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Flavor structure of the nucleon sea

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Abstract. The recent progress on our understanding of the flavor structure of unpolarized and polarized nucleon sea is reviewed. The large flavor asymmetry between the up and down sea quark distributions is now well established. This asymmetry strongly suggests the importance of the mesonic degrees of freedom in the description of the nucleon sea. The strong connection between the flavor structure and the spin structure of the nucleon sea is emphasized. Possible future measurements for testing various theoretical models are also discussed.

PACS. 14.20.Dh Properties of specific particles: Protons and neutrons – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes

1 Introduction

One of the most active areas of research in nuclear and particle physics during the last several decades is the study of quark and gluon distributions in the nucleons and nuclei. Several major surprises were discovered in Deep-Inelastic Scattering (DIS) experiments which profoundly changed our views of the partonic substructure of hadrons. In the early 1980s, the famous "EMC" effect found in muon DIS provided the first unambiguous evidence that the quark distributions in nuclei are significantly different from those in free nucleons. More recently, surprising results on the spin and flavor structures of the nucleons were discovered in DIS experiments. The so-called "spin crisis", revealed by the polarized DIS experiments, has led to extensive efforts to understand the partonic content of proton's spin. Subsequently, the observation [1] of the violation of the Gottfried Sum Rule [2] in DIS revealed a surprisingly large asymmetry between the up and down antiquark distributions in the nucleon, shedding new light on the origins of the nucleon sea.

In this article, we review the status of our current knowledge on the flavor dependence of the sea quark distributions in hadrons. In sect. 2, we summarize the experimental evidence for the flavor asymmetry of the nucleon sea. Implications of various theoretical models for explaining the $\bar{d}/\bar{u}$ asymmetry are also discussed. Section 3 is devoted to the subject of the flavor structure of polarized nucleon sea. Finally, we present future prospects and conclusion in sect. 4.

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2 Flavor structure of unpolarized nucleon sea

The earliest parton models assumed that the proton sea was flavor symmetric, even though the valence quark distributions are clearly flavor asymmetric. Inherent in this assumption is that the content of the sea is independent of the valence quark's composition. The flavor symmetry assumption was not based on any known physics, and it remained to be tested by experiments. Neutrino-induced charm production experiments [3,4], which are sensitive to the $s \to c$ process, showed that the strange-quark content of the nucleon is only about half of the up or down sea quarks. Such flavor asymmetry is attributed to the much heavier strange-quark mass compared to the up and down quarks. The similar masses for the up and down quarks suggest that the nucleon sea should be nearly up-down symmetric.

The issue of the equality of $\bar{u}$ and $\bar{d}$ was first encountered in measurements of the Gottfried integral [2], defined as

$$I_{\mathrm{G}} = \int_0^1 \left[F_2^p\left(x,Q^2\right) - F_2^n\left(x,Q^2\right)\right]/x\,\mathrm{d}x, \qquad (1)$$

where F_2^p and F_2^n are the proton and neutron structure functions measured in DIS experiments. Under the assumption of a $\bar{u}$, $\bar{d}$ flavor-symmetric sea in the nucleon, the Gottfried Sum Rule (GSR) [2], $I_{\mathrm{G}} = 1/3$, is obtained. The most accurate test of the GSR was reported by the New Muon Collaboration (NMC) [1], which measured F_2^p and F_2^n over the region $0.004 \le x \le 0.8$. They determined the Gottfried integral to be 0.235 ± 0.026, significantly below 1/3. This surprising result has generated much interest. Although the violation of the GSR can be explained by assuming unusual behavior of the parton distributions at

