Isovector EMC effect from global QCD analysis with MARATHON data

C. Cocuzza,[1] C. E. Keppel,[2] H. Liu,[3] W. Melnitchouk,[2] A. Metz,[1] N. Sato,[2] and A. W. Thomas[4]

[1]*Department of Physics, SERC, Temple University, Philadelphia, Pennsylvania 19122, USA*
[2]*Jefferson Lab, Newport News, Virginia 23606, USA*
[3]*Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[4]*CSSM and CoEPP, Department of Physics, University of Adelaide SA 5005, Australia*

Jefferson Lab Angular Momentum (JAM) Collaboration

(Dated: April 14, 2021)

We report the results of a Monte Carlo global QCD analysis of unpolarized parton distribution functions (PDFs), including for the first time constraints from ratios of ^{3}He to ^{3}H structure functions recently obtained by the MARATHON experiment at Jefferson Lab. Our simultaneous analysis of nucleon PDFs and nuclear effects in $A=2$ and $A=3$ nuclei reveals the first indication for an isovector nuclear EMC effect in light nuclei. We find that while the MARATHON data yield relatively weak constraints on the F_2^n/F_2^p neutron to proton structure function ratio and the d/u PDF ratio, they suggest a strongly enhanced nuclear effect on the d-quark PDF in the bound proton.

Introduction — The quest to unravel the 3-dimensional structure of the nucleon has recently taken on new impetus with the development of experimental programs at modern accelerator facilities at CEBAF at Jefferson Lab, RHIC at BNL and COMPASS at CERN aimed at studying processes sensitive to transverse momentum dependent (TMD) distributions and generalized parton distributions (GPDs). These complement the more traditional observables, such as from lepton-nucleon deep-inelastic scattering (DIS), that provide information on the 1-dimensional structure encoded in parton distribution functions (PDFs). Whilst these are in contrast relatively well understood [1, 2], even there one finds important unanswered questions.

Amongst the most notable gaps in our knowledge of PDFs, we mention the decomposition of the proton sea into individual flavor components, and the structure of valence quark PDFs carrying a large fraction x ($x \to 1$) of the nucleon's light-cone momentum. While a wealth of data has been accumulated on protons, which have placed significant constraints on the u-quark PDF, the absence of free neutron targets has meant that the d-quark distribution at large x has remained much more elusive [3, 4]. The traditional method of extracting neutron structure from inclusive deuteron DIS has been shown to be rather problematic and handicapped by significant uncertainties in the nuclear corrections at high x [5, 6].

To remedy this lamentable situation, several dedicated experimental efforts have been launched in recent years to map out PDFs, and particularly the ratio of d to u PDFs, at large values of x. Amongst these are spectator proton tagging in semi-inclusive DIS from the deuteron [7, 8], to measure the (nearly) free neutron structure function, and weak vector boson production in pp or $p\bar{p}$ collisions, which at large rapidities selects the valence u or d PDFs [9]. An alternative experiment was proposed [10, 11] to exploit the mirror symmetry of $A=3$ nuclei to extract the neutron to proton F_2^n/F_2^p structure function ratio from the ratio of ^{3}He and ^{3}H cross sections, in which the nuclear effects are expected to largely cancel. The results from the subsequent MARATHON experiment that was performed at Jefferson Lab Hall A were recently presented [12].

In particular, the experiment measured the ^{3}He/^{3}H ratio in the range of Bjorken-x values between 0.195 and 0.825 and Q^2 between 2.7 and 11.9 GeV^2, with the deuteron/proton ratio taken over a smaller x range as a normalization check. Assuming that the super-ratio of EMC ratios in ^{3}He and ^{3}H, $\mathcal{R} = R(^3\text{He})/R(^3\text{H}) \approx 1$, where $R(^3\text{He}) = F_2^{^3\text{He}}/(2F_2^p + F_2^n)$ and $R(^3\text{H}) = F_2^{^3\text{H}}/(F_2^p + 2F_2^n)$, the neutron to proton ratio F_2^n/F_2^p can be directly extracted from $\mathcal{R}$ and the measured $F_2^{^3\text{He}}/F_2^{^3\text{H}}$ ratio.

