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Shape of the $\bar{d} - \bar{u}$ asymmetry

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Abstract

Using data from a recent reanalysis of neutron structure functions extracted from inclusive proton and deuteron deep-inelastic scattering (DIS), we re-examine the constraints on the shape of the $\bar{d} - \bar{u}$ asymmetry in the proton at large parton momentum fractions x. A global analysis of the proton–neutron structure function difference from BCDMS, NMC, SLAC and Jefferson Lab, and Fermilab Drell-Yan lepton-pair production cross sections, suggests that existing data can be well described with $\bar{d} > \bar{u}$ for all values of x currently accessible. We compare the shape of the fitted $\bar{d} - \bar{u}$ distributions with expectations from nonperturbative models based on chiral symmetry breaking, which can be tested by upcoming Drell-Yan data from the SeaQuest experiment at larger values of x.

I. INTRODUCTION

The microscopic structure of the proton's quark–antiquark sea has intrigued and stimulated nuclear and particle physicists for several decades, providing a valuable window on the nonperturbative dynamics governing quarks and gluons in QCD (see Refs. [1–5] for reviews). One of the most spectacular examples of how this endeavor has produced important insights into the partonic nature of the nucleon has been the flavor asymmetry in the light antiquark sea of the proton, $\bar{d} - \bar{u}$. This is expected to be negligibly small on the basis of perturbative gluon radiation alone [6], with a scale dependence that is suppressed by the strong coupling, $\alpha_s(Q)$. Predicted by Thomas [7] on the basis of chiral symmetry breaking in the strong interactions, a large excess of $\bar{d}$ over $\bar{u}$ was, however, confirmed by several experiments involving inclusive deep-inelastic scattering (DIS) from protons and deuterons [8, 9], semi-inclusive DIS with tagging of π^+ and π^- mesons [10], and most directly by Drell-Yan lepton-pair production in pp and pd scattering at high energies [11–13]. A quarter of a century of experimental and theoretical efforts have together led to a general consensus that a sizeable positive $\bar{d} - \bar{u}$ asymmetry exists, and that its origin is likely related to the role of the pion cloud in the nucleon, and more generally of chiral symmetry breaking in QCD [14].

While the integrated value of the $\bar{d} - \bar{u}$ asymmetry is an important indicator of nonperturbative physics, the shape of the $\bar{d} - \bar{u}$ asymmetry itself contains even more detailed information about the quark-gluon dynamics in the proton's sea. In particular, the shape of the asymmetry as a function of the parton momentum fraction, x, has been the source of much interest, especially regarding its sign at large parton momentum fractions x. Analysis of the Drell-Yan data from the Fermilab E866 experiment [12, 13] has suggested that the ratio of pd to pp lepton-pair production cross sections drops below unity at small values of the Feynman-x variable, $x_F = 2p_L/\sqrt{s}$, which corresponds to large values of the partonic fraction carried by $\bar{d}$ and $\bar{u}$ quarks in the target. This has been interpreted as evidence for a sign change in $\bar{d} - \bar{u}$ beyond $x \approx 0.3$, which has not been possible to accommodate in any natural way in calculations based on chiral symmetry breaking and the pion cloud [15].

Excess of $\bar{u}$ over $\bar{d}$ was found in other approaches, based on antisymmetrization of quark-antiquark pairs in the sea with the valence quarks in the core of the proton. Using a simple 3-quark model of the nucleon with pair creation mediated by one gluon exchange [16], Steffens and Thomas [17] found that interference effects between the radiated $q\bar{q}$ pairs and the core

valence quarks actually generates more $u\bar{u}$ pairs than $d\bar{d}$ pairs. Confirmation of a sign change in the $\bar{d}-\bar{u}$ difference would therefore be a unique signal for the presence of nonperturbative phenomena in the nucleon sea beyond those associated with chiral symmetry breaking. Such effects may also be needed to explain a possibly large polarized sea quark asymmetry $\Delta\bar{d}-\Delta\bar{u}$ in the proton [18, 19], which to leading order does not receive contributions directly from pseudoscalar meson loops.

In an interesting recent analysis, Peng *et al.* [20] in fact argued that a sign change in $\bar{d}-\bar{u}$ at intermediate x is supported by an analysis of the proton and deuteron DIS structure functions. Combining the isovector $F_2^p - F_2^n$ structure function derived from the NMC measurements [21, 22] with parametrizations of the valence quark PDFs, Peng *et al.* used a leading order (LO) approximation for the structure functions to extract the x dependence of $\bar{d}-\bar{u}$ at $Q^2 = 4$ GeV^2, which displayed a sign change at $x \approx 0.4$. This intriguing behavior, along with the apparent indication of a sign change in $\bar{d}-\bar{u}$ from the E866 data [12, 13], will soon be tested experimentally by the new SeaQuest Drell-Yan experiment at Fermilab [23], which will extend the kinematical coverage to almost $x \approx 0.5$.

