Improved determination of $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry in the proton by data from the BONuS experiment at JLAB and using an approach by Brodsky, Hoyer, Peterson, and Sakai

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The experimental data taken from both Drell-Yan and deep-inelastic scattering experiments suggest a sign change in $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry in the proton at large values of momentum fraction x. In this work, we present a phenomenological study of $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry. First, we extract the $\bar{d}(x) - \bar{u}(x)$ distribution using the more recent data from the BONuS experiment at Jefferson Lab on the ratio of neutron to proton structure functions, F_2^n/F_2^p, and show that it undergoes a sign change and becomes negative at large values of momentum fraction x, as expected. The stability and reliability of our obtained results are examined by including target mass corrections as well as higher twist terms which are particularly important in the large-x region at low Q^2. Then, we calculate the $\bar{d}(x) - \bar{u}(x)$ distribution using the Brodsky-Hoyer-Peterson-Sakai model and show that if one chooses a mass for the down quark smaller than the one for the up quark it leads to a better description for the Fermilab E866 data. To prove this claim, we determine the masses of down and up sea quarks by fitting to the available and up-to-date experimental data for the $\bar{d}(x) - \bar{u}(x)$ distribution. In this respect, unlike the previous theoretical studies, we have shown that this distribution has a sign change at $x > 0.3$ after evolution to the scale of available experimental data.

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I. INTRODUCTION

The parton distribution function (PDF) content for nucleons is usually determined from global fits to experimental data at the large momentum transfer Q^2. Over the past decade, our knowledge of the quark and gluon substructure of the nucleon has been extensively improved due to the high-energy scattering data from the fixed target experiments, the data from the ep collider HERA [1–3], and also from high-energy $p\bar{p}$ scattering at the Tevatron [4,5]. More recently, the data taken from various channels in pp collisions at the CERN Large Hadron Collider (LHC) play a main role in constraining the sea quarks and gluon distributions at the proton [6]. In recent years, various up-to-date efforts have been made to extract more complete information about the nucleon's quark and gluon structure in the form of parton distribution functions for the unpolarized PDF [7–14] and the polarized PDF [15–21] cases. These analyses are mainly focused on the extraction of the parton distribution functions at small and large values of x up to next-to-next-to-leading-order (NNLO) accuracy. Similar efforts have also been made for the case of fragmentation functions (FFs) [19,22–28], nuclear PDFs [29–33], and generalized parton distributions (GPDs) [34–37].

Since the Gottfried sum rule [38] was proposed in 1967, much experimental and theoretical research has been widely performed to check the validity or violation of it and also to study the antiquark flavor asymmetry $\bar{d} - \bar{u}$ in the nucleon sea (see Ref. [39] and references therein). If we adopt that the $\bar{u}$ and $\bar{d}$ distributions in the nucleon are the same and the isospin invariance is also valid, then the Gottfried sum rule is obtained by integrating the difference between the F_2 structure functions of the proton and neutron over x as $I_G \equiv \int_0^1 [F_2^p(x) - F_2^n(x)]/x dx = 1/3$, where x is the Bjorken scaling variable. However, assuming the flavor asymmetry of the nucleon sea, the Gottfried sum rule is violated by an extra term as $2/3 \int_0^1 [\bar{u}(x) - \bar{d}(x)] dx$. In this way, if there is a $\bar{d}$ excess over $\bar{u}$ in the nucleon, we expect a smaller value for the Gottfried sum than 1/3.

In 1991, the New Muon Collaboration (NMC) obtained the value $I_G = 0.235 \pm 0.026$ in measuring the proton and deuteron F_2 structure functions [40] from deep-inelastic muon scattering on hydrogen and deuterium targets, which is approximately 28% smaller than the Gottfried sum. This measurement provided the first clear evidence for the breaking of this sum rule. In addition to the deep-inelastic scattering (DIS) experiments, the violation of the Gottfried sum rule can be investigated from semi-inclusive DIS (SIDIS) and Drell-Yan cross section measurements. The related study was performed by the HERMES collaboration [41] in the case of the SIDIS experiment. In this study a measurement of $\bar{d}(x) - \bar{u}(x)$ was reported over the range $0.02 < x < 0.3$, but with a rather large experimental uncertainty. However, the NA51 [42] and FNAL E866/NuSea [43] collaborations studied this violation by measuring pp and pd Drell-Yan processes and established again that there is a $\bar{d}$ excess over $\bar{u}$ in the nucleon sea, although the ratio $\bar{d}/\bar{u}$ was only measured at the mean x value of $\langle x \rangle = 0.18$ in the NA51 experiment. The x dependence of this ratio and the $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry were also measured over the kinematic region, $0.015 < x < 0.35$, in the Fermilab E866 experiment.

