Letter

Sea-quark loop contributions to the $\bar{d}-\bar{u}$ asymmetry in the proton

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QCD interactions for equal-mass fermion flavors are flavor blind. This fact is often used to state that disconnected sea-quark loop contributions are equal for u and d quarks in the mass symmetric case and therefore these disconnected sea-quark loop contributions cannot contribute to the well-known $\bar{d}-\bar{u}$ asymmetry in the proton. Instead, it is argued that one must look to the connected sector of lattice QCD correlation functions to find this difference. In this presentation, we note that these statements are true provided unphysical contributions in the sea-quark loop sector are included, contributions from baryons that do not appear in the physical spectrum. To respect the Pauli principle, these unphysical contributions from the disconnected sea-quark loop sector must cancel equally unphysical contributions in the connected sector. The remaining disconnected sea-quark loop contributions no longer have a balance between $\bar{d}$ and $\bar{u}$. Upon considering only physically observed baryons in the loop contributions, we illustrate an important contribution from the sea-quark loop sector to $\bar{d}-\bar{u}$ that enhances the leading connected contribution by 12%.

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Introduction. Understanding the structure of the nucleon remains an exciting challenge for modern nuclear and particle physics [1]. One of the great surprises of the past few decades in this area was the discovery that there is an asymmetry between the anti-down ($\bar{d}$) and anti-up ($\bar{u}$) sea quarks in the proton. While this was in fact predicted on the basis of chiral symmetry [2], it was almost a decade later that a hint of such an asymmetry [3] was verified experimentally by the New Muon Collaboration [4], as a significant discrepancy in the Gottfried sum rule [5,6].

Since then, the shape of $\bar{d}-\bar{u}$ as a function of Bjorken-x has been studied in detail at leading twist through the Drell-Yan process [7,8] as well as further measurements of $F_2^p - F_2^n$ [9]. There have also been extensive studies of the capacity of chiral field theory to constrain this and other asymmetries in the sea of the nucleon [10–21].

Apart from the intrinsic interest in nucleon structure, modern tests of the Standard Model demand that the parton distribution functions (PDFs) be known very accurately [22–28]. Such considerations have led to interesting suggestions that constraints from lattice QCD might supplement experimental data in constraining hadronic PDFs [29–32].

In describing the structure of the proton in the context of deep inelastic scattering and parton distribution functions, the convention is to distinguish between a three-quark valence sector and a quark-number zero sea sector consisting of quark-antiquark pairs and gluons [33]. Here our focus is on the connected and disconnected quark flows considered in lattice QCD calculations of three-point correlation functions, where a flavor-diagonal quark-bilinear current probes the structure. While the disconnected sector generates quark-number zero sea contributions, the connected sector contributes to both the three-quark valence- and the zero-quark sea-quark contributions, due to the ability of the connected quark flows to include additional quark-antiquark sea contributions. The relationship between the valence and sea sectors of phenomenology and the connected and disconnected sector of quantum field theory was established long ago [34,35].

Here we focus on suggestions that the difference in the sea-quark contributions from connected and disconnected diagrams in lattice QCD could be used to improve phenomenological PDF extractions. In particular, we examine the suggestion that the disconnected diagrams have a physical interpretation and do not contribute to the $\bar{d}-\bar{u}$ asymmetry.

In the following we demonstrate that neither the connected nor the disconnected diagrams in lattice QCD have a physical meaning on their own. Each sector contains only a subset of the Wick contractions generated in performing the Grassmann algebra of the QCD path integral. Only the combination of both sectors ensures that the particles propagating are physical.

Indeed, we will show the presence of unphysical states propagating in the valence and sea sectors and demonstrate how some of the disconnected sea-quark loop sector is used

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to cancel off unphysical states propagating in the connected sector. Two consequences follow from this. First, any suggestion that the sum of all the disconnected diagrams must have a physical interpretation is false. Part of this contribution is used to remove unphysical hadrons propagating in the connected sector. Second, the disconnected sea-quark loop contributions remaining no longer have a balance between $\bar{d}$ and $\bar{u}$ contributions. This latter point admits a nontrivial contribution to $\bar{d} - \bar{u}$ asymmetry from the disconnected sea-quark loop sector.

