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Drell-Yan scattering at Fermilab: SeaQuest and beyond

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Summary. — The E906/SeaQuest experiment at Fermilab will use the 120 GeV/c proton beam extracted from the Main Injector to measure the light antiquark flavor asymmetry, $\bar{d}/\bar{u}$, in the nucleon sea, and how it is altered in nuclei. It will provide direct input to the parton distribution fits, and provide a better understanding on the physical mechanism which generates the sea of the proton. The experiment will start in the fall of 2011 and run until the end of 2014. After completion of the SeaQuest experiment, the spectrometer will be available for a polarized Drell-Yan program, either with a polarized beam or a polarized target. The first in a long list of possible experiments at the Main Injector is a polarized Drell-Yan experiment, motivated by a fundamental prediction of QCD that postulates a sign change in the Sivers function measured in Drell-Yan as compared to deep inelastic scattering.

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1. – Introduction

Many years of deep inelastic scattering and Drell-Yan experiments have led to a rich set of nucleon structure function data that span five orders of magnitude in x, the fractional momentum of the quarks, and Q^2, the four momentum transfer squared of the incident virtual photon. Since perturbative QCD cannot (yet) predict the origin of parton distribution functions (PDFs), parton distributions must be determined by phenomenological fits [1-3] to the data. These global fits show the complementary nature of deep inelastic scattering (DIS) and Drell-Yan, and highlight the essential roles they play in placing constraints on the PDFs. In particular, Drell-Yan experiments provide direct sensitivity to the sea quark distributions.

In the Drell-Yan process [4], a lepton-antilepton pair is produced from quark-antiquark annihilation of target and beam partons. Since the Drell-Yan process is an electromagnetic process, there are no final state QCD effects between the di-leptons and the target and beam partons, allowing for a clean probe to study the structure of nucleons and nuclei. The cross section for this process is given in lowest order by

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_b\mathrm{d}x_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right] , \tag{1}$$

where the sum is over all quark flavors, x_b and x_t are the parton momentum fractions in the beam and target, respectively, $q(x)$ and $\bar{q}(x)$ are the quark and antiquark distributions, and s is the center-of-mass energy squared. While the structure functions extracted from DIS contain both quark and anti-quark contributions, Drell-Yan scattering on fixed target configurations can provide direct sensitivity to the antiquark sea of target nuclei by kinematically separating the terms in eq. (1).

2. – Light antiquark flavor asymmetry

Until recently there has been little experimental constraint on the flavor asymmetry in the quark distributions of the light quark sea in the nucleon. Though no known symmetry requires equality of the $\bar{d}$ and $\bar{u}$ distributions in the proton, early expectations were that $\bar{d}(x) = \bar{u}(x)$. This was motivated by the perturbative picture of the nucleon sea being generated through gluon splitting. First evidence to the contrary [5] came from a comparison of inclusive deep inelastic scattering on the proton and neutron to determine the Gottfried sum [6]. The NMC Collaboration observed that $\int_0^1[\bar{d}(x) - \bar{u}(x)]\mathrm{d}x \approx 0.15$, *i.e.*, the nucleon sea is not flavor symmetric. Confirmation of this surprising result at CERN [7], Fermilab [8] and DESY [9] suggested that gluon splitting alone cannot account for the sea quarks, indicating a significant non-perturbative component in the nucleon's sea. This led to substantial revisions in the global fits [10]. The ratio of Drell-Yan cross sections on hydrogen and deuterium targets can be reduced to([1])

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right] , \tag{2}$$

illustrating the sensitivity to the experimental ratio $\bar{d}(x)/\bar{u}(x)$. In the simple gluon splitting picture, the ratio would be unity.