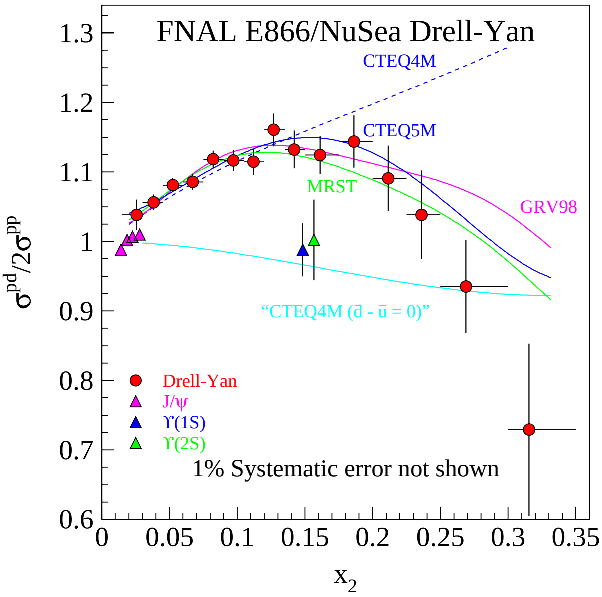

Fig. 1. Cross-section ratios of $p+d$ over $2(p+p)$ for Drell-Yan, J/Ψ, and Υ production from FNAL E866. The curves are the calculated next-to-leading-order cross-section ratios for the Drell-Yan using various parton distribution functions.

very small x, a more natural explanation is to abandon the assumption $\bar{u} = \bar{d}$.

The proton-induced Drell-Yan (DY) process provides an independent means to probe the flavor asymmetry of the nucleon sea [5]. An important advantage of the DY process is that the x-dependence of $\bar{d}/\bar{u}$ can be determined. The NA51 Collaboration at CERN carried out the first dedicated dimuon production experiment to study the flavor structure of the nucleon sea [6]. Using a 450 GeV proton beam, NA51 obtained $\bar{u}/\bar{d} = 0.51 \pm 0.04(\text{stat}) \pm 0.05(\text{syst})$ at $x = 0.18$ and $\langle M_{\mu\mu}\rangle = 5.22\,\text{GeV}$. This important result established the asymmetry of the quark sea at a single value of x. What remained to be done was to map out the x-dependence of this asymmetry.

At Fermilab, a DY experiment (E866/NuSea) aimed at a higher statistical accuracy with a much wider kinematic coverage than the NA51 experiment, has been completed [7–9]. The DY cross-section ratio per nucleon for $p+d$ to that for $p+p$ is shown in fig. 1. At positive x_F this ratio is given as

$$\sigma_{\text{DY}}(p+d)/2\sigma_{\text{DY}}(p+p) \simeq \big(1 + \bar{d}(x_2)/\bar{u}(x_2)\big)/2. \qquad (2)$$

Figure 1 shows that the DY cross-section per nucleon for $p+d$ clearly exceeds $p+p$, and it indicates an excess of $\bar{d}$ with respect to $\bar{u}$ over an appreciable range in x_2. In contrast, the $\sigma(p+d)/2\sigma(p+p)$ ratios for J/Ψ and Υ production, also shown in fig. 1, are very close to unity. This reflects the dominance of gluon-gluon fusion process for quarkonium production and the expectation that the gluon distributions in the proton and in the neutron are identical.

The Drell-Yan cross-section ratios from E866 were analysed to obtain $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$

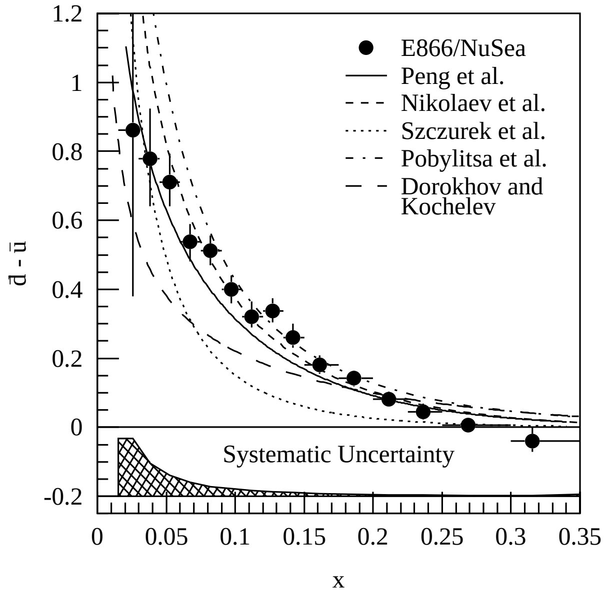

Fig. 2. Comparison of the measured $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 54\,\text{GeV}^2/c^2$ to predictions of several models of the nucleon sea. The solid and short-dashed curves show pion cloud calculations [8, 14]. The dotted curve is a chiral-quark model calculation [15], while the dot-dashed curve shows the chiral-quark soliton calculation [16]. The long-dashed curve shows the instanton model prediction [17].

