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\bar{d}/\bar{u} Asymmetry in the Nucleon Sea

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Fermilab E866 has performed a precise measurement of the ratio of Drell-Yan yields from an 800 GeV/c proton beam incident on hydrogen and deuterium targets, leading to the first determinations of \bar{d}/\bar{u} and $\bar{d} - \bar{u}$ in the proton as functions of x . The results show that $\bar{d} > \bar{u}$ over a broad range of x and provide valuable information regarding the origins of the \bar{d}/\bar{u} asymmetry and the antiquark sea in the nucleon.

No known symmetry requires equality of the \bar{d} and \bar{u} distributions in the proton. However, until recently it had been generally assumed that $\bar{d}(x) \approx \bar{u}(x)$, where x is the fraction of the proton's momentum (Bjorken- x) carried by the antiquark, based both on the assumption that the majority of the antiquark sea in the nucleon originates from gluon splitting into $q - \bar{q}$ pairs and the lack of experimental evidence to the contrary. The first clear evidence that $\bar{d} \neq \bar{u}$ came from the NMC measurements of the structure functions

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$F_2^p(x)$ and $F_2^n(x)$ in deep-inelastic muon scattering on hydrogen and deuterium [1]. Assuming charge symmetry between the proton and neutron (i.e., $u_p = d_n$, $\bar{d}_p = \bar{u}_n$, etc.), they concluded that $\int_0^1 (\bar{d}_p - \bar{u}_p) dx = 0.147 \pm 0.039$, a surprisingly large excess of \bar{d} relative to \bar{u} . However, the x -dependence of the excess could not be determined. Following publication of the NMC result, Drell-Yan lepton pair production was suggested [2] as a means by which the x -dependence of the light antiquark content of the proton could be investigated. CERN experiment NA51 [3] then carried out a comparison of the Drell-Yan muon pair yields from hydrogen and deuterium at $\langle x \rangle = 0.18$, using a 450 GeV/c proton beam, and found $\bar{u}_p/\bar{d}_p = 0.51 \pm 0.04 \pm 0.05$. See [4] for a recent review.

Recently, Fermilab Experiment 866 (E866) performed a high-precision measurement of the relative Drell-Yan muon pair yields from 800 GeV/c proton bombardment of liquid deuterium and hydrogen targets over a broad range of x [5]. E866 used a 3-dipole magnet spectrometer [6] employed previously in experiments E605, E772 and E789, modified by the addition of new drift chambers and hodoscopes with larger acceptance at the first tracking station, a programmable trigger system [7], and a VME-based data acquisition system. An 800 GeV/c extracted proton beam, with up to 2×10^{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 – that were alternated every five beam spills. After passing through the target, the remaining beam was intercepted by a copper beam dump located inside the second dipole magnet. The beam dump was followed by a thick absorber wall which blocked the entire aperture of the magnet. This removed hadrons produced in the target and the dump, ensuring that only muons traversed the spectrometer's detectors, which consisted of four tracking stations and a momentum analyzing magnet. The trigger required a pair of triple hodoscope coincidences having the topology of a muon pair from the target. Over 330,000 Drell-Yan events were recorded, using three different spectrometer settings which focused low, intermediate and high mass muon pairs. The data collected with the low and intermediate mass settings have systematic effects which are still under investigation. Therefore, the results presented here are from the high mass setting alone, with over 140,000 Drell-Yan events.

Figure 1 shows the measured ratio of the Drell-Yan cross section per nucleon for $p + d$ to that for $p + p$ as a function of x_2 , the Bjorken- x of the target quark in the parton model. (The Bjorken- x of the beam parton is denoted by x_1 .) Figure 1 also shows both leading order (dotted curve) and next-to-leading order (solid curve) calculations of the cross section ratio, weighted by the E866 spectrometer's acceptance, using the CTEQ4M [8] parton distribution functions (PDF) and a next-to-leading order calculation using MRS(R2) [9] (dashed curve). The lower (dash-dot) curve shows the predicted ratio for a modified CTEQ4M PDF in which $\bar{d} = \bar{u} = (\bar{d} + \bar{u})_{\text{CTEQ4M}}/2$. The data are in reasonable agreement with the unmodified CTEQ4M and the MRS(R2) predictions for $x_2 < 0.15$. It is clear that $\bar{d}_p \neq \bar{u}_p$ in this range. Above $x_2 = 0.15$, the data lie well below both parameterizations.

