Light Antiquark Flavor Asymmetry in the Nucleon Sea

C.A. Gagliardi[j], T.C. Awes[i], M.E. Beddo[h], M.L. Brooks[f], C.N. Brown[c], J.D. Bush[a], T.A. Carey[f], T.H. Chang[h*], W.E. Cooper[c], G.T. Garvey[f], D.F. Geesaman[b], E.A. Hawker[j,f], X.C. He[d], L.D. Isenhower[a], D.M. Kaplan[e], S.B. Kaufman[b], P.N. Kirk[g], D.D. Koetke[k], G. Kyle[h], D.M. Lee[f], W.M. Lee[d], M.J. Leitch[f], N. Makins[b*], P.L. McGaughey[f], J.M. Moss[f], B.A. Mueller[b], P.M. Nord[k], V. Papavassiliou[h], B.K. Park[f], J.C. Peng[f], G. Petitt[d], P.E. Reimer[f], M.E. Sadler[a], J. Selden[h], W.E. Sondheim[f], P.W. Stankus[i], T.N. Thompson[f], R.S. Towell[a,f], R.E. Tribble[j], M.A. Vasiliev[j†], Y.C. Wang[g], Z.F. Wang[g], J.C. Webb[h], J.L. Willis[a], D.K. Wise[a], G.R. Young[i]
(FNAL E866/NuSea Collaboration[‡])

[a] Abilene Christian University; [b] Argonne National Laboratory; [c] Fermi National Accelerator Laboratory; [d] Georgia State University; [e] Illinois Institute of Technology; [f] Los Alamos National Laboratory; [g] Louisiana State University; [h] New Mexico State University; [i] Oak Ridge National Laboratory; [j] Texas A&M University; [k] Valparaiso University

Fermilab E866 has performed a precise measurement of the ratio of Drell-Yan yields in 800 GeV/c pp and pd collisions, leading to determinations of $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ in the proton as functions of x. The results 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 assumed that $\bar{d}(x) \approx \bar{u}(x)$, where x is the fraction of the proton's momentum carried by the antiquark, based on the assumption that most of the antiquark sea in the nucleon originates from gluon splitting into $q\bar{q}$ pairs. But several experiments have now given clear evidence that $\bar{d} \neq \bar{u}$ [1–4]. To date, Fermilab experiment 866 (E866) has provided the most precise and detailed information regarding the $\bar{d}/\bar{u}$ asymmetry in the nucleon sea [3]. E866 performed a high-precision measurement the ratio of Drell-Yan yields per nucleon in 800 GeV/c proton-induced reactions on hydrogen and deuterium targets. The initial E866 results reported in [3] represent an analysis of $\approx 40\%$ of the E866 data. Here we present the results of the analysis of the full data set.

E866 used a 3-dipole magnet spectrometer [5] employed previously in experiments E605, E772 and E789, modified by the addition of new detectors with larger acceptance at the first tracking station. An 800 GeV/c proton beam bombarded identical 50.8-cm long target flasks containing liquid hydrogen, liquid deuterium and vacuum that were alternated every few minutes. After passing through the target, the remaining beam

*Present address: University of Illinois, Urbana, IL.
†On leave from Kurchatov Institute, Moscow 123182, Russia.
‡This work was supported in part by the U.S. Department of Energy.

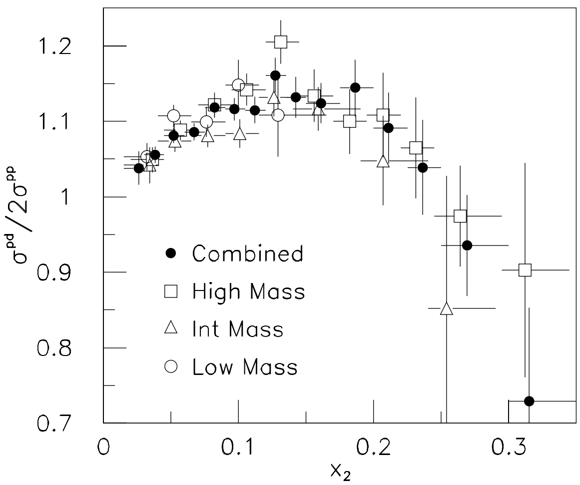

Figure 1. Preliminary ratios $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* x_2 for the various data sets, as well as the combined result.