Table 1. Values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

Experiment	$\langle Q^2\rangle$ (GeV^2/c^2)	$\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$
NMC/DIS	4.0	0.147 ± 0.039
HERMES/SIDIS	2.3	0.16 ± 0.03
FNAL E866/DY	54.0	0.118 ± 0.012

as shown in fig. 2. The HERMES Collaboration has reported a semi-inclusive DIS measurement of charged pions from hydrogen and deuterium targets [10]. Based on the differences between charged-pion yields from the two targets, $\bar{d} - \bar{u}$ is determined in the kinematic range, $0.02 < x < 0.3$ and $1\,\text{GeV}^2/c^2 < Q^2 < 10\,\text{GeV}^2/c^2$. The HERMES results are consistent with the E866 results obtained at significantly higher Q^2. In table 1 we list the values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ determined from the NMC, HERMES, and FNAL E866 experiments. The agreement among these results, obtained using different techniques including DIS, semi-inclusive DIS, and Drell-Yan, is quite good.

Many theoretical models, including meson cloud model, chiral-quark model, Pauli-blocking model, instanton model, chiral-quark soliton model, and statistical model, have been proposed to explain the $\bar{d}/\bar{u}$ asymmetry. For details of these various models, we refer to several recent review articles [11–13]. As shown in fig. 2, these models can describe the $\bar{d} - \bar{u}$ data very well. However, they all have difficulties explaining the $\bar{d}/\bar{u}$ data at large x $(x > 0.2)$ [18]. Thus, it would be very important to

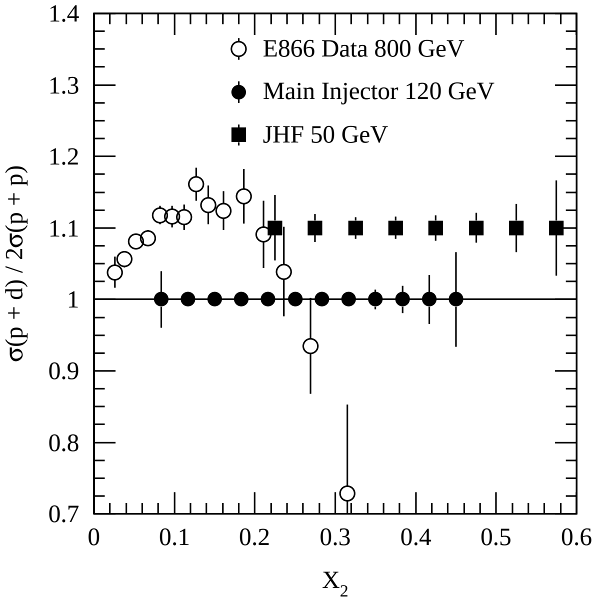

Fig. 3. Projected statistical accuracy for $\sigma(p+d)/2\sigma(p+p)$ in a 100-day run at JHF [20]. The E866 data and the projected sensitivity for a proposed measurement [21] at the 120 GeV Fermilab Main Injector are also shown.

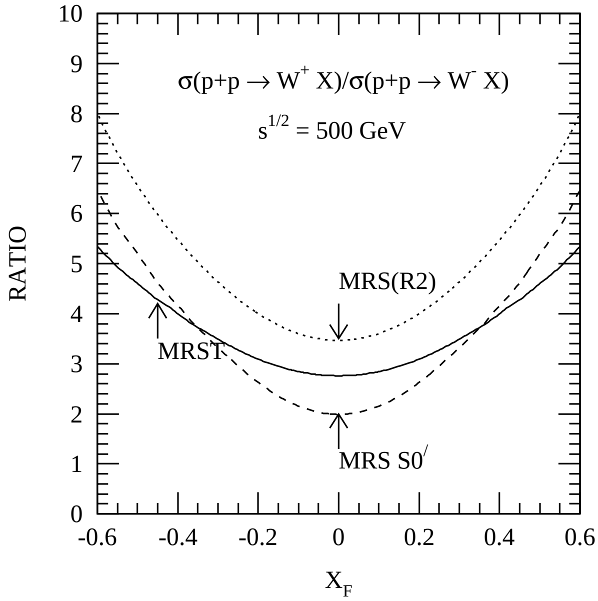

Fig. 4. Predictions of $\sigma(p+p \to W^+x)/\sigma(p+p \to W^-x)$ as a function of x_F at $\sqrt{s} = 500$ GeV. The dashed curve corresponds to the $\bar{d}/\bar{u}$ symmetric MRS S0′ structure functions, while the solid and dotted curves are for the $\bar{d}/\bar{u}$ asymmetric structure function MRST and MRS(R2), respectively.

