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Opportunities with Drell-Yan scattering: Probing sea quarks in the nucleon and nuclei

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Abstract. The large $\bar{d}(x)/\bar{u}(x)$ ratio observed by Fermilab E866/NuSea convincingly demonstrated that the sea is not simply a result of pQCD. Moreover, meson cloud models also failed to explain fully the observed kinematic dependence. The Drell-Yan mechanism offers a unique, selective probe of antiquarks in the nucleon. Fermilab has approved a new Drell-Yan experiment, E906, that will exploit this feature to probe $\bar{d}(x)/\bar{u}(x)$ by measuring the ratio of cross-sections for the proton-induced Drell-Yan process on hydrogen to deuterium. When the nucleon is contained in a nucleus, the nucleon's parton distributions should to be modified; although this effect was not seen in the sea quark distributions obtained by Fermilab E772 with Drell-Yan scattering. The upcoming E906 Drell-Yan experiment will provide much more precise measurements over a wider kinematic range in order to guide and challenge the theoretical models.

PACS. 14.20.Dh Protons and neutrons – 14.65.Bt Light quarks

1 Introduction

The quark-level structure of the nucleon and the nucleus has been studied extensively with deep inelastic scattering (DIS). The electromagnetic DIS probe, while yielding a remarkable amount of information on this structure, lacks the basic ability to distinguish between quark and antiquark (or alternatively valence and sea) distributions of the target nucleon, thus leaving unanswered questions about sea quark distributions, their origins and their modifications in a nucleus. The Drell-Yan process provides a probe that is sensitive to the antiquark distributions of the interacting hadrons.

In leading order, the Drell-Yan process [1] is the annihilation of a quark in one hadron with an antiquark in a second hadron to form a virtual photon. The virtual photon decays into a lepton-antilepton pair which is detected. The cross-section is dependent on the charge-weighted sum of the distributions of quarks and antiquarks in the interacting hadrons:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}x_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2\left[q_{1i}(x_1,Q^2)\bar{q}_{2i}(x_2,Q^2)\right.$$
$$\left.+\bar{q}_{1i}(x_1,Q^2)q_{2i}(x_2,Q^2)\right], \quad (1)$$

where q_{1i} (q_{2i}) are the beam (target) quark distributions, the sum is over all quark flavors (u, d, s, c, b, t) and e_i is the quark charge. The fraction of the longitudinal momentum of the beam (target) carried by the participating quarks is $x_{1(2)}$. For a fixed target experiment, the squared total energy of the beam-target system is $s = 2m_2E_1 + m_1^2 + m_2^2$ with beam energy E_1 and $m_{1(2)}$ the rest mass of the beam (target) hadron.

In a fixed target environment, Drell-Yan scattering has a unique sensitivity to the antiquark distribution of the target hadron. The decay leptons are boosted far forward. This, combined with the acceptance of the typical dipole-based spectrometer, restricts the kinematic acceptance of the detector to $x_F \gtrsim 0$ and, consequently, to very high values of x_1 where the antiquark distributions are suppressed by several orders of magnitude relative to the quark distributions. These beam valence quarks must then annihilate with an antiquark in the target, thus preferentially selecting the first term in (1). This feature has been used by several recent experiments to study the sea quark distributions in the nucleon and in nuclei.

2 Isospin symmetry of the light-quark sea

For many years, it was believed that the proton's sea quark distributions were $\bar{d}$-$\bar{u}$ symmetric, because of approximately equal splitting of gluons into $d\bar{d}$ and $u\bar{u}$ pairs. The observation of a violation of the Gottfried Sum Rule [2] in muon DIS by the New Muon Collaboration [3,4] forced this belief to be reconsidered. The sensitivity of Drell-Yan

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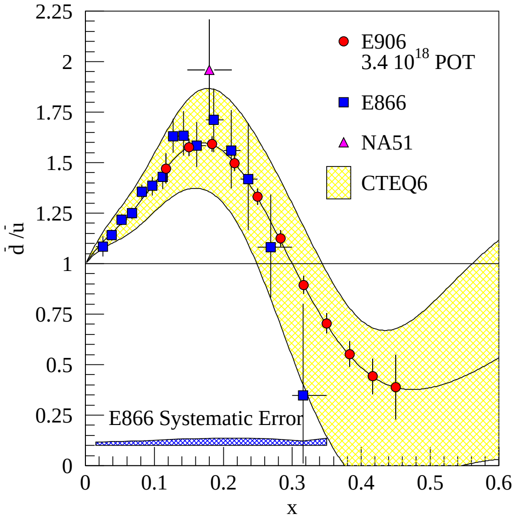

