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Flavor Asymmetry of the Nucleon Sea: Consequences for Dilepton Production

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Parton distributions derived from a chiral quark model that generates an excess of down quarks and antiquarks in the proton's sea satisfactorily describe the measured yields of muon pairs produced in proton-nucleus collisions. Comparison of dilepton yields from hydrogen and deuterium targets promises greater sensitivity to the predicted flavor asymmetry.

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In a recent article [1], we showed that the fluctuation of constituent quarks into quarks plus Goldstone bosons generates a flavor-asymmetry in the light-quark sea of the nucleon that is a plausible origin for the violation of the Gottfried sum rule reported by the New Muon Collaboration (NMC) at CERN [2]. Fermilab experiment E772 has now presented measurements of the yields of massive muon pairs in collisions of 800-GeV/c protons with nuclear targets that are sensitive to the flavor content of the nucleon sea [3]. We show in this paper that our picture of the Gottfried-sum-rule defect also accounts for the new dilepton data, and we make predictions for a more sensitive test using hydrogen and deuterium targets.

Forward (Feynman-$x_F \gtrsim 0.1$) production of massive dilepton pairs in high-energy collisions of protons with nuclear targets is dominated by the annihilation of a u-quark from the beam with a $\bar{u}$-antiquark from the target, and so is sensitive to the distribution of antiquarks in the target nucleons. Charge symmetry relates the distribution of up-antiquarks in the neutron to the distribution of down-antiquarks in the proton,

$$\bar{u}^{(n)}(x, Q^2) = \bar{d}^{(p)}(x, Q^2) \quad , \tag{1}$$

where x is Bjorken's scaling variable and Q^2 labels the scale on which the parton distributions are measured. The yield per nucleon σ_A in proton collisions with nucleus A differs from the yield per nucleon $\sigma_{\text{isoscalar}}$ in proton collisions with an isoscalar target by the factor

$$R_A(x) \equiv \frac{\sigma_A(x)}{\sigma_{\text{isoscalar}}(x)} \approx 1 + \frac{(N-Z)}{A} \frac{\bar{d}(x) - \bar{u}(x)}{\bar{d}(x) + \bar{u}(x)} \quad , \tag{2}$$

where A, Z, and N are the atomic weight, atomic number, and number of neutrons in the target, and the antiquark densities refer to the proton. The approximate equality follows upon neglect of $d\bar{d}$ annihilations. The deviation of $R_A(x)$ from unity measures the flavor-asymmetry of the light-quark sea.

The possibility that the light-quark sea contains unequal numbers of up and down quarks has been raised by the New Muon Collaboration's determination [2] of the integral

$$I_G = \int_0^1 dx \, \frac{[F_2^{\mu p}(x,Q^2) - F_2^{\mu n}(x,Q^2)]}{x} = 0.240 \pm 0.016 \quad . \tag{3}$$

In the quark-parton model, the integral can be expressed as

$$I_G = \frac{1}{3} + \frac{2}{3}\int_0^1 dx \left[\overline{u}(x,Q^2) - \overline{d}(x,Q^2)\right] \quad . \tag{4}$$

The Gottfried sum rule [4], $I_G = 1/3$, follows from the assumption that the sea is up-down symmetric. The observed defect implies a small excess,

$$\int_0^1 dx \left[\overline{u}(x,Q^2) - \overline{d}(x,Q^2)\right] = -0.14 \pm 0.024 \quad , \tag{5}$$

of down quarks in the sea.

Because we expect I_G to be essentially independent of Q^2 [5], it is convenient to analyze the flavor content of the sea at a momentum scale relevant to hadron structure, where the important degrees of freedom are constituent quarks, Goldstone bosons, and gluons. Consider a proton composed of three constituent quarks: *uud*. An excess of down quarks over up quarks in the sea arises naturally from the isospin-respecting fluctuation of the constituent quarks into quarks and pions, the lightest of the Goldstone bosons, *viz.* $u \to (\pi^+ d, \pi^0 u)$ and $d \to (\pi^0 d, \pi^- u)$. If a denotes the probability for a constituent up quark to turn into a down quark and a π^+ (containing a u-quark and a $\bar{d}$-antiquark), the proton composition after one iteration is $(2+7a/4)u + (1+11a/4)d + (7a/4)\overline{u} + (11a/4)\overline{d}$. The valence composition remains $u_v = (u - \overline{u}) = 2$ and $d_v = (d - \overline{d}) = 1$, but the sea contains an excess of down quarks and antiquarks over up quarks and antiquarks.