In other words, the symmetry required to ensure the disconnected sea-quark loop sector cannot contribute to the $\bar{d} - \bar{u}$ asymmetry necessarily requires the inclusion of unphysical baryon contributions, baryons that do not appear in the physical spectrum.

Because these unphysical contributions must be eliminated from the disconnected sea-quark loop sector through a cancellation with appropriate contributions in the connected sector, the assertion that the physical $\bar{d}$ and $\bar{u}$ disconnected sea-quark loop contributions cancel in $\bar{d} - \bar{u}$ is incorrect. Upon considering only physically observed baryons in the loop contributions, we illustrate an important contribution from the disconnected sea-quark loop sector to the $\bar{d} - \bar{u}$ asymmetry.

Quark flow analysis. We begin our analysis through the consideration of quark flow diagrams included in lattice QCD calculations of three-point functions of standard proton interpolating fields and a flavor-diagonal quark-bilinear current. In performing the Wick contractions, one encounters two topologically distinct diagrams, one in which the quark flow is connected through the creation interpolating field to the annihilation interpolating field of the proton, and a second in which the quark fields of the current are contracted to form a loop. Such a diagram is commonly referred to as a quark-flow disconnected diagram. However, it is connected to the two-point function through gluon interactions. The elementary considerations of interpolating fields, the direct and exchange Wick contractions included in the connected quark-flow diagrams, and the contractions of the fermion fields in the bilinear current of the three-point function giving rise to quark-flow disconnected contributions may be reviewed in Ref. [36].

In drawing the diagrams associated with the disconnected sea-quark loop contribution, one can consider flavor-singlet constructions where the quark-antiquark pair of the loop annihilates to gluons, and flavor-octet contributions where the loop pairs with one of the quark-flow lines of the proton interpolating fields to form flavor-octet mesons. As the flavor-singlet mesons have an equal balance of $\bar{u}u$ and $\bar{d}d$ components in the mass-symmetric limit neglecting electromagnetic interactions, these contributions do not generate a $\bar{d} - \bar{u}$ asymmetry and we do not consider them further.

Figure 1 illustrates the quark-flow diagrams having overlap with meson dressings of the proton contributing to the $\bar{d} - \bar{u}$ asymmetry of the proton. The eight diagrams are associated with two choices for the light quark propagating in the meson dressing, times two choices for the antiquark, times two topologically different quark flows giving rise to the meson dressing. Connected Wick contractions, including both the direct and exchange contractions, are listed in the left column and the corresponding quark-bilinear current contractions generating a disconnected sea-quark-loop contribution appear in the right-hand column.

There are three connected flows to consider as the d quark can be placed on each of the quark flow lines. With the intermediate-state quark-flows identified, the corresponding diagram incorporating a disconnected sea-quark loop is illustrated. In obtaining the physical contribution, both the connected and disconnected sea-quark loop contributions are summed. The final row, illustrating the $d\bar{d}$ component of the meson dressings emphasizes that there is no connected contribution to this component. One would need two d quarks in the valence sector of the proton. Thus, in this case, only the disconnected sea-quark loop contributes.

We now turn our attention to the symmetries manifest in lattice QCD calculations. These calculations are not restricted to specific choices for the mesons and baryons participating in the intermediate state. Rather, the lattice correlation functions have overlap with all baryons and mesons associated with the quantum numbers specified by the quark flow. Thus, in this discussion of the symmetries of lattice QCD correlation functions, we will ignore the hadron labels on the intermediate states of Fig. 1.