Figure 1 shows the results of Fermilab Experiment E866/NuSea (blue squares). E866 observed a large asymmetry in the $\bar{d}(x)/\bar{u}(x)$ ratio at moderate x using Drell-Yan production of di-muon pairs. As x increased, however, the sea appeared to become more flavor symmetric, possibly indicating that the perturbatively generated sea is becoming dominant, thus implying a significantly larger gluon distribution at high x than given by global fits at the time (*e.g.*, CTEQ4m in fig. 1). At the same time the statistical precision of the data decreased significantly, thus losing the power to distinguish between models which predict that the $\bar{d}(x)/\bar{u}(x)$ ratio should continue to increase or should approach unity. To study $\bar{d}(x)/\bar{u}(x)$ at higher x, the SeaQuest Collaboration will use proton-induced Drell-Yan production of muon pairs on hydrogen, deuterium and heavier nuclear targets using the Fermilab Main Injector as a proton source [11].

([1]) Note that the actual extraction of $\bar{d}(x)/\bar{u}(x)$ is performed using eq. (1) and verified with full NLO cross section measurements.

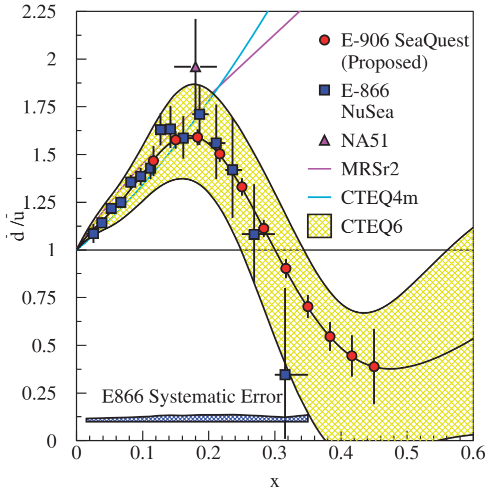

Fig. 1. – Results from the E866 [10] experiment, together with projected uncertainties for the $\bar{d}(x)/\bar{u}(x)$ ratio for SeaQuest as a function of x. The yellow band illustrates the uncertainty from the CTEQ6 fit on the E866 data set.

3. – Nuclear modifications

The distributions of partons in a free nucleon differ from those of a nucleon bound in heavy nuclei, an effect first seen by the European Muon Collaboration (EMC) in 1983 [12] through muon-induced DIS on an iron target. The effect has been observed over a wide range of nuclear targets, and although several phenomenological models have been suggested as possible explanations, the underlying cause of the effect remains unknown. If nuclear structure functions were a convolution of proton and neutron structure functions, nuclear modification effects could be caused either by modifications of the individual structure functions inside a nucleus, or by nuclear binding effects such as pion exchange. The pion excess model [13], for example, was suggested as a reason for the enhancement of the cross section ratio at small x (*i.e.*, the antishadowing region).

While structure functions extracted from DIS experiments are sensitive only to the charge-weighted sum of all quark and antiquark distributions, efforts have been made with Drell-Yan measurements to isolate the sea contribution to the nuclear modification effect. Experiment E772 at Fermilab measured ratios of Drell-Yan cross sections on nuclear targets to deuterium and found no enhancement in the antishadowing region [14]. In fact little nuclear dependence was found over the entire measured x-range, except in the shadowing region ($x < 0.1$). The E772 result suggested that the enhancement seen in electron and muon scattering may be a valence effect, and that the nuclear effects in the sea quark distributions maybe entirely different from those in the valence sector. The non-observation of a pion excess in Drell-Yan scattering presents a real challenge to phenomenological models that must be able to reproduce both results.

The expected enhancement to the sea distribution is illustrated in fig. 2, which shows the expected Drell-Yan ratio in iron to deuterium, based on a nuclear convolution model calculation by Coester [15]. More recent calculations, made in light of the E772 data, predict a smaller nuclear dependence, consistent with the large statistical uncertainties of

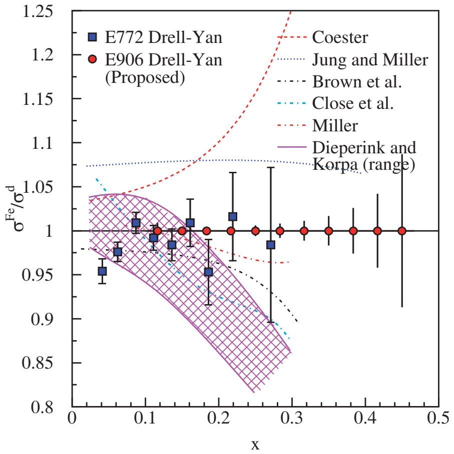

Fig. 2. – Results for cross section ratio of iron to deuterium from the E772 [14] experiment, together with projected uncertainties for SeaQuest as a function of x. Curves based on several different models are shown to illustrate the various predictions.

