Exploring the Antiquark Structure of Matter with Drell-Yan Scattering: Fermilab E-906/SeaQuest

Paul E. Reimer
representing the Fermilab E-906/SeaQuest Collaboration *

Physics Division, Argonne National Laboratory,
Argonne, IL 60439 USA

Deep inelastic scattering (DIS) is an excellent tool for probing the quark structure of hadrons. It has been used to determine precisely the distributions of quarks and to determine the spin they carry. DIS is only sensitive to the charge-squared weight sum of all (valence and sea) quarks and cannot easily probe just the sea quark distributions. The Drell-Yan mechanism provides a complementary approach that can select only the antiquark distributions in the target. A remarkable asymmetry has been observed in the difference of anti-down to anti-up quarks in the proton, which cannot simply be generated through perturbative QCD, but rather indicates an underlying and fundamental antiquark component in the proton. The Fermilab E-906 Drell-Yan experiment will extend earlier measurements of this difference to larger values of x_{Bj} and increase statistical precision at lower x_{Bj}. Using the same technique, E-906/SeaQuest will investigate the differences between the antiquark distributions of a free and bound proton. Nuclear binding should modify the quark distributions and DIS data has shown that the overall quark distributions are different (the EMC effect). Surprisingly, present data suggests that the antiquark distributions are not modified. To accomplish these goals, the experiment will use a 120 GeV proton beam extracted from the Fermilab Main Injector. The lower beam energy requires several upgrades and configuration changes to the spectrometer which are underway. The collaboration expects to begin data collection summer, 2010.

1 Introduction

The quark-level composition of both the nucleon and the nucleus has been studied extensively with a variety of processes and probes. The electromagnetic deep inelastic scattering (DIS) process has been used to elucidate a wealth of information on this structure, but lacks the basic ability to distinguish between quark and antiquark distributions of nucleon, 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.

The Drell-Yan process [1] to leading order in α_s 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

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hadrons:

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2} \sum_{i\in\{udcs\}} e_i^2 \left[q_{1i}(x_1,Q^2)\bar{q}_{2i}(x_2,Q^2) + \bar{q}_{1i}(x_1,Q^2)q_{2i}(x_2,Q^2) \right], \tag{1}$$

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 fractional quark charge. The fraction of the longitudinal momentum of the beam (target) carried by the participating quarks is $x_{1(2)}$. In 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 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, 3, 4, 5].

2 Isospin Symmetry of the Light Quark Sea

Because of approximately equal splitting of gluons into $d\bar{d}$ and $u\bar{u}$, it was widely believed that the proton's sea quark distributions were $\bar{d}$-$\bar{u}$ symmetric. The observation of a violation of the Gottfried Sum Rule [6] in muon DIS by the New Muon Collaboration [7, 8] proved this assumption to be incorrect. The CERN NA51 experiment [9] verified, at $x = 0.18$, the inequality of $\bar{d}$ and $\bar{u}$ suggested by the Gottfried Sum Rule violation using Drell-Yan scattering.

The sensitivity of Drell-Yan scattering to antiquark distributions makes it an ideal probe of this asymmetry [10]. 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.*

The Fermilab E-866/NuSea experiment used this sensitivity to measure x-dependence of the $\bar{d}/\bar{u}$ ratio with an 866 GeV/c proton beam from the Fermilab Tevatron incident on hydrogen and deuterium targets. From the measured ratio of Drell-Yan yields, $\sigma^{pd}/(2\sigma^{pp})$, E-866/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 [11, 12, 13] validated this extraction and completely changed the perception of the sea quark distributions in the nucleon. 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

