Measuring the Antiquark Sea Asymmetry at High-x: Fermilab P906

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Recent measurements of the ratio of antidown to antiup quark distributions in the proton, $\bar{d}(x)/\bar{u}(x)$, have shown a considerable fractional momentum, x, dependence; although, at larger x the statistical uncertainty in the data is large. Fermilab P906 will measure the ratio of hydrogen to deuterium Drell-Yan cross sections at the Main Injector to extend this range to higher x where the ratio appears to return to unity. This ratio, and the difference, $\bar{d}(x) - \bar{u}(x)$ are sensitive to the non-perturbative origins of the proton sea. In addition, data will be collected on nuclear targets to study partonic energy loss and other nuclear effects.

Until the last decade, it was believed that the quark-antiquark ($q\bar{q}$) sea of the proton was generated perturbatively through gluons (g) splitting into $q\bar{q}$ pairs. Because of the similar masses of the light down (d) and up (u) quarks, this process would have generated a sea with similar numbers of $\bar{u}$ and $\bar{d}$ quarks. While it was not required by any known symmetry, this assumption was universally adopted by the parton distributions. Recent experimental data [1, 2, 3, 4, 5] has shown, however, that this is not the case.

Fermilab E866 used the Drell-Yan mechanism to measure the fractional momentum (x) dependence of the ratio $\bar{d}(x)/\bar{u}(x)$ and the difference $\bar{d}(x) - \bar{u}(x)$ in the proton (shown in Figure 1). Drell-Yan, in leading order, proceeds through the annihilation of a quark (or antiquark) in the beam with an antiquark (quark) in the target, and thus is directly sensitive to the antiquark distributions. The ratio of proton–proton to proton–deuterium Drell-Yan cross sections, in leading order in the limit of large x_1, can be expressed as

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

where $x_{1(2)}$ is the fractional momenta carried by the struck quark in the target (beam). To derive this expression, isospin symmetry between the proton and neutron has been assumed. Thus, buy simply measuring this cross section ratio, $\bar{d}(x)/\bar{u}(x)$ can easily be determined. The E866 measurements found an interesting and unexpected downturn in the ratio of $\bar{d}/\bar{u}$ near $x = 0.2$. The rise of $\bar{d}/\bar{u}$ for $x < 0.2$ was expected, but the apparent return to a symmetric sea at only marginally larger x was not (see Figure 1). Unfortunately, this larger-x region is also where the statistical uncertainty of the E866 data become large. To study this unexpected return to a symmetric sea, the Fermilab P906 collaboration has proposed using a 120 GeV proton beam extracted from the Main Injector (MI) to extend these measurements to larger x [6].

The lower-energy 120 GeV proton beam has two distinct advantages over the 800 GeV beam used by FNAL E866. First, the Drell–Yan cross section scales a $1/s$, where s is the center-of-mass energy squared. Hence, for the same values of x_1 and x_2, the Drell–Yan cross section using a 120 GeV beam is 7 times greater than with an 800 GeV beam. At the same time, the backgrounds scale with the beam energy, so the expected background trigger rate will be much smaller, allowing for greater beam intensities to be used. The expected statistical uncertainty on the extracted values of $\bar{d}/\bar{u}$ from a 6 month run with the proposed apparatus using the MI are also shown in Figure 1.

While providing direct input to the parton distribution fits (see *e.g.* [7]), the ultimate goal of experiment will be to provide a better understanding on the physical mechanism which generates the sea of the proton. The $\bar{d}(x) - \bar{u}(x)$ difference, also extracted from the cross section measurement, is a pure flavor non-singlet quantity: its integral is Q^2 independent and its Q^2 evolution at leading order does not depend on the gluon distribution of the proton. Early expectations were