In addition to the large-x behavior, there are also questions about the sign of $\bar{d}-\bar{u}$ at low values of x, below where the current Drell-Yan data extend. In particular, there have been indications in some global PDF analyses for a pull to negative $\bar{d}-\bar{u}$ at low x, driven by the HERA charged and neutral current DIS data [24]. However, the constraining power of the HERA data for the light flavor asymmetry at high x is not as strong as the Drell-Yan data.

In this paper we revisit the question of the shape of the $\bar{d}-\bar{u}$ asymmetry in the light of a new global analysis of neutron structure functions [25] extracted from inclusive proton and deuteron DIS data from experiments at BCDMS [26], NMC [21, 22], SLAC [27, 28] and a new compilation of Jefferson Lab data [29]. Data obtained at matched kinematics, that is data obtained from both targets with one experimental apparatus or within a single experiment at the same kinematic setting, were selected for this analysis [30–38]. Data providing ratios of the two targets, as well as a spectator-tagged neutron structure function [39, 40] measurement, were also utilized. In particular, we compare the $F_2^p - F_2^n$ data with the structure function difference computed self-consistently from the recent next-to-leading order (NLO) CJ15 parton distributions [41], taking into account effects from nuclear corrections in the deuteron and power corrections at finite Q^2.

We find that the existing $F_2^p - F_2^n$ data show no evidence for a sign change in $\bar{d} - \bar{u}$ at any x values, with the zero crossing in $F_2^p - F_2^n$ entirely attributable to NLO effects. Furthermore, in contrast to the E866 Collaboration's extracted $\bar{d}/\bar{u}$ ratio, the pd to pp Drell-Yan cross section ratio is well described in terms of the CJ15 PDFs, for which $\bar{d} > \bar{u}$ at all values of x. Finally, we compare the shape of the $\bar{d} - \bar{u}$ asymmetry with expectations from nonperturbative models of the nucleon based on chiral symmetry breaking, and stress the need for consistent, global QCD analysis of all data before robust conclusions about the shape and sign of $\bar{d} - \bar{u}$ can be drawn.

II. ISOVECTOR NUCLEON STRUCTURE FUNCTION

As observed by Peng *et al.* [20], if one writes the proton and neutron F_2 structure functions at LO in terms of PDFs, then the difference $\bar{d} - \bar{u}$ can be obtained from the isovector $F_2^p - F_2^n$ structure function combination and the difference between the u and d valence quark PDFs in the proton,

$$\Delta(x) \equiv \frac{1}{2}\Big[u_v(x) - d_v(x)\Big] - \frac{3}{2x}\Big[F_2^p(x) - F_2^n(x)\Big]. \tag{1}$$

At LO, one obviously has $\Delta(x) = \bar{d}(x) - \bar{u}(x)$. At higher orders, the quantity defined in (1) will not be identical to $\bar{d}(x) - \bar{u}(x)$. In their analysis, Peng *et al.* proceed to extract $\Delta(x)$ from the $F_2^p - F_2^n$ difference derived from the NMC data [21, 22] by combining this with the valence PDFs obtained from the JR14 [42] and CT10 [43] parametrizations at NNLO. The result was found to produce a sign change at $x \sim 0.3$, which was interpreted as a zero crossing of $\bar{d}(x) - \bar{u}(x)$.

Peng *et al.* argue [20] that since the integrated value of $\bar{d} - \bar{u}$, and the associated Gottfried sum [44], receive very small $\mathcal{O}(\alpha_s)$ [6] and $\mathcal{O}(\alpha_s^2)$ [45] corrections, the LO approximation (1) should be accurate. However, while the correction to the integrated value of $\bar{d} - \bar{u}$ is indeed small [6], the higher order effects on the x dependence of the asymmetry may not be negligible. This could in practice then lead to misidentification of perturbative higher order effects with the behavior of the nonperturbative parton distributions as a function of x, as we discuss in the following.

To quantify this effect, we compute the quantity $\Delta(x)$ in Eq. (1) using the CJ15 NLO parton distributions [41] for all terms on the right hand side of the equation. This is shown in Fig. 1 at $Q^2 = 4$ GeV^2, where the calculated $\Delta(x)$ is compared with the corresponding

