Measurements of the Antiquark Flavor Asymmetry in the Proton by the Drell-Yan Experiment SeaQuest

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Abstract

The antiquark flavor asymmetry $\bar{d}/\bar{u}$ in the proton gives an insight on the non-perturbative structure of the proton. The SeaQuest experiment measured the Drell–Yan cross section ratio of proton-deuterium to proton-proton to determine the antiquark flavor asymmetry $\bar{d}/\bar{u}$ precisely in the range of $0.13 < x < 0.45$. SeaQuest provides the evidence of $\bar{d}/\bar{u} > 1.0$ over a wide range of momenta. Some theoretical models reproduce this result.

Contents

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1 Introduction

The structure of the proton has been investigated via the deep inelastic scattering (DIS): the interaction of the lepton with a parton in a hadron. DIS gave a great improvement on the parton distribution functions (PDFs). The cross section of DIS covers both the quarks and antiquarks in the nucleon.

The Drell–Yan process is a reaction where an antiquark in a hadron and a quark in another hadron annihilate and then decay into a lepton pair via a virtual photon in a high energy hadron-hadron collision ($q+\bar{q}\rightarrow\gamma^{\star}\rightarrow l+\bar{l}$) [1]. The Drell–Yan process is a suitable probe to investigate the property of the antiquarks since an antiquark is always involved in the Drell–Yan process.

Most of the antiquarks in the proton are generated from the gluon splitting ($g\rightarrow q+\bar{q}$). The amounts of light antiquarks, $\bar{d}$ and $\bar{u}$, in the proton were expected to be the same because the the strong coupling constant is flavor-independent and the masses of the current quarks are more or less equal for u and d quarks: $\int_0^1 \bar{u}(x)dx = \int_0^1 \bar{d}(x)dx$, where x is the momentum fraction of the parton to the proton (Bjorken x). If this flavor symmetry of antiquarks holds, the Gottfried sum rule is satisfied:

$$S_G = \int_0^1 dx \frac{F_2^p - F_2^n}{x} = \frac{1}{3} + \int_0^1 dx(\bar{u}(x) - \bar{d}(x)) = \frac{1}{3}, \tag{1}$$

where F_2^p and F_2^n are the structure functions of the proton and neutron, respectively [2].

The NMC experiment at CERN was the first experiment to test the Gottfried sum rule precisely using the deep inelastic scattering [3,4]. NMC found that the Gottfried sum is less than 1/3: $S_G = 0.235 \pm 0.026$. Therefore, the amount of $\bar{d}$ is larger than that of $\bar{u}$ in the proton:

$$\int_0^1 dx\bar{d}(x) - \int_0^1 dx\bar{u}(x) = 0.147 \pm 0.039. \tag{2}$$

The NA51 experiment at CERN and E866 experiment at Fermilab measured the Bjorken x dependence of the flavor asymmetry (the PDF ratio of $\bar{d}$ to $\bar{u}$) at $x = 0.19$ and $0.015 < x < 0.35$, respectively, using the Drell–Yan process [5,6]. They found $\bar{d}/\bar{u} > 1.0$ in $0.015 < x < 0.25$. In particular, a 70% asymmetry at maximum has been found at $x \sim 0.2$. On the other hand, although with large statistical uncertainty, E866 indicated $\bar{d}/\bar{u} < 1.0$ at $x \sim 0.3$. It is important to obtain the flavor asymmetry precisely in a large and wide x range including this intriguing region to understand the antiquark structure of the proton. In this paper, we present a new result [7] of the Drell-Yan process by SeaQuest experiment.

2 SeaQuest experiment

The SeaQuest experiment is a Drell–Yan experiment performed at Fermilab. The purpose of the SeaQuest is to determine the flavor asymmetry of antiquarks as a function of Bjorken x in the range $0.13 < x < 0.45$. SeaQuest measured the muon pairs generated by the Drell–Yan process using a magnetic spectrometer. The details of the experimental setup are described in [8]. The incident proton beam is provided by Fermilab Main Injector and collides with the targets. Its energy is 120 GeV. The fixed targets are liquid hydrogen (LH_2), liquid deuterium (LD_2), carbon, iron and tungsten. The LH_2 and LD_2 targets are for the flavor asymmetry analysis. Four tracking stations which consist of hodoscope arrays and drift chambers or proportional tubes detect the muon pairs. A magnet is placed between the first and second tracking stations to determine the muons momenta. A hadron absorber is located between the third and fourth tracking stations for the muon identification.