In the MARATHON analysis of the measured ^{3}He/^{3}H ratios, the model calculation of Kulagin and Petti (KP) [13] was used for $\mathcal{R}$ to extract the F_2^n/F_2^p ratio. The KP model was used to determine the overall normalization of the ^{3}He/^{3}H ratio data, as well as the deuteron to proton cross section ratio data, so that both ratios produce the same extracted F_2^n/F_2^p as in the KP analysis [12]. Furthermore, the MARATHON analysis assumed that all EMC ratios for $A = 2$ and $A = 3$ nuclei cross unity at $x = 0.31$. While this is approximately established empirically from measurements of the EMC effect in heavy nuclei, F_2^A/F_2^D, it has not been verified experimentally for light nuclei, such as for $R(^3\text{He})$ or $R(^3\text{H})$, or for the deuteron EMC ratio, $R(D) = F_2^D/(F_2^p + F_2^n)$.

In this paper we present an alternative analysis which does not assume prior knowledge of $\mathcal{R}$, using the JAM Monte Carlo global QCD framework [14, 15] to fit all available high-energy scattering data on protons, deuterons, and $A = 3$ nuclei, including the MARATHON data. While the MARATHON experiment alone is not able to unambiguously determine both PDFs and the nuclear effects in $A \leq 3$ nuclei, by combining those results with the global set of high-energy scattering data we are able to *simultaneously* extract information on nucleon PDFs *and* nuclear effects in $A \leq 3$ nuclei. In contrast, by assuming the KP model [13] for the nuclear corrections, the analysis [12] introduces significant bias into the extracted F_2^n/F_2^p ratio and underestimates the true uncertainties associated with the model dependence of the super-ratio. In particular, while the KP model assumes that the off-shell modifications of bound protons and neutrons are equal and identical for all nuclei [13], our analysis allows a data-driven identification of possible isospin dependent nuclear effects.

Theoretical framework — Our theoretical framework is based on the JAM iterative Monte Carlo approach to QCD global analysis [15, 16], which utilizes Bayesian inference sampling methodology that allows thorough exploration of the parameter space and robust error quantification. Unlike attempts to extract partonic physics information from a single experiment, which invariably requires model-dependent inputs and assumptions, the virtue of a global analysis is its ability to determine the nucleon PDFs and nuclear effects simultaneously and with minimal theoretical bias.

Our analysis uses data from a variety of high-energy scattering processes, including deep-inelastic scattering (DIS) from protons, deuterons and $A = 3$ nuclei at fixed target and collider facilities, Drell-Yan lepton-pair production at Fermilab, weak vector boson production at the Tevatron and LHC, and jet cross sections in $p\bar{p}$ and pp collisions at the Tevatron and RHIC. For DIS, QCD factorization theorems [17] allow us to write the F_2 structure function as a sum of leading-twist contributions, expressed as convolutions of hard scattering functions, $C_{q,g}$, and nonperturbative quark and gluon PDFs, with higher twist (HT) power corrections,

$$F_2^N(x,Q^2) = \Big(\sum_q e_q^2 \big[C_q \otimes q_N^+\big] + \big[C_g \otimes g_N\big]\Big)(x,Q^2) \times \left(1 + \frac{C_N^{\rm HT}(x)}{Q^2}\right), \qquad (1)$$

where $q_N^+ \equiv q_N + \bar{q}_N$, and x here is the Bjorken scaling variable with Q^2 the four-momentum squared of the exchanged photon. (Note that beyond leading order in α_s the Bjorken variable no longer coincides with the parton momentum fraction, x; however, for ease of notation we will distinguish between the two only when necessary.)

