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Opportunities with Drell-Yan Scattering at Fermilab

Paul E. Reimer, Representing the Fermilab SeaQuest Collaboration

Physics Division, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439 USA

E-mail: reimer@anl.gov

Abstract. The proton is a composite object made of fundamental, strongly-interacting quarks. Many of the features of the proton can be described by a simple picture based on three valence quarks bound by the exchange of gluons. However, protons are much more complex objects with the vast majority of their mass dynamically generated by the strong force and manifest in the sea quark and gluon distributions. While deep inelastic scattering cannot differentiate between quark and antiquarks, the Drell-Yan process inherently involves the antiquark distributions of either the beam or target hadron. By measuring Drell-Yan scattering, the Fermilab E-906/SeaQuest experiment will study the sea quarks in the proton and in nuclei. The primary goals of this measurement include elucidating the anti- d to anti- u quark asymmetry in the proton and a study of the EMC effect in sea quarks. With the same data, the angular distribution of Drell-Yan scattering will be studied. Previous measurements of these distributions have been interpreted as evidence for transverse momentum dependent Boer-Mulders h_1^\perp distribution; although, pion and proton induced Drell-Yan data disagree. The increased statistical precision of the anticipated data will allow for better extraction of the angular distributions. To accomplish these goals, the experiment will use a 120 GeV proton beam extracted from the Fermilab Main Injector. While the experiment will be taking advantage of equipment from earlier Drell-Yan experiments, the changes in kinematics of the experiment require several, significant upgrades to the spectrometer. The collaboration expects to begin data collection in late fall of 2010.

1. Introduction

The quark composition of both the nucleon and the nucleus has been studied extensively with a variety of processes. In particular, electromagnetic deep inelastic scattering (DIS) has been used to elucidate a wealth of information on this structure, but lacks the basic ability to distinguish between quark and antiquark distributions within the nucleon. 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-squared-weighted sum of the quark and antiquark distributions in the interacting hadrons:

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

where $q_{1i(2i)}$ are the beam (target) quark distributions, the sum is over all quark flavors (u , d , s , c) and e_i is the fractional quark charge. The fraction of the longitudinal momentum of the beam (target) carried by the participating quark is $x_{1(2)}$ and s is the center-of-mass energy squared.

The leading order cross sections formula given in Eq. (1) account over half of the cross section. Including terms of next-to-leading in α_s will account for the full, observed cross section.

In a fixed-target, forward-acceptance spectrometer, Drell-Yan scattering has a unique sensitivity to the antiquark distribution of the target hadron where the acceptance restricts the event kinematics to $x_1 \gg x_2$. At very high values of x_1 , the antiquark distributions are suppressed by several orders of magnitude relative to the quark distributions. These beam valence quarks annihilate with antiquarks in the target, preferentially selecting the first term in Eq. (1). This feature has been exploited by several experiments to study antiquark distributions [2, 3, 4, 5].

This paper will discuss measurements of the antiquark distributions in the proton and in nuclei. Building on this, it will motivate and describe a new experiment at Fermilab, E-906/SeaQuest [6]. E-906/SeaQuest is currently under construction and will begin collecting data in the late fall of 2010.

2. Origins and Isospin Symmetry of the Light Quark Sea

Initially, the quark sea was believed to originate through gluon splitting—starting with three valence quarks of the correct distribution, the remaining sea quarks could be dynamically generated through QCD evolution [7]. Fits to data, however, indicated the need for an intrinsic sea quark distributions as well [8]. Even though it was clear that the sea distributions were not purely dynamically generated, because of approximately equal mass of the u and d quarks, it was widely believed that the sea distributions were \bar{d} - \bar{u} symmetric. The observation of a violation of the Gottfried Sum Rule [9, 10] by the New Muon Collaboration [11] proved this assumption to be incorrect.