E772 [16-19]. SeaQuest will provide the sensitivity needed to differentiate these models from those that predict an enhancement in the Drell-Yan ratio, shown in fig. 2. SeaQuest will further extend the E772 measurements to larger x, allowing a comparison of DIS with Drell-Yan data into the "EMC Effect" region ($x > 0.3$). Finally, if large enhancements were seen in the nuclear ratios, it would provide an important indication that nuclear effects may be important in the deuterium to hydrogen ratio.

4. – SeaQuest

SeaQuest will extend the measurements made by E866 to relatively large x_t with substantially improved statistical precision, as illustrated in figs. 1 and 2. The experiment will employ the 120 GeV/c proton beam from the Fermilab Main Injector using a slow extraction mode. It is scheduled to receive each minute a 5-s long pulse of 2×10^{12} protons/s, resulting in a total integrated charge of 3.4×10^{18} protons over a 2 year period.

In contrast to E866, which used Tevatron's 800 GeV/c beam, SeaQuest will use the 120 GeV/c Fermilab Main Injector. Since the Drell-Yan cross section scales as $1/s$ (see eq. (1)), this leads to a seven times larger Drell-Yan cross section than at the Tevatron's 800 GeV/c beam. At the same time, background rates, stemming primarily from J/Ψ decays, scale as s, allowing a seven times larger instantaneous luminosity. Thus, the combination of these two effects is expected to increase the number of Drell-Yan events by about a factor of 50 for the same running time.

The SeaQuest apparatus is very similar to the apparatus used for E866, with many of the detector components being reused. Due to the lower beam energy at the Main Injector, the entire layout of the apparatus had to be contracted along the beam axis. This necessitated the construction of a new muon focussing magnet, about one third as long as the magnet used for E866. While it was originally planned to use an existing (open aperture) magnet with new coils, budget constraints at Fermilab forced the SeaQuest

Collaboration to consider using a solid iron magnet instead. This solid iron magnet did cost a fraction ($< 10\%$) of a new open aperture magnet, led to an increased acceptance (*i.e.*, better statistical precision), but to a slightly poorer (but still acceptable) resolution.

It is currently foreseen that SeaQuest will start data taking in November 2011 and run until the end of March 2012 to collect roughly twice the amount of data collected in E866. Fermilab has then scheduled a 9 month shutdown to perform a luminosity upgrade to the Main Injector to benefit the neutrino program at Fermilab. In early 2013, SeaQuest will resume collecting data until close to the end of 2014.

5. – Beyond SeaQuest — Polarized Drell-Yan at Fermilab

Once the SeaQuest experiment has finished data collection, the apparatus will be available for future programs, for example at Fermilab or at RHIC. There is significant interest from within the SeaQuest Collaboration for a continued program in Drell-Yan scattering. The first in a long list of possible experiments at the Fermilab Main Injector is a polarized Drell-Yan experiment, motivated by a fundamental prediction of QCD that postulates a sign change in the Sivers function [20] measured in Drell-Yan scattering as compared to semi-inclusive deep inelastic scattering [21, 22]. The Sivers function is described by a transverse-momentum dependent distribution function that captures non-perturbative spin-orbit effects inside a polarized proton. The experimental verification of the sign change goes to the heart of the gauge formulation of QCD and would fundamentally test the factorization approach to the description of processes sensitive to transverse parton momenta. It would be crucial to confirm the validity of our present conceptual framework for analyzing hard hadronic reactions.