The coefficients of the HT terms, $C_N^{\rm HT}$, can be determined phenomenolgically from low-Q^2 data, and can be different for protons and neutrons. In addition to HT corrections, at finite Q^2 the right hand side of Eq. (1) includes also the effects of target mass corrections, which can be implemented within collinear factorization as described in Refs. [18, 19]. In this analysis, we parameterize the PDFs at the input scale Q_0^2 using the standard form,

$$f(x,Q_0^2) = N x^\alpha (1-x)^\beta (1 + \gamma\sqrt{x} + \eta x) \qquad (2)$$

as in the recent JAM19 analysis [14].

For nuclear DIS, the same factorization allows F_2^A to be expressed in terms of the nuclear PDFs q_A^+ as in (1). In the nuclear impulse approximate, at $x \gg 0$ the scattering takes place incoherently from individual (off-shell) nucleons in the nucleus, and one can generally write the nuclear PDF as a sum of on-shell and off-shell nucleon contributions [20–23],

$$q_A(x,Q^2) \equiv q_{N/A}^{\rm (on)}(x,Q^2) + q_{N/A}^{\rm (off)}(x,Q^2). \qquad (3)$$

In the weak binding approximation (WBA) [22, 23], appropriate for light nuclei such as D, ^{3}He or ^{3}H, both the on-shell and off-shell terms in (3) can be expressed as convolutions of nucleon smearing functions and quark distributions in the nucleon,

$$q_{N/A}^{\rm (on)}(x,Q^2) = \big[f_{N/A}^{\rm (on)} \otimes q_N\big](x,Q^2), \qquad (4)$$

$$q_{N/A}^{\rm (off)}(x,Q^2) = \big[f_{N/A}^{\rm (off)} \otimes \delta q_{N/A}\big](x,Q^2), \qquad (5)$$

where the symbol $\otimes$ represents the convolution $[f \otimes g](x) \equiv \int_x^A (dy/y)\, f(x)\, g(x/y)$. The functions $f_{N/A}^{\rm (on)}$ and $f_{N/A}^{\rm (off)}$ are on-shell and off-shell light-cone momentum distributions of nucleons N in nucleus A, respectively [24, 25], and can be computed from the nuclear wave functions or spectral functions. The main difference between the on-shell and off-shell smearing functions is that the integrand of the latter is weighted by the nucleon virtuality, $v(p^2) \equiv (p^2 - M^2)/M^2 < 0$, where M is the nucleon mass, which reduces the magnitude of the off-shell functions $q_{N/A}^{\rm (off)}$ by about two orders of magnitude compared with the on-shell functions.

Since the focus of the MARATHON experiment is on the F_2^n/F_2^p (and d/u) ratio at large $x \gg 0$, we will restrict the discussion of the nuclear effects to the valence quark sector, which is also where the main features of the nuclear EMC effect appear. Previous global QCD analyses of proton and deuteron DIS and other high-energy data [5, 6] found strong evidence, within the WBA framework, for the presence of nucleon off-shell effects, beyond the traditional binding and Fermi motion corrections, needed to obtain a good fit to the data. The off-shell corrections in the deuteron were implemented at the nucleon structure function level [5, 6, 13], with the deuteron data sensitive to one combination of the proton and neutron off-shell functions. A later structure function analysis [25], including ^{3}He$/D$ ratios measured in Jefferson Lab Hall C [26], explored possible differences between proton and neutron off-shell functions. The analysis found potentially significant isospin dependence of the off-shell functions, albeit within sizeable uncertainties. However, the formulation in terms of the off-shell functions at the nucleon level necessarily introduces explicit charge symmetry breaking, which one ultimately would want to test [27].

On the other hand, by formulating the off-shell corrections at the quark level one can ensure that charge symmetry is respected. In particular, for the deuteron we require the u and d off-shell corrections to satisfy

$$\delta u_{p/D} = \delta d_{n/D}, \quad \delta d_{p/D} = \delta u_{n/D}, \tag{6}$$

and similarly for ^{3}He and ^{3}H nuclei,

$$\delta u_{p/^3\mathrm{He}} = \delta d_{n/^3\mathrm{H}}, \quad \delta d_{p/^3\mathrm{He}} = \delta u_{n/^3\mathrm{H}}, \tag{7a}$$

