LA-UR-98-4410

Title: Measurement of the Light Quark Flavor Asymmetry in the Nucleon Sea

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Submitted to: *Proceedings of the XXIX International Conference on High Energy Physics*
Vancouver, BC, Canada
July 23–28, 1998

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# MEASUREMENTS OF THE LIGHT QUARK FLAVOR ASYMMETRY IN THE NUCLEON SEA

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The Drell-Yan cross section ratios, $\sigma(p+d)/\sigma(p+p)$, measured in Fermilab E866, have led to the first determination of $\bar{d}(x)/\bar{u}(x)$, $\bar{d}(x)-\bar{u}(x)$, and the integral of $\bar{d}(x)-\bar{u}(x)$ for the proton over the range $0.02 \leq x \leq 0.345$. The E866 results are compared with predictions based on parton distribution functions and various theoretical models. The relationship between the E866 results and the NMC measurement of the Gottfried integral is discussed. The agreement between the E866 results and models employing virtual mesons indicates these non-perturbative processes play an important role in the origin of the $\bar{d},\bar{u}$ asymmetry in the nucleon sea.

## 1 Introduction

No known symmetry requires equality of the $\bar{d}$ and $\bar{u}$ distributions in the proton. Until recently it had been assumed that $\bar{d}(x)=\bar{u}(x)$. This is a plausible assumption if antiquarks originate primarily from the perturbative process of gluons splitting into $q-\bar{q}$ pairs. As the masses of the up and down quarks are small compared to the confinement scale, nearly equal numbers of up and down pairs should result. Thus a significant $\bar{d}/\bar{u}$ asymmetry would require a non-perturbative origin for an appreciable fraction of these light antiquarks. The interplay between the perturbative and non-perturbative components of the nucleon sea can be revealed through an accurate determination of the $\bar{d}/\bar{u}$ asymmetry.

The issue of the equality of $\bar{u}$ and $\bar{d}$ was first encountered in measurements of the Gottfried integral[1], defined as

$$I_G = \int_0^1 \left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right]/x\ dx, \qquad (1)$$

where $F_2^p$ and $F_2^n$ are the proton and neutron structure functions measured in deep inelastic scattering (DIS) experiments. Under the assumption of a $\bar{u}$, $\bar{d}$ flavor-symmetric sea in the nucleon, the Gottfried Sum Rule (GSR) [1], $I_G = 1/3$, is obtained. Measurements of muon DIS on hydrogen and deuterium by the New Muon Collaboration (NMC) [2] determined the Gottfried integral to be $0.235 \pm 0.026$, significantly below 1/3.

Although the violation of the GSR observed by NMC can be explained by assuming unusual behavior of the parton distributions at small $x$ or by assuming a large charge-symmetry-breaking effect, a more natural explanation is to abandon the assumption $\bar{u}=\bar{d}$. Specifically, the NMC result implies

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.148 \pm 0.039. \qquad (2)$$

Note that only the integral of the $\bar{d}-\bar{u}$ was deduced from the NMC measurement. The $x$-dependence of $\bar{d}-\bar{u}$ remained unspecified.

It was suggested that the proton-induced Drell-Yan process provides an independent means to probe the flavor asymmetry of the nucleon sea[3]. An important advantage of the Drell-Yan process is that the $x$-dependence of $\bar{d}/\bar{u}$ can be determined. The CERN experiment NA51 [4] carried out a comparison of the Drell-Yan muon pair yield from hydrogen and deuterium at $\langle x \rangle = 0.18$ using a 450 GeV/c proton beam and found $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$, a surprisingly large difference between the $\bar{u}$ and $\bar{d}$.

## 2 Fermilab E866

At Fermilab, a Drell-Yan experiment (E866) aimed at a higher statistical accuracy and a much wider kinematic coverage than the NA51 experiment was recently completed[5]. This experiment measured the Drell-Yan muon pairs from 800 GeV/c proton interacting with liquid deuterium and hydrogen targets. A proton beam with up to $2 \times 10^{12}$ protons per 20 s spill bombarded one of three identical 50.8 cm long cylindrical target flasks containing either liquid hydrogen, liquid deuterium or vacuum. The targets alternated every few beam spills in order to minimize time-dependent systematic effects. The dimuons accepted by a 3-dipole magnet spectrometer were detected by four tracking stations. An integrated flux of $1.3 \times 10^{17}$ protons was delivered for this measurement.

