions [22] and even raises the discussion of breaking of the factorization [23]. It should be mentioned that the general analysis of nuclear effects in massive lepton pair production was already done in Ref. [24]. Here we use this formalism in the context of the parton recombination ideas.

This paper is organized as follows. In Sec. II we present a study of the shadowing effects present in the recent DIS experimental data for small x values based on the parton recombination model. In Sec. III a similar description of DY processes is considered in order to discuss the A dependence of the cross section. Finally in Sec. IV we summarize our results and present our conclusions.

II. SHADOWING EFFECTS IN DIS

One of the most interesting features of the recent lepton-nucleus DIS data is the so-called shadowing effect: the suppression of the ratio of structure functions $R=F_2^A/F_2^N$ in the region of small x values [9,25]. It is found that this effect is more pronounced as A increases and when x decreases, being essentially independent of the momentum transfer Q^2.

A possible QCD description of these phenomena was proposed by Mueller and Qiu [15] in terms of parton recombination effects through a modification of the Gribov-Lipatov-Altarelli-Parisi (GLAP) equations [26]. In this model the nuclear distributions of sea quarks $xq_i{}^A(x,Q^2)$ and gluons $xg^A(x,Q^2)$, respectively, are given by

$$xq_i{}^A(x,Q^2)=Axq_i^N(x,Q^2)-\delta xq_i^N(x,Q^2)\ , \qquad (1a)$$

$$xg^A(x,Q^2)=Axg^N(x,Q^2)-\delta xg^N(x,Q^2)\ . \qquad (1b)$$

The first term on the right-hand side of both expressions grows linearly with A, as expected in a naive parton model while the second term includes perturbative recombination effects through the appropriate ladder graph contributions. The minus sign, coming from the explicit calculation, shows the induced reduction of nu-

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clear parton distributions when compared with the free nucleon one.

For a low density parton recombination the previously introduced nuclear distributions can be written, for a fixed value of $Q^2=Q_0^2$ [15], as

$$\frac{1}{A} q_i^A(x,Q_0^2)=R_s(x,Q_0^2,A)q_i^N(x,Q_0^2) , \quad (2a)$$

$$\frac{1}{A} g^A(x,Q_0^2)=R_g(x,Q_0^2,A)g^N(x,Q_0^2) . \quad (2b)$$

The factors R_s and R_g are given by

$$R_{s,g}(x,Q_0^2,A)=\begin{cases} 1, \quad x_C<x , \\ 1-k_{s,g}(A^{1/3}-1)\left[\dfrac{1/x-1/x_C}{1/x_A-1/x_C}\right] , \\ \qquad x_A<x<x_C , \\ 1-k_{s,g}(A^{1/3}-1), \quad x<x_A , \end{cases} \quad (3)$$

where the parameters k_s and k_g measure the recombination amount of the corresponding distributions.

Notice that the shadowing effect arises when the longitudinal size of the parton $\Delta Z \approx 1/xP$ exceeds the nucleon size $\Delta Z_N \approx 2r_0 M/P$ for $x<x_C \approx 1/2Mr_0$, where P, M, and r_0 are the nucleon momentum, mass, and radius, respectively. A saturation effect occurs when ΔZ, referred to the parton, is greater than the nucleus longitudinal size

$$\Delta Z_A \approx 2RM/P(x<x_A \approx \tfrac{1}{2}MR) .$$

In the intermediate region $x_A<x<x_C$, the parton recombination is proportional to the degree of parton superposition measured by

$$\left[\frac{\Delta Z-\Delta Z_N}{\Delta Z_A-\Delta Z_N}\right]=\left[\frac{1/x-1/x_C}{1/x_A-1/x_C}\right] . \quad (4)$$

Because recombination occurs only in the very low x region, it should be dominant for gluons and sea quarks. Using these distributions as an input in the modified GLAP equations, a small Q^2 dependence of shadowing phenomena is obtained in accordance with experimental data. This fact together with the mentioned sea quark distribution dominance in the very small x region allows us to approximate the $R_{\rm EMC}$ ratio as

$$R_{\rm EMC}=F_2^A/F_2^N \approx R_s(x,Q_0^2,A)R_a(x) . \quad (5)$$

The R_a factor takes into account the European Muon Collaboration (EMC) effect in the intermediate x region [17].

