Drell-Yan Experiment: Studying Anti-Quarks in the Proton

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Abstract. The internal structure of the proton is one of the most vital topics in the present hadron physics. At a high-energy scale, the proton reveals its complicated parton structure which is beyond the scope of the Quark Parton Model (QPM), 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. The dynamics of the proton structure is being investigated in both experiment and theory.

The Drell-Yan process in proton-proton collisions is the reaction in which a quark in one proton and an anti-quark in the other proton annihilate into a virtual photon and then create a muon pair: $q + \bar{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$. This process is suited to study the anti-quarks in the proton, and many experiments measuring the Drell-Yan process have been carried out in the past 20 years. The E906/SeaQuest experiment at Fermi National Accelerator Lab (FNAL) in USA is a Drell-Yan experiment being prepared now to explore a new kinematic region with very high statistics. The main purpose of this experiment is to precisely measure the asymmetry of $u$ and $d$ distributions in the proton at the $x_{Bj}$ range from 0.25 to 0.45.

In this paper, the anti-quark flavor asymmetry in the proton and the past Drell-Yan experiments are summarized, and the status of the E906 experiment is reported.

1. Introduction
The proton in a low-energy (static) condition can be expressed with three valence quarks, namely two up quarks and one down quark. But the proton in a high-energy condition consists of a huge number of quarks ($q$), anti-quarks ($\bar{q}$) and gluons ($g$), where 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 is well described with the DGLAP evolution equation [1, 2, 3].

Starting from the naive parton model [4], recent developments in both measurement and theory are revealing rich features of the proton internal structure. A flavor asymmetry between the light anti-quarks, i.e., $\bar{u}$ and $\bar{d}$, has been observed by many experiments, and is the main topic of this paper. Another example is the proton spin problem initiated by the EMC Collaboration in 1988 [5, 6]. The contribution of the quark spin to the proton spin has been measured to be only 30% [7, 8]. The remaining component should be carried by the gluon spin and the orbital angular momenta of quarks and gluons, although it has not been determined well by neither measurement nor theory. The state of partons in the proton is the key information to understand the detailed characteristics of Quantum ChromoDynamics (QCD).
2. 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 [9] was proposed in 1967,

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

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 measured the structure functions and examined the Gottfried sum rule [10, 11]. The result is shown in Fig. 1 and demonstrates $S_G = 0.2281(65)$ at $x_{Bj} \in (0.004, 0.8) \& Q^2 = 4 \text{ GeV}^2$. This result was the first indication that the flavor symmetry is broken.

![Figure 1](image-url)  
**Figure 1.** Structure functions and Gottfried Sum measured by NMC [10, 11]. The filled and open circles are $F_{2p}(x_{Bj}) - F_{2n}(x_{Bj})$ and $\int_{x_{Bj}}^1 (F_{2p}^p(x_{Bj}) - F_{2p}^n(x_{Bj})) dx_{Bj}/x_{Bj}$ as functions of $x_{Bj}$, respectively. The vertical bar at $x_{Bj} = 0$ is $S_G$ extrapolated from the open circles. The expected $S_G$ value, $1/3$, based on the flavor-symmetry assumption is indicated by the dashed line labeled “QPM” (Quark Parton Model).

The NA51 experiment at CERN in 1994 [12] and the E866/NuSea experiment at FNAL in 1998 [13, 14, 15] directly measured the flavor asymmetry with the Drell-Yan process. As shown in Fig. 2, the measured asymmetry is as large as $\bar{d}/\bar{u} = 170\%$ at $x_{Bj} \sim 0.2$. After this observation, many theoretical models [16, 17, 18, 19, 20] 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 [21].
3. Drell-Yan Process

The Drell-Yan process [23, 24] is, as shown in Fig. 3, 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 create a muon pair: \( q + \bar{q} \to \gamma^* \to \mu^+ + \mu^- \). The Drell-Yan cross section is written as

\[
\frac{d^2 \sigma}{dx^1 dx^B} = \frac{4\pi\alpha^2}{9x^1 x^B} \sum_i \sum_j e_i^2 \left( q_i^T (x^T) q_i^B (x^B) + \bar{q}_i^T (x^T) \bar{q}_i^B (x^B) \right),
\]

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

The distribution of invariant mass \( M \) of \( \mu^+ \mu^- \) pairs in proton+proton collisions is shown in Fig. 4, which was measured by the E866/NuSea experiment. The continuum is of the Drell-Yan process. It is contaminated by backgrounds, namely accidental \( \mu^+ \mu^- \) pairs and the tail of the meson resonances, and should be experimentally corrected. From this distribution the Drell-Yan cross section at the invariant-mass region outside the meson resonances can be derived in measurement. The parton distribution functions can be extracted from the measured cross

**Figure 2.** 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 [12] and the blue squares are the result of FNAL E866/NuSea in 1998 [13, 14, 15]. The solid line with the yellow band is the CTEQ6 fit result with one-standard-deviation interval [22], 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.
section via Eq. (2).

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 $x_{Bj}$ of two scattered partons can be reconstructed event-by-event to resolve the $x_{Bj}$ dependence of the flavor asymmetry.

![Diagram of Drell-Yan reaction.](image)

**Figure 3.** Diagram of Drell-Yan reaction.

![Distribution of invariant mass ($M$) of $\mu^+\mu^-$ pairs in proton+proton collisions measured by E866/NuSea.](image)

**Figure 4.** Distribution of invariant mass ($M$) of $\mu^+\mu^-$ pairs in proton+proton collisions measured by E866/NuSea.
4. 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 ($\sqrt{s} = 15$ 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:

$$\frac{\sigma_{pd}}{2\sigma_{pp}} \approx \frac{1}{2} \left( 1 + \frac{d}{u} \right),$$

where taking this ratio cancels out most systematic errors. E906/SeaQuest aims to achieve high precision at high $x_{Bj}$ by

- using a beam from the Fermilab Main Injector, which is of high intensity and low energy (where, as $\sqrt{s}$ decreases, the cross section of Drell-Yan process increases in proportion to $1/s$ and that of background decreases in proportion to $s$), and
- designing the spectrometer so that muon pairs with large invariant mass are efficiently measured (where invariant mass correlates with $x_{Bj}$ as $M^2 = x_{Bj}^2 s$).

The anticipated accuracy is 10 times better at $x_{Bj} \sim 0.3$ than E866/NuSea, as shown in Fig. 2.

Figure 5 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.

Figure 5. Schematic drawing of E906/SeaQuest spectrometer.
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.

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