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Pion Excess for the Observed Nuclear Effects in Deep Inelastic Scattering and Drell-Yan Production

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In light of recent developments on nucleon and pion parton distributions as well as on meson excess in the nuclear medium, we reinvestigate the role of pion excess as the primary source for nuclear effects observed in deep inelastic scattering (DIS) and Drell-Yan (DY) production. We show that after inclusion of shadowing the pion excess model explains satisfactorily the EMC data in DIS. There is also considerable improvement in the description of the E772 DY production data, given the uncertainties in the pion distribution functions.

The European Muon Collaboration (EMC) [1] observed a modification of the nucleon structure in nuclear medium, as compared to that in free space, using deep inelastic scattering (DIS) by muons on nuclear targets. The nuclear effect in the intermediate x region ($0.3 < x < 0.6$ with x the fraction of the longitudinal momentum carried by the parton), as immediately confirmed by other experiments [2,3] and later by several others [4], is now dubbed as the "EMC effect". At a very small x region ($x < 0.1$), there is also a well-established phenomenon of "nuclear shadowing" [5,4].

Continuum di-lepton production in high-energy hadron-nucleus collisions, known as the Drell-Yan (DY) production [6], offers an independent measure of the modification of the nucleon structure in nuclear medium. Indeed, it is possible to pick a kinematical region with $x_F \equiv x_1 - x_2 \geq 0.1$, so that the DY production in proton-nucleus collisions is dominated by annihilation of valence quarks in the projectile proton with antiquarks in the target nucleus, thereby providing a means of probing the modification of the antiquark distribution in a bound nucleon. The recent E772 data [7] appear to suggest that there is little modification to the antiquark sector in the range $0.1 \le x_t \le 0.2$ for the target nucleon bound in a nucleus.

Explanations of the original EMC effect fall primarily into three distinct categories: (1) conventional nuclear physics models [8-16] employing nucleonic and pionic degrees of freedom, (2) models postulating the existence of multiquark clusters in nuclei [17-24], and (3) rescaling models [25-27] where the scale Q^2, or the variable x, for a bound nucleon is assumed to differ somewhat from that of a free nucleon. As noted by some authors [28,7], it seems that the pion excess picture [8-11] is not capabale of explaining the nuclear dependence observed in the E772 DY data, nor is the early quark cluster model [17-19]. In this paper, however, we wish to point out that, granting the widely accepted uncertainties in relation to the parton distributions associated with the pion, the pion excess model, with inclusion of shadowing, explains satisfactorily the EMC data in DIS while there is also considerable improvement in the description of the E772 DY production data. Thus, it might be premature to rule out the pion excess picture as a viable alternative.

The role in DIS played by the pion cloud was first noted in 1972 by Sullivan [29]. Specifically, Sullivan pointed out that the process in which the virtual photon strikes the pion emitted by the nucleon and smashes the pion into debris will scale like the original DIS process where the virtual photon strikes and smashes the nucleon itself (the core). In other words, the process will contribute by a finite amount to cross sections in the Bjorken limit, $Q^2 \to \infty$ and $\nu \equiv E_l - E_l' \to \infty$ with $x \equiv Q^2/(2m_N\nu)$ fixed. Sullivan obtained

$$\delta F_{2N}^{\pi}(x,Q^2) = \int_x^1 dy f_\pi(y) F_{2\pi}\left(\frac{x}{y},Q^2\right), \tag{1a}$$

$$f_\pi(y) = \frac{3}{4\pi}\frac{1}{4\pi}\left(f_{\pi NN}\frac{2m_N}{\mu}\right)^2 y \int_{-\infty}^{t^m} dt \frac{(-t)|F_\pi(t)|^2}{(-t+\mu^2)^2}, \tag{1b}$$

where $t^m = -m_N^2 y^2/(1-y)$ with m_N the nucleon mass. $F_{2\pi}(x)$ is the pion structure function as would be measured in deep inelastic electron (or muon) scattering with the pion as the target. $\delta F_{2N}(x)$ is the correction to the nucleon structure function due to the Sullivan process. $f_\pi(y)$ is the probability of finding a pion carrying the nucleon momentum fraction y. μ is the pion mass. $f_{\pi NN}$ is the πNN coupling in the form of a pseudovector coupling (as dictated by chiral symmetry) with $F(t)$ characterizing its t-dependence. For the sake of simplicity, one may adopt the dipole form for the sake of illustration:

$$F_\pi(t) = \left(\frac{\Lambda_\pi^2 - \mu^2}{\Lambda_\pi^2 - t}\right)^2. \tag{1c}$$

