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Excess pions in Drell-Yan and deep inelastic scattering experiments

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Abstract. Recent data on Drell-Yan processes induced by protons on nuclear targets gives non trivial information about nuclear effects. A very simple model for excess pions in nuclei reproduces the main features of these data, and also of those comming from deep inelastic experiments. This simple scheme gives an unified treatement of nuclear effects highlighting its importance in the deuteron and provides a precise prediction for future $p-p$ and $p-d$ Drell-Yan experiments.

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Introduction

Recently, Fermilab experiment E772 has presented measurements of the yields of massive muons pairs in collisions of 800 GeV/c protons with nuclear targets that are sensitive to the flavour content of the nucleon sea [1]. These measurements set limits on the $\bar{d}/\bar{u}$ asymmetry, which has been proposed to be a possible physical origin of the violation of the Gottfried sum rule by several authors [2, 3].

Contrary to the generalized expectations, E772 found no indiation of a large asymmetry breaking in the antiquark sea of nucleons, neither when these are bounded in light nuclei, as the deuteron, nor in the case of a nucleus as heavy as the tungsten.

These results are of great importance for two reasons: if one leaves aside nuclear effects and considers the experiments as sources of information about nucleons, they seem to rule out explanations of the Gottfried sum rule violation based on a manifest symmetry breaking at intermediate values of the Bjorken variable x. The same can be said about parton distribution parametrizations, with asymmetric sea, constrained to fit world data and fulfill the Gottfried sum rule at the same time. The emphasis in the intermediate x range is due to the fact that there is where NMC data [4] differ from parametrizations based on previous data and also with the predictions of QCD [5, 6].

The second reason is related to the fact that the experiment confirms that the sea quark distributions of a nucleon in a nucleus do not differ significantly from those of a free nucleon. This justifies the initial assumption in the analysis of the experiment and at the same time tell us something more about nuclear effects in Drell-Yan processes. In fact, it has been interpreted as an indication of a weak role of excess pions in nuclear effects at high energy experiments [7]. Excess pions in a nucleus contain valence antiquarks which enhance the effective antiquark density of the effective nucleons of the nucleus.

Notwithstanding this clear argument and the present experimental evidence, in the present letter we advocate the role of pions in Drell-Yan processes and also deep inelastic scattering. For that we show how a very simple model in which pions carry a small fraction of the nucleus momentum reproduces E772 Drell Yan data for heavy and light targets, treating them in an unified scheme. At variance with earlier pictures [8], the effects are more prominent in the valence quark region and have less importance at smaller values of x. Applied to deep inelastic scattering, the model gives an excellent description of nuclear effects for intermediate and high values of x highlighting the importance of these effects in the special case of the deuteron. In fact, in recent articles [6, 9] we have shown that all the unpleasant features of NMC data can be understood as consequences of having neglected nuclear effects in the deuteron structure function.

The ratio of Drell-Yan yields from protons on protons to protons on deuterium is an ideal bench mark for studying the structure of the deuteron. Two experiments of this kind have been proposed recently aiming at the flavour asymmetry issue [10, 11]. However, our model estimate for the yields combined with the considerations of the previous paragraphs indicate that the true protagonists of the experiment will be the hitherto neglected nuclear effects which come from the deuteron structure.

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Drell-Yan processes

It is well known that the proton-induced Drell-Yan process in the kinematic range $x_F \geqq 0.2$ (with x_F the Feynman scaling variable) is sensitive to the antiquark distribution of targets nucleons due to the dominance of the term $u_{\text{beam}}\,\bar{u}_{\text{target}}$ in the corresponding yield. Neglecting nuclear corrections and under the same conditions, the Drell-Yan yield per nucleon from a target with Z protons and N neutrons compared to yield from an isoscalar target is

$$R_A(x_t) \equiv \left.\frac{\sigma^{p+A}}{\sigma^{p+IS}}\right|_{x_F > 0.2} \approx 1 + \frac{(N-Z)}{A}\,\frac{\bar{d}(x_t) - \bar{u}(x_t)}{\bar{d}(x_t) + \bar{u}(x_t)} \qquad (1)$$

where $x_F \equiv x_b - x_t$, x_b is the fraction of momentum carried by the incident quark and x_t is the fraction of momentum carried by the target antiquark. Although this equation is valid up to leading order in QCD, it has been demonstrated that next to leading order effects almost cancel in the ratio giving a negligible correction [12].