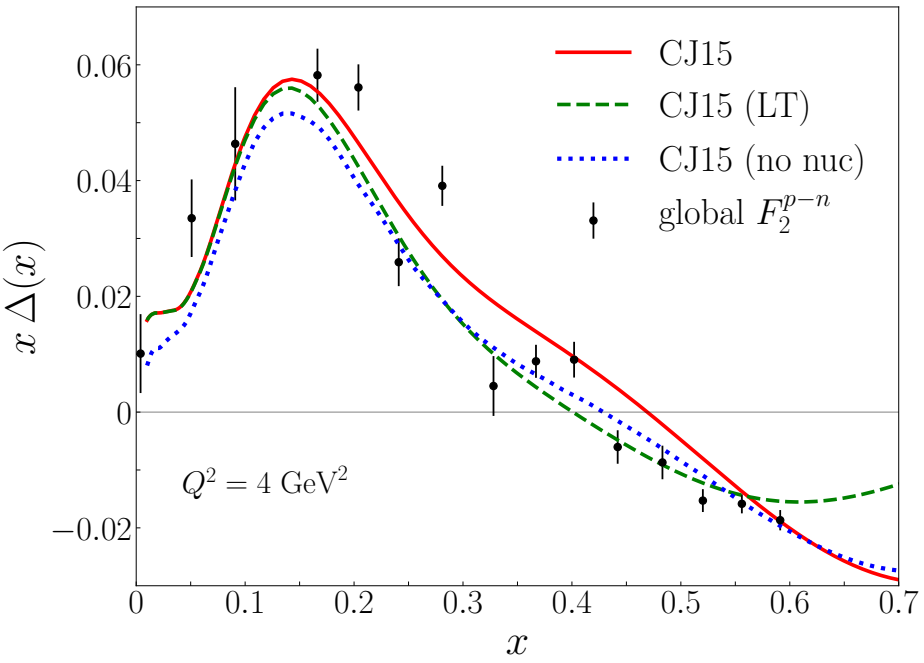

FIG. 1. Isovector combination $x\Delta$, defined in Eq. (1), computed from the CJ15 NLO PDFs [41] (red solid curve) at $Q^2 = 4$ GeV^2, and compared with Δ calculated in the leading twist approximation (green dashed curve), and neglecting nuclear corrections in the deuteron (blue dotted curve). The data points (black circles) are from the global neutron structure function analysis [25] using the CJ15 valence quark PDFs.

quantity constructed from the global $F_2^p - F_2^n$ data [25], using with the CJ15 parametrization for the valence $u_v - d_v$ PDFs. Both the calculated $\Delta(x)$ and the result extracted from the global data peak at $x \sim 0.1 - 0.2$, before decreasing at higher x and turning negative at $x \gtrsim 0.4$. The general agreement between the calculated and phenomenological Δ results suggests that the CJ15 fit is able to describe well the global $F_2^p - F_2^n$ data, including the change in sign at large x.

This remains the case irrespective of finite-Q^2 power corrections or nuclear effects, as Fig. 1 illustrates. In particular, since the value of $Q^2 = 4$ GeV^2 is not particularly high, one could imagine that finite-Q^2 corrections, associated with target mass effects or higher twists [46, 47], may impact the shape of $\Delta(x)$. To examine this possibility we compute the $F_2^p - F_2^n$ structure function difference in Eq. (1) from the CJ15 PDFs at leading twist (LT) only, without the finite-Q^2 corrections. Comparison with the full result in Fig. 1 shows that

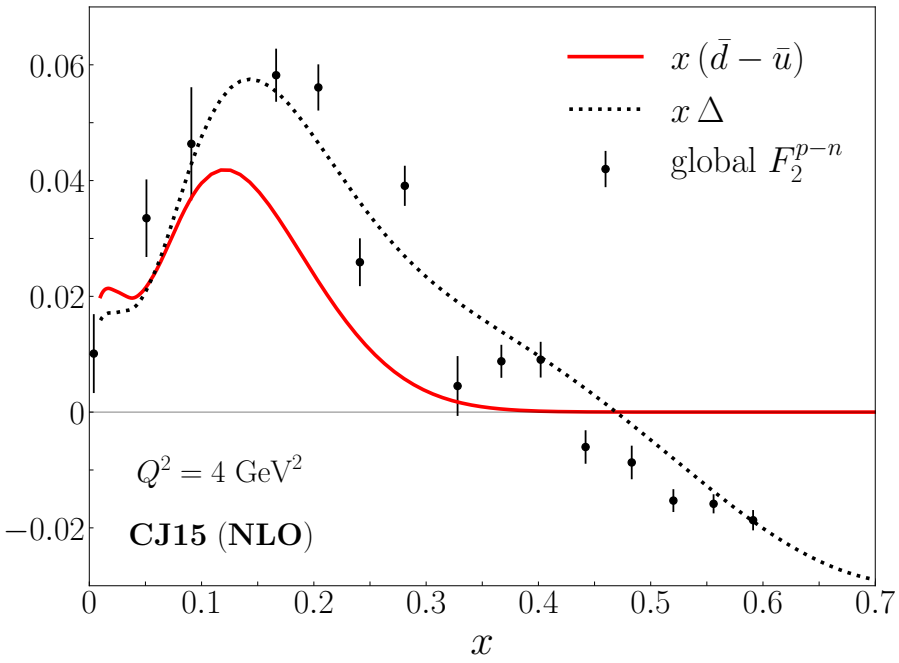

FIG. 2. Antiquark asymmetry $x(\bar{d}-\bar{u})$ from the CJ15 global QCD analysis [41] at $Q^2 = 4$ GeV^2 (red solid curve) compared with the phenomenological $x\Delta$ constructed from the proton–neutron structure function data [25] (black circles), and with Δ computed from the CJ15 fit (black dotted curve).

the result is only slightly modified by the finite-Q^2 effects, with the zero crossing of Δ at $x \approx 0.4$ remaining.