Fig. 1. (Colour on-line) Measurement of $\bar{d}(x)/\bar{u}(x)$ by E866/NuSea [10,11] (blue squares) and NA51 [6] (green triangle) are shown. The central curve in the cross filled band shows the $\bar{d}/\bar{u}$ ratio and uncertainty from the CTEQ5M fit, which included the E866/NuSea and NA51 data. The red circles represent the expected statistical uncertainties of the E906 experiment. The expected systematic uncertainty is approximately 1% [12].

scattering to antiquark distributions makes it an ideal probe of this asymmetry [5], and this was used by the CERN NA51 experiment [6] to verify, at $x = 0.18$, the inequality of $\bar{d}$ and $\bar{u}$ suggested by the Gottfreid Sum Rule violation. In leading order, assuming $x_1 \gg x_2$ and the dominance of the $u\bar{u}$ annihilation term, the ratio (per nucleon) of the proton-proton to proton-deuterium Drell-Yan yields can be expressed as

$$\left.\frac{\sigma_{pd}}{2\sigma_{pp}}\right|_{x_1 \gg x_2} = \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]. \tag{2}$$

The next–to–leading-order terms in the cross-section provide a small correction to this *ratio* and were considered in the analysis of the data, as well as the deviation from the $x_1 \gg x_2$ limit.

The Fermilab E866/NuSea experiment used this sensitivity to measure the x-dependence of the $\bar{d}/\bar{u}$ ratio. The E866/NuSea spectrometer consisted of two dipole magnets, the first primarily focused the muons into the spectrometer while the second performed a momentum measurement. This experiment used 800 GeV protons extracted from the Fermilab Tevatron incident on hydrogen and deuterium targets. The remainder of the beam that did not interact in the targets was intercepted by a copper beam dump contained within the first magnet. By using three different magnetic-field settings in the first two spectrometer magnet, the experiment was able to collect data over a broad range of kinematics covering $0.015 \leq x_2 \leq 0.35$. From the measured ratio of Drell-Yan yields, $\sigma^{pd}/(2\sigma^{pp})$, E866/NuSea was able to extract the ratio $\bar{d}(x)/\bar{u}(x)$ shown in fig. 1. The inclusion of the measured cross-section ratios in global parton distribution fits [7–9] validated this extraction and completely changed the perception of the sea quark distributions in the nucleon.

The E866/NuSea data present an interesting picture of the sea quark distributions of the nucleon that may shed light on the origins of the sea quarks. At moderate values of x the data show more than 60% excess of $\bar{d}$ over $\bar{u}$, but as x grows larger, this excess disappears and the sea appears to be symmetric again. If the sea's origins are purely perturbative, then it is expected to exhibit only a very small asymmetry between $\bar{d}$ and $\bar{u}$. Non-perturbative explanations for the origin of the sea including meson cloud models, chiral perturbation theory or instantons can explain a large asymmetry, but not the return to a symmetric sea seen as $x \to 0.3$. (For a brief review of these models see [13] and referenced therein.) None of the models predicts an excess of $\bar{u}$ over $\bar{d}$ as shown by the CTEQ [7], MRST [8] or GRV [9] global parton distribution *fits*.

Unfortunately, as x increases beyond 0.25, the data become less precise and the exact trend of $\bar{d}/\bar{u}$ is not clear. To help understand this region better, the Fermilab E906 experiment has been approved to make collect Drell-Yan data in this region. The E906 experiment will use a 120 GeV proton beam rather than the 800 GeV beam used by E866. The Fermilab E906/Drell-Yan spectrometer [12] is modeled after its predecessors, Fermilab E772 and E866/NuSea. Experimentally, the lower beam energy has two significant advantages. First, the primary background in the experiment comes from J/ψ decays, the cross-section of which scales roughly with s, the square of the center-of-mass energy. The lower beam energy implies less background rate in the spectrometer and allows for a correspondingly higher instantaneous luminosity. Second, as seen in (1) the Drell-Yan cross-section is inversely proportional to s; thus, the lower beam energy provides a larger cross-section. The muons produced in a 120 GeV collision have a significantly smaller boost, which forces the apparatus to be shortened considerably in order to maintain the same transverse momentum acceptance. The expected statistical uncertainties of the E906/Drell-Yan experiment are shown in fig. 1. Systematic uncertainty in $\bar{d}/\bar{u}$ is expected to be approximately 1%.