The symmetry of the $\bar{u}$ and $\bar{d}$ contributions is manifest in the right-hand column of Fig. 1. When a u valence quark is contributing to a meson dressing, both the $\bar{d}$ and $\bar{u}$ sea quarks contribute in diagrams (b) and (d) respectively. For equal-mass u and d flavors, and neglecting electromagnetic effects, these sea-quark loop contributions are equal. While the gluonic interactions are sensitive to the mass of the quarks, they do not differentiate flavor. Similarly, when a d valence quark is contributing to a meson dressing, both the $\bar{u}$ and $\bar{d}$ sea quarks contribute in diagrams (f) and (h) respectively, again maintaining the symmetry. The naive conclusion is that this symmetry prevents a contribution to the $\bar{d} - \bar{u}$ asymmetry. However there is a subtlety that has been overlooked.

If one considers the connected and disconnected diagrams on their own, without taking the sum, one must expand the list of baryons and mesons having overlap with the quark flows to include unphysical states that do not appear in the physical spectrum. Indeed, the Pauli exclusion principle is enforced by summing both of the aforementioned Wick contractions leading to connected and disconnected quark flows. On their own, a connected or disconnected graph will receive contributions from baryons that do not satisfy the Pauli exclusion principle. Fortunately, the symmetries highlighted in the previous paragraph can be used to determine the properties of these unphysical states.

