$\bar{d}$ over $\bar{u}$ asymmetry in a proton and Drell-Yan processes

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(Received 23 November 1992)

We investigate the extent to which Drell-Yan processes may be used to shed light on the $\bar{d}$ over $\bar{u}$ asymmetry in a proton, as implied by the recent finding of the New Muon Collaboration. To this end, we consider the Drell-Yan production experiment either with an 800 GeV proton beam or with a 200 GeV $\pi^\pm$ or $K^\pm$ beam, readily feasible at Fermilab (as a fixed target experiment). Numerical results indicate that the measurement of the p/N (proton-to-nucleon, i.e., normalized proton-to-deuteron) Drell-Yan production cross-section ratio is a suitable choice for unraveling the $\bar{d}$ over $\bar{u}$ asymmetry in a proton. The results also suggest that an experiment with a 200 GeV π^- or K^- beam is not suitable for this particular purpose although the calculated ratio differs significantly from unity.

PACS number(s): 12.40.Aa, 11.50.Li, 13.15.-f, 13.60.Hb

Much interest has been raised by the recent finding [1] by the New Muon Collaboration (NMC) on the violation of the Gottfried sum rule (GSR) [2]. The GSR has to do with the integral

$$I_G \equiv \int_0^1 \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] , \quad (1)$$

which is, in the context of the quark parton model [3],

$$\begin{aligned} I_G &= \frac{1}{3} \int_0^1 dx [u_p(x) - d_p(x) + \bar{u}_p(x) - \bar{d}_p(x)] \\ &= \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}_p(x) - \bar{d}_p(x)] , \end{aligned} \quad (2)$$

where $u_p(x)$ is the u -quark distribution in the proton and similarly for the other quark distributions $d_p(x)$, $\bar{u}_p(x)$, and $\bar{d}_p(x)$. In obtaining Eq. (2), one has used [3] *isospin invariance* in relating the distributions in a neutron to those in a proton to obtain $u_n(x) = d_p(x)$, $d_n(x) = u_p(x)$, $s_n(x) = s_p(x)$, etc. The Gottfried sum rule [2] may then be derived by assuming *isospin independence* of the sea distributions in the *proton*:

$$\bar{u}_p(x) = \bar{d}_p(x) , \quad (3)$$

so that $I_G = \frac{1}{3}$. Here we emphasize [3] that *isospin invariance*, or *isospin symmetry*, is *not* violated even if Eq. (3) is *not* true, since as a member of an isospin doublet the proton already has different valence u - and d -quark distributions. Thus, perhaps the recent finding [1] of the NMC group,

$$\begin{aligned} \int_{0.004}^{0.8} \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] \\ = 0.227 \pm 0.007(\text{stat}) \pm 0.014(\text{syst}) , \end{aligned} \quad (4)$$

with $\langle Q^2 \rangle = 4 \text{ GeV}^2$, should not be considered as a major surprise. As emphasized by Preparata, Ratcliffe, and

Soffer [4], the observed deviation of the Gottfried sum I_G from $\frac{1}{3}$ is at variance with the standard hypothesis used for years by practitioners in the area of parton distributions:

$$\bar{u}_p(x) = \bar{d}_p(x) \approx 2\bar{s}_p(x) . \quad (5)$$

Such a difference may be considered as a *surprise* but, as mentioned earlier, the deviation of the Gottfried sum I_G from the value of $\frac{1}{3}$ is *not* a signature for violation of isospin invariance or isospin symmetry.

As the standard hypothesis [Eq. (5)] may be nullified by the NMC data [Eq. (4)] it implies that almost all of the existing parametrized parton distributions, as well as the analyses of the high-energy experiments in extracting the sea quark distributions for the nucleon or other hadrons, suffer, to a certain degree, from the commonly accepted *bias*. In this regard, we might echo the criticisms raised by Preparata, Ratcliffe, and Soffer [4]. Indeed, the fact that the sea quark distributions $\bar{u}(x)$, $\bar{d}(x)$, $\bar{s}(x)$, and others, including their QCD evolutions, all differ from one another makes the effort of obtaining parametrized parton distributions a cumbersome and difficult task.