3 Antiquark distributions of nuclei

The distributions of partons within a free nucleon differ from those of a nucleon bound within a heavy nucleus, an effect first discovered by the European Muon Collaboration (EMC) in 1983 [14]. (For a review of the Nuclear EMC effect, see [15].) Almost all of the data on nuclear dependencies is from charged lepton DIS experiments, which are sensitive only to the charge-weighted sum of all quark and antiquark distributions. This type of experiment is unable to distinguish between valence and sea effects. Sea quark nuclear effects may be entirely different from those in the valence sector [16], but an electron or muon DIS experiment would not be sensitive to this.

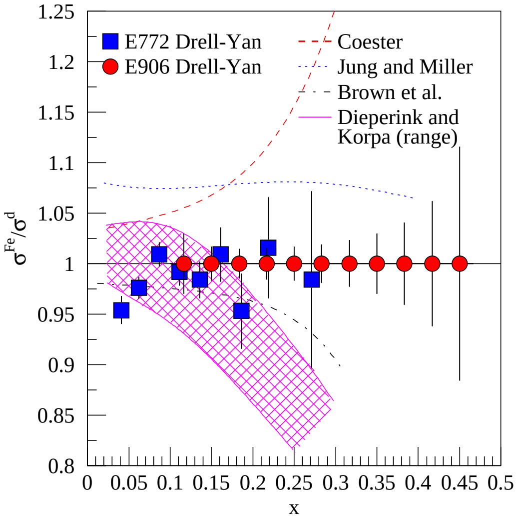

Fig. 2. (Colour on-line) Ratio of iron to deuterium Drell-Yan cross-sections measured by Fermilab E772 (blue squares) [17]. The expected sensitivity of the E906 experiment is shown by red circles. To illustrate the level of effects expected, curves based on several different representative models are also plotted.

In fact, no modification to the sea quark distributions, aside from shadowing at low x, was observed by Fermilab E772 [17] which studied the nuclear dependence of Drell-Yan scattering. (See fig. 2.) Because the widely accepted models of nuclear binding rely on the exchange of virtual mesons [18], a significant enhancement in the antiquark distribution in nuclei compared with deuterium was expected from the antiquarks in the virtual mesons. The non-observation of this enhancement calls these models into question. The expected enhancement of $\bar{u}$ quarks in iron relative to deuterium based on the nuclear convolution model calculations by Coester [19–21] is illustrated in fig. 2.

The lack of sea quark nuclear effects prompted a number of newer models. Jung and Miller [22] revisited the calculations of Berger and Coester [19,20] and examined the effect of the quantization of the pions on the light cone *versus* at "equal time", finding a roughly flat 8% increase in the Drell-Yan iron cross-section over deuterium. Brown *et al.* [23] argue that with the partial restoration of chiral symmetry, the mass of light-quark hadrons decreases with density. This rescaling leads to altered couplings and to an overall *decrease* in the Drell-Yan cross-section in nuclei. Based on a particle- and delta-hole model, which results in a strong distortion of the free-pion structure function, Dieperink and Korpa [24] also find cross-section decrease in nuclei. Finally, Smith and Miller [25] in a chiral quark-soliton model, find no nuclear dependence in Drell-Yan scattering. This model is significant in that it is able to simultaneously describe the EMC effect.

For $x > 0.2$, the E772 statistical uncertainties allow some freedom for these models and the data are not able to distinguish between them. To understand these models and nuclear binding better, higher precision data at larger x are needed. E906/Drell-Yan will be able to provide these data with the statistical precision shown in fig. 2.

4 Conclusions

Previous Drell-Yan experiments have contributed greatly to the understanding of the antiquark distributions of the nucleon and their modifications by a nuclear environment. The Fermilab E906/Drell-Yan experiment will revisit many of these measurements with improved statistical precision and greater kinematic reach. The E906/Drell-Yan experiment has been approved by the Fermilab PAC and should begin collecting data in 2009. These data will allow E906/Drell-Yan to extend the measurement of $\bar{d}/\bar{u}$ to $x = 0.45$, thereby probing the region in which the sea appears to become flavor symmetric. They will also determine the nuclear dependence of the sea over the same range in x, with a statistical precision that will challenge the current models of nuclear binding.

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