Over 330,000 Drell-Yan events were recorded in E866, using three different spectrometer settings which covered the regions of low, intermediate and high mass muon pairs. The data presented here are from the high mass setting, with over 140,000 Drell-Yan events. The Drell-Yan cross section ratio per nucleon for $p+d$ to that for $p+p$ is shown in Fig. 1 as a function of $x_2$, the Bjorken-$x$ of the target quark. The acceptance of the spectrometer was largest for $x_F = x_1 - x_2 > 0$. In this kinematic regime the Drell-Yan cross section is dominated by the annihilation of a beam quark with a target antiquark. To a very good approximation the Drell-Yan cross section ratio at positive $x_F$ is given as $\sigma_{DY}(p+d)/2\sigma_{DY}(p+p) \simeq (1+\bar{d}(x_2)/\bar{u}(x_2))/2$. In the case that $\bar{d} = \bar{u}$, the ratio is 1. Fig. 1 shows that the Drell-Yan 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 $x_2$.

Figure 1 also shows the predictions for a next-to-leading order calculation of the cross section ratio, weighted by the E866 spectrometer's acceptance, using the CTEQ4M [6] and MRS(R2) [7] parton distributions. The lower curve shows the predicted ratio for a modified CTEQ4M parton distribution which maintains the parameterization for $\bar{d}+\bar{u}$ but sets $\bar{d}-\bar{u}=0$. The data are in reasonable agreement with the unmodified CTEQ4M and the MRS(R2) predictions for $x_2 < 0.15$. It is clear that $\bar{d} \neq \bar{u}$ in this range. Above $x_2 = 0.15$ the data lie well below the CTEQ4M and the MRS(R2) values.

Values for $\bar{d}/\bar{u}$ were extracted iteratively by calculating the leading order Drell-Yan cross section ratio using a set of parton distribution functions as input and adjusting $\bar{d}/\bar{u}$ until the calculated cross section ratio agreed with the measured value. In this procedure, the values for the $\bar{d}+\bar{u}$ and valence distributions given by parton distribution functions were assumed to be correct. This procedure was followed using both the CTEQ4M and MRS(R2) parameterizations and negligible differences were seen. The extracted $\bar{d}/\bar{u}$ ratio is shown in Fig. 2 along with the predictions made by CTEQ4M and MRS(R2). A qualitative feature of the data, not seen in either parameterization of the parton distributions, is the rapid decrease towards unity of the $\bar{d}/\bar{u}$ ratio beyond $x_2 = 0.2$. At $x_2 = 0.18$, the extracted $\bar{d}/\bar{u}$ ratio is somewhat smaller than the value obtained by NA51. Although the average value of $Q^2$ ($M^2_{\mu^+\mu^-}$) is different for the two data sets, the change in $\bar{d}/\bar{u}$ predicted by the parton distributions due to $Q^2$ evolution is small.

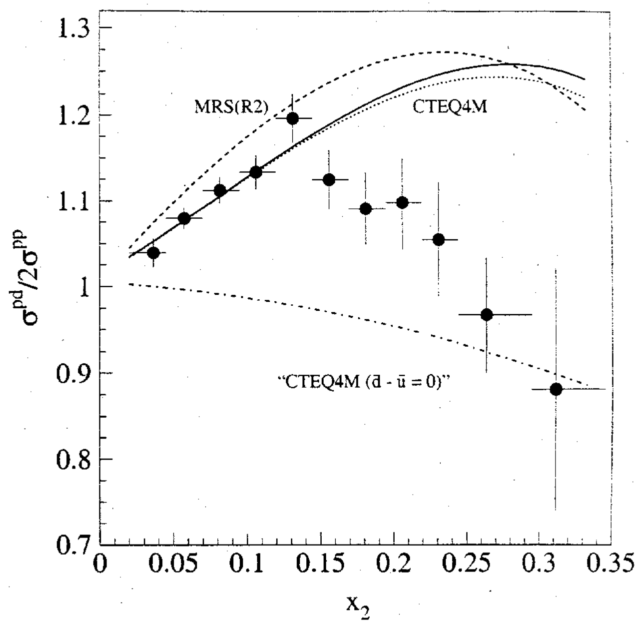


Figure 1: The ratio $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* $x_2$. The curves are next-to-leading order calculations, weighted by acceptance, of the Drell-Yan cross section ratio using the CTEQ4M and MRS(R2) parton distributions. Also shown is a leading-order calculation using CTEQ4M (dotted). In the lower CTEQ4M curve $\bar{d}-\bar{u}$ has been arbitrarily set to 0 as described in the text. The errors are statistical only. There is an additional 1% systematic uncertainty common to all points.