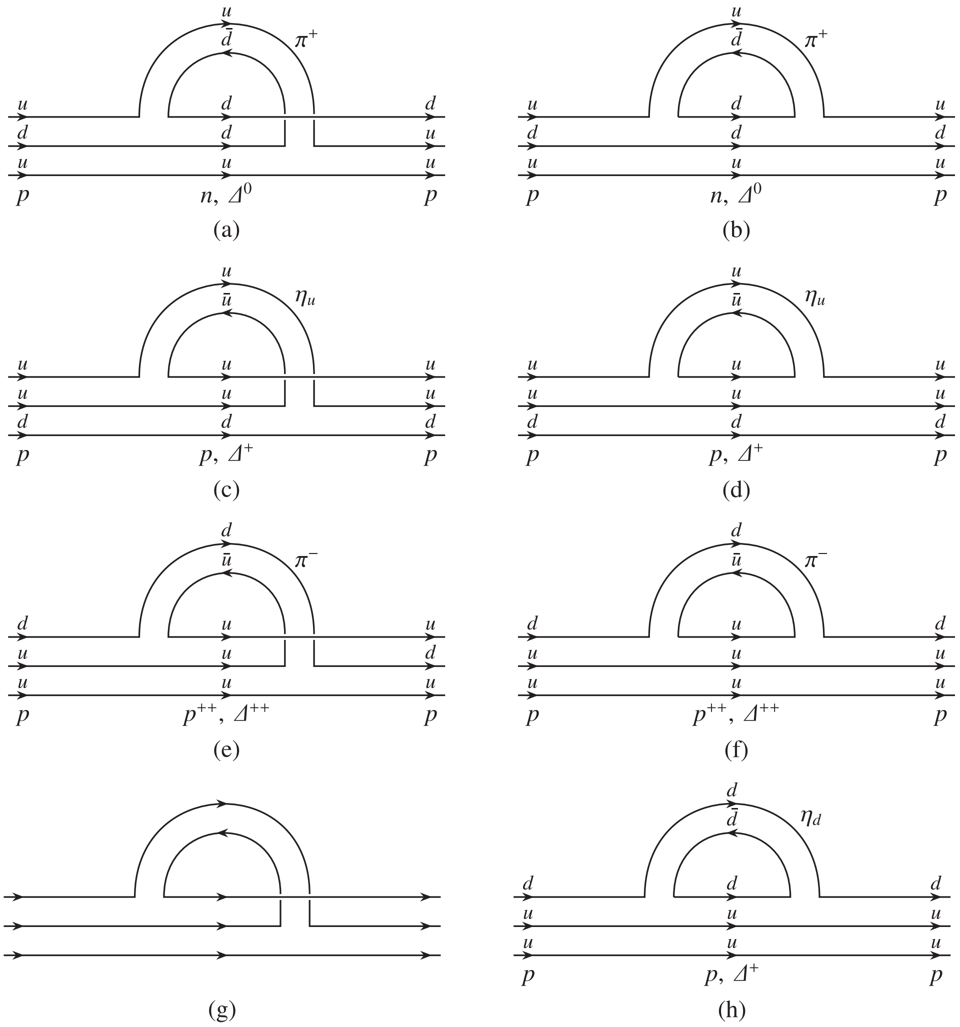

FIG. 1. Quark flow diagrams describing the one-loop meson dressings contributing to the $\bar{d}-\bar{u}$ asymmetry of the proton. The connected flows are listed in the left column as diagrams (a), (c), (e), and (g). The corresponding flows incorporating a disconnected sea-quark loop contribution appear in the right-hand column as diagrams (b), (d), (f), and (h). Diagram (g) contains no quark labels and serves to illustrate there is no connected contribution to the $d\bar{d}$ meson component. We focus on contributions where the external current acts on the anti-quark loop.

At this point, it is helpful to become more specific on the hadrons contributing to the quark flows of Fig. 1. Thus we turn our attention to light pseudoscalar meson dressings having intermediate nucleon or Δ-baryon intermediate states. These dressings provide the most important contributions to the $\bar{d}-\bar{u}$ asymmetry. Dressings with intermediate baryons degenerate with the nucleon not only isolate the leading nonanalytic contribution in chiral perturbation theory [10,37–39] but also serve to expose the presence of unphysical baryon contributions. The consideration of Δ intermediate states serves to further illustrate the necessity of an unphysical baryon degenerate with the nucleon.

We commence by focusing on dressings with intermediate baryons degenerate with the nucleon. Diagrams (a) and (b) of Fig. 1 sum to provide the physical $n\pi^+$ dressing of the proton. In diagrams (c) and (d), we are introduced to the η_u meson, a meson composed of a $u\bar{u}$ pair. Similarly, the $d\bar{d}$ meson in diagram (h) is labeled as η_d. The masses of these neutral pseudoscalar mesons can be inferred from the symmetries manifest at the level of lattice QCD correlation functions.

Because the sea-quark loop contributions from diagrams (b) and (d) are equal, we conclude that when the $\bar{d}u$ meson of diagram (b) is a π^+, the η_u meson of diagram (d) has a mass degenerate with the pion. Similarly, because the sea-quark loop contributions from diagrams (f) and (h) are equal, when the $\bar{u}d$ meson of diagram (f) is a π^-, the η_d meson of diagram (h) has a mass degenerate with the pion.

The axial couplings of these mesons are provided in a meson basis in which the diagonal entries of the nonet pseudoscalar meson matrix are η_u, η_d, and η_s. In other words, the square of the axial couplings of the η_u and η_d mesons is associated with a linear combination of π^0, η, and

η' mesons in the proportion 3 : 1 : 2 respectively for standard SU(3) symmetry. We emphasize this is simply a change of basis. The masses of the mesons are governed by the symmetries encountered in lattice QCD calculations.

The low-lying baryons associated with the quark flows are also labeled in Fig. 1. It is here that one encounters an unphysical baryon labeled "p^{++}" in diagrams (e) and (f). While the charge of $+2$ is manifest in the presence of a π^- and the necessity of charge conservation, the label of a p emphasizing the propagation of a baryon degenerate with the proton requires further explanation.

Because QCD interactions are flavor blind when $m_u = m_d$, diagrams (f) and (h) make equal contributions. It is clear that diagram (h) has overlap with the normal proton propagating in the intermediate state. Indeed diagrams (c), (d), and (h) sum to provide the physical $p\pi^0$ dressing of the proton. Thus, through the equivalence of diagrams (f) and (h) established by the symmetries of lattice QCD calculations, one concludes that the mass of the p^{++} is also that of the proton. The mass of the intermediate proton in diagram (h) excludes the identification of the p^{++} as the physical Δ^{++}.