This has led to adoption of the pion excess picture [8-11] for the interpretation of the original EMC effect. The "Sullivan process" was also used to account for the observed differences in the sea, first [30] for the quantity $\frac{1}{2}(\bar{u}(x) + \bar{d}(x)) - \bar{s}(x)$ and very recently [31] for d,(s) $-u\bar{u}_p(x)$ in relation to the observed violation [32] of the Gottfried sum rule [33]. In considering the question of trying to identify the observed difference $\frac{1}{2}(\bar{u}(x) + \bar{d}(x)) - \bar{s}(x)$ with the Sullivan process, Hwang, Speth, and Brown [34] observed that the entire sea distributions of a nucleon at moderate Q^2 are in fact saturated by generalized Sullivan processes which include other mesons besides the pion. The calculated sea distributions are in good agreement with experiments [35-38], and yet the picture provides a simple explanation of the violation of the Gottfried sum rule, including the shape (as a function of x)[39]. Therefore, it seems that the meson-baryon picture remains to be quite successful for Q^2 at a few GeV^2.

In what follows, we emphasize three aspects which all improve the pion excess picture as an interpretation of the nuclear effects observed in DIS and DY. In Figs. 1 and 2, we display the compiled data, respectively, on the nuclear effects associated with DIS and DY production, together with our model predictions which we shall esplain in some detail. Note that the. DIS data are taken directly from the 1990 compilation by the Particle Data Group [4]. The DY data are from the E772 experiment [7] employing different nuclei as the target – in solid squares from the carbon target, open circles for Ca, solid circles for Fe, and open diamonds for W. The three aspects which we wish to address include: (1) the treatment of pion excess in nuclear medium, (2) the updated parton distributions for the nucleon, and (3) the uncertainty associated with the pion parton distribution.

First, we consider the treatment of pion excess in nuclei. In going from the nucleon structure function $F_{2N}(x, Q^2)$ to the nuclear structure function $F_{2A}(x, Q^2)$, we adopt the standard convolution formulae [40,8-11,16] and contend [16] that a proper treatment of the nuclear binding may account for up to about 20 % of the observed EMC effect in the mid-s region. As it is not our intention to dispute if the nuclear binding effect is relevant for the problem, we use and find it sufficient for our purpose to use the pion excess picture in a traditional sense in order to decide if the DIS and E772 DY data can be understood simultaneously.

It is well known that the propagation of nucleons in the nuclear medium is modified due to Pauli Blocking and interactions with other nucleons. Similarly the meson propagators are modified through creation of virtual particle-hole pairs (nucleon-hole (NN^{-1}) and isobar-hole (ΔN^{-1}) pairs). The random phase approximation (RPA) provides a well-established means of calculating the amount of pion excess, or more generally the excess or depletion of any elementary meson, in the nuclear medium. To determine the pion excess from the RPA it is essential to note that, while the couplings of the initial and final pions to the particle-hole pairs are characterized by the form factors extracted from the deep-inelastic data on the nucleon itself [34], the subsequent interaction among particle-hole pairs proceeds through the full nucleon-nucleon spin-isospin interaction [9]. Here shortrange correlations are crucial which are commonly parameterized by a constant Landau-Migdal parameter g_0'. In a better treatment, however, this parameter acquires a momentum dependence especially through p-meson exchange. We take this into account through a realistic treatment via Brueckner correlations based on the Bonn potential. The resulting momentum-dependent functions are renormalized at $q = 0$ to the empirical strength of the spin-isospin interaction known from Gamow-Teller resonances, β decays, and magnetic moments, as well as the position of the A-resonance observed in charge-exchange reactions on nuclear targets [41]. Incorporating an effective mass m_N^*/m_N for the nucleon which, in nuclear matter, is known [42] to be in the range between 0.8 and 0.9 and including Fermi motion in the ΔN^{-1} Lindhard function, the number of excess pions in nuclear medium is cut down from a previous value of about **13 %** (for constant $g_0' = 0.6$) to a lower value of about 9.5 % for $m_N^*/m_N =$ 0.8. This improvement decreases the EMC ratio in DIS at