A further complication in the application of Eq. (1) arises from the possible nuclear effects that may obscure the extraction of the neutron F_2^n structure function from the inclusive proton and deuteron DIS data. In the CJ15 global analysis the nuclear effects in the deuteron were taken into account through a systematic expansion in the weak binding approximation [48, 49], in which nuclear binding and Fermi motion effects are described through nucleon smearing functions, and nucleon off-shell corrections [48, 50–52] are parametrized phenomenologically. To quantify the nuclear effect we therefore compute Δ from the CJ15 PDFs, but with the F_2^n calculated as the difference between the deuteron and proton structure functions, without any nuclear corrections, $F_2^n = F_2^d - F_2^p$. Again, we see no qualitative difference between the uncorrected and nuclear corrected neutron structure function.

While the x dependence of the phenomenological Δ is consistent with the calculation

based on the CJ15 NLO PDFs [41], we should note that the same global QCD analysis has, by construction, a $\bar{d}-\bar{u}$ asymmetry that is positive definite for all x, as illustrated in Fig. 2. In particular, while at LO the quantities Δ and $\bar{d}-\bar{u}$ coincide, at NLO or at higher order there is no reason for a sign change in Δ to require a sign change in $\bar{d}-\bar{u}$. A negative Δ is naturally generated by higher order α_s effects and other corrections that significantly modify the shape of the x dependence at intermediate and large values of x.

The comparisons in Figs. 1 and 2 plainly demonstrate that the apparent sign change in the $\bar{d}-\bar{u}$ difference extracted from $F_2^p - F_2^n$ is indeed an artifact induced by higher order QCD corrections, which affect in a nontrivial way the shape of the x distribution of the structure functions. On the other hand, it has long been accepted that the Fermilab E866 Drell-Yan data clearly indicate that the $\bar{d}/\bar{u}$ ratio, extracted from the ratio of pd to pp lepton-pair production cross sections, drops below unity at $x \gtrsim 0.3$ [12, 13]. We discuss the Drell-Yan data and their implications in more detail next.

III. DRELL-YAN CROSS SECTIONS

The strongest evidence for a nonzero $\bar{d}-\bar{u}$ asymmetry has come from the Fermilab E866 Drell-Yan experiment [12, 13], which measured the ratio of pd to pp lepton-pair production cross sections at an average $Q^2 = 54$ GeV^2. At LO, the cross section is proportional to a sum over flavors q of products of PDFs in the beam (b) and target (t) hadrons, evaluated at parton momentum fractions x_b and x_t, respectively [53],

$$\frac{d\sigma}{dx_F dQ^2} \;\propto\; \sum_q e_q^2 \left[q_b(x_b)\, \bar{q}_t(x_t) + \bar{q}_b(x_b)\, q_t(x_t) \right], \tag{2}$$

where $x_F = x_b - x_t$ is the Feynman scaling variable, and $x_b\, x_t \approx Q^2/s$, with Q the invariant mass of the dilepton pair, and $\sqrt{s} \approx 40$ GeV is the center of mass energy at the E866 kinematics. Furthermore, for $x_b \gg x_t$ the cross section ratio at LO simplifies to a ratio that depends only on the antiquark PDFs in the target [54],

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}. \tag{3}$$

In practice, the E866/NuSea Collaboration extracted the $\bar{d}/\bar{u}$ ratio using an iterative procedure to take into account experimental acceptance corrections, assuming that existing PDF