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In addition to the violation of the Gottfried sum rule as well as the existence of the $\bar{d}-\bar{u}$ flavor asymmetry in the nucleon sea, one could take another important result from the Fermilab E866 data. In fact, the last data point suggested a sign change for the $\bar{d}(x)-\bar{u}(x)$ distribution at $x \sim 0.3$, despite the large uncertainty. To be more precise, it indicates that this distribution must be negative at the x values approximately larger than 0.3. This can be a very important issue because the perturbative regime of quantum chromodynamics (QCD) cannot lead to a remarkable flavor asymmetry in the nucleon sea. Furthermore, according to the studies which have been performed to date (for a review see Refs. [39,44–46]), the current theoretical models, regardless of their ability to describe an enhancement of $\bar{d}$ over $\bar{u}$, cannot predict a negative value for the $\bar{d}(x)-\bar{u}(x)$ distribution at any value of x. These theoretical studies are based on, for example, Pauli-blocking [47–50], meson-cloud [51–54], chiral-quark [55–57], chiral-quark soliton [58–61], intrinsic sea [62–64], and statistical [65–67] models. Except for the Pauli-blocking model, which considers a perturbative mechanism to describe the enhancement of $\bar{d}$ over $\bar{u}$, other models consider a nonperturbative origin for this effect and are almost successful. However, the Pauli-blocking model is not successful in producing the $\bar{d}(x)-\bar{u}(x)$ distribution when it is compared with the experimental data.

Recently, Peng *et al.* [68] presented independent evidence for the $\bar{d}(x)-\bar{u}(x)$ sign change at $x \sim 0.3$ by analyzing the DIS data. They showed that, in addition to the Drell-Yan data, the analysis of the NMC DIS data for the $F_2^p - F_2^n$ [40] and F_2^d/F_2^p [69] can also lead to a negative value for the $\bar{d}(x)-\bar{u}(x)$ at $x \gtrsim 0.3$. They have also discussed the significance of this sign change and the fact that none of the current theoretical models can predict this asymmetry. Future Drell-Yan experiments at J-PARC P04 [70] and also Fermilab E906 [71] experiments will give us more accurate information on the $\bar{d}-\bar{u}$ flavor asymmetry, especially at the larger values of x. This motivates us to study this topic.

In the present paper, following the studies performed by Peng *et al.* for the extraction of $\bar{d}(x)-\bar{u}(x)$, we first investigate whether such behavior can be seen in the analysis of data from other experiments. If it is, we study the approximate position of the $\bar{d}(x)-\bar{u}(x)$ sign change in x and also estimate the magnitude of its negative area. In addition, since our study is in the low Q^2 region at high value of x, in which the target mass corrections (TMCs) and higher twist (HT) effects are significant, then we develop our analysis by considering these nonperturbative contributions. Therefore, we calculate the $\bar{d}(x)-\bar{u}(x)$ distribution using the Brodsky-Hoyer-Peterson-Sakai (BHPS) model [72] and show that the available experimental data for this quantity suggest a smaller value for the down quark mass than the up quark one in the BHPS formalism. Note that this is in contrast to the previous studies in this context [62–64], where equal masses were assumed for the down and up quarks in the proton. This difference between masses leads to a sign change for $\bar{d}(x)-\bar{u}(x)$ when we evolve this quantity to the scale of experimental data [43].

The content of the present paper goes as follows: We compare the Fermilab E866 [43] data with the prediction of the latest parton distribution functions from various groups

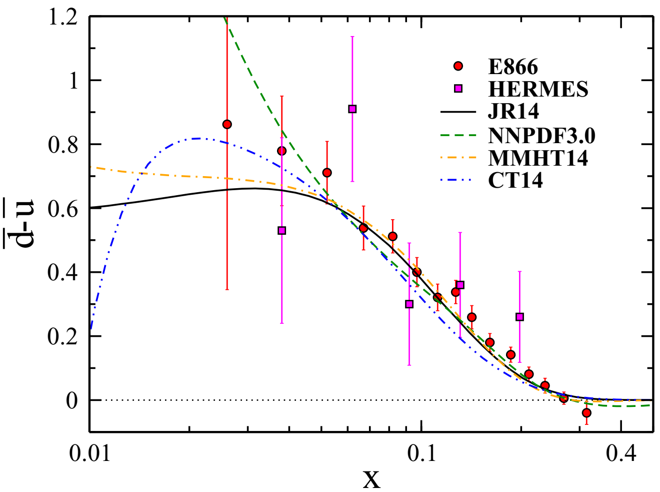

FIG. 1. A comparison between HERMES Collaboration [41] and Fermilab E866 [43] collaboration data for the $\bar{d}(x)-\bar{u}(x)$ and the NNLO theoretical predictions of JR14 [7], NNPDF3.0 [8], MMHT14 [9], and CT14 [10] PDFs at $Q^2 = 54$ GeV^2.

and also extract the $\bar{d}(x)-\bar{u}(x)$ using the updated CLAS Collaboration data for the F_2^n/F_2^p ratio in Sec. II. This section also includes detailed discussions on the nuclear corrections as well as the effects arising from the nonperturbative TMCs and HT terms. In Sec. III, we briefly introduce the BHPS model and explain the idea for choosing a smaller mass for the down quark than the up quark in the BHPS formalism. Then, we prove our claim and determine the masses of down and up sea quarks by fitting the available experimental data for the $\bar{d}(x)-\bar{u}(x)$. Finally, we summarize our results and present our conclusions in Sec. IV. The Appendix presents our FORTRAN package containing the $\bar{d}$ and $\bar{u}$ intrinsic distributions using the BHPS model.