The $\bar{d}/\bar{u}$ ratios measured in E866, together with the CTEQ4M values for $\bar{d}+\bar{u}$, were used to obtain $\bar{d}-\bar{u}$ over the region $0.02 < x < 0.345$ (Fig. 3). As a flavor non-singlet quantity, $\bar{d}(x) - \bar{u}(x)$ has the property that its integral is $Q^2$-independent [8]. Furthermore, it is a direct measure of the contribution from non-perturbative processes, since perturbative processes cannot cause a significant $\bar{d}$, $\bar{u}$ difference. As shown in Fig. 3, the $x$ dependence of $\bar{d}-\bar{u}$ at $Q = 7.35$ GeV can be approximately parametrized as $0.05x^{-0.5}(1-x)^{14}(1+100x)$.

Integrating $\bar{d}(x) - \bar{u}(x)$ from E866, one finds

$$\int_{0.02}^{0.345} [\bar{d}(x) - \bar{u}(x)]\, dx = 0.068 \pm 0.007(stat.) \pm 0.008(syst.) \quad (3)$$

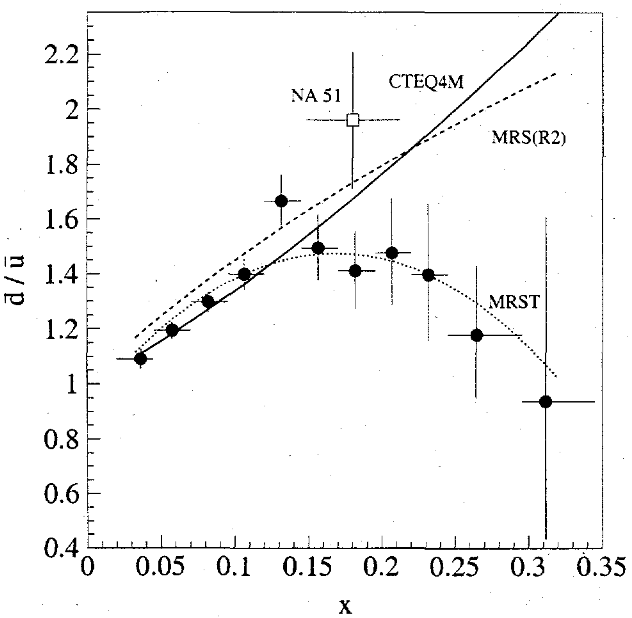


Figure 2: The ratio of $\bar{d}/\bar{u}$ in the proton as a function of $x_2$ extracted from the Fermilab E866 cross section ratio. The curves are from various parton distributions. The error bars indicate statistical errors only. An additional systematic uncertainty of $\pm 0.032$ is not shown. Also shown is the result from NA51, plotted as an open box.

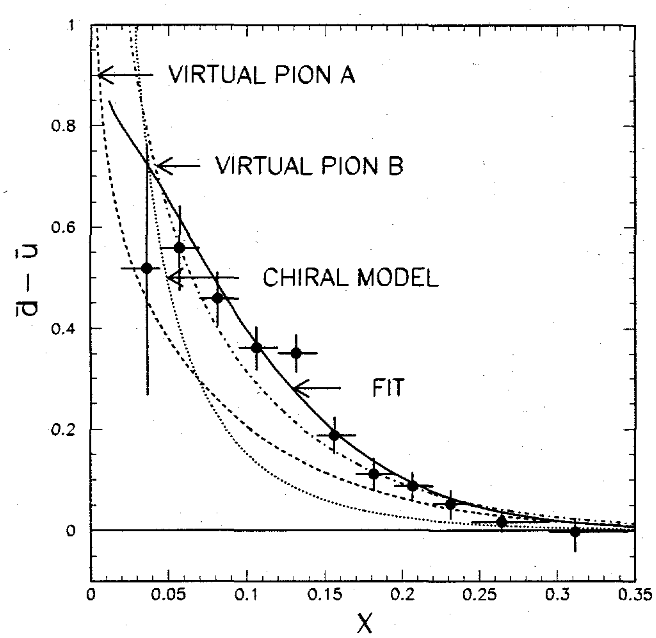


Figure 3: Comparison of the E866 $\bar{d} - \bar{u}$ results at $Q = 7.35$ GeV with the predictions of various models as described in the text.