extend the DY measurements to larger-x_2 regimes. The new 120 GeV Fermilab Main Injector (FMI) and the proposed 50 GeV Japanese Hadron Facility [19] (JHF) present opportunities for extending the $\bar{d}/\bar{u}$ measurement to larger x ($0.25 < x < 0.7$). Figure 3 shows the expected statistical accuracy for $\sigma(p+d)/2\sigma(p+p)$ at JHF [20] compared with the data from E866 and a proposed measurement [21] using the 120 GeV proton beam at the FMI. A definitive measurement of the $\bar{d}/\bar{u}$ over the region $0.25 < x < 0.7$ could indeed be obtained at FMI and JHF.

To disentangle the $\bar{d}/\bar{u}$ asymmetry from the possible charge-symmetry violation effect [22,23], one could consider W-boson production in $p+p$ collision at RHIC. An interesting quantity to be measured is the ratio of the $p+p \to W^+ + x$ and $p+p \to W^- + x$ cross-sections [24]. It can be shown that this ratio is very sensitive to $\bar{d}/\bar{u}$. An important feature of the W production asymmetry in $p+p$ collision is that it is completely free from the assumption of charge symmetry. Figure 4 shows the predictions for $p+p$ collision at $\sqrt{s} = 500$ GeV. The dashed curve corresponds to the $\bar{d}/\bar{u}$ symmetric MRS S0′ structure functions, while the solid and dotted curves are for the $\bar{d}/\bar{u}$ asymmetric structure function MRST and MRS(R2), respectively. Figure 4 clearly shows that W asymmetry measurements at RHIC could provide an independent determination of $\bar{d}/\bar{u}$.

Models in which virtual mesons are admitted as degrees of freedom have implications that extend beyond the $\bar{d}, \bar{u}$ flavor asymmetry addressed above. They create hidden strangeness in the nucleon via such virtual processes as $p \to \Lambda + K^+, \Sigma + K$, etc. Such processes are of considerable interest as they imply different s and $\bar{s}$ parton distributions in the nucleon, a feature not found in gluonic production of $s\bar{s}$ pairs. This subject has received a fair amount of attention in the literature [25–27] but experiments have yet to clearly identify such a difference. Thus, in contrast to the $\bar{d}, \bar{u}$ flavor asymmetry, to date there is no positive experimental evidence for $s\bar{s}$ contributions to the nucleon from virtual meson-baryon states [28–30].

A difference between the s and $\bar{s}$ distribution can be made manifest by direct measurement of the s and $\bar{s}$ parton distribution functions in DIS neutrino scattering, or in the measurement of the q^2-dependence of the strange-quark contribution ($F^p_{1s}(q^2)$) to the proton charge form factor. Measurement of these form factors allows extraction of the strangeness contribution to the nucleon's charge and magnetic moment and axial form factors. The portion of the charge form factor $F^p_{1s}(q^2)$ due to strangeness clearly is zero at $q^2 = 0$, but if the s and $\bar{s}$ distributions are different the form factor becomes nonzero at finite q^2. These "strange" form factors can be measured in neutrino elastic scattering [31] from the nucleon, or by selecting the parity-violating component of electron-nucleon elastic scattering, as is now being done at the Bates [32] and Jefferson Laboratories [33].

