Sea quark content of nucleons from proton-induced
Drell-Yan production

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Abstract We analyse the proton-induced Drell-Yan production in both
the flavor asymmetry and isospin breaking explanations for the violation of
the Gottfried sum rule. Consequences from three different forms of correc-
tions to the flavor and isospin symmetric parton distributions are examined.
It is found that the calculated results are sensitive to the choices of para-
ters and parton distributions, and to the ways the corrections are introduced.
All three forms of corrections could be consistent with the recent Fermilab
Experiment E772 data for the ratio of cross section \( R = \sigma_W/\sigma_{IS} \) and for
the shape of the differential cross section \( m^2d^2\sigma/dx_Fdm \) for \(^2\text{H}^\).
Recently, the violation of the Gottfried sum rule (GSR) reported by the New Muon Collaboration (NMC) \cite{1} has received attention and a number of papers have been devoted to discuss the explicit form of flavor sea distributions in the nucleons\cite{2}. Several different explanations for the origin of the GSR violation have been proposed, such as a flavor asymmetry of the nucleon sea\cite{3}, isospin symmetry breaking between the proton and the neutron\cite{4}, non-Regge behaviors at small $x$ \cite{5}, and nuclear effects like the mesonic exchanges in the deuteron \cite{6} and nuclear bindings \cite{7}. The possibilities to discriminate between these different explanations through other processes have also been analysed \cite{2},\cite{8}-\cite{12}. It was first pointed out by Ellis and Stirling \cite{8} that proton-induced Drell-Yan production is one of the sensitive processes that can provide some further information concerning the origin of the GSR violation. The Drell-Yan asymmetry $A_{DY}(x_1, x_2) = \frac{\sigma_{pp}(x_1, x_2) - \sigma_{pn}(x_1, x_2)}{\sigma_{pp}(x_1, x_2) + \sigma_{pn}(x_1, x_2)}$ for $x_1 = x_2$ was introduced and it was found that this quantity can change sign depending on whether the sea is flavor symmetric or not. The shape of the differential cross section was observed to be different for pp collisions and pn collisions. Kumano and Londergan examined the Drell-Yan asymmetry for several different quark distributions assuming flavor asymmetry and showed that the estimates for this quantity differ widely \cite{10}. The modification to the value of $A_{DY}$ from nuclear binding effects was found to be very small.
in comparison with the results in the flavor and isospin symmetry case\cite{12}. It has also been indicated by us \cite{2} that $A_{DY}$ has approximately the same value for the flavor asymmetry and isospin breaking explanations, thus it is difficulty to distinguish between these two explanations.

The recent proton-induced Drell-Yan production data reported by Fermilab Experiment E772 \cite{13} show no evidence for a large flavor asymmetric sea. However, in a most recent study it was shown that a sea flavor asymmetric parton distribution derived from a chiral quark model can provide a satisfactory description of the E772 data\cite{14}. Thus we need to study further the implications of the E772 data for the explicit flavor distributions in the quark sea of nucleons. We will examine in this paper three different forms of corrections to the flavor and isospin symmetric parton distributions in the flavor asymmetry and isospin breaking explanations. We will show that the results for a hard correction $a(1 - x)^b$ (i.e., a non-Pomeron form, referred to as I) and for a medium-hard correction $ax^{-1/2}(1 - x)^b$ (i.e., a pionic form, referred to as II) are rather sensitive to the parameters used, to the choices of parton distributions, and to the ways the corrections are introduced. They could be consistent with the E772 data for the ratio of cross section per nucleon $R = \sigma_W/\sigma_{IS}$ and for the shape of the differential cross section $m^3d^2\sigma/dx_Fdm$ for $^2\text{H}$. The results for a soft correction $ax^{-1}(1 - x)^b$
(i.e., a Pomeron form, referred to as III) are less sensitive to parameters and the ways the corrections are introduced, and can describe the E772 data. Thus the available Drell-Yan data pose constraints on the explicit form of the sea parton distributions and on how the corrections to the flavor and isospin symmetric sea distributions are introduced in the two explanations, but cannot rule out any possible explanations.