Table 1: Values for $\int \left[\bar{d}(x) - \bar{u}(x)\right] dx$ over various $x$ ranges, evaluated at $Q = 7.35$ GeV, for various PDF parametrizations. Values deduced from E866 are also listed.

| $x$ range | CTEQ4M | MRS(R2) | E866 |
|---|---|---|---|
| 0.345 - 1.0 | 0.00192 | 0.00137 | |
| 0.02 - 0.345 | 0.0765 | 0.1011 | $0.068 \pm 0.011$ |
| 0.0 - 0.02 | 0.0296 | 0.0588 | |
| 0.0 - 1.0 | 0.1080 | 0.1612 | $0.100 \pm 0.018$ |

at $Q = 7.35$ GeV. To investigate the compatibility of this result with the NMC measurement (Eq. 2), the contributions to the integral from the regions $x < 0.02$ and $x > 0.345$ must be estimated. Table 1 lists the values for the integral of $\bar{d} - \bar{u}$ over the three regions of $x$ for two different parton distribution function (PDF) parametrizations at $Q = 7.35$ GeV. For $x > 0.345$, the contribution to the integral is small (less than 2%). Both parametrizations predict that the bulk of the contribution to the integral comes from $0.02 < x < 0.345$. Since CTEQ4M provides a reasonable description of the E866 data in the low-$x$ region, and the contribution from the high-$x$ region is small, we have used CTEQ4M to estimate the contributions to the integral from the unmeasured $x$ regions. This procedure results in a value $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.100 \pm 0.007 \pm 0.017$, which is 2/3 the value deduced by NMC. The systematic error includes the uncertainty ($\pm 0.015$) due to the unmeasured $x$ regions, estimated from the variation between CTEQ4M and MRS(R2). This result is consistent with the integral of the parametrized fit shown in Fig. 3.

The E866 results on the $\bar{d}/\bar{u}$ clearly affect the curent PDF parametrization of the nucleon sea. The most recent PDF parametrization, MRST [9], included E866 data in its global fit, and the MRST parametrization for $\bar{d}/\bar{u}$, shown in Fig. 2, is very different from the previous MRS(R2) parametrization. It is interesting to note that the E866 data also affect the parametrization of the valence-quark distributions. Figure 4 shows the NMC data for $F_2^p - F_2^n$ at $Q^2 = 4$ GeV$^2$, together with the fits of MRS(R2) and MRST. It is instructive to decompose $F_2^p(x) - F_2^n(x)$ into contributions from valence and sea quarks:

$$F_2^p(x) - F_2^n(x) = \frac{1}{3}x\left[u_v(x) - d_v(x)\right] + \frac{2}{3}x\left[\bar{u}(x) - \bar{d}(x)\right] \quad (4)$$

As shown in Fig. 4, the E866 data provide a direct determination of the sea-quark contribution to $F_2^p - F_2^n$. In order to preserve the fit to $F_2^p - F_2^n$, the MRST's parametrization for the valence-quark distributions, $u_v -$