3 Flavor structure of polarized nucleon sea

The flavor structure and the spin structure of the nucleon sea are closely connected. Many theoretical models originally proposed to explain the $\bar{d}/\bar{u}$ flavor asymmetry also have specific implications for the spin structure of the nucleon sea. In the meson cloud model, for example, a quark would undergo a spin flip upon an emission of a pseudoscalar meson ($u^\uparrow \to \pi^\circ(u\bar{u}, d\bar{d}) + u^\downarrow$, $u^\uparrow \to \pi^+(u\bar{d}) + d^\downarrow$,

$u^\uparrow \to K^+ + s^\downarrow$, etc.). The antiquarks ($\bar{u}, \bar{d}, \bar{s}$) are unpolarized ($\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = 0$) since they reside in spin-0 mesons. The strange quarks (s), on the other hand, would have a negative polarization since the up valence quarks in the proton are positively polarized and the $u^\uparrow \to K^+ + s^\downarrow$ process would lead to an excess of $s^\downarrow$. By considering a vector meson (ρ) cloud, non-zero $\bar{u}, \bar{d}$ sea quark polarizations with $\Delta\bar{d} - \Delta\bar{u} > 0$ were predicted [34–37].

The Pauli-blocking model [38] predicts that an excess of $q^\uparrow(q^\downarrow)$ valence quarks would inhibit the creation of a pair of $q^\uparrow\bar{q}^\downarrow$ ($q^\downarrow\bar{q}^\uparrow$) sea quarks. Since the polarization of the $u(d)$ valence quarks is positive (negative), this model predicts a positive (negative) polarization for the $\bar{u}(\bar{d})$ sea ($\Delta\bar{u} > 0 > \Delta\bar{d}$).

In the instanton model [17], the quark sea can result from a scattering of a valence quark off a non-perturbative vacuum fluctuation of the gluon field, instanton. The interaction induced by an instanton is given by the 't Hooft effective Lagrangian which allows processes such as $u^\uparrow \to u^\downarrow d^\uparrow \bar{d}^\downarrow$, $d^\downarrow \to d^\uparrow u^\downarrow \bar{u}^\uparrow$, etc. Since the flavor of the quark-antiquark produced in this process is different from the flavor of the initial valence quark, this model readily explains $\bar{d} > \bar{u}$. Furthermore, the correlation between the sea quark helicity and the valence quark helicity in the 't Hooft effective Lagrangian (*i.e.* $u^\uparrow$ leads to a $\bar{d}^\downarrow$) naturally predicts a positively (negatively) polarized $\bar{u}(\bar{d})$ sea. In particular, this model predicts [39] a large $\Delta\bar{u}, \Delta\bar{d}$ flavor asymmetry with $\Delta\bar{u} > \Delta\bar{d}$, namely, $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]\mathrm{d}x = \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$.

In the chiral-quark soliton model [40,41], the large N_c limit of QCD becomes an effective theory of mesons with the baryons appearing as solitons. Quarks are described by single-particle wave functions which are solutions of the Dirac equation in the field of the background pions. In this model, the polarized isovector distributions $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ appear in leading-order (N_c^2) in a $1/N_c$ expansion, while the unpolarized isovector distributions $\bar{u}(x) - \bar{d}(x)$ appear in next-to-leading order (N_c). Therefore, this model predicts a large flavor asymmetry for the polarized sea $[\Delta\bar{u}(x) - \Delta\bar{d}(x)] > [\bar{d}(x) - \bar{u}(x)]$.

In the statistical approach, the nucleon is treated as a collection of massless quarks, antiquarks, and gluons in thermal equilibrium within a finite-size volume. The momentum distributions for quarks and antiquarks follow a Fermi-Dirac distributions function characterized by a common temperature and a chemical potential μ which depends on the flavor and helicity of the quarks. It can be shown that

$$\mu_{\bar{q}\uparrow} = -\mu_{q\downarrow}; \qquad \mu_{\bar{q}\downarrow} = -\mu_{q\uparrow}. \tag{3}$$

Equation (3), together with the constraints of the valence quark sum rules and inputs from polarized DIS experiments, can readily lead to the prediction that $\bar{d} > \bar{u}$ and $\Delta\bar{u} > 0 > \Delta\bar{d}$.

Predictions of various model calculations for I_Δ, the first moment of $\Delta\bar{u}(x) - \Delta\bar{d}(x)$, are listed in table 2. While the meson cloud model gives small negative values for I_Δ, all other models predict a positive I_Δ with a magnitude comparable or greater than the corresponding integral for unpolarized sea (recall that $\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x \simeq 0.12$). Several meson cloud calculations for the direct contribution of ρ-meson cloud are in good agreement. However, the large $\pi - \rho$ interference effect reported in [35] was not confirmed in a more recent study [36]. It is worth noting that a recent work [44] on $\pi - \sigma$ interference predicts a large effect on $\Delta\bar{d} - \Delta\bar{u}$, and with a sign opposite to other meson cloud model calculations.