According to the previous analysis, the asymmetry in the sea of nucleons should show up as a deviation from unity in the measured ratios. Several models and quark distribution parametrizations based on the idea of this asymmetry have been produced [2, 13, 14] since the Gottfried sum rule issue began, but none of them seems to reproduce the trend of E772 data points, leaving opened the question about NMC deep inelastic data and opening another on this Drell-Yan experiment.

Regarding the first question, we have shown in recent articles [6, 9] that both the presumed defect of the Gottfried sum rule integral and the unexpected Q^2 dependence of the ratio between neutron and the proton deep inelastic structure functions, which contradicts QCD, can be understood as a consequence of nuclear effects in the deuteron structure function. The correction of NMC data for these effects makes unnecessary the introduction of an asymmetric sea which neither have been seen in other phenomena nor, in any case, can explain the observed Q^2 dependence.

Although very small, these effects are amplified when the proton and the resulting structure function for the neutron are compared. Extracted from DIS data and parametrized as a function of x and Q^2 they seem to be a natural extrapolation of what is seen in deep inelastic off nuclei data. The main contribution is related to the almost A independent antishadowing peak at intermediate x values. In [6, 5] we have studied the consequences of pionic degrees of freedom in the deuteron structure function finding that for a very reasonable value of the deuteron momentum carried by pionic constituents a very simple model reproduced the main features of the nuclear effect, providing the magnitude, x and Q^2 dependence in a good approximation.

Having shown the non-trivial role of nuclear pions in the study of the relation between the neutron and the proton structure functions, it is natural investigate it in connection with the E772 experiment. For this aim, we apply to Drell-Yan processes the same ideas about deuteron pions used in references [6, 5], and extend them for the description of heavy nuclei just changing the fraction of the nucleus momentum carried by its pions.

The pion-excess model in its earliest forms [8] predicted for Drell-Yan an enhancement in the antiquark content of nuclei which is completely inconsistent with E772 data [16]. This feature is not present in our predictions because of the different way in which we reduce the momentum carried by nucleons, the more accurate quark distributions in pions, and the pertinent consideration of pionic effects in the deuteron.

In the simpler case of deuterium targets the Drell-Yan cross seccion is given by

$$\frac{d^2\sigma^{pD}}{dx_t\,dx_b} = \int_x^2 dy \left[\frac{d^2\sigma^{pp}}{dx_t'\,dx_b} f_{p/D}(y) + \frac{d^2\sigma^{pn}}{dx_t'\,dx_b} f_{n/D}(y)\right] + \int_x^2 dy\,\frac{d^2\sigma^{p\pi}}{dx_t'\,dx_b} f_{\pi/D}(y) \qquad (2)$$

where $x_t' = x_t/y$, $f_{p/D}(y)$ is the number density of protons in the deuteron whose momentum is a fraction $\frac{y}{2}$ of the momentum of the deuteron and can be taken to be equal to that of neutrons by isospin invariance. Each Drell-Yan cross section $d^2\sigma^{ph}/dx_t dx_b$, where h stands for protons, neutrons or pions, can be calculated using sets of parton distributions in nucleons and pions, [17] and [18] respectively. Charge conservation implies

$$1 = \int_0^2 dy\, f_{p/D}(y)\,. \qquad (3)$$

The simplest possible picture is that where each nucleon carry $\frac{1}{2}(1-\varepsilon)$ of the deuteron momentum so

$$f_{p/D}(y) = \delta(1 - \varepsilon - y)\,. \qquad (4)$$

In (2) we have, via isospin invariance, taken for the number density of excess pions, whose momentum is $\frac{y}{2}$ of the deuteron momentum

$$f_{\pi/D} \equiv f_{\pi^+/D} = f_{\pi^0/D} = f_{\pi^-/D}\,. \qquad (5)$$

Momentum consevation requires

$$1 = \int_0^2 dy\,\frac{y}{2}\,[2 f_{p/D}(y) + 3 f_{\pi/D}(y)] \qquad (6)$$

so

$$\int_0^2 dy\,\frac{y}{2}\,3 f_{\pi/D}(y) = \varepsilon \qquad (7)$$

i.e. ε is the fraction of the deuteron's momentum carried by its pionic constituents.