Because the Pauli exclusion principle does not allow octet baryons with charge $+2$, we must look to the other connected Wick contractions to cancel the unphysical contribution of the sea-quark loop in diagram (f). This is the role of diagram (e) and thus we conclude that the contribution of diagram (e) is equal and opposite to that of diagram (f). In other words, if we were to restrict our diagrams to those having physical intermediate baryons, we would need to eliminate diagrams (e) and (f) in the third row of Fig. 1. With the loss of diagram (f), the symmetry of the disconnected sea-quark loop contributions is lost. Flavor-blindness in QCD interactions equates the contributions of diagrams (b) and (d), leaving the contribution from diagram (h) to break the symmetry. Thus, we conclude that disconnected sea-quark loops do in fact make physical contributions to the $\bar{d} - \bar{u}$ asymmetry in the proton.

We now turn our attention to pion-loop dressings with Δ-baryon intermediate states. A survey of these baryon labels in Fig. 1 reveals all of the required charge assignments are associated with physical Δ states. Indeed, the problem encountered in considering diagrams (e) and (f) where a p^{++} baryon degenerate with the proton was required, now presents no problem. This time, diagram (h) has overlap with a Δ^+ propagating in the intermediate state. Now the equivalence of diagrams (f) and (h) established by the symmetries of lattice QCD calculations demands that the mass of the intermediate baryon propagating in diagram (f) is degenerate with the Δ^+. Noting the Δ baryons are degenerate in the mass-symmetric limit when electromagnetic effects are neglected, the Δ^{++} baryon of diagram (f) satisfies this condition.

In summary, all the intermediate Δ-baryon states can be associated with physical Δ states. Cancellation between diagrams (e) and (f) is not required for Δ-baryon intermediate states. In this case, diagram (f) remains available to complete the symmetry of $\bar{d}$ and $\bar{u}$ disconnected sea-quark loop contributions and the disconnected sea-quark loop sector does not generate a contribution to the $\bar{d} - \bar{u}$ asymmetry of the nucleon when the intermediate propagating baryon is a Δ baryon. As such, we will not consider Δ baryons further.

Partially quenched chiral perturbation theory. Partially quenched chiral perturbation theory for baryons [40–44] provides a mechanism for understanding the relative contributions of the connected and disconnected quark-flow diagrams. While the label "partially quenched" has a historical origin, the results presented here pertain to that of physical QCD. Here we draw on the results in Tables I and II of Ref. [43] using the diagrammatic approach for obtaining the meson-baryon couplings in terms of the familiar SU(3)-flavor axial couplings, F and D. There the physical basis was used for the axial couplings and the η_u and η_d couplings are obtained by summing over the π^0, η, and η' entries.

Our focus is now on the meson-loop dressings of Fig. 1 with intermediate baryons degenerate with the proton. These dressings provide the leading nonanalytic contributions to the $\bar{d} - \bar{u}$ asymmetry and we refer to them succinctly as the leading contributions in the following.

Diagrams (a) and (b) of Fig. 1 sum to generate the full physical π^+ dressing of the proton, The disconnected sea-quark loop coefficients are provided in Table II of Ref. [43] and the coefficients of the connected diagrams are obtained by subtracting the disconnected contributions from the full contributions provided in Table I of Ref. [43].

Working with the normalization of Ref. [43] where the contribution of the $n\pi^+$ dressing of the proton is proportional to $2(D + F)^2 = 2g_A^2$, the contribution of each diagram in Fig. 1 generating the leading contribution is summarized in Table I. Here the numerical values correspond to $D = 0.77$ and $F = 0.50$, such that $g_A = 1.27$.

Note how the symmetries discussed in the previous section in the context of lattice QCD quark-flow diagrams are manifest in Table I for pseudoscalar dressings of the proton. The equivalence of diagrams (b) and (d) is reflected in the equivalence of the axial couplings for these diagrams. The equivalence of diagrams (f) and (h) is similarly reflected in equal axial couplings for those diagrams.