From 2013 through 2017, 1.4×10^{18} protons were delivered to acquire the physics data. About 40% of the acquired data have been analyzed to extract the antiquark flavor asymmetry.

3 Drell–Yan cross section ratio

The differential cross section of proton-proton Drell–Yan process at leading order is described as

$$\frac{d^2\sigma}{dx_{\text{beam}}dx_{\text{target}}} = \frac{4\pi\alpha^2}{9x_{\text{beam}}x_{\text{target}}}\frac{1}{s}\sum_{i=u,d,s,\ldots} e_i^2[q_i(x_{\text{beam}})\bar{q}_i(x_{\text{target}}) + \bar{q}_i(x_{\text{beam}})q_i(x_{\text{target}})]. \quad (3)$$

The second term of Eq. 3 is negligible in forward detection ($x_{\text{beam}} \gg x_{\text{target}}$) because the antiquarks PDFs at large x is quite small. The following relation is then derived:

$$\frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right], \quad (4)$$

where σ_{pd} and σ_{pp} are the cross sections of the proton-deuteron and proton-proton Drell–Yan processes, respectively. SeaQuest measured the cross section ratio to extract the $\bar{d}/\bar{u}$. Figure 1 shows the invariant mass spectrum of reconstructed muon pairs obtained by SeaQuest spectrometer. The experimental data are well fitted with the simulated and measured components.

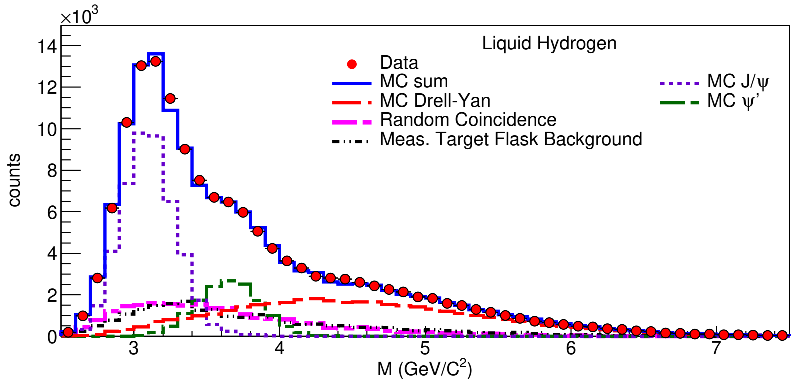

Figure 1: The invariant mass spectrum of reconstructed muon pairs. The data are shown with red points. The distributions of Drell–Yan (red), J/ψ (blue dotted line), and ψ' (green) are estimated by Monte Carlo simulation. The random background (magenta) is estimated with experimental data by event mixing method. The black line shows the target flask background. The blue line is the fit of the experimental data with those components.

The muon pairs with invariant mass > 4.5 GeV were used for the physics analysis because the Drell–Yan process dominates in that region.

Figure 2 shows the results of the Drell–Yan cross section ratio as a function of x_{target} [7]. The results of SeaQuest are shifted upward compared to the E866 results. This is because the x_{beam} range is different in these two experiments.

4 Flavor Asymmetry $\bar{d}/\bar{u}$

The $\bar{d}/\bar{u}$ extraction was performed with an iterative analysis. First, the cross section ratio was calculated using the CT18NLO PDF (u, d, s, c, $\bar{d}+\bar{u}$) and the estimate of $\bar{d}/\bar{u}$. The estimate of $\bar{d}/\bar{u}$ at the first iteration is 1.0. Then the ratio of $\bar{d}/\bar{u}$ was updated based on the difference between the calculated cross section ratio and the measured cross section ratio. This process was repeated until the difference becomes small enough. Figure 3 shows the results of