The NMC result has led to many theoretical analyses of the sea distributions in a proton. Preparata, Ratcliffe, and Soffer [4] and Ellis and Stirling [5] have modified structure functions by allowing $\bar{d}(x) \neq \bar{u}(x)$ to reconcile with the NMC data while trying to maintain fits to the global set of data. On the other hand, there have been considerations in relating the sea quark distributions of a nucleon to Sullivan processes [6], in which the probing virtual photon smashes the mesons emitted by the nucleon yielding, among others, antiquark or sea quark distributions. These analyses [7,8] have led Hwang, Speth, and Brown [9] to propose that the sea distributions of a hadron at low or moderate Q^2 (at least up to a few GeV^2) may be attributed primarily to generalized Sullivan processes [9]. Apart from the fact that good agreement with

the Chicago-Columbia-Fermilab-Rochester (CCFR) data [10] and the phenomenologically parametrized sea distributions may easily be reproduced, the NMC data on the deviation of the Gottfried sum I_G from the value of $\frac{1}{3}$ may be understood quantitatively. In addition to the agreement on the integrated value of GSR, it is shown [3] that the detailed x dependence of $F_2^{ep}(x) - F_3^{en}(x)$ is reproduced *without* any further adjustment of the input parameters adopted in the earlier study [9]. The agreement may be considered as a clear evidence toward the suggestion that the sea distributions of a hadron at low and moderate Q^2 may be attributed primarily to generalized Sullivan processes. This then gives the sea distributions which are not biased by the standard hypothesis [Eq. (5)] and may be used as input for QCD evolutions to higher Q^2 .

On a related front, there have been arguments in favor of the *effective* chiral quark model, in which pions are allowed to couple to the quarks in the constituent quark model. In particular, Eichten, Hinchliffe, and Quigg [11] use the model to show that the NMC data [1], as well as the earlier European Muon Collaboration (EMC) data [12] related to the proton spin, can be understood. It is clear that predictions using this picture are expected to be similar to what Hwang, Speth, and Brown [9] have proposed to do with the meson-baryon picture—except that in the latter there is an implied linkage between parton distributions at low and high Q^2 (or between nuclear and particle physics) while in the effective chiral quark model there may be simplifications (as the confinement issue of how quarks and antiquarks cluster into mesons and baryons has been set aside). In any event, we find it is difficult in general to distinguish between the two pictures. Accordingly, we shall not address the issue much further in this paper.

It is known that the proton-induced Drell-Yan (DY) process [13] in the kinematic range $x_F \geq 0.1$ (with x_F the Feynman scaling variable) is sensitive to the antiquark distribution of the target nucleons, as the cross section is dominated by the term $\frac{4}{3}u(x_b)\bar{u}(x_t)$. This had led to the Fermilab E772 experiment [14] which demonstrates, among others, that the sea quark distributions of a nucleon in a nucleus do not differ significantly from those of a free nucleon. Comparing the DY production data from isoscalar targets [2], H and C, to W which has a large neutron excess, we have

$$R \equiv 1 + \frac{N-Z}{A} \frac{\left. \frac{d^2\sigma}{dx_F dx_t} \right|_N - \left. \frac{d^2\sigma}{dx_F dx_t} \right|_p}{\left. \frac{d^2\sigma}{dx_F dx_t} \right|_N}. \quad (6)$$

The factor $(N-Z)/A$ is 0.183 (for W) which is not small, but it becomes unity if we could compare the DY production data on the proton target to that on the deuteron target.

The primary objective of this report is to investigate how the Drell-Yan asymmetry may be used to shed some light on the $\bar{d}$ over $\bar{u}$ asymmetry in the proton, as implied by the NMC data. To this end, we focus primarily on the

model prediction based on the meson-baryon picture [9]. In particular, we do not make any further adjustment of the input parameters adopted in the earlier study [9] and make predictions on the p/N (proton-to-nucleon) Drell-Yan production cross-section ratio using an 800 GeV proton beam (available at Fermilab), a 200 GeV $\pi^\pm$ beam, or a 200 GeV $K^\pm$ beam.

Specifically, the valence quark distributions are taken from Eichten, Hinchliffe, Lane, and Quigg (EHLQ) [15] while the parton distributions of a pion are taken from a recent work of Sutton *et al.* [16]. Parton distributions of baryons and mesons, as needed for the input for generalized Sullivan processes, are then obtained [9] through suitable flavor-SU(3) rotations. Note that the valence quark distributions of a nucleon do not depend much on the model while Sutton *et al.* consider extraction of parton distributions of a pion from the more recent NA10 [17], E615, [18], and WA70 [19] Drell-Yan and direct-photon data, instead of from the old NA3 data [20].

We then use the convolution formulas explained in Ref. [9] to generate sea quark distributions; for additional details (including values of the input parameters), an interested reader may consult Ref. [9]. The standard formula for the Drell-Yan production cross section is adopted. The Q^2 dependence is taken into account by first generating parton distributions at two different Q^2 and then performing necessary interpolations to obtain parton distributions at the desired Q^2 . This method is adopted as an approximation since it saves us a tremendous amount of effort in numerically generating (each time for given x_F and x_t) parton distributions which vary with x_F and x_t . The effect of additional higher-order QCD corrections, other than those included in QCD evolutions, is expected to be of negligible importance since we are interested in Drell-Yan production in the limited kinematic range where the so-called “ K factor” varies only slightly.