With regard to the $\bar{d} - \bar{u}$ asymmetry of the nucleon, we recall that diagram (f) is combined with (e) to eliminate the unphysical propagation of the p^{++}. While the contributions of diagrams (b) and (d) maintain the symmetry of $\bar{d}$ and $\bar{u}$ contributions in the disconnected sea-quark loop contributions, diagram (h) stands alone. As a result, there is an enhancement of $\bar{d}$ in the disconnected sea-quark loop sector coming from diagram (h). The symmetry is broken as

TABLE I. The leading contribution for each diagram of Fig. 1 from SU(3) partially quenched chiral perturbation theory. Here we use the normalization of Ref. [43] that sums diagrams (a) and (b) to give the physical $n\pi^+$ dressing of the proton equal to $2(D+F)^2 = 2g_A^2$. Numerical values correspond to $D = 0.77$ and $F = 0.50$. The right-hand column entitled relative contribution describes the percentage split of the strength between the connected and disconnected contributions in each row of Fig. 1.

Diagram	Contribution	Value	Relative contribution (%)
(a)	$2D^2/3 + 4DF - 2F^2$	1.44	44.5
(b)	$(D+3F)^2/3 + (D-F)^2$	1.79	55.5
(c)	$4(F^2 - D^2/3)$	0.21	10.5
(d)	$(D+3F)^2/3 + (D-F)^2$	1.79	89.5
(e)	$-2(D-F)^2$	−0.15	50.0
(f)	$2(D-F)^2$	0.15	50.0
(h)	$2(D-F)^2$	0.15	100.0

unphysical baryons are removed from the intermediate states. Thus, the assumption of equal $\bar{d}$ and $\bar{u}$ in the disconnected sector of the sea is wrong in principle.

The axial couplings of Table I allow one to quantify the relative contributions of the connected and disconnected sectors to $\bar{d} - \bar{u}$. Commencing with the connected sector, the third column of Table I provides the couplings for diagrams (a) and (c). Their difference leaves a net effect of $1.44 - 0.21 = 1.23$ favoring the $\bar{d}$ contribution. Now the disconnected sea-quark loop contribution of diagram (h) further enhances the $\bar{d}$ excess, raising it from $1.23 \to 1.23 + 0.15 = 1.38$. Thus a 12% enhancement of the pion-nucleon contribution to $\bar{d} - \bar{u}$ in the proton has its origin in the disconnected sea-quark loop sector.

Conclusions. We have analyzed the role of connected and disconnected quark-flow diagrams in generating a $\bar{d} - \bar{u}$ asymmetry in the sea of the proton. The formalisms of lattice QCD and partially quenched chiral perturbation theory have been considered. It has been shown that the naive assertion of the equality of the $\bar{d}$ and $\bar{u}$ contributions from disconnected sea-quark loops relies on contributions from an unphysical baryon. There is an unphysical contribution to $\bar{u}$ arising from the process involving an intermediate π^- and a charge 2^{++} baryon degenerate with the proton, illustrated in Fig. 1(f). In a full QCD calculation this unphysical contribution is precisely cancelled by the connected contribution to $\bar{u}$ shown in Fig. 1(e). Once the unphysical contribution associated with Fig. 1(f) is removed, one finds an enhancement of approximately 12% in the $\bar{d} - \bar{u}$ asymmetry arising from pion-baryon-octet components of the proton wave function.

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[1] F. Gross *et al.*, 50 years of quantum chromodynamics, Eur. Phys. J. C **83**, 1125 (2023).

[2] A. W. Thomas, A limit on the pionic component of the nucleon through SU(3) flavor breaking in the sea, Phys. Lett. **126B**, 97 (1983).

[3] A. S. Ito *et al.*, Measurement of the continuum of dimuons produced in high-energy proton-nucleus collisions, Phys. Rev. D **23**, 604 (1981).