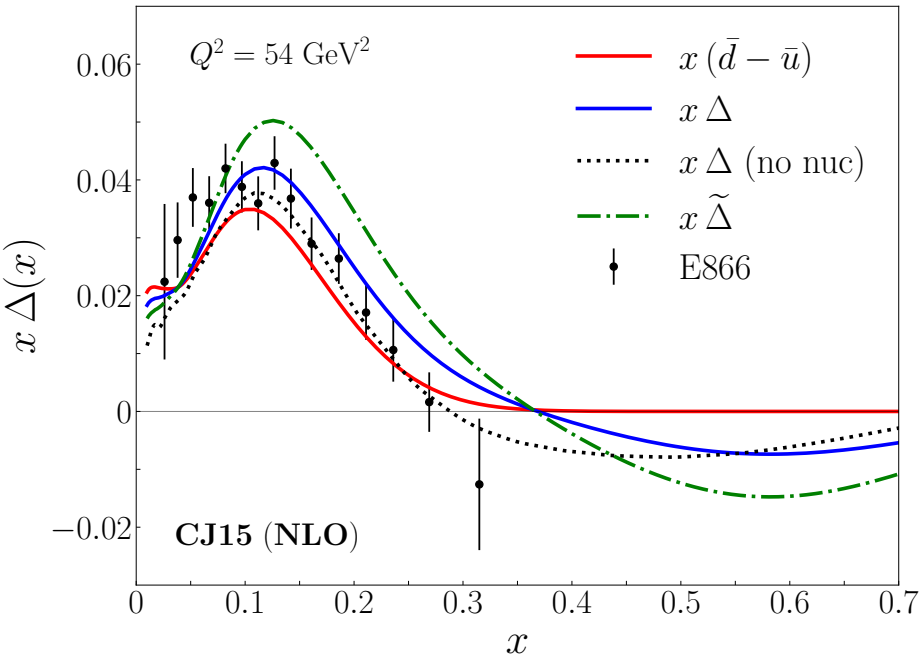

FIG. 3. Antiquark asymmetry $x(\bar{d}-\bar{u})$ from the CJ15 NLO parametrization [41] (red solid curve) at $Q^2 = 54$ GeV^2 compared with the values extracted from the ratio of pd to pp Drell-Yan cross sections, assuming $\bar{d}+\bar{u}$ from Ref. [56] (black circles), and with the isovector combination $x\Delta$ defined in Eq. (1) computed from the CJ15 PDFs (blue solid curve), with Δ computed neglecting nuclear effects in the deuteron (black dotted curve), and with an alternative definition in Eq. (4) (green dot-dashed curve) at the same Q^2 value.

parametrizations at the time [55, 56] accurately described the valence and heavy-quark distributions, as well as the sum, $\bar{d}+\bar{u}$, of the light antiquark PDFs [13]. From the $\bar{d}/\bar{u}$ ratio the difference $\bar{d}-\bar{u}$ was then computed at the E866 kinematics assuming $\bar{d}+\bar{u}$ from Ref. [56].

The resulting $\bar{d}-\bar{u}$ values are shown in Fig. 3 at the average $Q^2 = 54$ GeV^2, illustrating the strong enhancement of the asymmetry at $x \approx 0.1$, and the tendency towards negative values for $x \gtrsim 0.3$. The latter trend is similar to that displayed by the isovector combination Δ, computed from the CJ15 NLO PDFs [41] with or without nuclear effects in the deuteron, as in Fig. 1. On the other hand, the actual $\bar{d}-\bar{u}$ difference from the CJ15 parametrization at the same Q^2 remains positive definite at all x values, as in the comparison with the DIS data in Fig. 1 at the lower Q^2.

In fact, the relation (1) for the isovector distribution Δ, used as the basis for the analysis in Ref. [20], is not the only representation of the sea asymmetry. An alternative representation,

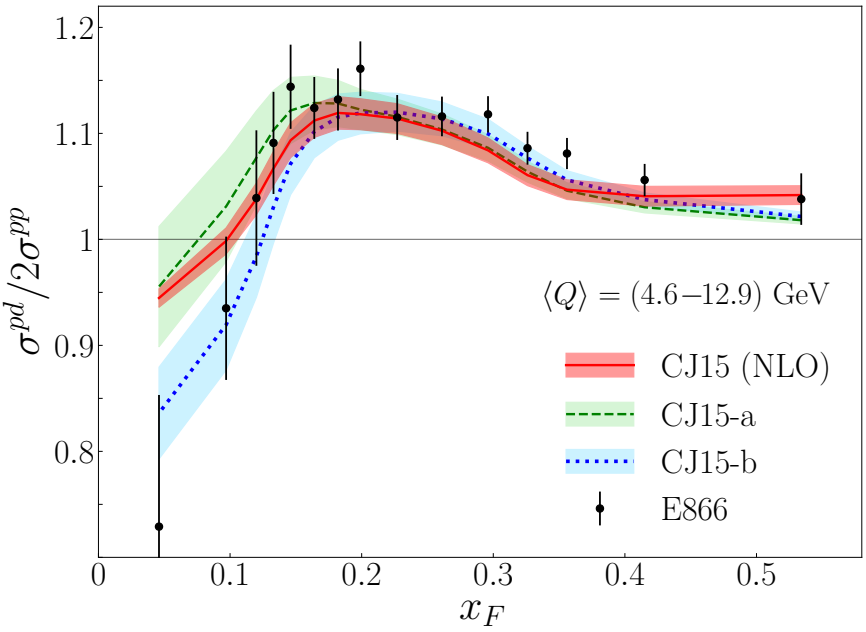

FIG. 4. Ratio of Drell-Yan lepton-pair production cross sections for pd and pp collisions from the Fermilab E866 experiment [13] versus the Feynman variable x_F, compared with the ratios calculated from the CJ15 [41] PDFs (red solid curve and band) and from a variation (CJ15-a) of the fit which parametrizes the difference $\bar{d} - \bar{u}$ instead of the ratio (green dashed curve and band), and a fit (CJ15-b) using data as in the CJ12 [60] analysis (blue dotted curve and band). The average values of Q range from 4.6 GeV (at the highest x_F) to 12.9 GeV (at the lowest x_F).