For the shape of the pion distribution in the deuteron we take the one used in [6]

$$3 f_{\pi/D}(y) = \frac{\varepsilon}{2} \frac{\Gamma(a+b+3)}{\Gamma(a+2)\Gamma(b+1)} \times \left(\frac{y}{2}\right)^a \left(1-\frac{y}{2}\right)^b \tag{8}$$

with $a=2$ and $b=5$, which is designed to satisfy (7).

The cross sections for heavier nuclei can be obtained, in a first approximation, just modifying the fraction ε of the nuclei momentum carried by pions. In principle, for a nucleus of atomic weight A the convolution integral and the pion number density should run from x to A.

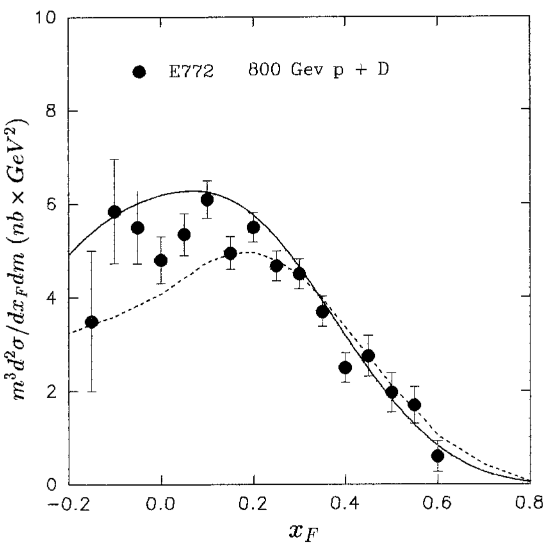

Fig. 1. The differential cross section $m^3\,\mathrm{d}^2\sigma/\mathrm{d}x_F\mathrm{d}m$ for a deuterium target at a mean mass of 8.15 GeV as calculated with the model together with E772 data and the prediction with $\bar{d}/\bar{u}$ asymmetry of [2] *(dashes)*

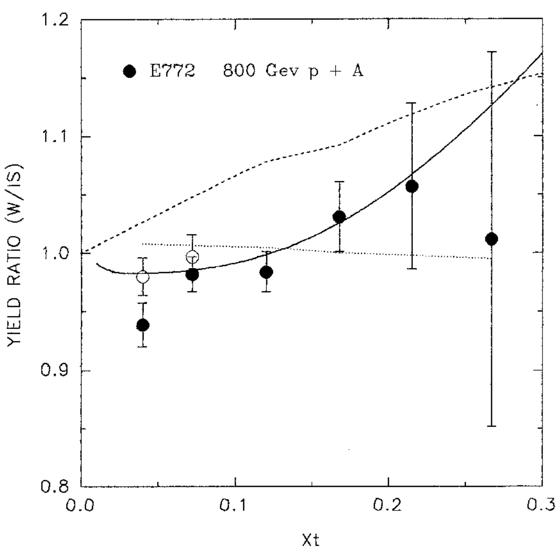

Fig. 2. Prediction for the ratio R_W where the W cross section was calculated for pions carrying 9.5% of the momentum *(solid)*. Data points are those produced by E772 experiment (without shadowing corrections). The *dashed line* corresponds to [2] and the *dotted* to [13]

However, for simplicity, in this approximation we neglect contributions for $y > 2$ and use the same functional form as in deuterium modifying only the mean y value and the normalization of the distribution. Both quantities are driven by the parameter ε. Although the momentum densities $\rho_\pi(\mathbf{k})$ and $\rho_N(\mathbf{k})$ for pions and nucleons in the nucleus rest frame are readily accesible in terms of conventional nuclear theory, there are no exact relations between them and the functions $f\pi(y)$, for excess pions, and $f_N(y)$ for nucleons, which correspond to the infinite momentum frame.

Figure 1 shows our model calculation for the differential cross section $m^3\,\mathrm{d}^2\sigma/\mathrm{d}x_F\mathrm{d}m$ for a deuterium target at a mean mass of 8.15 GeV together with E772 data. The prediction comming from the $\bar{d}/\bar{u}$ asymmetry is also included for comparison. Deuteron pions here are the same as those used in [6].

Figure 2 shows a prediction for the ratio $R_W(1)$ where the W cross section was calculated for pions carrying 9.5% of the tungsten momentum. Data points are those presented by the E772 experiment (without shadowing corrections) and the dashed lines correspond to other model calculations [2, 13].