[4] D. Allasia *et al.* (New Muon (NMC) Collaboration), Measurement of the neutron and the proton F_2 structure function ratio, Phys. Lett. B **249**, 366 (1990).

[5] K. Gottfried, Sum rule for high-energy electron-proton scattering, Phys. Rev. Lett. **18**, 1174 (1967).

[6] K. Gottfried and V. F. Weisskopf, *Concepts of Particle Physics. Vol. 2* (Oxford University Press, 1986).

[7] J. Dove *et al.* (SeaQuest Collaboration), The asymmetry of antimatter in the proton, Nature (London) **590**, 561 (2021); **604**, E26 (2022).

[8] R. S. Towell *et al.* (NuSea Collaboration), Improved measurement of the $\bar{d}/\bar{u}$ asymmetry in the nucleon sea, Phys. Rev. D **64**, 052002 (2001).

[9] M. Arneodo *et al.* (New Muon Collaboration), Reevaluation of the Gottfried sum, Phys. Rev. D **50**, R1 (1994).

[10] A. W. Thomas, W. Melnitchouk, and F. M. Steffens, Dynamical symmetry breaking in the sea of the nucleon, Phys. Rev. Lett. **85**, 2892 (2000).

[11] F. He, C.-R. Ji, W. Melnitchouk, Y. Salamu, A. W. Thomas, P. Wang, and X. G. Wang, Helicity-dependent distribution of strange quarks in the proton from nonlocal chiral effective theory, Phys. Rev. D **105**, 094007 (2022).

[12] S. Kretzer, F. Olness, J. Pumplin, D. Stump, W.-K. Tung, and M. H. Reno, The parton structure of the nucleon and precision determination of the Weinberg angle in neutrino scattering, Phys. Rev. Lett. **93**, 041802 (2004).

[13] Y. Salamu, C.-R. Ji, W. Melnitchouk, A. W. Thomas, P. Wang, and X. G. Wang, Parton distributions from nonlocal chiral SU(3) effective theory: Flavor asymmetries, Phys. Rev. D **100**, 094026 (2019).

[14] X. G. Wang, C.-R. Ji, W. Melnitchouk, Y. Salamu, A. W. Thomas, and P. Wang, Strange quark asymmetry in the proton in chiral effective theory, Phys. Rev. D **94**, 094035 (2016).

[15] M. Burkardt, K. S. Hendricks, C.-R. Ji, W. Melnitchouk, and A. W. Thomas, Pion momentum distributions in the nucleon in chiral effective theory, Phys. Rev. D **87**, 056009 (2013).

[16] M. Alberg and G. A. Miller, Chiral light front perturbation theory and the flavor dependence of the light-quark nucleon sea, Phys. Rev. C **100**, 035205 (2019).

[17] D. Diakonov, V. Petrov, P. Pobylitsa, M. V. Polyakov, and C. Weiss, Nucleon parton distributions at low normalization point in the large N_c limit, Nucl. Phys. **B480**, 341 (1996).

[18] B. Dressler, K. Goeke, M. V. Polyakov, P. Schweitzer, M. Strikman, and C. Weiss, Polarized anti-quark flavor asymmetry in Drell-Yan pair production, Eur. Phys. J. C **18**, 719 (2001).

[19] W. Melnitchouk, A. W. Thomas, and A. I. Signal, Gottfried sum rule and the shape of $F_2^p - F_2^n$, Z. Phys. A **340**, 85 (1991).

[20] E. M. Henley and G. A. Miller, Excess of $\bar{d}$ over $\bar{u}$ in the proton sea quark distribution, Phys. Lett. B **251**, 453 (1990).

[21] A. I. Signal and A. W. Thomas, Possible strength of the nonperturbative strange sea of the nucleon, Phys. Lett. B **191**, 205 (1987).

[22] R. D. Ball *et al.* (NNPDF Collaboration), The path to proton structure at 1% accuracy, Eur. Phys. J. C **82**, 428 (2022).