$$\delta u_{p/^3\mathrm{H}} = \delta d_{n/^3\mathrm{He}}, \quad \delta d_{p/^3\mathrm{H}} = \delta u_{n/^3\mathrm{He}}, \tag{7b}$$

so that the 12 off-shell functions (for u and d quarks in p and n in D, ^{3}He and ^{3}H) reduce to 6. The number can be further reduced by observing that, if isospin symmetry is preserved, the u and d off-shell functions in the deuteron and ^{3}H can be related by

$$\delta u_{p/D} = \delta u_{p/^3\mathrm{H}} \equiv \delta u, \tag{8a}$$

$$\delta d_{p/D} = \delta d_{p/^3\mathrm{H}} \equiv \delta d, \tag{8b}$$

Because for δu the product of the third component of isospin of the struck quark and the spectator nucleon(s) is negative, while for δd this is positive, an isovector nuclear correction would lead to changes of opposite sign between them [28, 29]. For the off-shell corrections in the proton in ^{3}He we expect the isovector effects to approximately cancel and take

$$\delta u_{p/^3\mathrm{He}} \approx \delta d_{p/^3\mathrm{He}} = \frac{1}{2}\big(\delta u + 2\,\delta d\big). \tag{9}$$

To preserve the number of valence quarks in the bound protons and neutrons in all nuclei, the off-shell functions must satisfy

$$\int_0^1 \mathrm{d}x\ \delta u(x) = \int_0^1 \mathrm{d}x\ \delta d(x) = 0. \tag{10}$$

Note that because the off-shell functions δq are convoluted with the off-shell smearing functions, $f^{(\mathrm{off})}_{N/A}$, the fact that the nucleon virtuality $v(p^2)$ averages to a number roughly twice as large in magnitude in $A = 3$ as $A = 2$ accounts for the expected increase in off-shell effects in the former. For the Paris [30] deuteron wave function and the KPSV [31] ^{3}He spectral function, for example, we find

$$\langle f^{(\mathrm{off})}_{p/D}\rangle \approx -4.3\%, \quad \langle f^{(\mathrm{off})}_{p/^3\mathrm{He}}\rangle \approx -6.8\%, \quad \langle f^{(\mathrm{off})}_{p/^3\mathrm{H}}\rangle \approx -9.5\%,$$

with corresponding values for the neutron, $\langle f^{(\mathrm{off})}_{n/D}\rangle = \langle f^{(\mathrm{off})}_{p/D}\rangle$, $\langle f^{(\mathrm{off})}_{n/^3\mathrm{He}}\rangle = \langle f^{(\mathrm{off})}_{p/^3\mathrm{H}}\rangle$ and $\langle f^{(\mathrm{off})}_{n/^3\mathrm{H}}\rangle = \langle f^{(\mathrm{off})}_{p/^3\mathrm{He}}\rangle$. Using other deuteron [32–35] and ^{3}He [36] wave function models does not change our conclusions.

For the parametrization of the off-shell functions at the input scale, we take the same form as for the PDFs in Eq. (2), and assume that all quark flavors for the off-shell functions except δu and δd are zero at the input scale. The $\delta q_{N/A}$ functions evolve with Q^2 in the same way as the on-shell PDFs. In our fits, we treat N, α, and β as free parameters, and without loss of generality set $\gamma = 0$, so that the parameter η is fixed by the sum rules.

Quality of fit — In addition to the new MARATHON data, we fit also F_2 data from fixed target experiments on p, d, and ^{3}He from BCDMS [37], NMC [38, 39], SLAC [40], and Jefferson Lab [8, 26, 41], with kinematic constraints $W^2 > 3.0$ GeV^2 and $Q^2 > m_c^2$. Under the same cuts, we also include the reduced neutral and charged current proton cross sections from the combined H1/ZEUS analysis from HERA [42], and Drell-Yan di-muon data in pp and pd collisions from the Fermilab E866 experiment [43]. For weak vector boson mediated processes, we use Z/γ^* and $W^\pm$ cross sections and asymmetries from the Tevatron [44–47]; $W^\pm$-lepton cross sections and asymmetries from CDF [48] and D0 [49, 50] at the Tevatron; and $W^\pm$-lepton asymmetries from the CMS [51–54] and ATLAS collaborations [55–57] at the LHC. Also fitted are jet production data from the Tevatron [58, 59] and RHIC [60].