In what follows, we present and discuss a few sample numerical results obtained in the analysis.

In Fig. 1, we discuss the implication of the E772 experiment in light [21] of the $\bar{d}$ over $\bar{u}$ asymmetry in the proton. The ratio as specified by Eq. (6) is plotted as a function of the target $x(x_t)$. Note that the data points for different x_t have different x_F (as listed in Table I of Ref. [21]) and as is for our theoretical result. The solid curve is from the theory based on the meson-baryon picture [9] and it agrees well with the data.

As we set $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values (for the isoscalar target nucleon), the predicted ratio, shown as a dot-dashed curve in Fig. 1, differs from unity. Note that it is the difference between the solid curve and the dot-dashed curve, which is caused by $\bar{d} \neq \bar{u}$. Note also that the E772 data is not capable of distinguishing between the solid curve (of which the difference from unity is caused primarily by $\bar{d} \neq \bar{u}$ as predicted by the meson-baryon picture [9]) and the dot-dashed curve (which has nothing to do with $\bar{d} \neq \bar{u}$). However, it is clear that the situation can be improved sharply for an experiment employing only the proton and deuteron targets—as an accuracy of about 1% for the ratio shown in Fig. 1 may in fact be attained from the amount of running time similar to the E772 measurement.

FIG. 1. The predictions on the E772 result, showing that the accuracy in the measured ratio must be significantly better than 5% in order to pin down the $\bar{d}$ over $\bar{u}$ asymmetry in the proton.

FIG. 2. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for an 800 GeV proton beam as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Sullivan processes, with the EHLQ valence distributions for a proton, are used to generate sea quark distributions, as in the work of Hwang, Speth, and Brown [9]. If we arbitrarily set $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values (in the isoscalar nucleon case), the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$.

On the other hand, the prediction from the distributions of Ellis and Stirling [5] is shown as the dashed curve in Fig. 1, which differs significantly from that obtained from the meson-baryon picture [9] and can barely agree with the E772 data. The result from the effective chiral quark model [11] is similar to the solid curve—as the theory differs from the meson-baryon picture [9] only at the question of how pions are introduced. (See Ref. [21].) It is clear from Fig. 1 that improvement is needed for the E772 experiment, if the effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry can be accurately pinned down by the experiment.

We therefore move on to survey the possibility of using the proton and the deuteron separately as the target and deduce the ratio

$$\frac{d^2\sigma}{dx_F dx_t} \Big|_p / \frac{d^2\sigma}{dx_F dx_t} \Big|_N.$$

As discussed earlier, this ratio may be far better than that used in the E772 experiment [21] as far as the effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry is concerned.

In Fig. 2, the calculated ratio

$$\frac{d^2\sigma}{dx_F dx_t} \Big|_p / \frac{d^2\sigma}{dx_F dx_t} \Big|_N$$

for an 800 GeV proton beam is shown as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). If

FIG. 3. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for an 800 GeV proton beam as a function of x_t for $x_1=0.1$ (solid curve) and $x_2=0.3$ (dashed curve). Setting arbitrarily $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values, the predicted ratio is shown as a dot-dashed curve for $x_1=0.1$ and as a dot-dot-dashed curve for $x_1=0.3$.

we arbitrarily set $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values (in the isoscalar nucleon case), the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$. Figure 3 is a similar plot except that x_F is replaced by x_1 , the beam x . Note that if we replace the EHLQ distribution by the recent update of Owens [22], the resultant curves are almost indistinguishable from those in the EHLQ case.

Figures 2 and 3 indicate that the effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry is of the order of 10–20 %, a sizable effect which is readily detectable if we may use the E772 experiment as a guide.

We have also surveyed the possibility of using a 200 GeV $\pi^\pm$ beam or a 200 GeV $K^\pm$ beam instead of an 800 GeV proton beam. The results are illustrated in Figs. 4–7, respectively. In each of these figures, the calculated ratio

$$\left. \frac{d^2\sigma}{dx_F dx_t} \right|_p / \left. \frac{d^2\sigma}{dx_F dx_t} \right|_N$$

is shown as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Sullivan processes, with the EHLQ valence distributions for a proton, are used to generate sea quark distributions, as in the work of Hwang, Speth, and Brown [9]. If we arbitrarily set $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values (for an isoscalar

nucleon), the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$. If we replace the EHLQ distribution by the recent update of Owens [22], the resultant ratio is shown as a dotted curve.

We may summarize the messages from Figs. 4–7 as follows.