We show that the Ellis-Stirling sign criterion \[8\] of the Drell-Yan Asymmetry \(A_{DY}(x_1, x_2)\) is also correct in the case \(x_1 \neq x_2\). The expression for the cross section is

\[
\sigma^{pN}(x_1, x_2) = \frac{d^2 \sigma^{pN}}{dx_1 dx_2} = \frac{4\pi \alpha^2}{9m^2} K \sum_i e_i^2 [q_i^p(x_1)\overline{q}_i^N(x_2) + \overline{q}_i^p(x_1)q_i^N(x_2)], \tag{1}
\]

where \(x_1\) and \(x_2\) are the Bjorken variables for the beam hadron \((p)\) and the target hadron \((N)\), \(m^2 = Sx_1x_2\) with \(m\) denoting the mass of the dilepton and \(\sqrt{S} = \sqrt{2M_p(E_{lab} + M_p)}\) denoting the total energy of the beam and the target in the center of mass frame, and \(K\) is a normalization factor due to complicated higher-order processes. We thus obtain, in the flavor asymmetry explanation,

\[
A_{DY}(x_1, x_2) = \frac{(4\overline{u}_1 - \overline{d}_1)(u_2 - d_2) - (\overline{d}_2 - \overline{u}_2)(4u_1 - d_1)}{(4\overline{u}_1 + \overline{d}_1)(u_2 + d_2) + (\overline{d}_2 + \overline{u}_2)(4u_1 + d_1) + 4\overline{s}_1 \overline{s}_2}, \tag{2}
\]
and, in the isospin breaking explanation,

\[ A_{DY}(x_1, x_2) = \frac{3q_1^p(u_2 - d_2) - (\bar{q}_2^p - \bar{q}_2^n)(4u_1 + d_1 + 5\bar{q}_1^p)}{5q_1^p(u_2 + d_2 + \bar{q}_2^p - \bar{q}_2^n) + (\bar{q}_2^p + \bar{q}_2^n)(4u_1 + d_1) + 4s_1s_2}, \tag{3} \]

where \( u_1 = u(x_1), \) \( u_2 = u(x_2), \) \( d_1 = d(x_1) \) and \( d_2 = d(x_2) \) et al. are the quark distributions in the proton. It can be easily found that the quantity \( A_{DY}(x_1, x_2) \) is always positive in the flavor and isospin symmetry case (as \( u_2/d_2 \geq 1 \)) whereas it can change sign for the flavor and/or isospin asymmetry cases. The ratio \( R = \sigma_W/\sigma_{IS} \) can be expressed as

\[ R = \frac{N\sigma^{pn} + Z\sigma^{pp}}{A/2(\sigma^{pn} + \sigma^{pp})} = 1 - \frac{N - Z}{A}A_{DY}. \tag{4} \]

This quantity is always smaller than unity for the flavor and isospin symmetry case whereas it is possible to get values above unity for the flavor and/or isospin asymmetry cases. Therefore a confirmation of any point larger than unity will be the evidence for flavor asymmetry in the nucleon sea or the isospin breaking between the proton and the neutron. The consideration of further nuclear effects could complicate the above analysis. To calculate the differential cross section \( m^3 d^2\sigma/dx_F dm \) for \(^2\)H, we use the expression

\[ m^3 d^2\sigma^{AB}/dx_F dm = \frac{8}{9}\pi\alpha^2 \left( \frac{x_1x_2}{x_1 + x_2} \right) K \sum_i e_i^2[q_i^A(x_1)\bar{q}_i^B(x_2) + \bar{q}_i^A(x_1)q_i^B(x_2)], \tag{5} \]

where \( x_F = x_1 - x_2 \) and the \( K \) factor is adjusted to fit the large-\( x_F \) data.
We first modify the sea by

\[ \bar{d}(x) = \bar{q}_0(x) + \frac{5}{6} \Delta(x); \]
\[ \bar{u}(x) = \bar{q}_0(x) - \frac{5}{6} \Delta(x), \]

as adopted in Ref. [8], in the flavor asymmetry explanation. In the isospin breaking case we modify the sea by

\[ \bar{q}_n(x) = \bar{q}_0(x) + \Delta(x); \]
\[ \bar{q}_p(x) = \bar{q}_0(x). \]