II. $\bar{d}(x)-\bar{u}(x)$ FROM RECENT CLAS DATA

In recent years, our knowledge of nucleon structure has been developed to a large extent, but it is still not enough. In this respect, an updated global analysis of PDFs, including a broad range of the experimental data from the various observables and also theoretical improvements, can play an important role. In the theoretical studies, generally, an independent parametrization form is chosen for the $\bar{d}(x)-\bar{u}(x)$ distribution in the global analysis of PDFs at the initial scale Q_0. Figure 1 shows the $\bar{d}(x)-\bar{u}(x)$ data from the HERMES and the Fermilab E866 at $Q^2 = 2.5$ and 54 GeV^2, respectively, which have been compared with the NNLO theoretical predictions of JR14 [7], NNPDF3.0 [8], MMHT14 [9], and CT14 [10] PDFs for $Q^2 = 54$ GeV^2. But although all predictions are in good agreement with these data, they have major differences from each other. For example, there is no possibility to change the $\bar{d}(x)-\bar{u}(x)$ sign at large x in JR14 parametrization, unlike other PDF sets or the CT14 parametrization, which predicts $\bar{d}(x)-\bar{u}(x) < 0$ in the small-x region. There is also another important conclusion which can be taken from the E866 data. Asis clear from Fig. 1, the last data point, despite its large uncertainty, indicates that $\bar{d}(x) - \bar{u}(x)$ must be negative at x values approximately larger than 0.3.

Recently, Peng *et al.* [68] showed that, in addition to the Drell-Yan data, there is independent evidence for the $\bar{d}(x) - \bar{u}(x)$ sign change at $x \sim 0.3$. Their results have been achieved by analyzing the NMC DIS data for $F_2^p - F_2^n$ [40] and F_2^d/F_2^p [69]. In this section, we investigate if such behavior can be seen in the analysis of data from other experiments such as the Barely Off-shell Nucleon Structure (BONuS) experiment at Jefferson Lab. In this way, we can compute the position of the $\bar{d}(x) - \bar{u}(x)$ sign change in x and it is also possible to estimate the magnitude of its negative area.

From the parton model, one knows that the $F_2^{p,n}$ structure function of the nucleon at leading order (LO) of the strong coupling constant α_s is expressed as an expansion of parton distributions $f_i(x)$, $F_2^{p,n}(x) = \sum_i e_i^2 \, x f_i(x)$, where i denotes the flavor of the quarks and e_i is the charge of the ith quark. It should be noted that, in general, the parton distributions and in conclusion the structure functions depend on the four-momentum transfer squared Q^2. Now, if we adopt the charge symmetry of parton distributions in proton and neutron and also assume that the perturbatively generated s, c, b quark distributions are equal in different nucleons, the following relation is obtained for the $F_2^p - F_2^n$ at LO:

$$F_2^p(x) - F_2^n(x) = \tfrac{1}{3}x[u(x) + \bar{u}(x) - d(x) - \bar{d}(x)]. \quad (1)$$

In consequence, using the definition of valence quark, $q_v = q - \bar{q}$, the above relation can be used to extract the $\bar{d}(x) - \bar{u}(x)$ as follows:

$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}[u_v(x) - d_v(x)] - \frac{3}{2x}\left[F_2^p(x) - F_2^n(x)\right]. \quad (2)$$

According to Eq. (2), having two quantities $u_v(x) - d_v(x)$ and $F_2^p(x) - F_2^n(x)$ for a given value of x, one can extract the $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry. For the first term in Eq. (2), we can use the related parametrizations from the various PDFs [7–10] and the last term $[F_2^p(x) - F_2^n(x)]$ in the second bracket can be calculated, for example, from the new CLAS Collaboration data reported for F_2^n/F_2^p [73]. Since we are looking for a possible sign change in $\bar{d}(x) - \bar{u}(x)$ at a large value of x, in this work we use the NNLO JR14 parametrization [7] for $u_v - d_v$ such that its prediction for $\bar{d}(x) - \bar{u}(x)$ is clearly positive in all x, as seen in Fig. 1. In this way, if this sign change occurs, we ensure that it is not a result of the selected PDFs. However, the CLAS Collaboration [73] recently published the data for the neutron structure function F_2^n, and its ratio to the inclusive deuteron structure function (F_2^n/F_2^d) as well as an updated extraction of Ref. [74] for the ratio $R(x) = F_2^n/F_2^p$ from the BONuS experiment at Jefferson Lab. The data cover both the resonance and deep-inelastic regions, including a wide range of x for Q^2 between 0.7 and 5 GeV^2 and invariant mass W between 1 and 2.7 GeV. In this way, the term $F_2^p(x) - F_2^n(x)$ in Eq. (2) can be calculated from the data for the ratio $R(x)$ and by using the parametrization of $F_2^d(x)$ from Ref. [75], according to the following relation:

$$F_2^p - F_2^n = 2F_2^d\left(1 - F_2^n/F_2^p\right)/\left(1 + F_2^n/F_2^p\right). \quad (3)$$