The HERMES [23-25] and COMPASS [26, 27] experiments have measured single-transverse-spin asymmetries, and global fits to the Sivers asymmetries have been performed [28] to high precision. In order to make a meaningful comparison of sign and shape, comparable measurements are needed for single spin asymmetries in the Drell-Yan process. While many experiments around the globe aim to measure polarized Drell-Yan either with a polarized beam or a polarized target (see table I), none of them is optimized for Drell-Yan, except for the SeaQuest dimuon spectrometer at the Fermilab Main Injector. COMPASS is scheduled to take data in 2014 for one year and expects to measure the sign of the Sivers function in the same kinematics as semi-inclusive DIS [24] with a statistical precision of $\delta A_N/A_N$ of 1–2%. AnDY has a possible window starting in 2013 and ending in July 2014, and awaits funding decision to collect $100\,\mathrm{pb}^{-1}$ to measure the sign of the Sivers function to within 5σ. A polarized Drell-Yan experiment such as SeaQuest is needed, however, to measure not only the sign, but also the magnitude and shape of the Sivers function with high precision.

The big attraction for a polarized Drell-Yan program at the Fermilab Main Injector is a spectrometer and hydrogen target that are well-understood, fully functioning, and optimized for Drell-Yan at the end of data collection for the SeaQuest experiment(2). Furthermore, the SeaQuest spectrometer accommodates a large coverage in x, *i.e.* $x_b =$ 0.3–0.9, covering the valence quark region, and $x_t = 0.1$–0.5 covering the sea quark region. Although the Sivers function can be measured for both the valence quarks or the sea quarks, sea quark effects might be small, while valence quark effects are generally

(2) It is anticipated, that SeaQuest will have collected the approved 3.4×10^{18} protons on target by the end of 2014.

Table I. – *Planned polarized Drell-Yan experiments. Note that the common notation for beam and target parton momentum fractions are slightly different than in the text. Here,* $x_1 = x_b$*, and* $x_2 = x_t$

Experiment	Particles	Energy (GeV)	x_1 or x_2	Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	Timeline
COMPASS (CERN)	$\pi^\pm + p^\uparrow$	160 $\sqrt{s} = 17.4$	$x_2 = 0.2 - 0.3$ $x_2 \approx 0.05$ (low mass)	2×10^{33}	2014
PAX (GSI)	$p^\uparrow + \overline{p}$	collider $\sqrt{s} = 14$	$x_1 = 0.1 - 0.9$	2×10^{30}	> 2017
PANDA (GSI)	$\overline{p} + p^\uparrow$	15 $\sqrt{s} = 5.5$	$x_2 = 0.2 - 0.4$	2×10^{32}	> 2016
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s} = 20$	$x_1 = 0.1 - 0.8$	1×10^{30}	> 2014
AnDY RHIC (IP-2)	$p^\uparrow + p$	collider $\sqrt{s} = 500$	$x_1 = 0.1 - 0.3$	2×10^{32}	2013
PHENIX (RHIC)	$p^\uparrow + p$	collider $\sqrt{s} = 200$	$x_1 = 0.05 - 0.1$	2×10^{32}	> 2018
RHIC internal target phase-1	$p^\uparrow + p$	250 $\sqrt{s} = 22$	$x_1 = 0.25 - 0.4$	2×10^{33}	> 2015
RHIC internal target phase-2	$p^\uparrow + p$	250 $\sqrt{s} = 22$	$x_1 = 0.25 - 0.4$	3×10^{34}	> 2018
SeaQuest (FNAL)	$p + p$	120 $\sqrt{s} = 15$	$x_1 = 0.3 - 0.9$	3.4×10^{35}	2011
pol. SeaQuest (FNAL)	$p^\uparrow + p$	120 $\sqrt{s} = 15$	$x_1 = 0.3 - 0.9$	1×10^{36}	> 2014

expected to be large [28-30]. Thus, using a polarized beam might have a substantial advantage over a polarized target. Anselmino and his group have made a prediction [30] of the Sivers asymmetry as a function of $x_F (\approx x_b - x_t)$ for a 120 GeV/c polarized beam on an unpolarized hydrogen target, shown in the left panel of fig. 3. The red line indicates the prediction for the Sivers asymmetry, and the gray shaded area represents the $\sqrt{20}$ sigma error band(3).