The acceptance of the spectrometer was largest for $x_1 > x_2$. In this kinematic regime the Drell-Yan cross section is dominated by the annihilation of a beam quark with a target antiquark. This fact, coupled with the assumption of charge symmetry between the neutron and proton and the assumption that the deuteron parton distributions can be expressed as the sum of the proton and neutron distributions, yields a simple approximate

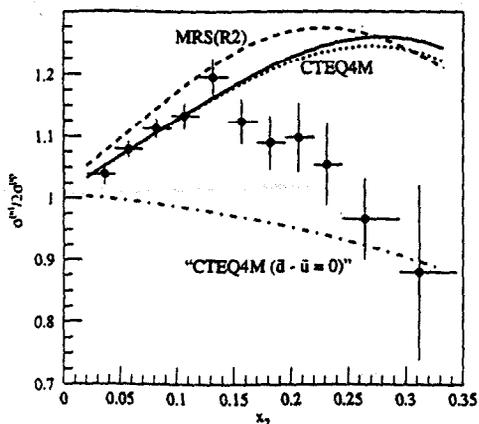


Figure 1. The ratio $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* x_2 . An additional 1% systematic uncertainty is common to all points. The curves are calculations using various parton distributions.

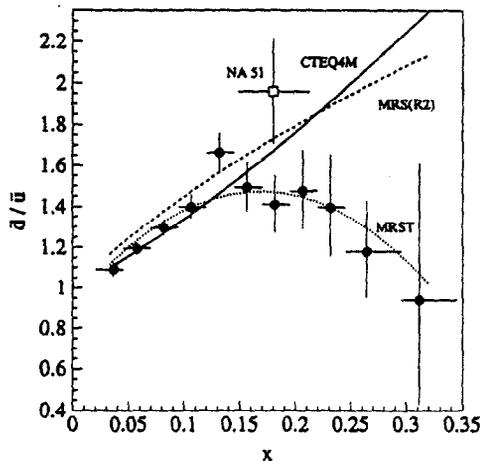


Figure 2. The ratio \bar{d}/\bar{u} in the proton as a function of x extracted from the cross section ratios. An additional systematic uncertainty of ± 0.032 is not shown. The curves are from various parton distributions.

form of the Drell-Yan cross section ratio:

$$\left. \frac{\sigma^{pd}}{2\sigma^{pp}} \right|_{x_1 \gg x_2} \approx \frac{1}{2} \frac{\left(1 + \frac{d_1}{4u_1}\right)}{\left(1 + \frac{d_1}{4u_1} \frac{d_2}{u_2}\right)} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right). \quad (1)$$

The subscripts 1 and 2 denote parton distributions in the proton as functions of x_1 and x_2 , respectively. In the case that $\bar{d} = \bar{u}$, the ratio is 1. This equation illustrates the sensitivity of the Drell-Yan measurement to \bar{d}/\bar{u} , but is valid only for $x_1 \gg x_2$. It does, however, imply an excess of \bar{d} with respect to \bar{u} for the data.

Some of the data, especially at higher x_2 , do not satisfy the $x_1 \gg x_2$ criterion of Eq. 1. Consequently, \bar{d}/\bar{u} was extracted iteratively by calculating the leading order Drell-Yan cross section ratio using the valence, heavy quark and $\bar{d} + \bar{u}$ values from a PDF as input, and adjusting \bar{d}/\bar{u} until the calculated cross section ratio agreed with the measured value. 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 of various PDFs. A qualitative feature of the data, not seen in CTEQ4M or MRS(R2), is the rapid decrease towards unity of the \bar{d}/\bar{u} ratio beyond $x = 0.2$. At $x = 0.18$, the extracted \bar{d}/\bar{u} ratio is somewhat smaller than the value obtained by NA51. The average Q^2 is different for the two experiments, but this has only a small influence on \bar{d}/\bar{u} .

The \bar{d}/\bar{u} ratios measured in E866, together with the CTEQ4M values for $\bar{d} + \bar{u}$, were

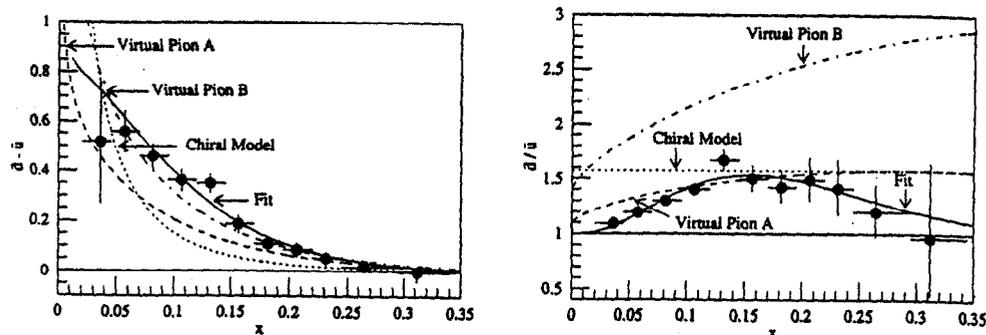


Figure 3. Comparison of the E866 $\bar{d} - \bar{u}$ results (left) and \bar{d}/\bar{u} results (right) at $Q = 7.35$ GeV with the predictions of various models and parametric fits.

used to obtain $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$. Figure 3 shows the results at $Q = 7.35$ GeV, the average value of the full data set. Nearly identical results were obtained when MRS(R2) was used rather than CTEQ4M.