We applied this model to the recent $R_{\rm EMC}$ experimental data. In Fig. 1 we present the result of our analysis based on the parton recombination model of Eq. (5). Being mostly interested in the small x region we decided to parametrize the R_a factor simply as a straight line

$$R_a(x)=x/x_1+k_a(1-x/x_1) ,$$

where x_1 is the x value for $R_a=1$ and k_a is the value for $R_a(0)$, in order to describe data in the EMC region ($x>0.2$). In this way we are also able to simulate the antishadowing present in the region $0.1<x<0.2$ [21,27]. In the shadowing region the recombination prediction was calculated for $x_C=0.18$ and three values of the k_s parameter (0.1,0.15,0.2) in the case of $C/^2H$ and $Cu/^2H$ ratios. In the $Sn/^2H$ case only the best description is shown, obtained with the parameters $k_s=0.2$ and $x_C=0.8$ in accordance with the parameters used in Refs. [16,17]. Figure 1 shows that the parton recombination model is able to describe low-x DIS data quite well.

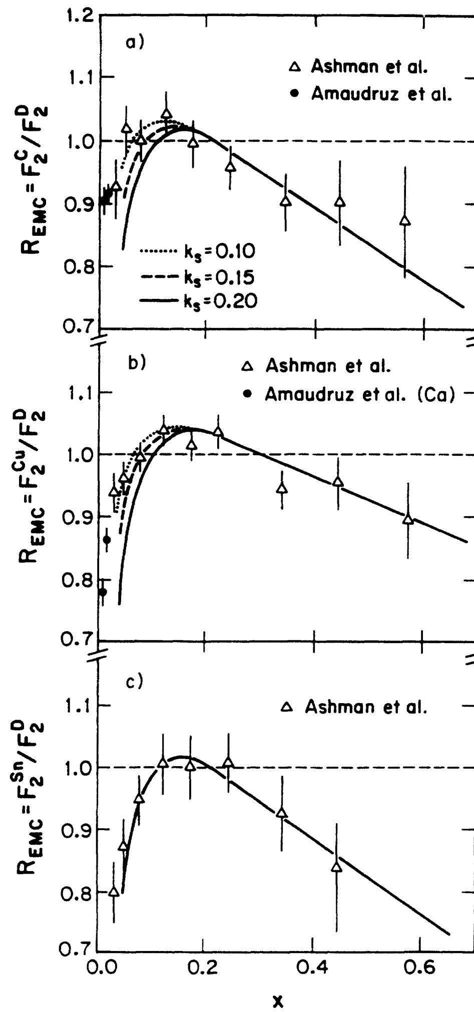

FIG. 1. The parton recombination model predictions are compared with the $R_{\rm EMC}$ data [9].

We focused our analysis on this EMC data since a larger variation in A is covered and their presentation as a ratio allows a more substantial comparison between DIS and DY. In fact, other DIS data is available in the literature [28]. Those that are presented as F_2^A alone are not useful for the purposes of this work, and those concerning very small x attain the saturation region, which is critical for the recombination model, due to increasing higher twist contributions [29,30].

III. *A* DEPENDENCE OF THE DRELL-YAN CROSS SECTION

As stated in the Introduction, the result obtained in describing the $R_{\rm EMC}$ ratio within the theoretical ideas of the parton recombination model suggests studying DY processes, in particular, in the small x (x_2) region, in the same framework.

It is well known that the DY processes $hN \to \mu^+\mu^- + \chi$ have a simple partonic description: one quark (or antiquark) of the hadron h annihilates with an antiquark (quark) of the nucleon N. This annihilation generates a photon γ^- with momentum $Q^2 > 0$, which decays into a pair of leptons with the invariant mass $M^2_{\mu^+\mu^-} = Q^2$. If x_1 and x_2 are the momentum fraction carried by the incident and target quarks, respectively, the invariant mass M^2 may be written as $M^2 = x_1 x_2 s$, where s is the square of the c.m. energy. The fraction x_F of the longitudinal momentum P_- carried by the muon pair is given by