In Ref. [1], we implemented this picture in the framework of the effective chiral quark model formulated by Manohar and Georgi [6]. A straightforward calculation

of the probability for a constituent quark to fluctuate leads to $I_G = 0.278$, encouragingly close to the experimental value (3). After adjusting the ultraviolet cutoff of the chiral quark model to better reproduce the observed Gottfried-sum-rule defect, we constructed parton distributions based on the Eichten-Hinchliffe-Lane-Quigg (EHLQ) Set 1 distributions [7]. These new distributions give a good account of the NMC measurements of the Gottfried integral, the difference $F_2^{\mu p} - F_2^{\mu n}$, and the ratio $F_2^{\mu n}/F_2^{\mu p}$. Details of the construction of the parton distributions and the comparison with data may be found in Ref. [1]. For present purposes, it is important to note that the flavor-asymmetric sea generated by chiral field theory, which is concentrated at small values of x, is a small perturbation on the flavor-symmetric sea of EHLQ Set 1 [7], $x\bar{u}(x) = x\bar{d}(x) = 0.182(1-x)^{8.54}$.

The production of massive muon pairs in proton-nucleus collisions offers another window on the composition of the sea. Fermilab experiment E772 has compared yields from the isoscalar targets ^{2}H and C with yields from a neutron-rich target, W. According to Eq. (2), the ratio of yields per nucleon [8] is $R_W(x) \approx 1 + 0.195(\bar{d}(x) - \bar{u}(x))/(\bar{d}(x) + \bar{u}(x))$. Because the measured ratio shown in Figure 1 is consistent with unity, the authors of Ref. [3] concluded that there is no evidence for a large flavor-asymmetry in the light-quark sea of the nucleon. There is, however, no conflict between the dilepton results and the Gottfried-sum-rule defect observed by NMC.

The chiral field theory calculation reviewed above leads with no readjustment of parameters to the thick solid curve [9] shown in Figure 1. That prediction is entirely consistent with the E772 data. So, too, is the flavor-asymmetric fit ("D0") made to deeply inelastic lepton scattering data by Martin, Roberts, and Stirling [10]. The effect on R_W is small because the ratio of $\bar{u}(x)/\bar{d}(x)$ is everywhere close to unity for both the chiral quark model and the MRS(D0) fit.

The data do discriminate against *ad hoc* modifications of the EHLQ structure

functions considered by Ellis and Stirling [11] and by us [1]. The dashed line in Figure 1 shows the prediction of the modified EHLQ structure functions with $\bar{u}(x)/\bar{d}(x) = (1-x)^{5.4}$ that we examined in Ref. [1]. This form magnifies the effect of a flavor asymmetry upon R_W at large values of x, whereas the Gottfried integral is determined by the magnitude of the $(\bar{d}-\bar{u})$ excess, which is determined at small x. Even in the interval $0.04 < x < 0.15$, however, the *ad hoc* form predicts a larger asymmetry than is observed.

Ellis and Stirling [11] proposed to examine the shape near $x_F = 0$ of the differential cross section $m^3 d\sigma/dx_F dm$ for the reaction $pd \to \mu^+\mu^- +$ anything as a probe of the difference between the proton and neutron sea distributions. We show in Figure 2 the Drell-Yan cross section predicted using the structure functions obtained from the chiral quark model. The lowest-order calculation has been normalized to the large-x_F data using a K-factor of 1.4. It gives an excellent fit to the E772 data, without the suppression of the $x_F < 0$ cross section given by the *ad hoc* parton distributions of Ellis and Stirling (cf. Figure 2 of Ref. [3]).

Direct comparison of the yield of dileptons from hydrogen and deuterium targets maximizes the sensitivity of the ratio R_A to a flavor asymmetry, because $R_p \approx 1 - (\bar{d}(x) - \bar{u}(x))/(\bar{d}(x) + \bar{u}(x))$. A new experiment has been proposed using the E772 apparatus to make this measurement [12]. The prediction of the chiral quark model, shown as the thick solid curve in Figure 3, is slightly below unity because hydrogen is a (maximally) neutron-*poor* nucleus. The effect of the flavor asymmetry in the nucleon sea is again small, as it is for the MRS(D0) structure functions plotted as the dotted curve. As expected, the *ad hoc* modification of the EHLQ structure functions produces a very large effect. Future experiments should be able to discriminate against this extreme possibility. Making the case for or against the flavor-asymmetric sea predicted by the chiral quark model presents a considerable challenge to dilepton

experiments.