Based on a study submitted to the Fermilab directors in August 2011 [31], and experience gathered from current polarized ion sources, it is expected that an ion source that produces 1 mA at the source could deliver up to 150 nA (9.5×10^{11} p/s) average beam current to the experiment, using 30 two-second cycles and slip stacking in the Main Injector. Since the liquid targets are designed for average beam currents of about 80 nA, *i.e.*, three times the beam current foreseen for SeaQuest, a luminosity of $1 \times 10^{36}/\mathrm{cm}^2/\mathrm{s}$ could be

(3) The χ^2 analysis and the statistical uncertainty bands are discussed in the appendix of ref. [28]. The error band corresponds to a $\Delta\chi^2 = 20$.

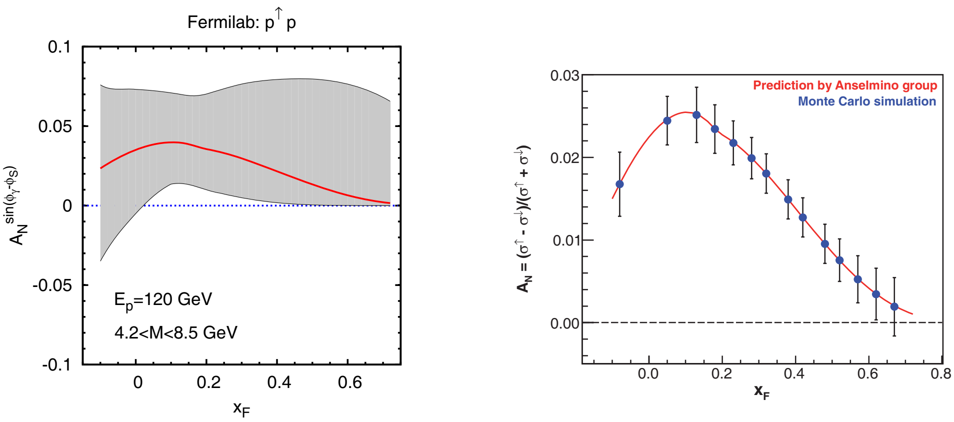

Fig. 3. – (Colour on-line) Left panel: Sivers asymmetry, $A_N^{\sin(\phi-\phi_S)}$, *vs.* Feynmann x for a 120 GeV/c polarized proton beam on an unpolarized hydrogen target [28]. Right panel: Prediction for single spin asymmetry, A_N, which is related to the Sivers asymmetry by $A_N = \frac{2}{\pi} A_{TU}^{\sin(\phi-\phi_S)}$, for polarized beam on an unpolarized target, assuming an integrated luminosity of 100 fb^{-1}.

obtained if 50% of the total beam time was allocated to the experiment. However, during initial discussions with the Fermilab directorate in Spring 2011, it became clear that a polarized Drell-Yan program at Fermilab is only feasible if not more than 10% of the available beam time is diverted from the neutrino program. Thus, assuming 10% of the available beam time was allocated to the experiment, which corresponds to a luminosity of 2.0×10^{35}/ cm^2/s, not only the sign, but also the size and shape of the Sivers function could be measured, as illustrated in the right panel of fig. 3. By running for a 2 year period with an average beam current of 15 nA and an efficiency of 50%, resulting in an integrated luminosity of 100 fb^{-1}, 6.6 million Drell-Yan events could be collected.

This demonstrates that the combination of high luminosity, large x-coverage and a high-intensity polarized beam makes Fermilab arguably the best place to measure polarized Drell-Yan scattering with high precision. To carry this project forward, further discussions will take place with the Fermilab directorate and division heads in the coming months about the feasibilities of polarizing the Main Injector. It is expected that if no substantial technical hurdles shop up, the project will be presented to the Fermilab program advisory committee for evaluation. Current estimates suggest that for $4 million and two years of construction, a 150 nA proton beam with 80% polarization could be available by the end of 2014, and would coincide with the end of data collection for SeaQuest.

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