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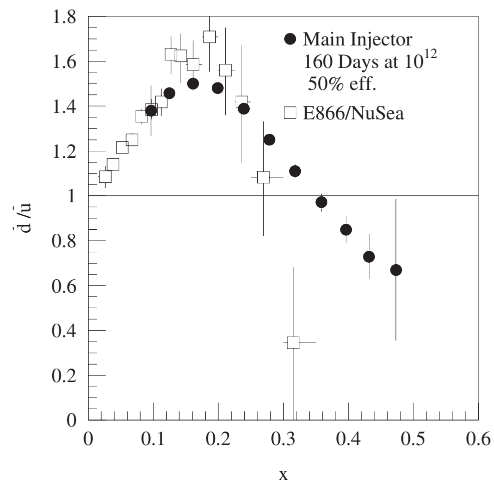

Figure 1: Projected results for the extraction of $\bar{d}/\bar{u}$ from a 160 day, 50% efficiency run with 10^{12} protons per pulse on 50 cm long liquid hydrogen and deuterium targets with the proposed apparatus. The shape of the distribution for the projected P906 results is based on the MRST [7] distribution of $\bar{d}/\bar{u}$. This, in turn, is primarily determined by a fit to the E866/NuSea Drell-Yan cross sections. Also shown are the E866/NuSea results [3, 4]. Note that the large statistical uncertainties in the high-x E866/NuSea data give considerable latitude to the MRST fit.

that Pauli blocking due to the extra valence u quark in the proton would lead to a suppression of $g \to u\bar{u}$ which would contribute significantly to differences in the light sea [8]. These expectations were not, however, borne out by calculations [9, 10]. In perturbative QCD, differences between the $\bar{d}(x)$ and $\bar{u}(x)$ distributions arise only at second order and are calculated to be very small [9]. The large differences seen in Figures 1 must be non-perturbative in nature and are likely explained in terms of collective degrees of freedom of QCD at low energy.

There are three significant non-perturbative approaches which can accommodate large $\bar{d}(x) - \bar{u}(x)$ differences: (1) hadronic models of the meson cloud of the nucleon [5, 11, 12], (2) chiral quark models which couple mesons directly to constituent quarks [13, 14] and (3) instanton models [15]. An intriguing feature is that in each of these models the flavor and spin distributions of the proton are intimately linked. As these non-perturbative models are considered, it is important to remember that they must be combined with perturbative sources to generate the entire quark sea of the proton, which produces the shape measured by experiment.

In addition to hydrogen and deuterium data, FNAL P906 will collect data on nuclear targets. This data will serve several purposes. First, the nuclear target data will provide a check on possible nuclear corrections at large-x in the deuterium data. Second, it will be directly comparable with neutrino Deep Inelastic Scattering (DIS) data in this region. Most of the current knowledge of the strength of the sea in this intermediate- to large-x region comes from neutrino DIS on nuclear targets and possible nuclear effects in this data have never been measured. Absolute Drell–Yan cross sections with both light and heavy targets will provide a measurement of these effects. A comparison of the expected uncertainty of P906 data with previous Drell–Yan [18] and DIS nuclear data [19] is shown in Figure 2. Finally, Drell–Yan proton-nucleus data has been used to extract the energy loss of a colored parton moving through a strongly interacting media [16, 17]. Different analyses have used different models of this process and produced different results. With the lower incident parton energy, the effects of energy loss in all models are expected to increase, and it will be possible to differentiate between the models.

The design of the experimental apparatus is based previous Fermilab Drell–Yan Experiments [3, 4]; although some aspects have been redesigned for the smaller boost produced by the lower energy beam. The apparatus uses relatively short liquid hydrogen, deuterium and solid nuclear targets. The muons produced in the target travel through two independent magnetic fields which focus the muons and measure their momentum. Within the first magnet a beam dump absorbs the uninteracted beam and a wall of hadronic absorber prevents hadrons from traversing the remaining detector. The detector is shown schematically in Figure 3. Most of the equipment used in the 906 detector is being recycled from other experiments, primarily FNAL E866 (the