Dilepton production in hadron-nucleus collisions complements deeply inelastic lepton scattering as a probe of the composition of the light-quark sea of the nucleon. Lepton scattering is the more sensitive probe at small x, because the difference $F_2^{\mu p} - F_2^{\mu n}$ is determined by the difference $\bar{d}(x) - \bar{u}(x)$, whereas the Drell-Yan process has greater sensitivity at large x, where the parton densities are small, because it measures the fractional difference $(\bar{d}(x) - \bar{u}(x))/(\bar{d}(x) + \bar{u}(x))$. We find the chiral quark model mechanism compelling and we look forward to new experimental tests of the small excess of $\bar{d}$ over $\bar{u}$ it implies at low values of x.

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[9] We have evolved the chiral quark model distributions to values of Q^2 corresponding to the E772 data points and evaluated the Drell-Yan cross section. The thin solid line results from neglecting the effects of Q^2-evolution and of $d\bar{d}$ annihilations. Those effects are seen to be are small.

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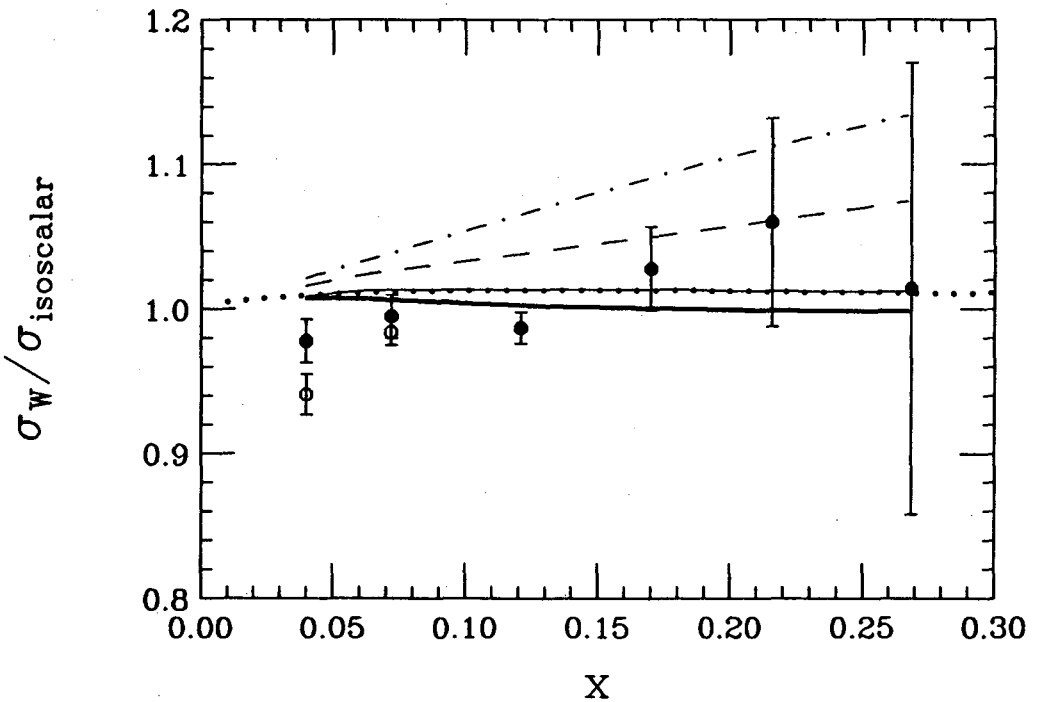
FIGURES