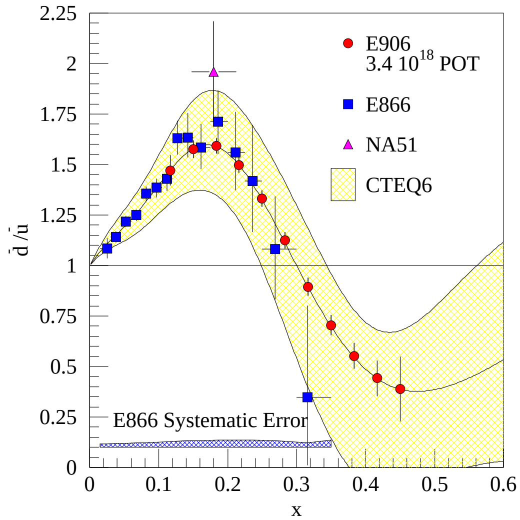

Figure 1: Measurement of $\bar{d}(x)/\bar{u}(x)$ by E-866/NuSea [3] (blue squares) and NA51 [9](green triangle) are shown. The central curve in the band shows the $\bar{d}/\bar{u}$ ratio and uncertainty from the CTEQ5M fit, which included the E-866/NuSea data. The red circles represent the expected statistical uncertainties of the E-906 data. The expected systematic uncertainty is approximately 1% [14].

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 [4] and references therein.) None of the models predicts an excess of $\bar{u}$ over $\bar{d}$ as shown by the CTEQ [11], MRST [12] or GRV [13] global parton distribution *fits*.

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 E-906 experiment has been approved to collect Drell-Yan data in this region. The E-906 experiment will use a 120 GeV proton beam rather than the 800 GeV beam used by E-866. The Fermilab E-906/SeaQuest spectrometer [14] is modeled after its predecessors, Fermilab E-772 and E-866/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 center-of-mass energy squared. 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 E-906/SeaQuest experiment are shown in Fig. 1.

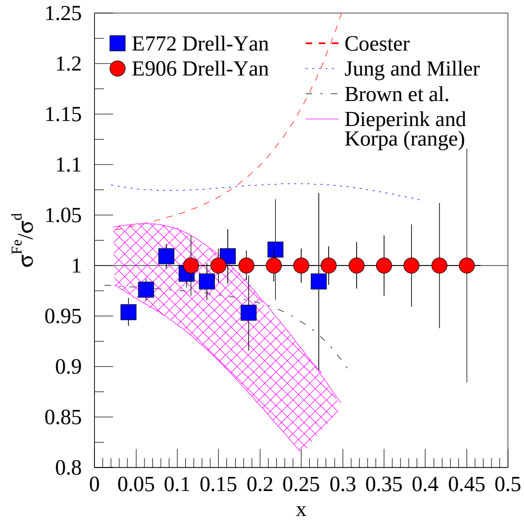

Figure 2: Ratio of iron to deuterium Drell-Yan cross sections measured by Fermilab E-772 (blue squares)[5]. The expected sensitivity of the E-906 experiment is shown by red circles. Curves based on several different representative models are also plotted.

3 Antiquark Distributions of Nuclei

The distributions of partons within a free nucleon and a bound nucleon are different, an effect first discovered by the European Muon Collaboration (EMC) in 1983 [15]. (For a review of the Nuclear EMC effect, see [16].) Almost all of the data on nuclear dependencies is from DIS experiments. Sea quark nuclear effects may be entirely different from those in the valence sector [17], but DIS experiment would not be sensitive to this.

In fact, no modification to the sea quark distributions, aside from shadowing at low-x, was observed by Fermilab E-772 [5] 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. 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, 20, 21] is plotted in Fig. 2. The lack of sea-quark nuclear effects prompted a number of newer models which are also shown in Fig. 2[22, 23, 24, 25].

For $x > 0.2$, the E-772 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. E-906/SeaQuest 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 anti-quark distributions of the nucleon and their modifications by a nuclear environment. The Fermilab E-906/SeaQuest experiment will revisit many of these measurements with improved statistical precision and greater kinematic reach. The E-906/SeaQuest experiment has been approved by the Fermilab PAC and should begin collecting data in 2010. These data will allow E-906/SeaQuest 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 statistical precision that will challenge the current models of nuclear binding.

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