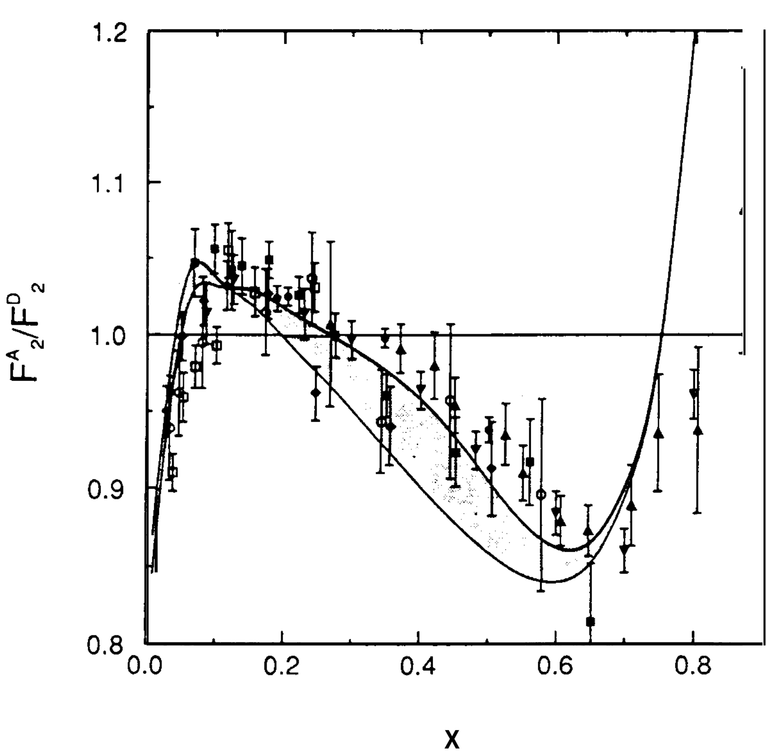

FIG. 1. The EMC ratio in DIS is shown as a function of x together with our model prediction. The data points are from the compilation of the Particle Data Group [4]. The model predictions are explained in the text. Note that the curve as the upper boundary for $0.15 < x < 0.7$ is obtained with $\beta = 1.08$.

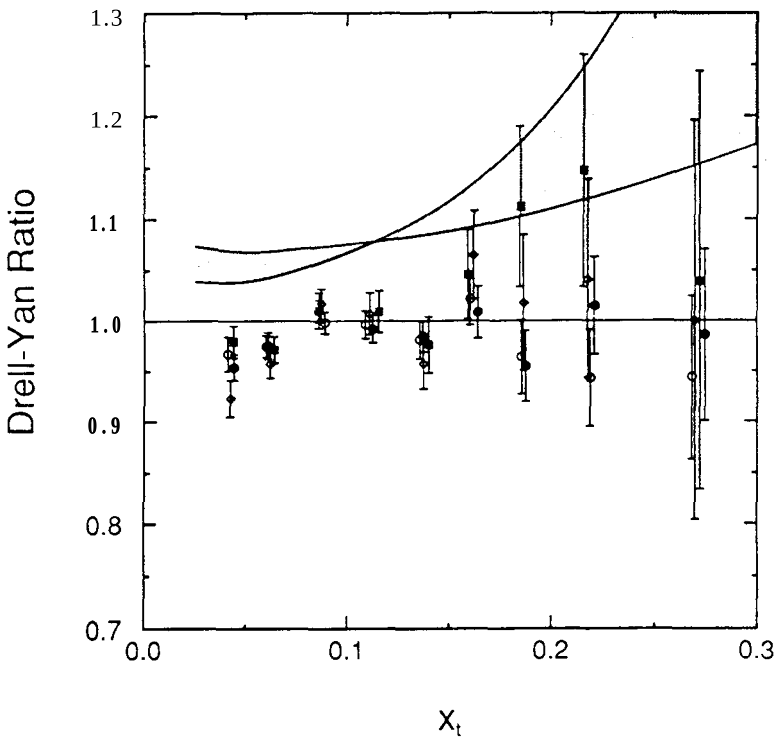

FIG. 2. The Drell-Yan ratio as measured in the Fermilab E772 experiment, together with our model predictions which are explained in the text. Note that the DY data are from the E772 experiment [7] employing different nuclei as the target – in solid squares from the carbon target, open circles for Ca, solid circles for *Fe,* and open diamonds for W. Note that the curve obtained with $\beta = 1.08$ enters as the lower boundary on the left and as the upper boundary on the right.

small 2 by 30 % as compared to previous results. It reduces the DY ratio for the E772 experiment at smaller x_t by a similar factor.