Deep inelastic data

Now, having seen how well our scheme for excess pions in nuclei describes nuclear effects in Drell-Yan processes with deuterons and also a heavy nucleus, it is worthwile to reanalize its predictions for deep inelastic data.

As we did for Drell-Yan cross sections, we compute deep inelastic nuclear structure functions adding the contributions of each bounded nucleon, whose momenta have been scaled due to the presence of pions, to the probabity of the incoming lepton scattering off a pion. This last contribution is given by the usual convolution formula

$$A F_2^{A\,\mathrm{pionic}}(x) = 3 \int_x^A \mathrm{d}y\, F_2^\pi\left(\frac{x}{y}\right) f_{\pi/A}(y) \tag{9}$$

where

$$F_2^\pi(z) = \tfrac{1}{3}[F_2^{\pi^+}(z) + F_2^{\pi^0}(z) + F_2^{\pi^-}(z)] \tag{10}$$

and $f_{\pi/A}$ is again the average number density of pions for which we make the same considerations as in the Drell-Yan case.

Figure 3 shows the corresponding predictions for the ratios between different nuclei and deuteron compared to available experimental data. Figure 4 shows that the values of ε used for each nucleus have an approximated linear $A^{1/3}$ dependence. This behaviour was also found for the nucleon effective mass in connection with the related approach to the EMC effect based on x rescaling [20].

It is worth noticing that the agreement shown between predictions and experimental data would not be possible if the deuteron structure were not considered. In that sense, the inclusion of nuclear effects in the deuteron structure function in the analysis of the ratios is crucial

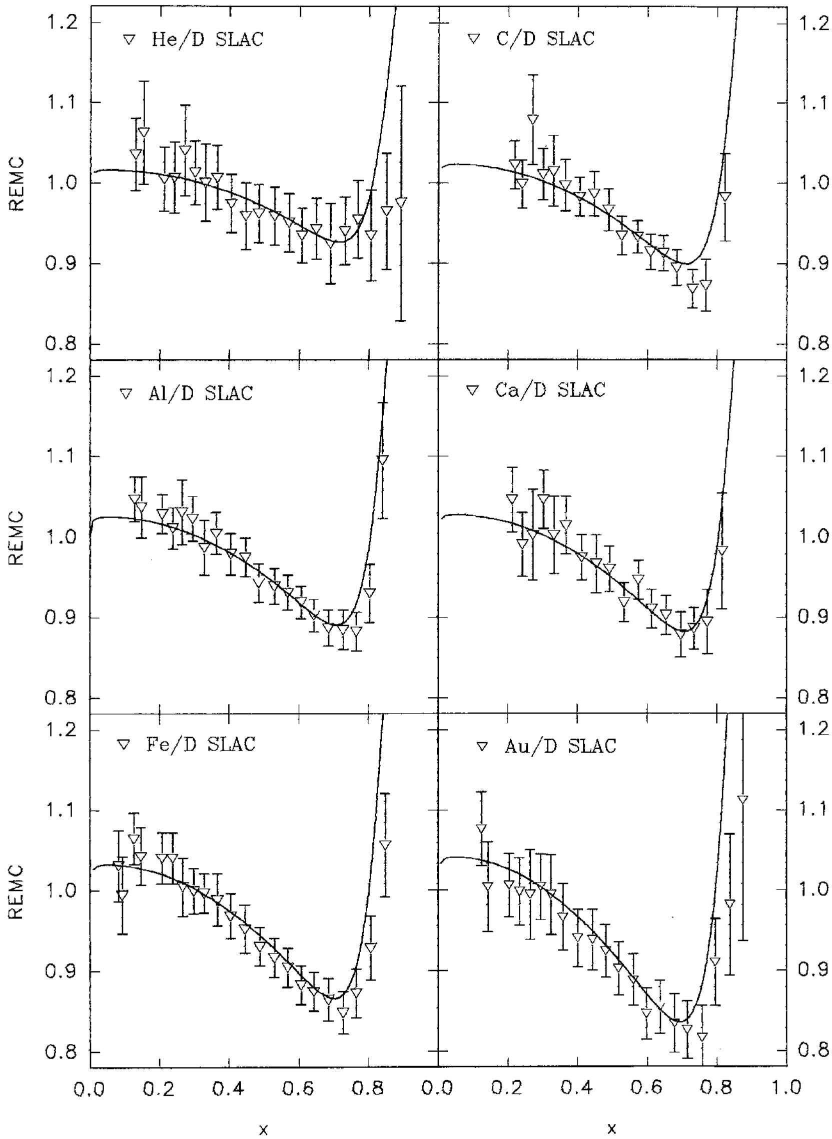

Fig. 3. Prediction for the ratios between different nuclei and deuterons compared to updated SLAC data [19]