$$x_F = P_-/P_{-\text{maximum}} = (x_1 - x_2) ,$$

and the τ fraction, $\tau = M^2/s = x_1 x_2$. The above considerations are obviously extended to the case $hA \to \mu^+\mu^- + X$, when the target is a nucleus A. Using the QCD factorization of the hadronic process, the differential cross section can be written as follows:

$$\frac{d^2\sigma^{hA-\mu^+\mu^-+X}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3Q^2}\frac{K}{3}\sum_i \epsilon_i^2 [q_i^h(x_1,Q^2)\bar{q}_i^A(x_2,Q^2) + \bar{q}_i^h(x_1,Q^2)q_i^A(x_2,Q^2)] , \quad (6)$$

where α is the electromagnetic coupling constant and the factor K takes into account higher-order QCD corrections [5]. In fact, the QCD leading log corrections exponentiate, while the nonleading ones appear as calculable multiplicative contributions.

The above description of the DY process presents a useful feature for the understanding of nuclear effects because the incident hadron distributions $q_i^h(x_1,Q^2)$ and $\bar{q}_i^h(x_1,Q^2)$ behave as weight functions to the target distributions $\bar{q}_i^A(x_2,Q^2)$ and $q_i^A(x_2,Q^2)$, respectively. Thus different hadrons with different quark content can enhance alternatively the quark or antiquark target distributions. For example, in $\pi^- A \to \mu^+\mu^- + X$ processes, the incident hadron carries a valence antiquark $\bar{u}_i$ and the dominant subprocess is $\bar{u}_v^{\pi^-} + u_v^A \to \mu^+\mu^-$ (v and s denote the valence and sea quarks, respectively). In $pA \to \mu^+\mu^- + X$, no valence antiquarks are present in the incident hadron and the dominant subprocesses is $q_v^p + \bar{q}_s^A \to \mu^+\mu^-$, where we use the notation $q_v = \sum_i q_{vi}$. Then the πA DY process is useful in the investigation of the nucleus valence quark distributions while the pA process is sensitive to the sea content of the nucleus. These features together with the fact that the muon pair has a negligible interaction with the nucleus, show that the DY process is a powerful experimental tool in the investigation of parton distributions in nuclei.

Nuclear effects in DY processes, as in DIS, are usually measured by differential cross section ratios. We are particularly interested in the $R_{\text{DY}}^{hN}(x_2)$ defined by

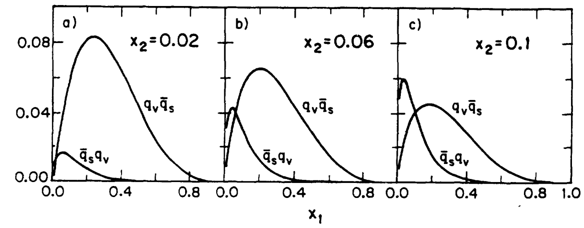

FIG. 2. The curves represent the product of the distributions $q_v\bar{q}_s$ and $\bar{q}_s q_v$ plotted as a function of x_1, keeping x_2 as a fixed parameter. Each subprocess contribution is proportional to the area below the curve.

$$R_{\text{DY}}^{hA}(x_2) = \frac{d\sigma^{hA}}{dx_2} \Bigg/ \left[A\frac{d\sigma^{hN}}{dx_2} \right] , \quad (7)$$

where the differential cross section there are obtained by integrating Eq. (6) in the x_1 variable. Notice that in this expression, the mentioned K factors cancelled out [24]. This assumption implies that the main A-dependent dynamical corrections are effectively taken into account by the recombination approach.

The nuclear effects in DY processes have already been studied in the EMC region $0.2 < x_2 < 0.6$, within the Q^2- [24] and x-rescaling models [31] in connection with the NA10 data [7] $\pi^- W \to \mu^+\mu^- + X$ at 140 and 280 GeV. This result based on QCD factorization in the intermediate x region supports the validity of the rescaling models in DY processes.