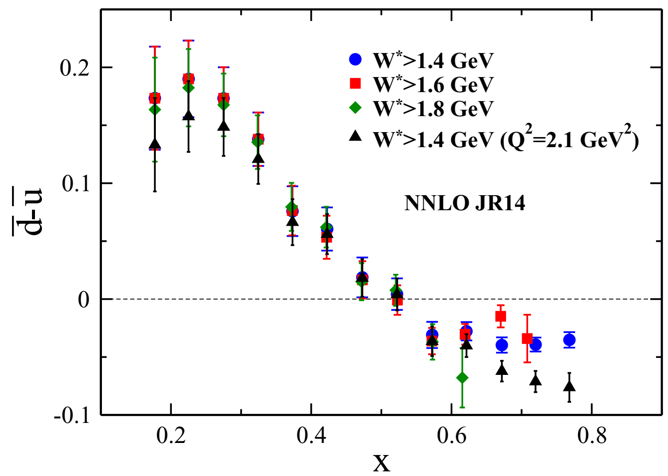

FIG. 2. The $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry as a function of x. The results obtained by the NNLO JR14 parametrization [7] and the CLAS data [73] related to the three lower cuts on the range of final-state invariant mass W^*. A detailed explanation is given in the text.

Figure 2 shows our final results for the $\bar{d}(x) - \bar{u}(x)$ distribution, related to three lower cuts on the range of final-state invariant mass: $W^* > 1.4$ GeV (blue circles), $W^* > 1.6$ GeV (red squares), and $W^* > 1.8$ GeV (green diamonds). Note that, since the CLAS data are also Q^2 dependent and not related to a fixed value of Q^2, we have allowed all quantities in Eqs. (2) and (3) to be also Q^2 dependent. Therefore, the extracted $\bar{d}(x) - \bar{u}(x)$ data points in x are related to the different Q^2 values approximately between 1 and 4.5 GeV^2. For example, for the case in which $W^* > 1.6$, the first and last data points are related to $Q^2 = 1.086$ and 4.259 GeV^2, respectively. However, we could also choose an average value for all data, i.e., $Q^2 = 2.1$ GeV^2. We examined this simplification and found it leads to an overall reduction in the magnitude of $\bar{d}(x) - \bar{u}(x)$, specifically at small and large values of x. The related results are shown in Fig. 2 as black triangles. To estimate the uncertainties, we included the uncertainties of both F_2^n/F_2^p and F_2^d in our calculation for $F_2^p - F_2^n$ (3), and also the JR14 PDF uncertainties in the extraction of $\bar{d}(x) - \bar{u}(x)$ by using Eq. (2). As can be seen from Fig. 2, the high-quality data from the BONuS experiment lead to rather smaller uncertainties. It should be noted that Eq. (2) is extracted at the LO approximation but in our analysis, shown in Fig. 2, we used the NNLO PDF parametrization for more accuracy. However, as we show in Fig. 3, if one uses the LO PDF parametrizations from CT14 [10], the results show a sign change as well.

The last important issue that should be considered in our analysis is the effect of the nonperturbative TMCs and HT terms. At the region of low Q^2, nucleon mass correction cannot be neglected. Therefore, the power-suppressed corrections to the structure functions can make an important contribution in some kinematical regions. In addition to the pure kinematical origin TMCs, the structure functions also receive remarkable contributions from HT terms. In the range of large values of x, their contributions are increasingly important. In this

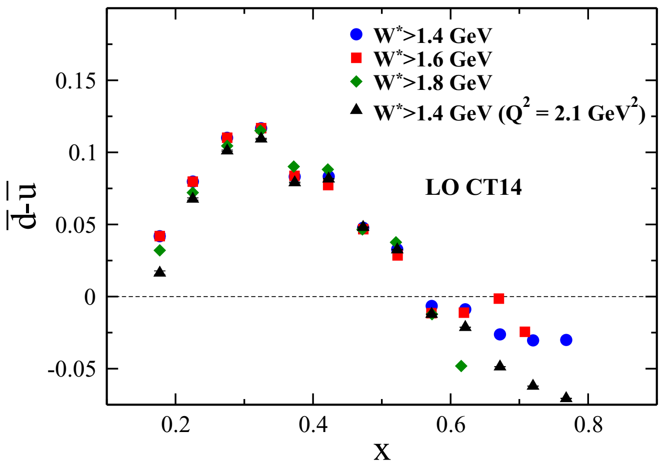

FIG. 3. As in Fig. 2 but obtained from the LO CT14 parametrization [10] using the CLAS data [73]. The plot is related to the three lower cuts on the range of final-state invariant mass W^*.