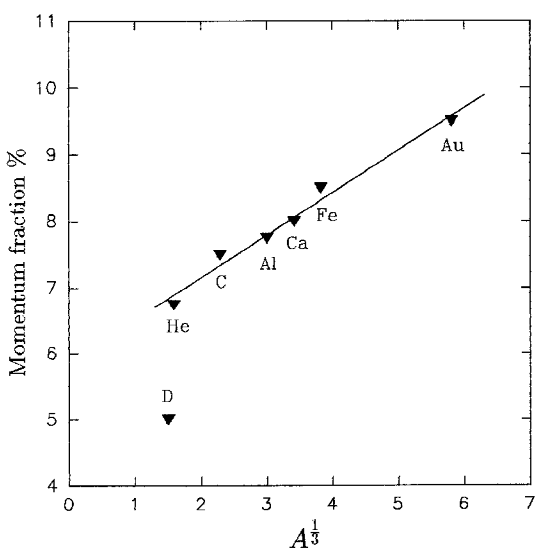

Fig. 4. Values of ε used for each nucleus

and allows this simple and unified description of nuclear effects.

The agreement is good in a wide range of the variable x, even in the region of large x, where fermi motion effects have been traditionally supposed to dominate the ratios. The shadowing phenomenon at small values of x is not taken into account by the model, but this clearly can be done adding the corresponding underlying mechanism in the model.

Predictions for Drell Yan yields from protons on protons and deuterons

Two experiments on Drell-Yan yields from protons on protons and protons on deuterium have recently been proposed [10, 11]. One of them, FNAL experiment E866, intends to measure the ratio

$$R(x_t) \equiv \frac{\sigma^{p+p}}{\sigma^{p+D}} \tag{11}$$

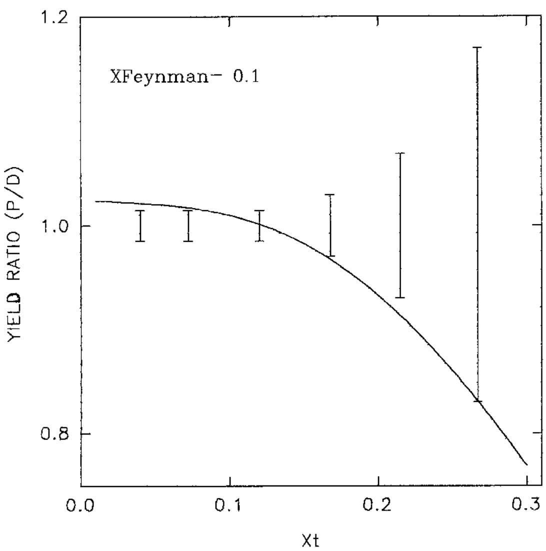

Fig. 5. Predictions for the ratio R (11) coming from the model *(solid)* and from [14] *(dashes)* together with the expected systematic errors

which under the same conditions asked for (1)

$$R(x_t) \equiv \frac{\sigma^{p+p}}{\sigma^{p+D}}\bigg|_{x_F > 0.2} \approx 1 - \frac{\bar{d}(x_t) - \bar{u}(x_t)}{\bar{d}(x_t) + \bar{u}(x_t)}. \qquad (12)$$

This experiment is analogous to that of E772, but five times more sensitive. With experimental systematic errors of, at most, 1.5%, it can clearly discriminate between an asymmetry in the sea and our picture of nuclear effects in the deuteron as Figure 5 clearly shows.

Conclusions

At variance with the common expectation [7], a picture for excess pions in nuclei given a fairly good description of nuclear effects in deep inelastic scattering and also in Drell-Yan experiments. The very simple model presented here gives accurate predictions for different phenomena which have been cause of intense speculation recently. The model relates the effects occuring in different nuclei in a very natural way highlighting those on deuterons, which are shown to have much more importance than the one given in the past. Recent and future experiments aimed so study the sea of nucleons, but using nuclear targets, give an excellent opportunity to confirm the main underlying ideas of the scheme proposed here for nuclear effects.

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