which is equivalent to Eq. (1) at LO, relates $\bar{d} - \bar{u}$ to the isovector nucleon structure function $F_2^p - F_2^n$ and the total u and d quark PDF difference, rather than to the $u_v - d_v$ valence distributions,

$$\widetilde{\Delta}(x) \equiv u(x) - d(x) - \frac{3}{x}\Big[F_2^p(x) - F_2^n(x)\Big]. \tag{4}$$

At LO in α_s, obviously $\Delta = \widetilde{\Delta} = \bar{d} - \bar{u}$; however, at higher orders Eqs. (1) and (4) are not identical. The differences between Δ and $\widetilde{\Delta}$ at $Q^2 = 54$ GeV^2 are shown in Fig. 3, and reveal discrepancies of $\sim 20\% - 30\%$ at $x \sim 0.1 - 0.3$, and even greater at larger x values, $x \sim 0.5$. Of course, other definitions for the isovector combination Δ could also be used, which all have the same LO limit, but introduce arbitrary differences at higher orders.

This illustrates the intrinsic ambiguities inherent in comparing quantities extracted from cross sections with inconsistent use of perturbative QCD corrections. The most robust and

unambiguous way to compare experimental data with theory is to directly compute the observables in terms of PDFs at a given order in α_s, using universal PDFs extracted from other data sets at the same order, as is typically done in global QCD analyses [57–59]. We highlight this in Fig. 4, which shows the actual experimentally measured ratio of pd to pp Drell-Yan cross sections from the E866 experiment versus the Feynman variable x_F, with the average Q ranging from 4.6 GeV at the highest x_F to 12.9 GeV at the lowest x_F points. From the kinematics of the Drell-Yan process, high x_F values correspond to low x_t values, and the lowest x_F correspond to the highest x_t, which are most sensitive to the $\bar{d}/\bar{u}$ ratio in the target hadron.

The ratio computed from the CJ15 PDFs is generally in good agreement with the measured ratio across all x_F. Note that the CJ15 analysis fitted the absolute pp and pd Drell-Yan cross sections, rather than the derived cross section ratio, giving an overall χ^2 per datum of $284/250 \approx 1.14$, using a cut on dimuon masses of $Q > 6$ GeV [41]. As illustrated in Figs. 1 and 3, a $\bar{d} - \bar{u}$ difference that is always positive (or, equivalently, $\bar{d}/\bar{u}$ ratio always above unity) can nonetheless give rise to observables (structure functions or cross sections) that naively would suggest a sign change at LO. The dip below unity of the Drell-Yan cross section ratio evident at low x_F, $x_F \lesssim 0.1$, in Fig. 1 is an example of this.

In fact, a similar behavior is also found if one replaces the positive-definite parametrization of $\bar{d}/\bar{u}$ used in the CJ15 fit with the more conventional parametrization of the difference, $(\bar{d} - \bar{u})(x) = Nx^\alpha(1 - x^\beta)(1 + \gamma\sqrt{x} + \delta x)$, as employed for example in the earlier CJ12 analysis [60]. This parametrization then allows the $\bar{d}$ PDF to be smaller than the $\bar{u}$ in some regions of x. The resulting fit, however, which we denote by "CJ15-a", also reproduces the E866 cross section ratio quite well, as Fig. 4 illustrates, with a similar χ^2 per datum of $294/250 \approx 1.18$. Interestingly, the $\bar{d}/\bar{u}$ ratio in the CJ15-a fit remains above unity up to parton momentum fractions $x \approx 0.4$, and is even slightly higher than in the standard CJ15 fit, as Fig. 5 illustrates, before dipping below 1 at $x \gtrsim 0.4$. This shows that the positivity of the antiquark ratio is driven by data and is not an artifact of the chosen parametrization. Note that with more parameters in the CJ15-a parametrization, the resulting error band on the $\bar{d}/\bar{u}$ ratio is larger. Conversely, in standard CJ15 parametrization is less flexible and is therefore more tightly constrained by the data with the resulting error band being smaller.