The sensitivity of Drell-Yan scattering to antiquark distributions makes it an ideal probe of this asymmetry [12]. 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 is

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

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 the x -dependence of the \bar{d}/\bar{u} ratio with an 800 GeV/c proton beam incident on hydrogen and deuterium targets. From the measured ratio of Drell-Yan yields, E-866/NuSea extracted the ratio $\bar{d}(x)/\bar{u}(x)$ shown in Fig. 1. While Eq. (2) is illustrative of the sensitivity, the actual E-866/NuSea extraction was done in next-to-leading order without the $x_1 \gg x_2$ and $u\bar{u}$ dominance assumptions. The inclusion of the *measured cross section ratios* in global parton distribution fits [13, 14, 15] 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} quarks over \bar{u} quarks, but as x grows larger, this excess disappears. A purely perturbative sea would 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 [4, 19, 20, 21, 22, 23], but they fail to predict the return to a symmetric sea seen as $x \rightarrow 0.3$ and none predicts an excess of \bar{u} over \bar{d} as seen in the parton distribution *fits* [13, 14, 15]. As x increases beyond 0.25, the data become less precise. To help understand this region better, the Fermilab E-906/SeaQuest experiment has been approved to collect Drell-Yan data in this region. The expected statistical uncertainties of the E-906/SeaQuest experiment are shown in Fig. 1, based on a redesigned spectrometer—see Sec. 5.

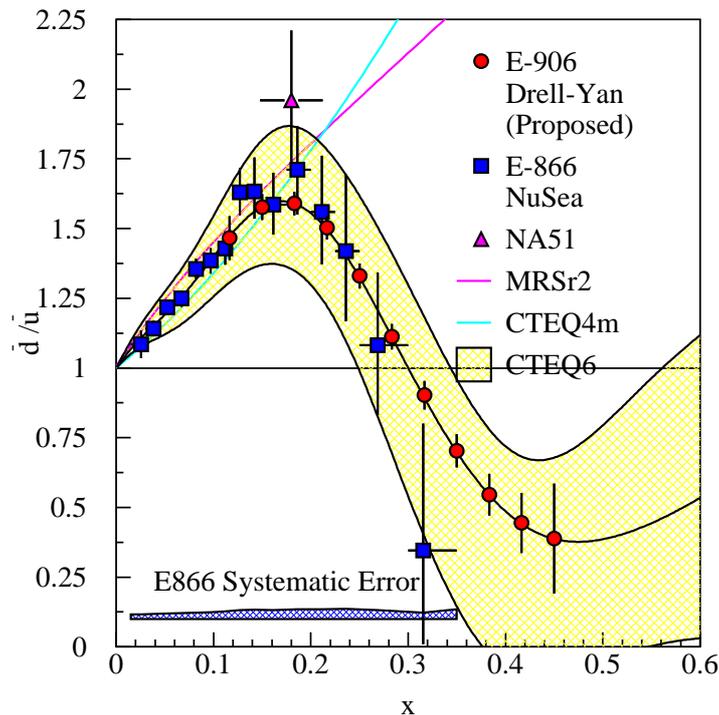


Figure 1. Measurement of $\bar{d}(x)/\bar{u}(x)$ by E-866/NuSea [2, 3] (blue squares) and NA51 [16] (magenta triangle) are shown. The central curve shows the \bar{d}/\bar{u} ratio and uncertainty from the CTEQ5M fit, which included the E-866/NuSea data. The red circles represent the expected statistical uncertainties of the E-906/SeaQuest data. [6]. The MRSr2 [17] and CTEQ4m [18] curves show parametrizations of the \bar{d}/\bar{u} ratio prior to the inclusion of the E-866/NuSea data.

3. Drell-Yan Angular Distributions and Transverse Momentum

The general expression for angular distributions in Drell-Yan scattering is given by [24, 25]