The results of our Monte Carlo analysis for the χ^2 values per number of points N_{dat} are shown in Table I for each type of process, along with the individual values for the MARATHON and other nuclear DIS data and the overall normalizations. The overall χ^2/N_{dat} of 1.11 shows that the analysis is able to describe the data quite well. The W and lepton asymmetry data are the most difficult to fit, with χ^2/N_{dat} of 1.48 and 1.57 respectively, because of the high precision of the data. For the MARATHON data, we obtain an excellent description with a χ^2/N_{dat} of 0.64 for ^{3}He/^{3}H and 0.72 for D/p.

The resulting fits to the MARATHON F_2^D/F_2^p and $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$ data are shown in Fig. 1. For D/p we find some tension with the rest of the world fixed target data, which is resolved by reducing the theoretical values with a fitted normalization of 1.016(4) for this dataset. This allows a simultaneous fit to the NMC D/p data, which achieves a χ^2/N_{dat} of 0.89 and a fitted normalization of 0.991.

TABLE I. Summary of the χ^2 values per number of points N_{dat} for the data used in this analysis. The MARATHON, JLab E03-103 ^{3}He/D, and NMC D/p datasets are separated from the rest of the fixed target data, and their fitted normalizations are shown.

process	N_{dat}	χ^2/N_{dat}	fitted norm.
DIS			
MARATHON ^{3}He/^{3}H	22	0.64	1.009(5)
MARATHON D/p	7	0.72	1.016(4)
JLab E03-103 ^{3}He/D	16	0.20	1.012(8)
NMC D/p	189	0.89	0.991(5)
other fixed target	2489	1.06	
HERA	1185	1.28	
Drell-Yan	250	1.08	
lepton rapidity	156	1.57	
W charge asym.	27	1.48	
Z rapidity	56	0.94	
jet	196	0.87	
total	**4593**	**1.11**	

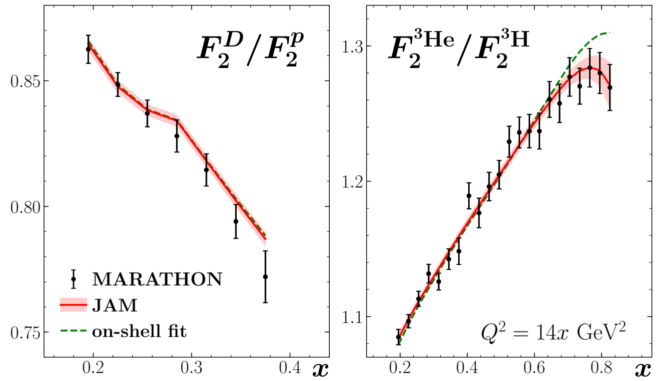

FIG. 1. Ratios F_2^D/F_2^p (left) and $F_2^{^3\text{He}}/F_2^{^3\text{H}}$ (right) from MARATHON [12] (black circles) at $Q^2 = 14x$ GeV^2 compared with the full JAM fit (red solid lines and 1σ uncertainty bands) and with an on-shell fit (green dashed lines) which sets the off-shell corrections to zero.