In order to examine the effect on the $\bar{d} - \bar{u}$ shape at large x from the interplay between the choice of parametrization and the data sets used in the global analysis, we perform

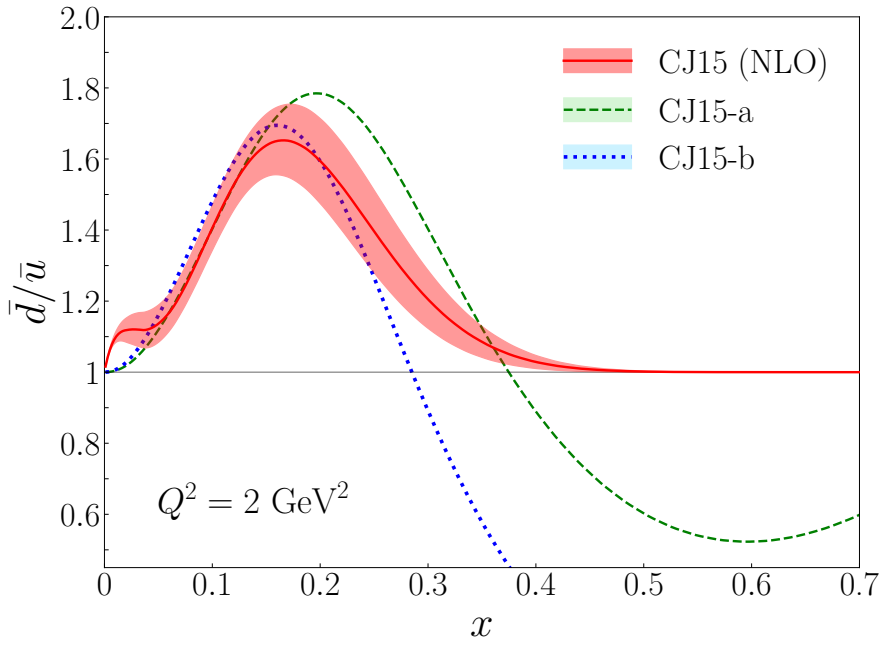

FIG. 5. Ratio of $\bar{d}/\bar{u}$ PDFs at a scale $Q^2 = 2$ GeV^2 from the CJ15 [41] NLO parameterizations (red solid curve and band), compared with the ratio from the variant CJ15-a (green dashed curve and band) and CJ15-b (blue dotted curve and band) fits, both of which dip below 1 at large values of x.

a further fit in which the CJ15 data sets are replaced by the data that were used in the CJ12 analysis [60], while retaining the QCD theory setup as in CJ15 [41], but using a parametrization as for CJ15-a. We refer to this fit as "CJ15-b". As far as the impact on the antiquark PDFs, the main difference between the data sets utilized in the two global analyses is the more stringent cut on the dilepton mass of $Q > 6$ GeV in the E866 Drell-Yan data [13] in CJ15, and the use of newer W-boson charge asymmetry data from D0 at the Tevatron [61, 62]. The more relaxed cut of $Q > 4$ GeV, as in the CJ12 analysis [60], increases by $\sim 50\%$ the number of available data points, allowing better constraints on the low-x_F cross section ratio, as evident in Fig. 4. This is achieved through the generation of a stronger dip in the $\bar{d}/\bar{u}$ ratio below unity at $x \gtrsim 0.3$, as illustrated in Fig. 5. However, the overall fit to the E866 cross sections across all kinematics becomes somewhat worse, with a χ^2 per datum of $593/375 \approx 1.58$, mostly due to the difficulty in fitting the pd cross section data at large x_F values. When the earlier, less precise D0 W asymmetry data are replaced by the more

recent and more precise results [61, 62], the dip is reduced significantly to about midway to the CJ15-a result. In fact, it has also been observed that there are tensions between low-x_F data and perturbative QCD calculations, suggesting these may bias the value of the $\bar{d}/\bar{u}$ ratio in global fits at large x [63].

Note also that for the E866 pd data, the lowest x_F kinematics involve deuteron parton momentum fractions $x_t \approx 0.25 - 0.35$, at which Fermi smearing and binding effects may start to become relevant. Ehlers *et al.* [64] studied these effects quantitatively within the same framework as used for DIS from the deuteron [48, 49], including the possible off-shell modifications of the nucleon PDFs in medium [50, 51]. While increasing in strength at higher x values, where there is greater sensitivity to the large momentum components of the deuteron wave function, the nuclear effects were found to be relatively small on the scale of the uncertainties on the E866 cross section ratio data. However, the nuclear corrections will become more important at the higher x values of the new SeaQuest experiment [23], especially with the expected reduction in experimental uncertainties.