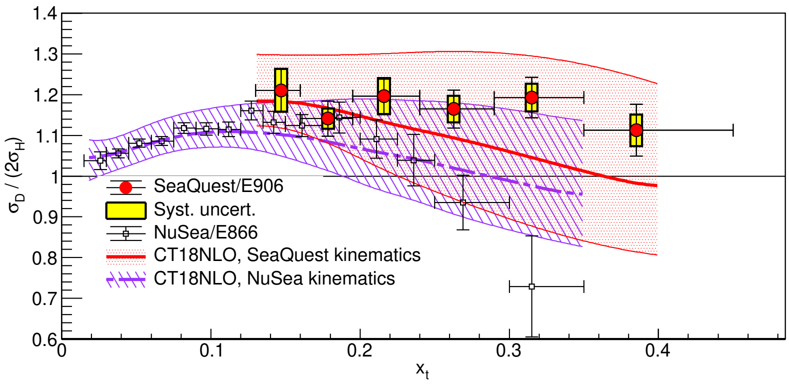

Figure 2: Drell–Yan cross section ratio as a function of x_{target} [7]. Red points with yellow systematic bands show the SeaQuest data. Rectangle blank points are the results of E866. CT18NLO at SeaQuest kinematics (red) and that at E866 kinematics (blue) are also shown with curves and bands of uncertainty.

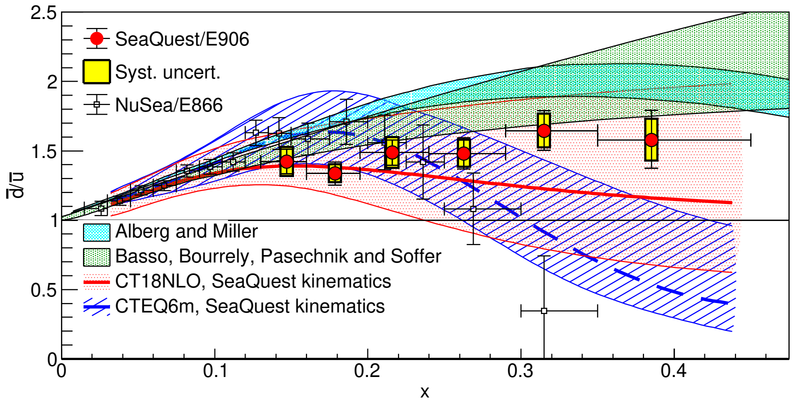

Figure 3: Antiquark flavor asymmetry $\bar{d}/\bar{u}$ as a function of Bjorken x [7]. The red points with yellow bands show the SeaQuest results with the systematic uncertainty. The rectangle blank points are the results by E866. The meson cloud model prediction (Alberg and Miller, light blue band), the statistical model prediction (Basso, Bourrely, Pasechnik and Soffer, green band), and calculations of CT18NLO (red band) and CTEQ6m (blue band) are drawn together.

$\bar{d}/\bar{u}$. This is the first measurement of $\bar{d}/\bar{u}$ at high Bjorken x region. The SeaQuest data show $\bar{d}/\bar{u} > 1.0$ for the entire measured range ($0.13 < x < 0.45$). The trend of the SeaQuest results is different from that of E866 at the large x region. No explanation has been found so far for this difference.

Many non-perturbative mechanisms of the QCD structure of the proton have been proposed to explain the antiquark flavor asymmetry in the last few decades. The meson cloud model predicts a large flavor asymmetry [9]. In this model, the virtual pion contributes to the PDFs. The proton wave function is described as $|p\rangle = |p_0\rangle + \alpha|n\pi^+\rangle + \beta|\Delta^{++}\pi^-\rangle + \cdots$. The process $|p\rangle \to |n\pi^+\rangle$ is more likely than $|p\rangle \to |\Delta^{++}\pi^-\rangle$, and it results in $\bar{d} > \bar{u}$. Although the size of the asymmetry depends on the parameters, a significant flavor asymmetry is reproduced by this model. The statistical model also gives a significant flavor asymmetry [10]. In this model, quarks are regarded as Fermi gas and gluons are regarded as Bose gas. They obey the Fermi-Dirac and Bose-Einstein functions, respectively. The meson cloud model and the statistical model predictions are shown in Fig. 3 for comparison. The SeaQuest results are reasonably described by these two models.

5 Conclusion

The Drell–Yan process is a suitable probe to investigate the antiquark structure of the proton. The SeaQuest experiment measured the cross section ratio of the proton-deuterium to proton-proton Drell–Yan processes to extract the antiquark flavor asymmetry $\bar{d}/\bar{u}$ in $0.13 < x < 0.45$. It is the first $\bar{d}/\bar{u}$ measurement at the higher region ($0.35 < x < 0.45$). The data show $\bar{d}/\bar{u} > 1.0$ for the entire measured range. The meson cloud model and the statistical model, which include non-perturbative mechanisms of the QCD structure of the proton, reasonably describe the SeaQuest data. Theoretical studies will be further enhanced based on the result of SeaQuest.

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