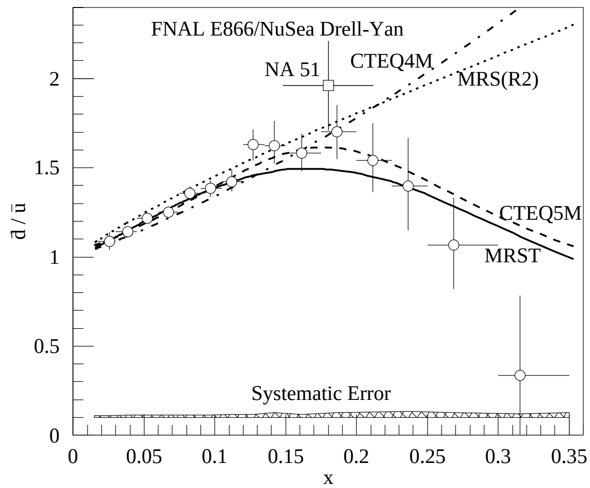

Figure 2. The ratio $\bar{d}/\bar{u}$ in the proton as a function of x, together with the predictions of several recent parton distributions.

was intercepted by a copper beam dump. The beam dump was followed by a thick absorber which removed hadrons produced in the target and the dump, ensuring that only muons traversed the spectrometer's detectors, consisting of four tracking stations and a momentum analyzing magnet. Over 370,000 Drell-Yan events were recorded, using three different spectrometer settings which focused low, intermediate and high mass muon pairs and provided good acceptance from below the J/ψ to above 15 GeV.

Figure 1 shows the measured ratios of the Drell-Yan cross section per nucleon as a function of x_2, the Bjorken-x of the target parton. (The Bjorken-x of the beam parton is x_1.) These ratios may be used to determine $\bar{d}/\bar{u}$ as a function of x. The acceptance of the spectrometer was largest for $x_1 > x_2$, where the Drell-Yan cross section is dominated by the annihilation of a beam quark with a target antiquark. This fact, coupled with the assumptions of charge symmetry and negligible shadowing in the deuteron, yields a simple approximation for the Drell-Yan cross section ratio:

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

The subscripts 1 and 2 denote parton distributions as functions of x_1 and x_2, respectively.

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 the MRST [6] parton distribution function (PDF) as input, and adjusting $\bar{d}/\bar{u}$ until the calculated cross section ratio agreed with the measured value. Leading-order and next-to-leading-order calculations of the cross section ratio give similar results, and negligible differences are found when using other recent PDF fits in place of MRST. The extracted $\bar{d}/\bar{u}$ ratios at Q = 6.4 GeV/c are shown in Fig. 2 along with the predictions of various PDFs. The MRST and CTEQ5M [7] PDF fits, both of which included the initial E866 results as important new inputs, provide a good description of the results, whereas previous state-of-the-art

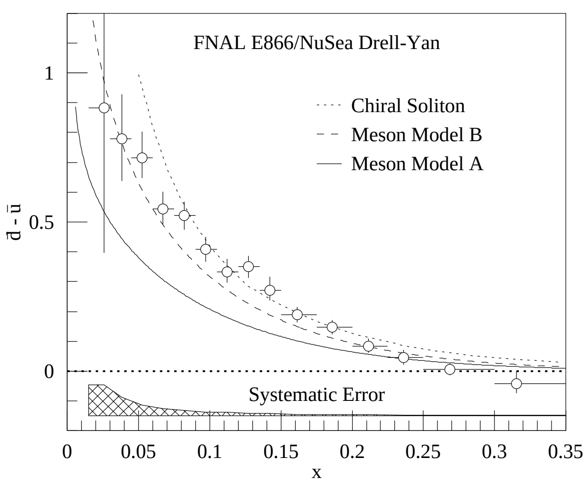

Figure 3. Comparison of the E866 $\bar{d}-\bar{u}$ results with the predictions of various models.

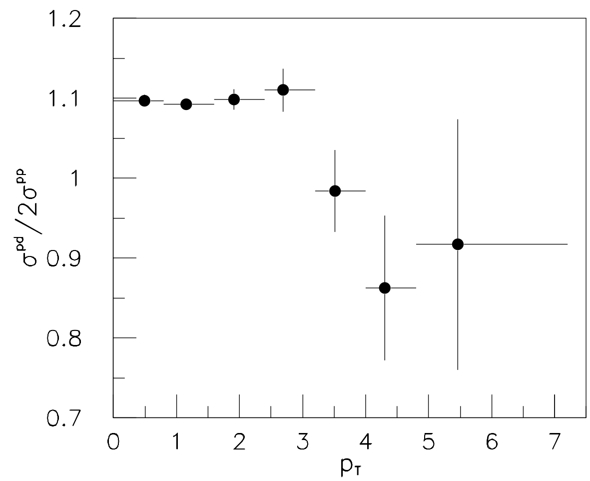

Figure 4. Preliminary ratios $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* p_T.

PDF fits fail to describe $\bar{d}/\bar{u}$ above $x \approx 0.18$. This demonstrates the significant impact that the E866 results have already had on global PDF fits.

The $\bar{d}/\bar{u}$ ratios measured in E866, together with the MRST values for $\bar{d}+\bar{u}$, have been used to obtain $\bar{d}-\bar{u}$ as shown in 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 to the nucleon sea from non-perturbative processes, since perturbative QCD alone cannot generate a significant $\bar{d}, \bar{u}$ difference [9]. Integrating $\bar{d}-\bar{u}$ from E866, one finds $\int_{0.015}^{0.35}(\bar{d}-\bar{u})dx = 0.0818 \pm 0.0082 \pm 0.0049$ at $Q = 6.4$ GeV. If we use the average of MRST and CTEQ5M to estimate the contributions to the integral from the unmeasured x regions, we find $\int_0^1(\bar{d}-\bar{u})dx = 0.118 \pm 0.011$, in agreement with the NMC [1] and HERMES [4] results, but considerably more precise.