[23] R. Abdul Khalek *et al.*, Snowmass 2021 white paper: Electron ion collider for high energy physics, arXiv:2203.13199.

[24] A. W. Thomas, X. G. Wang, and A. G. Williams, Constraints on the dark photon from deep inelastic scattering, Phys. Rev. D **105**, L031901 (2022).

[25] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, Eur. Phys. J. C **77**, 663 (2017).

[26] X. Zheng, J. Erler, Q. Liu, and H. Spiesberger, Accessing weak neutral-current coupling g_{AA}^{eq} using positron and electron beams at Jefferson Lab, Eur. Phys. J. A **57**, 173 (2021).

[27] W. Bentz, I. C. Cloet, J. T. Londergan, and A. W. Thomas, Reassessment of the NuTeV determination of the weak mixing angle, Phys. Lett. B **693**, 462 (2010).

[28] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Parton distributions for the LHC, Eur. Phys. J. C **63**, 189 (2009).

[29] W. Detmold, M. Illa, D. J. Murphy, P. Oare, K. Orginos, P. E. Shanahan, M. L. Wagman, and F. Winter (NPLQCD Collaboration), Lattice QCD constraints on the parton distribution functions of ^{3}He, Phys. Rev. Lett. **126**, 202001 (2021).

[30] P. C. Barry *et al.* (Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations), Complementarity of experimental and lattice QCD data on pion parton distributions, Phys. Rev. D **105**, 114051 (2022).

[31] T.-J. Hou, M. Yan, J. Liang, K.-F. Liu, and C. P. Yuan, Connected and disconnected sea partons from the CT18 parametrization of PDFs, Phys. Rev. D **106**, 096008 (2022).

[32] K.-F. Liu, W.-C. Chang, H.-Y. Cheng, and J.-C. Peng, Connected-sea partons, Phys. Rev. Lett. **109**, 252002 (2012).

[33] Y.-j. Zhang, B. Zhang, and B.-Q. Ma, Detailed balance and sea quark flavor asymmetry of proton, Phys. Lett. B **523**, 260 (2001).

[34] K.-F. Liu and S.-J. Dong, Origin of difference between $\bar{d}$ and $\bar{u}$ partons in the nucleon, Phys. Rev. Lett. **72**, 1790 (1994).

[35] K.-F. Liu, Parton degrees of freedom from the path integral formalism, Phys. Rev. D **62**, 074501 (2000).

[36] D. B. Leinweber, QCD equalities for baryon current matrix elements, Phys. Rev. D **53**, 5115 (1996).

[37] C.-R. Ji, W. Melnitchouk, and A. W. Thomas, Anatomy of relativistic pion loop corrections to the electromagnetic nucleon coupling, Phys. Rev. D **88**, 076005 (2013).

[38] J.-W. Chen and X.-d. Ji, Is the Sullivan process compatible with QCD chiral dynamics?, Phys. Lett. B **523**, 107 (2001).

[39] D. Arndt and M. J. Savage, Chiral corrections to matrix elements of twist-2 operators, Nucl. Phys. **A697**, 429 (2002).

[40] J. N. Labrenz and S. R. Sharpe, Quenched chiral perturbation theory for baryons, Phys. Rev. D **54**, 4595 (1996).

[41] M. J. Savage, The magnetic moments of the octet baryons in quenched chiral perturbation theory, Nucl. Phys. **A700**, 359 (2002).

[42] J.-W. Chen and M. J. Savage, Baryons in partially quenched chiral perturbation theory, Phys. Rev. D **65**, 094001 (2002).

[43] D. B. Leinweber, Quark contributions to baryon magnetic moments in full, quenched and partially quenched QCD, Phys. Rev. D **69**, 014005 (2004).

[44] J. M. M. Hall and D. B. Leinweber, Flavor-singlet baryons in the graded symmetry approach to partially quenched QCD, Phys. Rev. D **94**, 094004 (2016).