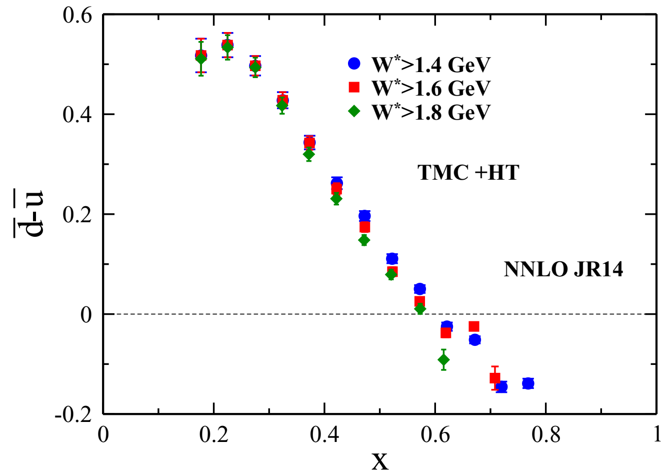

FIG. 4. The $\bar{d}(x) - \bar{u}(x)$ asymmetry considering the TMC and HT corrections.

respect, we examine the stability and reliability of our obtained results by including the TMCs as well as the HT terms which are particularly important at the large-x region and low Q^2. Actually, since the CLAS measurements belong to the kinematical regions of $W \approx 2.7$ GeV and $Q^2 \approx 1$–5 GeV^2, and Eq. (1) might be too naive to use for the data points at such low W and Q^2 regions, we should check the validity of our results by considering both the TMCs and HT terms. In this regard, we follow the formalization presented in Refs. [76,77] in order to take into account the TMC and HT corrections in the structure functions of Eq. (1). It should be also noted that for calculating the HT effect we use the results presented in Table 3 of Ref. [78]. Our final results are shown in Fig. 4, again for three lower cut values on W^*. Comparing Figs. 2 and 4, one can conclude that the TMCs and HT effect overall cause the results to have larger values than before for positive area and the data points, which were in the negative area, have become more negative. Although, considering the TMCs and HT effect lead to shift some data points from the negative area to the positive one, but we still have some data points which undergo the sign change. As a last point, note that if one uses the results obtained in Ref. [79] for calculating the HT term, similar results are achieved.

The most important conclusion of our analysis in this section is to show that the sign change of $\bar{d}(x) - \bar{u}(x)$ occurs at large x, as suggested by Peng *et al.* [68] in their analysis of the NMC DIS data for $F_2^p - F_2^n$ [40] and F_2^d/F_2^p [69], and also seen by the Drell-Yan experimental data measured in the Fermilab experiment (E866) [43]. Although this sign change has occurred at $x \sim 0.5$, which is larger in comparison to the case of Drell-Yan data, $x \sim 0.3$ (as shown in Fig. 1), it seems reasonable because the CLAS data include very much smaller values of Q^2 in comparison to the E866 data. As another considerable point, note that in the definition of Eq. (3) the nuclear effects in the deuteron, defined as $R^d_{\rm EMC} = F_2^d/(F_2^p + F_2^n)$, have been ignored. Actually, the nuclear corrections in the deuteron structure function are small and usually are neglected in calculations. This fact is checked in the recent studies of the European Muon Collaboration (EMC) effect in the deuteron by Griffioen *et al.* [80] through analyzing the recently published CLAS data at Jefferson Lab [73]. However, we recalculated $\bar{d}(x) - \bar{u}(x)$ considering the nuclear corrections in the deuteron but only for the last data point for which its related $R^d_{\rm EMC}$ $(= 1.07)$ is comparatively large (see Ref. [80]). We found that it changes the result by 10% so that the negativity of data at large x is still remaining.

III. $\bar{d}(x) - \bar{u}(x)$ FROM BHPS MODEL

In this section, we present the results of our study of $\bar{d}(x) - \bar{u}(x)$ in the basis of the BHPS model. As was already mentioned in the Introduction, since the Gottfried sum rule has been violated by the NMC measurement [40], many theoretical studies based on the various models have been extended to explain the $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry. Similar efforts have been also made in the case of strange-antistrange asymmetry of the nucleon sea (for instance, see Refs. [81–83]). Recently, Chang and Pang [62] demonstrated that a good description of Fermilab E866 data for $\bar{d}(x) - \bar{u}(x)$ can be also achieved using the BHPS model [72] for the intrinsic quark distributions in the nucleons. In the past three decades, intrinsic quarks have been a subject of interest in many studies including both intrinsic light and heavy quark components (see Refs. [82,84] and references therein). According to the BHPS model that is pictured in the light-cone framework, the existence of the five-quark Fock states $|uudq\bar{q}\rangle$ in the proton wave function is natural and the momentum distributions of the constituent quarks are given by

$$P(x_1,\ldots,x_5) = N \frac{\delta\left(1 - \sum_{i=1}^{5} x_i\right)}{\left(m_p^2 - \sum_{i=1}^{5} \frac{m_i^2}{x_i}\right)^2}, \tag{4}$$