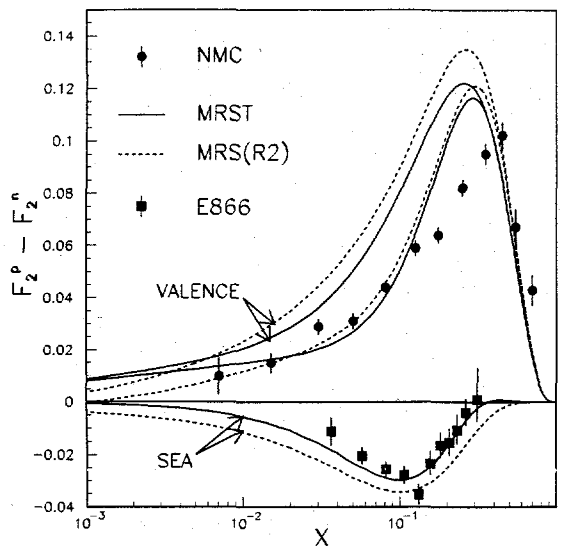


Figure 4: $F_2^p - F_2^n$ as measured by NMC at $Q^2 = 4$ GeV$^2$ compared with predictions based on the MRS(R2) and MRST parametrizations. Also shown are the E866 results, evolved to $Q^2 = 4$ GeV$^2$, for the sea-quark contribution to $F_2^p - F_2^n$. For each prediction, the top (bottom) curve is the valence (sea) contribution and the middle curve is the sum of the two.

$d_v$, are significantly different from that of MRS(R2).

Figure 4 shows that MRST predicts a large contribution to the Gottfried-sum from the small-$x$ ($x < 0.004$) region. If the MRST parametrization for $F_2^p - F_2^n$ at $x < 0.004$ were used together with the NMC data at $x > 0.004$, one would deduce a larger value for the Gottfried integral, and a value for the $\bar{d} - \bar{u}$ integral smaller than that of Eq. (2). This would bring better agreement between the E866 and the NMC results on the $\bar{d} - \bar{u}$ integral.

The E866 data also allow the first determination of the momentum fraction carried by the difference of $\bar{d}$ and $\bar{u}$. We obtain $\int_{0.02}^{0.345} x\left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.0065 \pm 0.0010$ at $Q = 7.35$ GeV. If CTEQ4M is used to estimate the contributions from the unmeasured $x$ regions, one finds that $\int_0^1 x\left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.0075 \pm 0.0011$, roughly 3/4 of the value obtained from the PDF parametrizations. Unlike the integral of $\bar{d}(x) - \bar{u}(x)$, the momentum integral is $Q^2$-dependent and decreases as $Q^2$ increases.

## 3 Interpretation of E866 Results

We now turn to the origin of the $\bar{d}/\bar{u}$ asymmetry [10]. As early as 1983, Thomas [11] pointed out that the virtual pions that dress the proton will lead to an enhancement of $\bar{d}$ relative to $\bar{u}$ via the (non-perturbative) "Sullivan process." Sullivan [12] previously showed that in DIS these virtual mesons scale in the Bjorken limit and contribute to the nucleon structure function. Following the publication of the NMC result, many papers[13–20] have treated virtual mesons as the origin of the asymmetry in the up, down sea of the nucleon.

Using the notion that the physical proton ($p$) may be expanded in a sum of products of its virtual meson-baryon (MB) states, one writes $p = (1-\alpha)p_0 + \alpha MB$, where $\alpha$ is the probability of the proton being in virtual states MB and $p_0$ is a proton configuration with a symmetric sea. It is easy to show [14,18] that

$$\int_0^1 \left[\bar{d}(x, Q^2) - \bar{u}(x, Q^2)\right] dx = (2a - b)/3 \qquad (5)$$

where $a$ is the probability of the virtual state $\pi N$ and $b$ the probability for $\pi\Delta$. These two configurations are the dominant intermediate MB states contributing to the asymmetry [18,19]. Further, most recent calculations of the relative probability of these two configurations find $a \approx 2b$ [18,19]. Using the value for the integral extracted from E866 and assuming $a = 2b$ yields $a = 2b = 0.20 \pm 0.036$, requiring a substantial presence of virtual mesons in the nucleon in this model.

Following the observation [17,21] that virtual pion configurations affect the spin structure of the nucleon because pion emission induces spin flip, it can be shown that

$$\begin{aligned} g_A &= \Delta u_p - \Delta d_p \\ &= \frac{5}{3} - \frac{20}{27}(2a+b) + \frac{32}{27}\sqrt{2ab} \\ &= 1.53 \pm 0.024 \end{aligned} \qquad (6)$$

using the above values of $a$ and $b$ determined from the E866 result. Here $\Delta u_p$ ($\Delta d_p$) is the total spin carried by the up (down) quarks in the proton. The resulting value for $g_A$ is reduced from the simple SU(6) value of 5/3, and is near the value (1.51) calculated by Weinberg who used chiral perturbation theory to calculate the effect of virtual pions [22]. However these results are far from the measured value of $g_A = 1.260 \pm 0.003$ [23]. Presumably relativistic effects [21] quench the spin of the constituent quarks allowing better agreement with experiment.