We adopt the three forms of corrections as mentioned above for \( \Delta(x) = \bar{q}_n(x) - \bar{q}_p(x) = \frac{2}{3}(\bar{d}(x) - \bar{u}(x)) \) in the two explanations respectively, with the parameters \( a \) and \( b \) adjusted to fit \( \int_0^1 dx \Delta(x) = 0.084 \) as required to reproduce the observed NMC result \( S_G = 0.240 \). We indicate that all three forms of corrections could be compatible with the NMC data \( F_2^u(x)/F_2^p(x) \), from which the Gottfried sum \( S_G = 0.240 \) is obtained. The reason is that there are many different parametrizations of the parton distributions which may give different detailed features. In Ref. [9] a correction of form I was suggested to represent the difference between the up and down quark sea in the flavor asymmetry explanation, based on an old parametrization MRS(B) [13].

The corrections of form II have been studied by many authors in a framework where the flavor asymmetry in the sea is attribute to the excess of \( p \to n + \pi^+ \) over \( p \to \Delta^{++} + \pi^- \) (or \( \pi^+ \) over \( \pi^- \)) [10], or from a more
microscopic point of view to the excess of $u \rightarrow d + \pi^+$ over $u \rightarrow u + \pi^0$ and $d \rightarrow u + \pi^-$ over $d \rightarrow d + \pi^0$\cite{17}. Considering that the sea parton distributions are of Pomeron form, we can attribute form III correction as a small perturbation in the sea distributions. In Fig. 1 we present the results of the calculated ratio $F_2^n/F_2^p$ by using three forms of corrections based on two parametrizations of parton distributions, i.e., EHLQ set 1 \cite{18} and the new MRS(S0) set \cite{19}. We see that form I and II corrections give good descriptions of the NMC data based on the old parametrization EHLQ set 1. The correction of form III is also consistent with the data based on the new parametrization MRS(S0) set. Changing the parameter $b$ causes very small changes in $F_2^n/F_2^p$. Therefore we can examine the influences from the three form corrections in the description of the ratio $R = \sigma_W/\sigma_{IS}$ and the shape of $m^3d^2\sigma^{pd}/dx_Fdm$ in Drell-Yan process, regardless of the detailed parametrization dependence.

In Figs. 2, 3 and 4 we compare the calculated results of $R = \sigma_W/\sigma_{IS}$ and $m^3d^2\sigma^{pd}/dx_Fdm$ with the E772 data. The data of $R$ at large $x_{target}$ do not exclude points larger than unity. The data at small $x_{target}$ have been corrected to remove the nuclear shadowing effect \cite{13}. Because W is significantly heavier than C and Ca, the targets used to determine the shadowing factor $\alpha_{sh}$, we can not exclude the possibility that the shadowing correction
is larger than estimated by using $\sigma_A = \sigma_N A^{\alpha_{sh}}$. This could increase the data slightly at small $x_{\text{target}}$. From Figs. 2 and 3 we find large parameter dependence in the calculated results for corrections of form I and II. For small $b$ we see that the calculated $R$ is larger than the E772 data in the flavor asymmetry explanation whereas it is compatible with the data in the isospin breaking explanation. $R$ is slightly dependent on $b$ in the isospin breaking case whereas it decreases significantly for large $b$ in the flavor asymmetry case. The value of $m^3 d^2 \sigma^{pd} / dx_F dm$ will decrease at negative $x_F$ for large $b$ in the two explanations. Because the shape of the calculated $m^3 d^2 \sigma^{pd} / dx_F dm$ is dependent on the the parton distributions, we can hardly say that this trend is in disagreement with the data. From Figs. 2 and 3 we see that the calculated results of $R$ and $m^3 d^2 \sigma^{pd} / dx_F dm$ could be consistent with both the data depending on the parametrization we choose. For example, we can list a number of results which are consistent with the data, e.g., form I correction with $b = 12.2$ using the MRS(S0) set parton distributions, form II correction with $b = 6.68$ using the MRS(S0) set parton distributions, form I correction in the isospin breaking explanation with $b = 5.02$ using the EHLQ set 1 parton distributions, etc. However, the calculated results are not so sensitive for form III corrections. From Fig. 4 we see that the calculated $R$ and $m^3 d^2 \sigma^{pd} / dx_F dm$ are not so different from those in the flavor and
isospin symmetry case, thus they are consistent with the data for both sets of parton distributions.