where m_p and m_i refer to the masses of the proton and quark i, and x_i stands for the momentum fraction carried by quark i. It should be noted that in Eq. (4) the effect of the transverse momentum in the five-quark transition amplitudes is neglected and the normalization factor N is also determined through the condition

$$\int dx_1 \cdots dx_5 P(x_1, \ldots, x_5) \equiv \mathcal{P}_5^{q\bar{q}}, \quad (5)$$

where $\mathcal{P}_5^{q\bar{q}}$ is the probability of finding the $|uudq\bar{q}\rangle$ Fock state in the proton. Considering Eq. (4), one can integrate over x_1, x_2, x_3, and x_4 to obtain the $\bar{q}$ distribution in the proton. As was mentioned in Ref. [72], the probability of the five-quark Fock state is proportional to $1/m_q^2$, where m_q is the mass of $q(\bar{q})$ in the Fock state $|uudq\bar{q}\rangle$. Although the BHPS model prediction for the $\mathcal{P}_5^{q\bar{q}}$ is suitable when the quarks are heavy, we expect that the light five-quark states have a larger probability in comparison to the heavy five-quark states.

It is worth noting that the BHPS model was applied, at first, to calculate the intrinsic charm distribution [72]. However, Chang and Pang [62] generalized it to the light five-quark states to calculate their intrinsic distributions in the proton and also to extract their probabilities ($\mathcal{P}_5^{q\bar{q}}$) using available experimental data. It is interesting to note that they obtained different values for $\mathcal{P}_5^{d\bar{d}}$ and $\mathcal{P}_5^{u\bar{u}}$ and therefore they extracted the $\bar{d}(x) - \bar{u}(x)$ distribution. This may lead us to a new idea so that we can choose different masses for down and up quarks in the BHPS formalism. To make this point more clear, note that on one hand, the $\mathcal{P}_5^{q\bar{q}}$ is proportional to $1/m_q^2$, and on the other hand, Eq. (4) completely depends on the constituent quark masses, so these facts inevitably lead to the difference in masses for the up and down quarks. Moreover, from Ref. [62], since $\mathcal{P}_5^{d\bar{d}}(= 0.294)$ is larger than $\mathcal{P}_5^{u\bar{u}}(= 0.176)$, one can conclude that $m_{d,\bar{d}}$ should be smaller than $m_{u,\bar{u}}$. Considering this assumption, if one evolves the $\bar{d}(x) - \bar{u}(x)$ distributions to the scale of the experimental data [43], it will provide a sign change at large values of x, $x > 0.3$.

To prove our claim, we should determine the real masses of down and up sea quarks by fitting the available experimental data for the $\bar{d}(x) - \bar{u}(x)$ distribution. To this end, considering the definition of the χ^2 function as [85]

$$\chi^2 = \sum_i \frac{\left(\Delta_i^{\text{data}} - \Delta_i^{\text{theory}}\right)^2}{\left(\sigma_i^{\text{data}}\right)^2}, \quad (6)$$

we must minimize it to obtain the optimum values for the up and down quark masses. Here, Δ_i^{data} are the experimental data for the $\bar{d}(x) - \bar{u}(x)$ distribution. In our analysis we use the HERMES [41] and E866 [43] data which are the only available data for this quantity. In Eq. (6), the theoretical result for the $\bar{d}(x) - \bar{u}(x)$ distribution (Δ_i^{theory}) is obtained from the BHPS model and σ_i^{data} is the experimental error related to the systematic and statistical errors as follows: $(\sigma_i^{\text{data}})^2 = (\sigma_i^{\text{stat}})^2 + (\sigma_i^{\text{syst}})^2$.

In our calculation of the theoretical result Δ_i^{theory}, the required probabilities of $|uudu\bar{u}\rangle$ and $|uudd\bar{d}\rangle$ states (in the proton) are taken from the recent analysis of Chang and Pang [64], who performed their analysis by considering the new measurements by the HERMES Collaboration [86] for $x(s + \bar{s})$. The related values are $\mathcal{P}_5^{u\bar{u}} = 0.229$ and $\mathcal{P}_5^{d\bar{d}} = 0.347$ for $\mu = 0.3$ GeV and also $\mathcal{P}_5^{u\bar{u}} = 0.178$ and $\mathcal{P}_5^{d\bar{d}} = 0.296$ for $\mu = 0.5$ GeV, where μ is the initial scale for the evolution of the nonsinglet $\bar{d}(x) - \bar{u}(x)$ distribution to the scale of experimental data.

TABLE I. The optimum values for the d-quark mass along with the corresponding χ^2/DOF values.

Approach	χ^2/DOF	$m_{d,\bar{d}}$
LO ($\mu = 0.3$)	6.3145	$0.2020 \pm 7.3357 \times 10^{-5}$
NLO ($\mu = 0.3$)	1.0682	$0.2779 \pm 4.7401 \times 10^{-3}$
LO ($\mu = 0.5$)	11.2947	$0.2020 \pm 5.1204 \times 10^{-5}$
NLO ($\mu = 0.5$)	4.4402	$0.2020 \pm 8.3806 \times 10^{-5}$

In this analysis, we merely extract the value of $m_{d,\bar{d}}$ by performing a fit to the experimental data. In fact, it is not necessary to extract $m_{u,\bar{u}}$ from the data analysis, because one can determine this quantity using the following equation:

$$m_{u,\bar{u}} = \frac{m_p - m_{d,\bar{d}}}{2}. \quad (7)$$

The equation above is obtained by the fact that the proton consists of two up quarks and one down quark in the ground state.