IV. OUTLOOK

With the SeaQuest Drell-Yan data anticipated in the very near future, the kinematic coverage over which the $\bar{d} - \bar{u}$ difference can be directly constrained is expected to extend to $x \approx 0.45$ [23]. In particular, in the region $x \approx 0.25 - 0.3$, where the E866 data [13] suggested a possible cross-over of the $\bar{d}/\bar{u}$ ratio, the experimental uncertainties on the new measurements should be sufficiently small to verify whether this is indeed a robust feature of the high-x data. This should allow more definitive conclusions to be reached about the sign of the $\bar{d} - \bar{u}$ difference, and whether chiral symmetry breaking considerations alone can account for the shape of the asymmetry or additional physical mechanisms are needed [15, 65–67].

As Fig. 6 demonstrates, precise data will be needed to discriminate between the different possible behaviors of the $\bar{d} - \bar{u}$ asymmetry at $x \gtrsim 0.2$. While all 3 analyses considered here (the standard CJ15 and the two variants, CJ15-a and CJ15-b) produce results for $x(\bar{d} - \bar{u})$ which display strong positive peaks at $x \approx 0.1$, the modified CJ15-b fit drops faster and crosses zero at $x \approx 0.25 - 0.3$, whereas the asymmetry in the standard CJ15 fit remains positive. As illustrated in Fig. 3, all 3 variants give good descriptions of the E866 Drell-Yan data, with equally good χ^2 values, and the differences between the sets of distributions

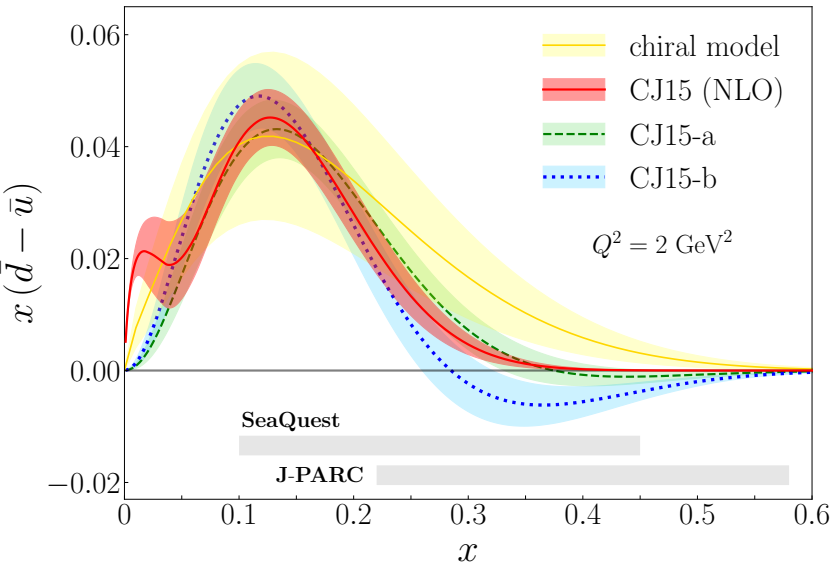

FIG. 6. Momentum dependence of the antiquark asymmetry $x(\bar{d}-\bar{u})$ at a scale $Q^2 = 2$ GeV^2 from the CJ15 [41] NLO fit (red dashed curve and band) and the CJ15-a (green dashed curve and band) and CJ15-b (blue dotted curve and band) variations, compared with a nonperturbative calculation of pion loop contributions from chiral effective theory [65–67]. The expected kinematical coverage of the future SeaQuest [23] and J-PARC [73] experiments is indicated by the horizontal gray bands.

reflect the limitations of existing data in constraining the high-x behavior. The differences between these parametrizations is also fairly indicative of the spread in $\bar{d} - \bar{u}$ from other global QCD analyses [68–72] that use the E866 data.

Upcoming data from the Fermilab SeaQuest experiment [23], as well as future data from the proposed Drell-Yan experiment at J-PARC [73], will constrain the $\bar{d} - \bar{u}$ asymmetry out to $x \approx 0.45$ and $\sim 0.55 - 0.6$, respectively. With sufficient precision, the new data should help answer the question whether $\bar{d} - \bar{u}$ changes sign or stays positive at high x, as predicted in models based on chiral symmetry breaking. In particular, the latter involve convolution of proton $\to$ baryon plus pion splitting functions and PDFs in the pion. The hadronic splitting is dominated by the (positive) contributions from the $p \to n\pi^+$ process, with smaller (negative) contributions from the $p \to \Delta^0\pi^-$ dissociation. Phenomenologically, it is very difficult to accommodate a negative overall contribution to $\bar{d} - \bar{u}$ at any value of x [15], and a typical result for the asymmetry from chiral loops is illustrated in Fig. 6 from Ref. [67].

Of course, additional mechanisms beyond those associated with chiral symmetry breaking, such as those based on the Pauli exclusion principle [16–18, 74], may play a role in generating some of the asymmetry. Whether and to what extent such mechanisms are important phenomenologically may be revealed with the upcoming Drell-Yan data [23, 73].

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