From the above discussions we see that for form I and II corrections there are large differences between the results in the two explanations. This feature, which disagrees with our previous conclusion [2] that the Drell-Yan asymmetry $A_{DY}$ has approximately the same value for the two explanations, is due to the fact that the assumption $4\bar{u} - \bar{d} \sim (\bar{u}^p + 8\bar{d})/3$ made in Ref. [4] is not satisfied for the corrections Eqs. (6) and (7). If we modify the sea by

$$
\bar{d}(x) = \bar{q}_0(x) + 5/3 \Delta(x);
$$

$$
\bar{u}(x) = \bar{q}_0(x) \quad (8)
$$
in the flavor asymmetry explanation, we can reduce the difference between the results in the two explanations significantly. This can be seen from Fig. 5, where the results for form I correction with $b = 5.02$ are presented. We see that the results for $R$ in the two explanations are approximately the same and are consistent with the data. The calculated $m^3 d^2 \sigma^{nd}/d x_F dm$ increases at negative $x_F$ compared with that in the flavor and isospin symmetry case, thus the shape is in agreement with the data for the EHLQ set 1 parton distributions. Therefore the Drell-Yan process is hardly able to settle whether the violation of the Gottfried sum rule is due to flavor asymmetry or isospin breaking, as we have concluded in Ref. [4].
In summary, we analysed the proton-induced Drell-Yan production in both the flavor asymmetry and isospin breaking explanations for the violation of the Gottfried sum rule. We examined three different forms of corrections to the flavor and isospin symmetric parton distributions, and found that the results are sensitive to parameters, parton distributions, and the ways the corrections are introduced. We conclude that the Drell-Yan process can settle whether the sea is flavor and isospin symmetric or not according to the Ellis-Stirling sign criterion, and it leads to constraints on the explicit form of the sea parton distributions and on how the sea is deformed from the flavor and isospin symmetry case.

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Figure Captions

Fig. 1. The ratio $F_2^n/F_2^p$ as a function of the Bjorken scaling variable $x$. The data are from the NMC measurement\cite{1}. The solid, dashed, and dotted curves are the calculations in the flavor and isospin symmetry, flavor asymmetry, and isospin breaking cases, respectively, with thin and thick curves corresponding to results based on the EHLQ set 1 \cite{18} and MRS(S0) set \cite{19} of parton distributions. In the figure the dashed and dotted curves are in coincidence. (a) The results for form I correction with $b = 9.6$. (b) The results for form II correction with $b = 6.68$. (c) The results for form III correction with $b = 6.06$.

Fig. 2. The ratio $R = \sigma_W/\sigma_{IS}$ as a function of the Bjorken variable for the target $x_{\text{target}}$ and the differential cross section $m^3d^2\sigma/dx_Fdm$ for $^2\text{H}$ as a function of $x_F$. The data are from Fermilab Experiment E772, Ref. \cite{13}. The curves, which have the same meaning as those in Fig. 1, represent the calculations for form I correction, with the following parameter: (a) $b = 9.6$; (b) $b = 12.2$; and (c) $b = 5.02$. The results of (c) in the flavor asymmetry case suffer the flaw of having negative $\pi(x_{\text{target}})$ at large $x$ for the EHLQ set 1 parton distributions.

Fig. 3. Same as Fig. 2, but the calculated results are for form II correction,
with the following parameter: (a) $b = 6.68$; (b) $b = 4.13$.

Fig. 4. Same as Fig. 2, but the calculated results are for form III correction, with the following parameter: (a) $b = 6.06$; (b) $b = 3.06$.

Fig. 5. Same as Fig. 2(c), but the results in the flavor asymmetry case are calculated by using Eq. (8), instead of Eq. (6). This removes the negative $\pi(x_{target})$ at large $x$ occurred in Fig. 2(c).