FIG. 1. The ratio $R_W \equiv \sigma_W/\sigma_{\rm isoscalar}$ of dilepton yields per nucleon from tungsten and isoscalar targets as a function of $x_{\rm target}$. The data are from Fermilab experiment E772, Ref. [3]. Open circles at small x are the ratio before correction for nuclear shadowing. The thick solid curve is our prediction based on chiral field theory, using the full Drell-Yan cross section with parton distributions evaluated at the dimuon mass. The thin solid curve is calculated using the parton distributions from chiral field theory at fixed $Q^2 = 5$ (GeV/c)^2 in Eq. (2). The dotted curve shows the prediction of the MRS(D0) parton distributions [10], using Eq. (2). An *ad hoc* modification of the EHLQ Set 1 structure functions (Ref. [7]) yields the dashed curve (Drell-Yan cross section, parton distributions evolved to $Q^2 = m^2$) and the dot-dashed curve (Eq. (2), fixed $Q^2 = 5$ (GeV/c)^2).

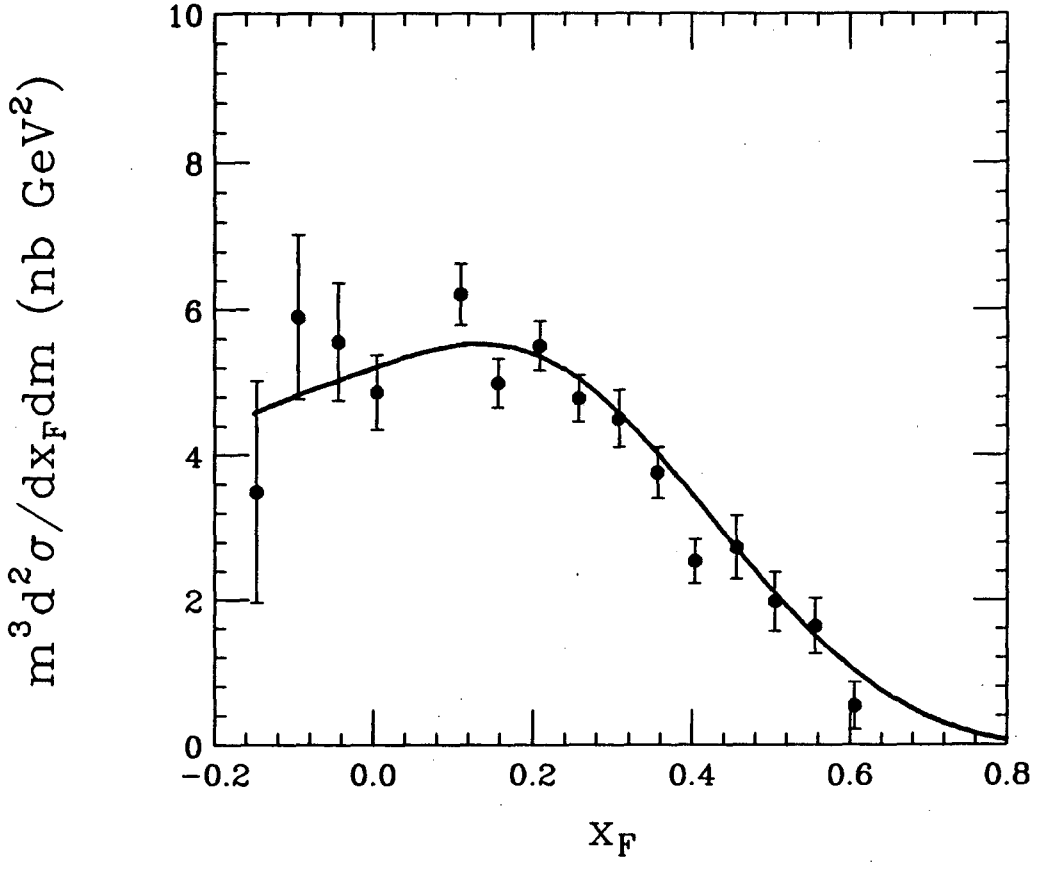
FIG. 2. Differential cross section $m^3 d\sigma/dx_F dm$ as a function of x_F for the reaction $pd \to \mu^+\mu^- +$ anything at 800 GeV from Fermilab experiment E772, Ref. [3]. The solid curve is our prediction based on chiral field theory for a dimuon mass $m = 8.15$ GeV/c^2.