To minimize the χ^2 function (6), we employ the CERN program MINUIT [87] and perform our analysis at the LO and next-to-leading-order (NLO) approximations. For both LO and NLO, our results are evolved from the initial scales $\mu = 0.3$ GeV and $\mu = 0.5$ GeV to the experimental data scales ($Q^2 = 54$ GeV^2 for the E866 data and $Q^2 = 2.5$ GeV^2 for the HERMES data). In Table I, our results for $m_{d,\bar{d}}$ along with the corresponding χ^2/DOF values are presented for four scenarios, depending on the order of perturbative QCD and the initial scale applied.

According to Table I and Eq. (7), the possible values for the $m_{d,\bar{d}}$ are smaller than the $m_{u,\bar{u}}$ in all scenarios applied. As can be seen from Table I, the value of χ^2/DOF for the NLO approach considering the initial scale $\mu = 0.3$ GeV is better than the other approaches. Another interesting point, shown in Table I, is that the values obtained for the $m_{d,\bar{d}}$ are the same when different scenarios are applied, i.e., LO ($\mu = 0.3$ GeV), LO ($\mu = 0.5$ GeV), and NLO ($\mu = 0.5$ GeV). Considering Table I and Eq. (7), our expectation value of the up quark mass is $m_{u,\bar{u}} = 0.330$ GeV using the second scenario where $\mu = 0.3$ GeV is considered at NLO and one has $m_{u,\bar{u}} = 0.368$ GeV considering other three scenarios.

We provided a code that gives the $\bar{d}$ and $\bar{u}$ intrinsic quark distributions in the proton for any arbitrary down quark mass and momentum fraction x (see the Appendix). Now, we can recalculate the BHPS model for the $\bar{d}(x) - \bar{u}(x)$ distribution using the new masses extracted for the up and down sea quarks. Because the minimum value of χ^2/DOF appears in the NLO scenario for $\mu = 0.3$, we expect that this scenario leads to a more convenient consistency with the experimental data. Figure 5 shows a comparison between the experimental data and obtained results for $\bar{d}(x) - \bar{u}(x)$ in four scenarios, using the BHPS model with the masses listed in Table I. Actually, these results show that our assumption is correct, so choosing a smaller mass for the down quark is logical.

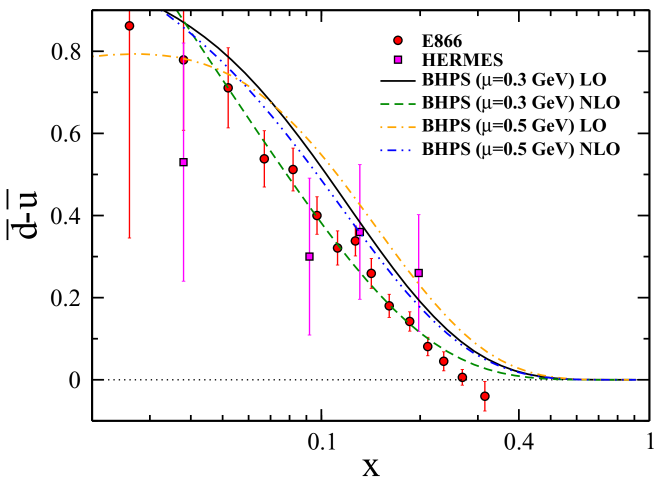

FIG. 5. A comparison between the experimental data from the HERMES [41] and E866 [43] experiments and the theoretical results obtained for $\bar{d}(x) - \bar{u}(x)$ in four situations, using the BHPS model with masses listed in Table I.

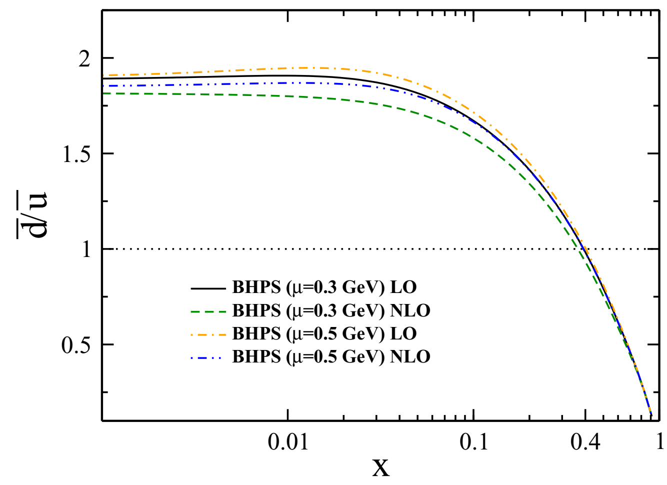

FIG. 6. $\bar{d}(x)/\bar{u}(x)$ versus x obtained in four situations, using the BHPS model with masses listed in Table I.