The $x$ dependences of $\bar{d} - \bar{u}$ and $\bar{d}/\bar{u}$ obtained in E866 provide important constraints for theoretical models. Fig. 3 compares $\bar{d}(x) - \bar{u}(x)$ from E866 with a virtual-pion model calculation following the procedure detailed by Kumano [14]. The curve labeled "virtual pion A" in Fig. 3 uses a dipole form with $\Lambda = 1.0$ GeV for the $\pi NN$ and $\pi N\Delta$ form factors, and is seen to underpredict the magnitude of $\bar{d} - \bar{u}$. However as has been noted [18,19], $\Delta$ production experiments [24] suggest a considerably softer form factor for $\pi N\Delta$ than for $\pi NN$. Indeed much better agreement with the E866 results is obtained by reducing $\Lambda$ for the $\pi N\Delta$ form factor to 0.8 GeV, as shown by the curve labeled "virtual pion B" in Fig. 3. This fit produces a value of 0.11 for the integral of $\bar{d} - \bar{u}$ and 1.52 for $g_A$. If $\Lambda$ is chosen to be 0.9 GeV (0.7 GeV) for the $\pi NN$ ($\pi N\Delta$) form factor, one finds nearly exact accord with the values cited in the previous paragraph.

A different approach for including the effects of virtual mesons has been presented by Eichten, Hinchliffe, and Quigg [17] and further investigated by Szczurek *et al.* [20]. In the framework of chiral perturbation theory, the relevant degrees of freedom are constituent quarks, gluons, and Goldstone bosons. In this model, a portion of the sea comes from the couplings of Goldstone bosons to the constituent quarks, such as $u \to d\pi^+$ and $d \to u\pi^-$. The excess of $\bar{d}$ over $\bar{u}$ is then simply due to the additional up valence quark in the proton. The predicted $\bar{d} - \bar{u}$ from the chiral model is shown in Fig. 3 as the dotted curve. We follow the formulation of Szczurek *et al.* [20] to calculate $\bar{d}(x) - \bar{u}(x)$ at $Q = 0.5$ GeV, and then evolve the results to $Q = 7.35$ GeV. In the chiral model, the mean-$x$ of $\bar{d} - \bar{u}$ is considerably lower than in the virtual-pion model just considered. This difference reflects the fact that the pions are softer in the chiral model, since they are coupled to constituent quarks which on average carry only 1/3 of the nucleon momentum. The $x$ dependence of the E866 data favors the virtual-pion model over the chiral model, suggesting that correlations between the chiral constituents should be taken into account.

Another non-perturbative process that can produce a $\bar{d}$, $\bar{u}$ asymmetry is the coupling of instantons to the valence quarks. An earlier publication [25] presented an asymmetry due to instantons but parametrized the result in terms of the asymmetry observed in NMC, and therefore has no independent predictive power. Also the *ad hoc* $x$ dependence used for $\bar{d}(x)/\bar{u}(x)$ is in poor agreement with the E866 result.

In summary, E866 has provided the first determination of $\bar{d}/\bar{u}$, $\bar{d} - \bar{u}$, and the integral of $\bar{d} - \bar{u}$ over the range $0.02 \leq x \leq 0.345$. It provides an independent confirmation of the violation of the Gottfried Sum Rule reported from DIS experiments. The magnitude of the integral of $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$ is smaller than obtained from some current PDF parametrizations. This indicates that the violation of the Gottfried Sum Rule is likely smaller than reported by NMC. Together with the NMC data, the E866 results impose stringent constraints on both sea- and valence-quark distributions. The good agreement between the E866 $\bar{d} - \bar{u}$ data and the virtual-pion model indicates that virtual meson-baryon components play an important role in determining non-singlet structure functions of the nucleon. Future experiments extending the measurements of $\bar{d}/\bar{u}$ to other $x$ and $Q^2$ regions can further illuminate the interplay between the perturbative and non-perturbative elements of the nucleon sea.

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