Recently, the E772 Fermilab experiment [8] has reported a measurement of $R_{\text{DY}}^{hA}(x_2)$ in the proton-nucleus interactions at 800 GeV for C, Ca, Fe, and W targets, within the x_2 interval $0.04 < x_2 < 0.3$. In the region $x_2 \geq 0.1$ the rescaling model predictions are consistent with the experimental data. However, in the small x_2 region ($x_2 < 0.1$), the $R_{\text{DY}}^{pA}(x_2)$ ratio presents a slight but significant depletion, which becomes more pronounced

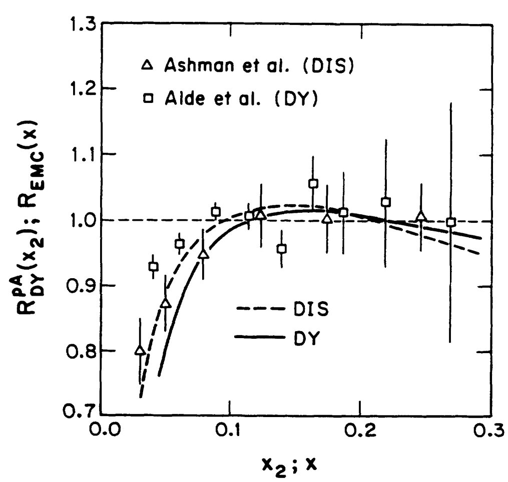

FIG. 3. The comparison of the DIS and DY results in the low-x (x_2) region is shown. The traced curve represents the R_{EMC} ratio calculated using parton recombination. The continuous curve represents the $R_{\text{DY}}^{pW}(x_2)$ ratio calculated using Eq. (8) with the same parameters.

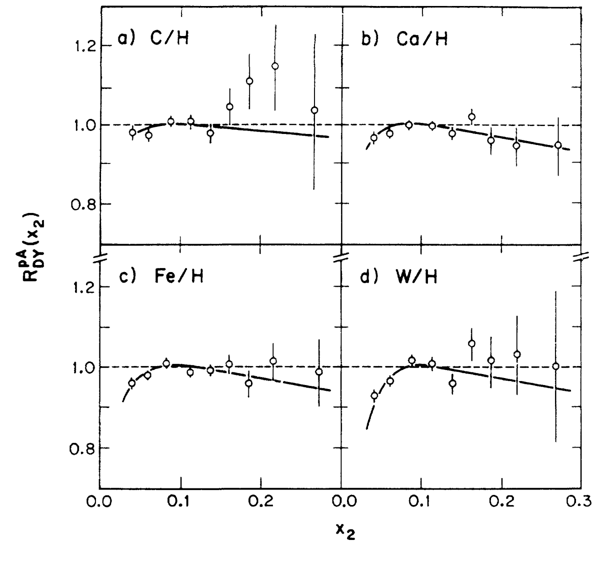

FIG. 4. The predictions of parton recombination are compared with the experimental $R_{\rm DY}^{pA}$ data.

TABLE I. The recombination factors of Fig. 4 compared with those of DIS.

Nucleus	A	Process	k_s	x_C
C	12	DY	0.03	0.1
		DIS	0.1	0.18
Ca	40	DY	0.04	0.1
Cu	64	DIS	0.1	0.16
Fe	56	DY	0.05	0.1
		DIS	0.1	0.18
W	184	DY	0.08	0.1
Sn	118	DIS	0.22	0.18

when the atomic weight of the target increases. This $R_{\rm DY}^{pA}(x_2)$ behavior is similar to that of $R_{\rm EMC}$ in the small x region, i.e., the DY presents a shadowinglike effect. These results and the dependence of cross sections on sea quark distributions as discussed above suggest that parton recombination effects should be present in these processes.