Another interesting finding that is achieved from our analysis is that the evolved distributions have a sign change at large values of x. In this study, the observed difference between $\bar{d}(x)$ and $\bar{u}(x)$ is not significant for large values of x, as presented in Fig. 5. In this regard, to show this sign change, in Fig. 6 we plotted the $\bar{d}(x)/\bar{u}(x)$ distribution as a function of x for four analyzed scenarios. As is seen, at $x \gtrsim 0.33$ and for all approaches, the ratio of $\bar{d}(x)/\bar{u}(x)$ is smaller than 1. From Fig. 6 one can conclude that, in the NLO scenario and for $\mu = 0.3$ GeV, the corresponding curve drops off faster than the others. The sign change presented in this study has a number of important implications for future practice and, hence, any possible future study of $\bar{d}(x) - \bar{u}(x)$ using the new and up-to-date experimental setup is most welcome.

IV. SUMMARY AND CONCLUSION

The experimental data taken from a Drell-Yan experiment by the FNAL E866/NuSea collaboration [43] can be recognized as the cleanest evidence for the violation of the Gottfried sum rule and the existence of the $\bar{d}(x) - \bar{u}(x)$ flavor asymmetry in the nucleon sea. Furthermore, these data suggest a sign change for $\bar{d}(x) - \bar{u}(x)$ at $x \sim 0.3$. Recently, by analyzing the DIS data, Peng *et al.* [68] presented independent evidence for the $\bar{d}(x) - \bar{u}(x)$ sign change at $x \sim 0.3$. They showed that, in addition to the Drell-Yan data, the analysis of the NMC DIS data for $F_2^p - F_2^n$ [40] and F_2^d/F_2^p [69] can also lead to a negative value for $\bar{d}(x) - \bar{u}(x)$ at $x \gtrsim 0.3$. They also discussed the significance of this sign change and the fact that none of the current theoretical models can predict this effect. Following their studies, we investigated this behavior in the DIS data analysis from other experiments. Then we tried to find the x position of $\bar{d}(x) - \bar{u}(x)$ in which the sign change occurs. In the following, we estimated the magnitude of the negative area of the $\bar{d}(x) - \bar{u}(x)$ distribution. We also enriched our formalism by considering the nonperturbative TMCs and HT terms. As a result, we found that by using the updated CLAS Collaboration data for the structure function ratio F_2^n/F_2^p [73] the extracted $\bar{d}(x) - \bar{u}(x)$ undergoes a sign change and becomes negative at large values of x, as suggested by Drell-Yan E866 data.

Then, we used the BHPS model [72] to calculate the $\bar{d}(x) - \bar{u}(x)$ distribution. According to the BHPS prediction, we assumed that the probability of the Fock state $|uudq\bar{q}\rangle$ in the proton wave function is proportional to $1/m_q^2$, where m_q is the mass of $q(\bar{q})$ in the five-quark Fock state. Under this assumption, the $d(\bar{d})$ quark has a smaller mass than the $u(\bar{u})$ quark in the proton. To prove that assumption, we obtained the real masses for the down and up sea quarks by fitting the available experimental data. We considered the χ^2 function and minimized it to obtain the optimum down and up sea quark masses. Our calculations were done in four scenarios: leading- and next-to-leading-order approximations considering two different initial scales $\mu = 0.3$ GeV and $\mu = 0.5$ GeV. Our results obtained from data analysis confirm the accuracy and correctness of our assumption.

The following short conclusions can be drawn from the present study. As a short summary, the present results are significant in, at least, two major respects. First, we have found that the $\bar{d}(x) - \bar{u}(x)$ distribution with the new extracted masses is in good agreement with the available up-to-date experimental data. In addition, unlike the previous theoretical studies [44–46], our results show a sign change on the $\bar{d}(x) - \bar{u}(x)$ distribution. The latter is a more significant result from our study. Any further information on the theory and the experimental observables on the $\bar{d}(x) - \bar{u}(x)$ asymmetry would help us to establish a greater degree of accuracy on this matter. These are important issues for future research and, hence, further studies with more focus on the $\bar{d}(x) - \bar{u}(x)$ asymmetry are suggested.

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APPENDIX: THE $\bar{d}$ AND $\bar{u}$ INTRINSIC DISTRIBUTIONS

We have provided a FORTRAN package containing the $\bar{d}$ and $\bar{u}$ intrinsic distributions using the BHPS model for any arbitrary down quark mass and momentum fraction x, which can be obtained via email from the authors. Note that in this code the probabilities $\mathcal{P}_5^{d\bar{d}}$ and $\mathcal{P}_5^{u\bar{u}}$ have not been multiplied by distributions so one can choose any arbitrary probabilities. Furthermore, the up quark mass $m_{u,\bar{u}}$ is obtained from Eq. (7) automatically.

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