Probing Anti-Quark Structure in Proton with Drell-Yan at FNAL

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Abstract. E906/SeaQuest at FNAL is a fixed-target experiment to measure the Drell-Yan process with a 120-GeV proton beam and liquid-hydrogen/deuterium targets. The main purpose of this experiment is to precisely measure the asymmetry of $\bar{u}$ and $\bar{d}$ distributions in the proton at an $x_{ Bj}$ range from 0.25 to 0.45. E906/SeaQuest is about to start a beam experiment. The physics capabilities and the current status of the experiment is reported in this paper.

Keywords: Proton Structure, Light Anti-Quarks, Flavor Asymmetry


INTRODUCTION

The internal structure of the proton is one of the most vital topic in the present hadron physics. When the proton is probed at a high-energy scale, it consists of a large number of partons, i.e. quarks ($q$), anti-quarks ($\bar{q}$) and gluons ($g$). Gluons and anti-quarks are dynamically created via $q \rightarrow q + g$ and $g \rightarrow q + \bar{q}$, respectively, by the strong force. For example, at a momentum scale of $Q^2 \gtrsim 100$ GeV$^2$, a half of the proton momentum is carried by quarks and the remaining half by gluons. The $Q^2$ dependence of the parton distributions are well described with the DGLAP evolution equation.

Starting from the naive parton model[1], recent developments in both measurement and theory are revealing rich features of the proton internal structure. The state of partons in the proton is the key information to understand the detailed characteristics of the strong force. One important observation is a flavor asymmetry between the light anti-quarks, i.e. $\bar{u}$ and $\bar{d}$.

ANTI-QUARK FLAVOR ASYMMETRY, $\bar{d}/\bar{u}$, IN PROTON

Because the masses of $\bar{u}$ and $\bar{d}$ are approximately equal to each other, the distributions of $\bar{u}$ and $\bar{d}$ in the proton were initially assumed to be flavor symmetric, namely $\bar{d} = \bar{u}$. Based on this assumption the Gottfried Sum Rule[6] was proposed in 1967,

$$S_G = \int_0^1 \frac{d x_{ Bj}}{x_{ Bj}} \left( F_{2p}(x_{ Bj}) - F_{2n}(x_{ Bj}) \right) = \frac{1}{3} \left( (u - \bar{u}) - (d - \bar{d}) \right) - \frac{2}{3} (\bar{d} - \bar{u}) = \frac{1}{3}$$

where $F_{2p}(x_{ Bj})$ and $F_{2n}(x_{ Bj})$ are the structure functions of the proton and the neutron, respectively. In 1990 the New Muon Collaboration (NMC) at CERN showed that $S_G =$
0.2281(65) at $x_{Bj} \in (0.004, 0.8) \& Q^2 = 4$ GeV$^2$[7, 8]. This result was the first indication that the flavor symmetry is broken.

The NA51 experiment at CERN in 1994[9] and the E866/NuSea experiment at FNAL in 1998[10, 11, 12] directly measured the flavor asymmetry with the Drell-Yan process. As shown in Fig. 1, the measured asymmetry is as large as $\bar{d}/\bar{u} = 170\%$ at $x_{Bj} \sim 0.2$. After this observation, many theoretical models[13, 14, 15, 16, 17] have been proposed to explain the large asymmetry. Although all models reproduces the basic shape of the measured asymmetry, no model can show a trend that the measured asymmetry reverses ($\bar{d} \gtrsim \bar{u}$) at $x_{Bj} \sim 0.3$. To further investigate the consistency between the measurement and the models, more precise data particularly at high $x_{Bj}$ is needed.

The HERMES experiment also measured the flavor asymmetry in the lepton-nucleon deep inelastic scattering and obtained a consistent result[18].

**FIGURE 1.** Anti-quark flavor asymmetry, $\bar{d}/\bar{u}$, as a function of $x_{Bj} (= p_{\text{parton}}/p_{\text{proton}})$. The pink triangle is the result of CERN NA51 in 1994[9] and the blue squares are the result of FNAL E866/NuSea in 1998[10, 11, 12]. The solid line with the yellow band is the CTEQ6 fit result[19], which includes the E866/NuSea data. The red circles with the vertical bars are the anticipated $x_{Bj}$ range and statistical accuracy measured by FNAL E906/SeaQuest.

**DRELL-YAN PROCESS**

The Drell-Yan process[20, 21] is, as shown in Fig. 2, a process of hadron+hadron reactions in which a quark in one hadron and an anti-quark in the other hadron annihilate into a virtual photon and then a muon pair is created: $q + \bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$. The distribution of invariant mass of $\mu^+\mu^-$ pairs in proton+proton collisions measured by the E866/NuSea experiment is shown in Fig. 2. The continuum is of the Drell-
Yan process. The Drell-Yan cross section is written as

\[
\frac{d^2 \sigma}{dx^T dx^B} = \frac{4 \pi \alpha^2}{9 x^T x^B} \sum_i e_i^2 \left\{ q^T_i (x^T) \bar{q}^B_i (x^B) + \bar{q}^T_i (x^T) q^B_i (x^B) \right\},
\]

where \( s \) is the square center-of-mass energy of two interacting hadrons, and the superscripts “T” and “B” denote partons in one hadron (target) and the other hadron (beam), respectively.

Since the Drell-Yan process always involve anti-quark, it is the ideal process for the measurement of the anti-quark flavor asymmetry. In addition, the final state and the kinematics are so simple that \( x_B \) of two scattered partons can be reconstructed event-by-event to resolve the \( x_B \) dependence of the flavor asymmetry.

**FIGURE 2.** Left: diagram of Drell-Yan reaction. Right: distribution of invariant mass of \( \mu^+ \mu^- \) pairs in proton+proton collisions measured by E866/NuSea.

**E906/SEAQUEST EXPERIMENT AT FNAL**

E906/SeaQuest at FNAL is a fixed-target experiment to measure the Drell-Yan process with a 120-GeV proton beam (\( \sqrt{s} = 15 \text{ GeV} \)). It measures the Drell-Yan cross sections in \( p + p \) and \( p + d \) reactions with hydrogen and deuterium targets, and derives the flavor asymmetry from the ratio of the cross sections: \( \sigma_{pd}/2\sigma_{pp} \approx (1 + \bar{d}/\bar{u})/2 \). The anticipated accuracy is 10 times better at \( x_B \sim 0.3 \) than E866/NuSea, as shown in Fig. 1. Figure 3 is a schematic drawing of the E906/SeaQuest spectrometer. The beam and a huge number of background particles are absorbed with the solid iron just after the target. Charged particles that penetrate the hadron absorber and hit the proportional tubes at Station 4 are identified as muons. The momentum vector of muons is reconstructed with the wire chambers at Station 1, 2 and 3 and the KTeV tracking magnet. All stations are equipped with a hodoscope array for trigger.

The spectrometer is being set up for data taking. Four sets of trigger hodoscopes have successfully been set up by February 2011 and are ready to measure the rates of signals and backgrounds with the first beam coming. The construction of a target system will be finalized in March 2011. The first beam for commissioning will be available in May.
2011. The beam experiment will be adjourned halfway for one year due to an upgrade of the Main Injector, and will finish in 2014.

REFERENCES