(1) The effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry is not more prominent than that in the case of the 800 GeV proton beam, although the ratio itself may differ more sharply from unity than in the proton case. In particular, the effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry is tiny for a 200 GeV π^- or K^- beam but the ratio is generally in the range of 20–40 %. This is due to an obvious fact that the valence antiquarks in the meson sees the valence quarks in the target—the proton and the deuteron differ significantly in their valence u and d quarks. By comparing the π^+p and π^-p Drell-Yan production cross sections, the E615 Collaboration [23] have been able to deduce the sea-to-valence ratio, as a function of x_t , in the proton target. It has been shown [9] that such ratio can be understood in the meson-baryon picture. We have made certain that these considerations are not affected in any significant way by the $\bar{d}$ over $\bar{u}$ asymmetry as observed in the NMC experiment [1] (and accounted for in the meson-baryon picture [9]).

(2) If we replace the EHLQ valence distribution by the

FIG. 4. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for a 200 GeV π^+ beam as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Setting arbitrarily $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values, the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$. If we replace the EHLQ distribution by the recent update of Owens [22], the resultant ratio is shown as a dotted curve.

FIG. 5. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for a 200 GeV K^+ beam as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Setting arbitrarily $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values, the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$. If we replace the EHLQ distribution by the recent update of Owens [22], the resultant ratio is shown as a dotted curve.

FIG. 6. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for a 200 GeV π^- beam as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Setting arbitrarily $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values, the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$.

FIG. 7. The calculated ratio $(d^2\sigma/dx_F dx_t)|_p / (d^2\sigma/dx_F dx_t)|_N$ for a 200 GeV K^- beam as a function of x_t for $x_F=0.1$ (solid curve) and $x_F=0.3$ (dashed curve). Setting arbitrarily $\bar{d}(x)$ and $\bar{u}(x)$ to the average of the calculated values, the predicted ratio is shown as a dot-dashed curve for $x_F=0.1$ and as a dot-dot-dashed curve for $x_F=0.3$.

recent update of Owens [22], the resultant ratio differs more visibly from the corresponding EHLQ result in the π^+ and K^+ case than in the proton case. This model dependence may further obscure the effort to pin down the $\bar{d}$ over $\bar{u}$ asymmetry in the proton, if a $\pi^\pm$ or $K^\pm$ beam is employed.

As a general remark, the calculated cross sections vary with the beam and its energy. As numerical examples, the double differential cross section

$$\left. \frac{d^2\sigma}{dx_F dx_t} \right|_N$$

at $x_F=0.1$ and $x_t=0.15$ (with the so-called K factors yet to be included) is $1.9 \times 10^{-4} \mu\text{b}$ for an 800 GeV proton beam and 1.3×10^{-2} , 2.1×10^{-3} , 2.7×10^{-2} , and $7.4 \times 10^{-3} \mu\text{b}$, respectively, for 200 GeV π^+ , K^+ , π^- , and K^- beams. However, it is clear that the (primary) proton beam intensity is considerably higher than the intensity of a secondary π or K beam, suggesting that a proton-beam experiment similar to the Fermilab E772 experiment [14,21] is more feasible. Nevertheless, the experimental feasibility of using a $\pi^\pm$ or $K^\pm$ beam to clarify the $\bar{d}$ over $\bar{u}$ asymmetry in the proton should be investigated further (especially since the asymmetry may sometimes affect the analysis of a $\pi^\pm p$ or $K^\pm p$ Drell-Yan ex-

periment aiming at other specific purposes, such as the E615 experiment [23]).

In conclusion, it appears to be feasible to use the Drell-Yan processes to extract the effect caused by the $\bar{d}$ over $\bar{u}$ asymmetry in the proton, as implied by the NMC data [1]. To this end, we have considered the Drell-Yan production experiment either with an 800 GeV proton beam or with a 200 GeV $\pi^\pm$ or $K^\pm$ beam. Numerical results indicate that the measurement of the p/N (proton-to-nucleon, i.e., normalized proton-to-deuteron) Drell-Yan production cross-section ratio is a suitable choice for unraveling the $\bar{d}$ over $\bar{u}$ asymmetry in a proton. The feasibility of such a specific fixed-target experiment at Fermilab is already demonstrated by the E772 experiment. Our results also suggest that an experiment with a 200 GeV π^- or K^- beam is not suitable for this particular purpose although the calculated ratio differs significantly from unity.

We would like to thank P. L. McGaughey (at Los Alamos) and J. Speth (at Jülich) for helpful conversations. W.-Y.P.H. wishes to acknowledge members of the P-2 group, especially J.-C. Peng and J. M. Moss, for the hospitalities extended to him during his 1992 summer visit. His research work was supported in part by the National Science Council of the Republic of China (NSC82-0208-M002-036).

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