Table 2. Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]\mathrm{d}x$.

Model	I_Δ prediction	Reference
Meson cloud (π-meson)	0	[42,43]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[34]
Meson cloud	$= -6\int_0^1 g^p(x)\mathrm{d}x$	[35]
($\pi - \rho$ interf.)	$\simeq -0.7$	
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[36]
Meson cloud (ρ-meson)	< 0	[37]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[44]
Pauli-blocking (bag-model)	$\simeq 0.09$	[36]
Pauli-blocking (ansatz)	$\simeq 0.3$	[45]
Pauli-blocking	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ $\simeq 0.2$	[46]
Chiral-quark soliton	0.31	[47]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$	[48]
Instanton	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ $\simeq 0.2$	[39]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ $\simeq 0.12$	[49]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]\mathrm{d}x$ > 0.12	[50]

If the flavor asymmetry of the polarized sea is indeed as large as the predictions of many models shown in table 2, it would imply that a significant fraction of the Bjorken sum, $\int_0^1 [g_1^p(x) - g_1^n(x)]\mathrm{d}x$, comes from the flavor asymmetry of polarized nucleon sea.

Measurements of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ are clearly of great current interest. The HERMES Collaboration has reported their preliminary results on the extraction of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ using polarized semi-inclusive DIS data [51]. A global analysis of inclusive spin asymmetries for π^+, π^-, K^+, and K^- has been carried out for longitudinally polarized hydrogen and deuterium targets. As a result, $\Delta u(x)$, $\Delta d(x)$, $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$, $\Delta s(x)(= \Delta\bar{s}(x))$ polarized quark densities were extracted for $0.03 < x$ at $Q^2 = 2.5\,\mathrm{GeV}^2$. These very interesting preliminary results showed that Δs has a trend of being positive, in disagreement with the predictions of theoretical models which attributed the violation of Ellis-Jaffe sum rule to a large negative polarization of the strange sea. Furthermore, the preliminary HERMES result does not support the prediction of a large positive $\Delta\bar{u} - \Delta\bar{d}$. Although the statistics are still limited, the HERMES preliminary result shows that $\Delta\bar{u}, \Delta\bar{d}, \Delta\bar{u} - \Delta\bar{d}$ are all consistent with being zero.

Another promising technique for measuring sea quark polarization is W-boson production [52] at RHIC. The longitudinal single-spin asymmetry for W production in polarized $p+p \to W^{\pm}+x$ can be written in leading order as

$$A_{\mathrm{L}}^{W^+} \approx -\frac{\Delta\bar{d}(x)}{\bar{d}(x)}, \qquad A_{\mathrm{L}}^{W^-} \approx -\frac{\Delta\bar{u}(x)}{\bar{u}(x)} \tag{4}$$

at suitable kinematic regions. Therefore, A_{L} gives a direct measure of sea quark polarization. The RHIC W production and the HERMES SIDIS measurements are clearly complementary tools for determining polarized sea quark distributions.

4 Conclusion

The flavor asymmetry of the nucleon sea has been clearly established by recent DIS and Drell-Yan experiments. The x-dependence of $\bar{d}/\bar{u}$ indicates that a $\bar{d}, \bar{u}$ symmetric sea dominates at small ($x < 0.05$) and large x ($x > 0.3$). But for $0.1 < x < 0.2$ a large and significant flavor non-symmetric contribution determines the sea distributions. The surprisingly large asymmetry between $\bar{u}$ and $\bar{d}$ is unexplained by perturbative QCD, and it strongly suggests the presence of virtual isovector mesons, mostly pions, in the nucleon sea. Additional clues on the origins of the flavor asymmetry will come from future studies including:

- Measurements of $\bar{d}/\bar{u}$ for $x > 0.25$.
- Measurements of $\Delta\bar{u}$ and $\Delta\bar{d}$ using semi-inclusive DIS, and W production in polarized p-p collision.
- Direct measurement of the meson cloud in DIS experiments tagging on forward-going nucleons. Interesting first measurements were performed recently at HERA [53].
- More precise measurements on the s *versus* $\bar{s}$ distributions in the nucleon.

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