Next, we wish to take note of the existence of several recent improved parton distributions for the nucleon, as compared to what one [7,28] adopted earlier [43,44] in calculating the DY ratio. Implementing the updates suggested by Owens [45] on the old Duke-Owens distributions we are surprised to find that, in the range of x relevant for the E772 experiment, the calculated DY ratio, measured as the deviation from unity, is scaled back by as much as about 50 % as compared to the EHLQ prediction [43] – noting that the old Duke-Owens distributions [44] yield predictions consistent, with EHLQ on this particular question. We would rather view this as the uncertainty, or the room for improvement: as to how the calculated DY ratio depends on the choice of parton distributions for the nucleon.

Another key input for the pion excess picture has to do with the rather poorly known parton distributions for the pion. The distributions which we [7,28] have used earlier are from the NA3 experiment [46]. Nevertheless, there are NA10 and E615 DY data [47,48] and WA70 prompt photon production data [49], all with pion beams. The extraction of pion distributions from these data remains highly uncertain. Standard practice is to start with certain constrained forms for the various parton distributions, such as $a_v x^\alpha (1-x)^\beta$ for the valence distribution and $ax^{-1}(1-x)^\eta$ for the sea and gluon distributions. If the valence distribution dominates completely over the sea quark distribution for, say, $x > 0.3$ (as in the nucleon case), we may then select a sample of the data to first extract the coefficients α and β. The WA70 prompt photon data [49] says something about the gluon distribution but this is much more uncertain. Sutton et al. [50] have recently performed analyses along this line, using $\eta_s = 5.0$ which forces the sea distributions to become negligibly small compared to the valence distribution for $x > 0.35$. They obtained $\beta \approx 1.08$ from the NA10 data [47] or $\beta \approx 1.15$ from the E615 data [48]. Nevertheless, the separation between valence and sea remains artificial in light of the very limited amount of the experimental information and it is often believed [51] that the sea quark distribution in a pion falls off much more slowly with x than that in a nucleon. As a highly constrained fit to the data, we therefore build in a grossly optimized small error associated with the extracted parton distributions. Note that, in a recent work of Eichten et al. [52] on the nucleon, the exponent for the $(1-x)$ dependence varies from 3.1 for $u_v(x)$ to 4.8 for $d_v(x)$. Accordingly, we choose to look into the dependence of the calculated DY ratio on the powers of $(1-x)$, including β and η_s, in a way consistent with the required momentum sum rule and the uncertainty on the amount of the sea (as found by Sutton et al. [50]). We find that for $\eta_s \geq 5.0$ there is little sensitivity of the calculated DY ratio to η_s. However, we also find that, unless η_s is small (say, in the range of (2-4)), the calculated DY ratio at $x > 0.15$ depends very sensitively on the value of β, which we then choose to vary from $\beta = 1.08$ gradually to $\beta = 3.0$. Combining this with the two aspects which we discussed earlier, we display in Figs. 1 and 2 our calculated EMC ratio and the DY ratio as a shaded area. It is clear that the EMC ratio is well reproduced while the consistency with the observed DY ratio is a bit marginal but represents a significant improvement over what has been shown previously [7,28].

Much work [53,54,55] has been done with respect to nuclear shadowing for the EMC ratio at very small x. Some authors [54,55] have attributed the shadowing effect at small x to scattering of the $(q\bar{q})$ component of the virtual photon off nucleons in a nucleus. For sufficiently small x, such $(q\bar{q})$ components has a size comparable with the nuclear radius. Then coherence effects become important, resulting in shadowing. In our calculated EMC ratio in DIS we have used results from such picture given recently by Nikolaev and his colleagues [55]. Shadowing has a visible effect only for $x < 0.1$. We suspect that there is a similar shadowing effect for the DY ratio for $x_t < 0.1$ as DY production already begins with $(q\bar{q})$ pairs which are far apart (from the beam and target separately), but such effect is yet to be incorporated for the DY ratio shown in Fig. 2.

In summary, our results suggest that pion excess may remain as the primary source for the nuclear effects observed in deep inelastic scattering (DIS) and Drell-Yan (DY) production. In particular, it has been shown that the quality of the overall fit to the data has improved considerably because of the recent developments.

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