As a flavor non-singlet quantity, $\bar{d}(x) - \bar{u}(x)$ has the property that its integral is Q^2 -independent [10]. 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 [11]. Integrating $\bar{d} - \bar{u}$ from E866, one finds $\int_{0.02}^{0.345} (\bar{d} - \bar{u}) dx = 0.068 \pm 0.007(\text{stat}) \pm 0.008(\text{syst})$ at $Q = 7.35$ GeV. To compare this result to the NMC measurement, the contributions to the integral from the regions $x < 0.02$ and $x > 0.345$ must be estimated. 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 $\int_0^1 (\bar{d} - \bar{u}) dx = 0.100 \pm 0.007 \pm 0.017$, in reasonable agreement with the NMC result, but more precise. The systematic error includes an uncertainty (± 0.015) due to the unmeasured x regions, estimated from the variation between CTEQ4M and MRS(R2).

The E866 results for \bar{d}/\bar{u} have a significant impact on the global PDF fits. The newest PDF parameterization, MRST [12], is the first to include the E866 results as inputs. The MRST parameterization for \bar{d}/\bar{u} is also shown in Fig. 2. This new parameterization fits the E866 results quite well, but it is very different from previous state-of-the-art fits like CTEQ4M and MRS(R2). It is interesting to note that the valence quark distributions in MRST are also somewhat different at very small x , implying that the value of $\int (\bar{d} - \bar{u}) dx$ inferred from the NMC results should be reduced, bringing it into better agreement with the E866 result.

We now turn to the origin of the \bar{d}/\bar{u} asymmetry [13]. As early as 1983, Thomas [14] 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 [15] previously showed that, in deep-inelastic scattering, these virtual mesons scale in the Bjorken limit and contribute to the nucleon structure function. Following the publication of the NMC

result, many papers [4,16–20] 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 its virtual meson-baryon (MB) states, one writes $p = (1 - \alpha)p_0 + \alpha MB$, where α 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 [16,18] that

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

where a is the probability of the virtual state πN 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. It is useful to note that these virtual pions also impact the spin structure of the nucleon because pion emission induces spin flip.

The x dependences of $\bar{d} - \bar{u}$ and \bar{d}/\bar{u} obtained in E866 provide important constraints for theoretical models. Figure 3 compares $\bar{d}(x) - \bar{u}(x)$ from E866 with a virtual-pion model calculation following the procedure detailed by Kumano [16]. The curve labeled “virtual pion A” in Fig. 3 uses a dipole form with $\Lambda = 1.0$ GeV for the πNN 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], Δ production experiments [21] suggest a considerably softer form factor for $\pi N\Delta$ than for πNN . Indeed much better agreement with the E866 results is obtained by reducing Λ 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 $\bar{d} - \bar{u}$.

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 $u \rightarrow d\pi^+$ and $d \rightarrow u\pi^-$. 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 less than 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.

It is also instructive to compare the model predictions of $\bar{d}(x)/\bar{u}(x)$ with the E866 results. Figure 3 shows that the two virtual-pion models and the chiral model give $\bar{d}(x)/\bar{u}(x)$ values very different from the E866 result. Note that these calculations do not include the perturbative processes $g \rightarrow u\bar{u}, d\bar{d}$ which generate additional symmetric sea. Indeed, the \bar{d}/\bar{u} data provide valuable information on the relative importance of the perturbative (symmetric) versus the non-perturbative sea. Figure 3 shows that all three models

substantially overestimate the observed \bar{d}/\bar{u} ratio at small x , allowing ample room for an additional contribution from the symmetric sea. However, for $0.1 < x < 0.2$, the predictions of the chiral model and the virtual-pion model A nearly saturate the observed ratio, leaving little room for any additional perturbatively generated symmetric sea in this interval. In contrast, the virtual-pion model B readily accommodates additional contributions from a symmetric sea over the full x range.

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 that $\bar{d} > \bar{u}$ in the proton over a broad range of x . The values of \bar{d}/\bar{u} and $\bar{d} - \bar{u}$ for $x > 0.2$, as well as the integral of $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$, are smaller than obtained from pre-existing PDF parameterizations [8,9], although new global fits that include the E866 results as inputs [12] are able to reproduce them quite well. 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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