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \quad (3)$$

where θ and ϕ denote the polar and azimuthal angle, respectively of the positive lepton in the dilepton rest frame and λ , μ and ν denoting the relative strengths of these terms. In a naïve, leading order model with no transverse-quark momentum, $\lambda = 1$ and $\mu = \nu = 0$. In a more physical picture, however, λ , μ and ν may vary from these values, but they should still satisfy the Lam-Tung relation [24, 25],

$$1 - \lambda = 2\nu. \quad (4)$$

The validity of this relationship has been explored using both pion beams on tungsten targets [26, 27, 28, 29] and proton beam on hydrogen and deuterium targets [30, 31]. A substantial deviation from the Lam-Tung relation was observed in the pion data at large virtual photon transverse momenta, p_T , primarily because of the ν coefficient of the $\sin^2 \theta \cos 2\phi$ term. Interestingly, a similar violation was not observed in the proton-induced data. Based on the pion-induced data, several possible explanations have been proposed [32, 33, 34, 35]. One of the more intriguing possibilities is that of the k_T -dependent Boer-Mulders parton distribution function $h_1^\perp(x, k_T)$ [36, 37]. In this case, because of the valence anti-quark in the pion, the pion-induced data would be measuring the nucleon's quark h_1^\perp distribution, while the proton induced

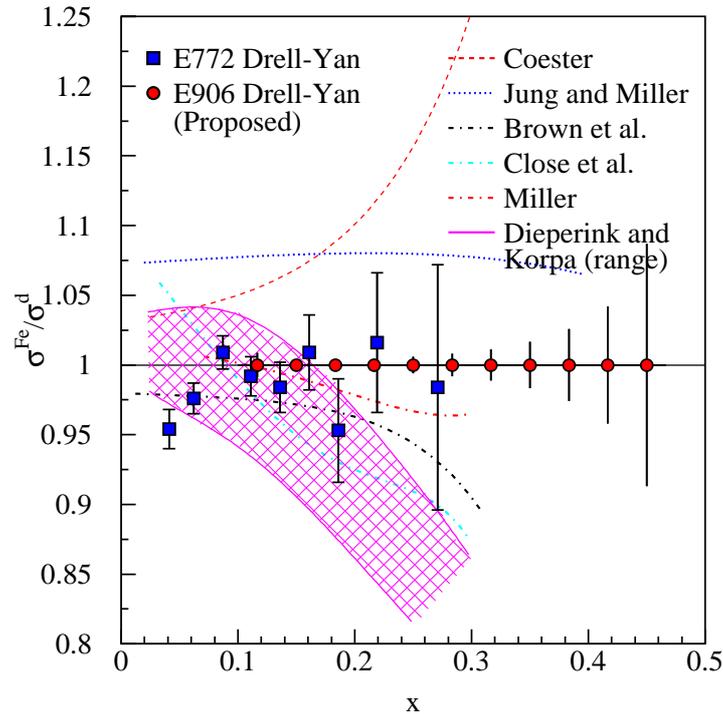


Figure 2. Ratio of iron to deuterium Drell-Yan cross sections (blue squares) [5] and the expected sensitivity of E-906/SeaQuest (red circles). Curves based on several different models are also plotted [40, 41, 42, 43, 44].

data is selectively measuring the nucleons anti-quark h_1^\perp distribution. The E-906/SeaQuest experiment will soon be able to provide more precise data on proton-induced Drell-Yan.

4. Antiquark Distributions of Nuclei

The distributions of partons within a free and bound nucleon are different, an effect discovered by the European Muon Collaboration (EMC) in 1983 [38]. Almost all of the data on nuclear dependencies of quark distributions is from DIS experiments. Sea quark nuclear effects may be entirely different from valence-quark nuclear effects, but DIS experiment would not be very sensitive to this.

In fact, no modification to the sea quark distributions was observed by Fermilab E-772 [5]—see Fig. 2. Several models of nuclear binding, which can explain the EMC effect, rely on the exchange of virtual mesons [39]. Based on these models a significant enhancement in the antiquark distributions in nuclei was expected [40]. The lack of sea-quark nuclear effects prompted a number of newer models which are also shown in Fig. 2 [41, 42, 43, 44]. For $x > 0.2$, the E-772 statistical uncertainties allow significant freedom for these models. E-906/SeaQuest will provide data on the nuclear dependence of the sea quarks with the statistical precision shown in Fig. 2.