The application of the recombination parton model in the $R_{\rm DY}^{pA}(x_2)$ ratio requires some further discussion. For a fixed value of the x_2 variable, the x_1 integration must lie in the interval $x_2 \le x_1 \le 1$. It includes the experimental cutoff in the muon pair mass $M \le 4$ GeV and $9 \le M \le 11$ GeV, present in the data in order to avoid quarkonium resonances. Another important point is the contribution of each subprocess to the DY cross section. As we have already stressed, the proton-induced DY processes are dominated by the quark-antiquark annihilation subprocesses $q_v^p + \bar{q}_s^A \to \mu^+\mu^-$. Nevertheless, the x_1 integration interval corresponds to the x_F interval $0 \le x_F \le 1 - x_2$. Then the calculation of the $R_{\rm DY}^{pA}(x_2)$ ratio will include a contribution from $x_F < 0.2$, where the $\bar{q}_s^p + q_v^A \to \mu^+\mu^-$ subprocess is also important. These contributions are shown in Fig. 2. The curves correspond to the product of the distributions $q_v\bar{q}_s$ and $\bar{q}_s q_v$ as a function of x_1, keeping x_2 as a fixed parameter. Each subprocess contribution is proportional to the area below the curve. The $q_v\bar{q}_s$ contribution decreases as x_2 increases, while the $\bar{q}_s q_v$ one increases. This result clearly indicates that the $\bar{q}_s q_v$ subprocess must be taken into account in the calculations. Numerical results are almost independent of the quark parametrization used.

As a consequence of the previous discussion and the fact that parton recombination effects are important only for the sea distributions, the ratio $R_{\rm DY}^{pA}(x_2)$ can be written as

$$R_{\rm DY}^{pA}(x_2) = \frac{R_a(x_2)\int_{x_2}^{1} \sum \epsilon_i^2 [\bar{q}_{si}^{\,p}(x_1,Q^2) q_{vi}^N(x_2,Q^2) + R_s q_{vi}^p(x_1,Q^2) \bar{q}_{si}^{\,N}(x_2,Q^2)]dx_1}{\int_{x_2}^{1} \sum \epsilon_i^2 [\bar{q}_{si}^{\,p}(x_1,Q^2) q_{vi}^N(x_2,Q^2) + q_{vi}^p(x_1,Q^2) \bar{q}_{si}^{\,N}(x_2,Q^2)]dx_1} , \tag{8}$$

where ϵ_i denotes the quark charge. In this expression the R_s factor takes care of the recombination while the $R_a(x_2)$ accounts for the EMC effect. The x_1 integration includes the mass cutoff already discussed.

In Fig. 3, the experimental data for $R_{\rm DY}^{pW}(x_2)$ and for $R_{\rm EMC} = F_2^{\rm Sn}/F_2^D$ are presented together with the corresponding parton recombination predictions. Notice that the $R_{\rm EMC}$ curve coincides with that of Fig. 1, while the $R_{\rm DY}^{pW}$ was obtained by using the DIS parameters $k_s = 0.2$ and $x_C = 0.18$. This difference could be originated in the $\int \bar{q}_s^p q_v^N$ term of Eq. (8) which is not affected by parton recombination. In any case, the amount of parton recombination which is needed to describe shadowing on DIS overestimates shadowing in DY processes.

The above conclusion is corroborated when the parton recombination prediction [Eq. (8)] is adjusted for each atomic nucleus with success. Figure 4 shows the results, while in Table I the parameters used are presented. In summary, DY parameters show that these processes are less sensitive to parton recombination than the DIS ones.

IV. CONCLUSIONS

In this paper we have presented a study of nuclear effects in the $R_{\rm DY}^{pA}(x_2)$ ratio for small values of x_2 in the framework of the parton recombination model and factorized QCD calculation. One of our main scopes here was to use the DY processes to distinguish initial state from final-state nuclear effects in hadron processes. Our results show that parton recombination effects can be detected in DY processes, but their magnitude is well below the deep inelastic scattering level. Both DY and DIS processes admit a unified description at small x region in the model of parton recombination for the sea, for different targets. We are not able to raise conclusions concerning the very small x, the saturation region on the basis of available data. As was already pointed out, high-order twist effects can play an important role [30].

Note added. After the completion of this work we received the preprint MKPH-T-93-04, IU/NTC 92-20, "Nuclear Shadowing in Parton Recombination Model" by S. Kumano, where parton recombination effects in DIS structure functions are investigated.

ACKNOWLEDGMENTS

One of the authors (M.B.G.D.) would like to thank the Phenomenology Institute at the University of Wisconsin-Madison for their hospitality and use of facilities during the completion of this work. This work was supported in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), by the Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Brasil, by the Consejo de Investigación Científica (CONICET), Argentina, by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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