The x dependence of $\bar{d}-\bar{u}$ provides important constraints for theoretical models [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." Following the publication of the NMC result, many papers have treated virtual mesons as the origin of the asymmetry in the up, down sea of the nucleon [12]. Figure 3 compares $\bar{d}(x)-\bar{u}(x)$ with a virtual-pion model calculation [10] following the procedure described in [13]. The curve labeled "Meson Model A" in Fig. 3 uses dipole form factors with $\Lambda = 1.0$ GeV for the πNN and $\pi N\Delta$ vertices, and underpredicts $\bar{d}-\bar{u}$. In contrast, 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 "Meson Model B" in Fig. 3.

Several other models have also been proposed to explain the sizable $\bar{d}/\bar{u}$ asymmetry in the nucleon. In chiral field 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 due to the additional up valence quark in the proton. However, the predicted $\bar{d}(x)-\bar{u}(x)$ from recent chiral field calculations [14] is even softer than that for "Meson Model A" in Fig. 3, suggesting that correlations between the chiral constituents must be taken into account. The chiral quark-soliton model has been used to predict $\bar{d}(x) - \bar{u}(x)$ in the large-N_c limit [15]. Figure 3 shows that this model reproduces the observed $\bar{d} - \bar{u}$ values well for $x > 0.08$, but it overestimates the asymmetry at small x. Finally, instanton models have also been proposed [16]. Their basic prediction is that the $\bar{d}/\bar{u}$ asymmetry should be primarily a large-p_T effect, but Fig. 4 shows that this is not the case.

It will also be instructive to compare model predictions of $\bar{d}(x)/\bar{u}(x)$ with the E866 results. However, unlike $\bar{d} - \bar{u}$, calculations for $\bar{d}/\bar{u}$ must include the contribution to the nucleon sea of the perturbative processes $g \rightarrow u\bar{u}, d\bar{d}$, which generate a symmetric sea, in addition to the non-perturbative processes which lead to the $\bar{d}/\bar{u}$ asymmetry. Hence, the E866 results will constrain future attempts to combine the effects of perturbative and non-perturbative QCD in the structure of the nucleon.

In summary, E866 has provided high-precision determinations of $\bar{d}/\bar{u}$ and $\bar{d} - \bar{u}$ over the range $0.015 \leq x \leq 0.35$. The values of $\bar{d}/\bar{u}$ and $\bar{d} - \bar{u}$ for $x > 0.18$ are much smaller than predicted by pre-existing PDF parameterizations, although new global fits that include the E866 results as important additional inputs are able to reproduce them quite well. These results provide strong constraints for models that attempt to describe the antiquark sea of the nucleon. Future experiments extending the measurements of $\bar{d}/\bar{u}$ to other x and Q^2 regions [17] will further illuminate the interplay between the perturbative and non-perturbative elements of the nucleon sea.

REFERENCES

1. New Muon Collaboration, M. Arneodo *et al.*, Phys. Rev. D 50 (1994) R1.
2. NA51 Collaboration, A. Baldit *et al.*, Phys. Lett. B 332 (1994) 244.
3. FNAL E866/NuSea Collaboration, E.A. Hawker *et al.*, Phys. Rev. Lett. 80 (1998) 3715.
4. HERMES Collaboration, K. Ackerstaff *et al.*, Phys. Rev. Lett. 81 (1998) 5519.
5. G. Moreno *et al.*, Phys. Rev. D 43 (1991) 2815.
6. A.D. Martin *et al.*, Eur. Phys. J. C 4 (1998) 463.
7. H.L. Lai *et al.*, hep-ph/9903282.
8. A.D. Martin, W.J. Stirling and R.G. Roberts, Phys. Lett. B 252 (1990) 653.
9. D.A. Ross and C.T. Sachrajda, Nucl. Phys. B 149 (1979) 497.
10. FNAL E866/NuSea Collaboration, J.C. Peng *et al.*, Phys. Rev. D 58 (1998) 092004.
11. A.W. Thomas, Phys. Lett. B 126 (1983) 97.
12. S. Kumano, Phys. Rep. 303 (1998) 183, and references therein.
13. S. Kumano, Phys. Rev. D 43 (1991) 3067; 43 (1991) 59; S. Kumano and J.T. Londergan, *ibid.* 44 (1991) 717.
14. A. Szczurek, A. Buchmans and A. Faessler, Jour. Phys. G: Nucl. Part. Phys. 22 (1996) 1741.
15. P.V. Pobylitsa *et al.*, Phys. Rev. D 59 (1999) 034024.
16. A.E. Dorokhov and N.I. Kochelev, Phys. Lett. B **259**, 335 (1991); **304**, 167 (1993).
17. D.F. Geesaman (spokesman) *et al.*, FNAL Proposal 906, 1999 (unpublished).