5. Fermilab E-906/SeaQuest

The E-906/SeaQuest experiment will achieve the sensitivities shown in Figs. 1 and 2 using a 120 GeV proton beam from the Fermilab Main Injector. This lower beam energy has two major advantages:

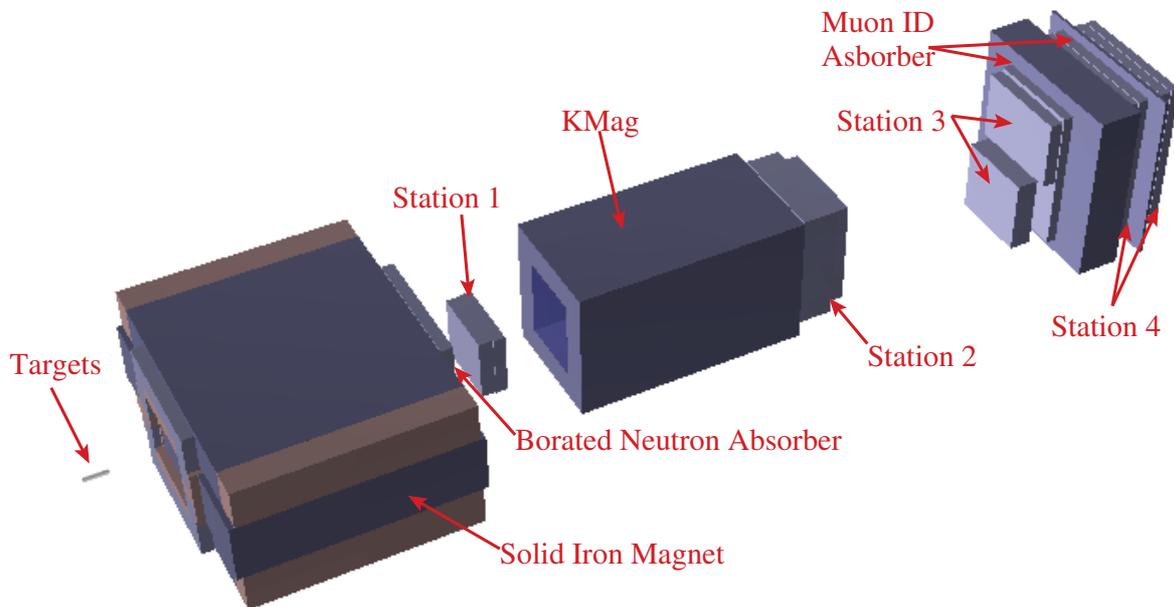


Figure 3. Schematic view of the E-906/SeaQuest detector. Each of the labeled stations consists of a tracking chamber and a set of hodoscopes for triggering.

- the cross section is proportional to the inverse of the center-of-mass energy squared, s . The lower energy beam will increase the cross section, and
- the predominant correlated dimuon background is from the dimuon J/ψ decay. J/ψ production scales approximately with the center-of-mass energy, and thus background will be decreased.

While reducing the energy results in a larger cross section, at some point, the energy will become so low that the interaction is no longer between uncorrelated partons. With a 120 GeV beam, this experiment is still well above this limit. In addition, as the energy decreases, the background from uncorrelated pion decay will increase.

The Fermilab E-906/SeaQuest spectrometer [6] is modeled after its predecessors. To take advantage of the lower beam energy, the spectrometer must be shortened in order to maintain the same transverse momentum acceptance. For much of the spectrometer, this was done by moving the locations of spectrometer elements. The first, focusing magnet had to be shortened as well. This was achieved by using existing coils and switching to a closed-aperture, solid-iron design. A schematic view of the E-906/SeaQuest spectrometer is shown in Fig. 3. The spectrometer is being assembled in the NM4 (KTeV) hall at Fermilab. Production with low intensity beam will begin in late the fall of 2010. The experiment will collect data for an equivalent of two years at full luminosity.

6. Conclusions

Drell-Yan experiments have contributed to the understanding of the antiquark 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 is under construction and will begin collecting data in the fall of 2010. These data will allow E-906/SeaQuest to extend the

measurement of \bar{d}/\bar{u} and also determine the nuclear dependence of the sea, with a statistical precision that will challenge the current models of nuclear binding.

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7. References

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