FIG. 3. The ratio $R_p \equiv \sigma_p/\sigma_d$ of dilepton yields per nucleon from hydrogen and deuterium targets as a function of $x_{\rm target}$. The thick solid curve is our prediction based on chiral field theory, using the full Drell-Yan cross section with parton distributions evaluated at the dimuon mass. The thin solid curve is calculated using the parton distributions from chiral field theory at fixed $Q^2 = 5$ (GeV/c)^2 in Eq. (2). The dotted curve shows the prediction of the MRS(D0) parton distributions [10], using Eq. (2). An *ad hoc* modification of the EHLQ Set 1 structure functions (Ref. [7]) yields the dashed curve (Drell-Yan cross

section, parton distributions evolved to $Q^2 = m^2$) and the dot-dashed curve (Eq. (2), fixed $Q^2 = 5\ (\mathrm{GeV}/c)^2$).



Eichten–Hinchliffe–Quigg
Fermilab–Pub–92/264–T Fig. 1



Eichten–Hinchliffe–Quigg
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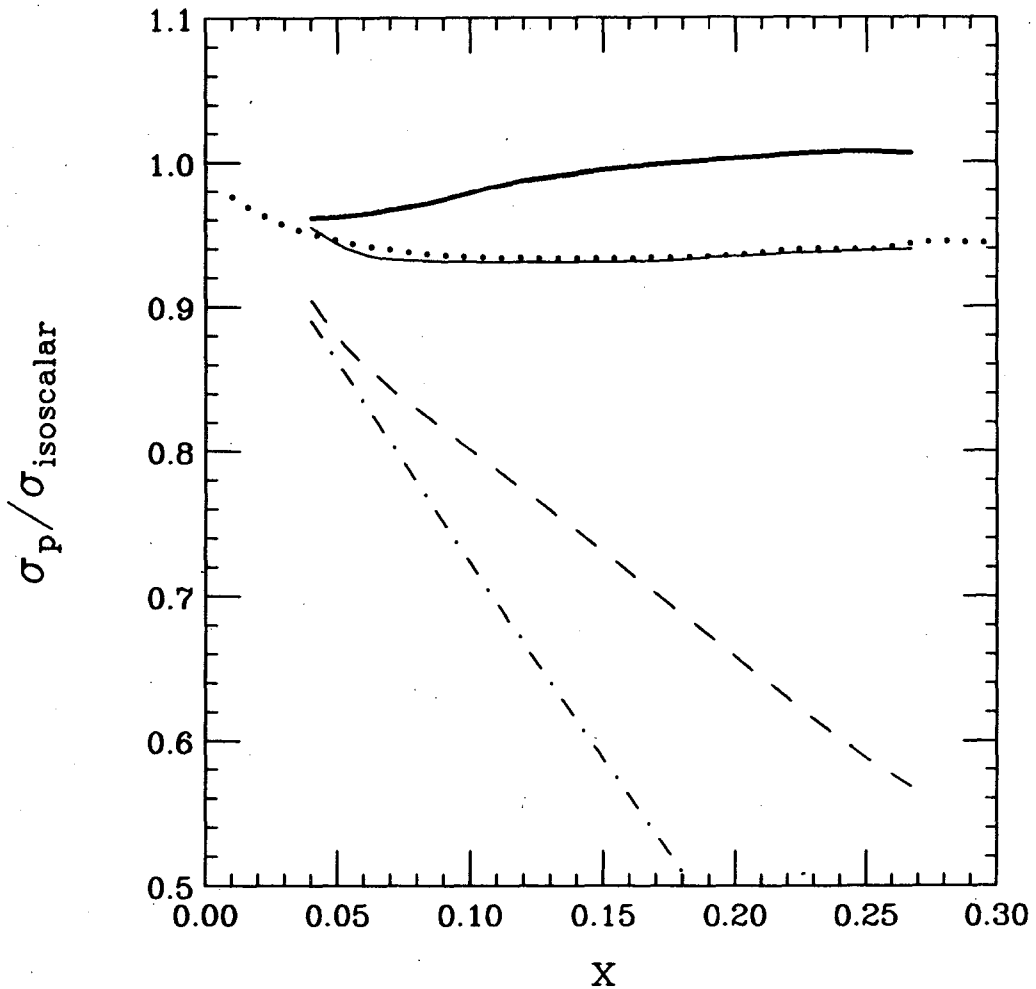

Eichten–Hinchliffe–Quigg
Fermilab–Pub–92/264–T Fig. 3