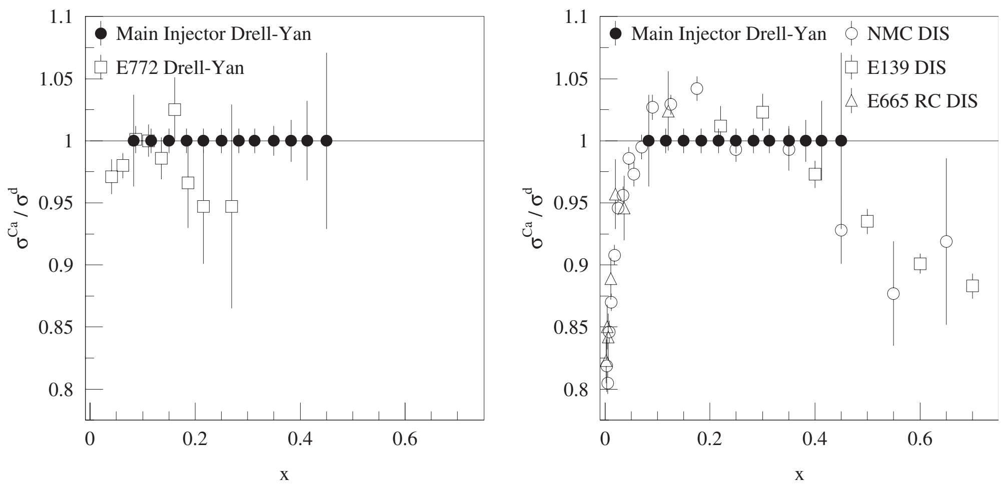

Figure 2: FNAL E772 Drell-Yan [18] results (left) and a compilation of deep inelastic scattering results [19] (right) on the ratio of cross sections of calcium to deuterium, compared with the statistical uncertainties of the proposed measurement, arbitrarily plotted at 1.0. The systematic error is expected to be less than 1%.

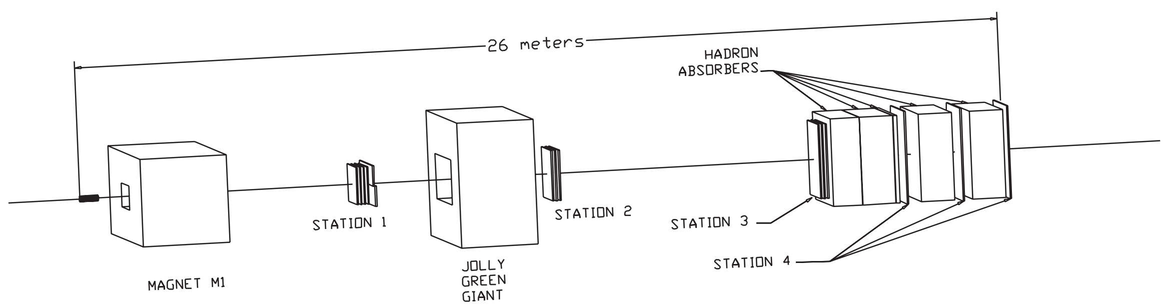

Figure 3: Schematic diagram of the proposed detector.

previous Fermilab Drell–Yan experiment) and the Fermilab HyperCP experiment. The major new component of the detector is the focusing magnet, denoted “M1” in Figure 3, which is necessary due to the very different energy of the muons produced with a 120 GeV beam.

Fermilab Proposal 906 will use an extracted 120 GeV proton beam from the Main Injector to measure the Drell–Yan yields from hydrogen and deuterium targets. From the ratio of these yields the ratio of $\bar{d}/\bar{u}$ in the proton will be extracted as a function of x, for $0.15 \leq x \leq 0.45$. This data will extend the range previously measured by FNAL E866 to higher x. The data will address questions of the origins of the nucleon sea and explore the nonperturbative nature of QCD. Drell–Yan data will also be collected using heavier nuclear targets, providing comparisons with the neutrino-based determinations of the total sea strength and measuring the possible nuclear effects in these data. The nuclear target data will also be used to measure the energy loss of colored partons traveling through strongly interacting media.

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