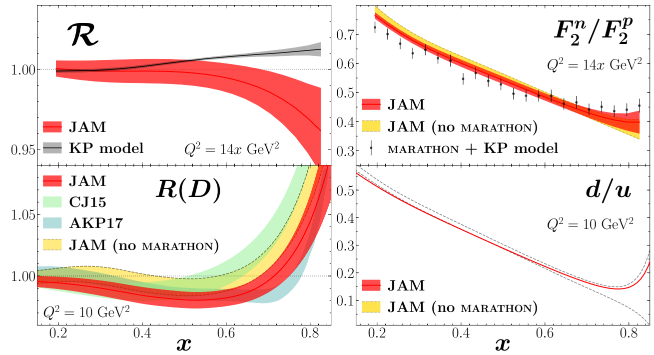

FIG. 2. Results from the present JAM analysis including MARATHON data (red bands) for the super-ratio $\mathcal{R}$ (top left), F_2^n/F_2^p ratio (top right), deuteron EMC ratio $R(D)$ (bottom left), and the d/u ratio (bottom right), compared with those without the MARATHON data (yellow bands). The super-ratio $\mathcal{R}$ is compared with the KP model input (gray band) used to extract the F_2^n/F_2^p ratio in [12]. The deuteron EMC ratio $R(D)$ is also compared with that from the CJ15 [5] (green band) and AKP17 [6] (light blue band).

For the ^{3}He/^{3}H ratio, the description of the high-x data clearly requires the inclusion of off-shell corrections, with the χ^2/N_{dat} increasing to 1.45 in the on-shell fit when the off-shell corrections are switched off. This dataset displays the largest sensitivity to off-shell corrections, and thus is critical for the extraction of these effects. In Ref. [12] a normalization of 1.025(7) was included for this dataset based on results from the KP model [13], which assumes that $R(d)$ and $\mathcal{R}$ are unity at $x = 0.31$. To avoid this model bias, we remove this normalization from the data and instead fit the normalization ourselves within the global fit. Our fitted value of 1.009(5) is in disagreement with the value above derived from the KP model.

QCD analysis — The final results of our extraction are illustrated in Fig. 2, where we show the fitted super-ratio $\mathcal{R}$, the deuteron EMC ratio $R(D)$, the F_2^n/F_2^p ratio, and the resulting d/u PDF ratio from the global fit. For the super-ratio $\mathcal{R}$, our analysis shows that it is consistent with unity until $x \approx 0.7$, at which point it dips and reaches a mean value of 4% below unity at $x = 0.825$. The uncertainties on the super-ratio range from $\pm 0.5\%$ at low x up to $\pm 2.5\%$ at the highest x. Without the MARATHON data the uncertainties on $\mathcal{R}$ (not shown in Fig. 2) vary between 4% and 15%. This improvement demonstrates that the ^{3}He/^{3}H data provide a significant amount of information on the super-ratio. Our results disagree with the KP model [13], which predicts a rise to $\mathcal{R} = 1.01$ at $x = 0.825$ [12]. They also suggest that the errors from the KP model, which are an order of magnitude smaller than our extraction even after the inclusion of the MARATHON data, are significantly underestimated.

Given the disagreement on the super-ratio, it is not surprising that we also find some differences between our result for F_2^n/F_2^p and the extraction in Ref. [12] using the KP model. We find that the MARATHON data decreases the n/p ratio by a moderate amount at low x and increases it by a small amount at high x. While this brings the results of our extraction closer to the KP model calculations, there are still significant disagreements at low and high x, with our extraction giving a value of 0.40(4) for the ratio at $x = 0.825$, compared to 0.46(2) in Ref. [12], although the deviation is within 1σ.

The impact on the d/u ratio from the inclusion of the MARATHON data is similar to that on F_2^n/F_2^p, with a slight decrease (increase) at low (high) x. The small changes for d/u at high x combined with the large differences between the on-shell and off-shell fits at high x (see Fig. 1) illustrate an important point: Due to the strong constraints placed on the d/u ratio by vector boson production data, and in particular the W asymmetry data from CDF [44] and D0 [45], the high-x MARATHON data primarily provide new information on nuclear effects, such as the off-shell corrections, which are most relevant in that region.

For the deuteron EMC ratio $R(D)$, in the intermediate-x region our result is generally in agreement with the CJ15 extraction [5], while at high x it is closer to the AKP17 fit [6]. Notably, we do not see a strong indication for a unity crossing at $x = 0.31$, as was assumed in Ref. [12]. The inclusion of the MARATHON D/p data reduces the ratio in the range $0.2 < x < 0.4$, as the theory must be adjusted downwards to accommodate the new data lying below the rest of the fixed target data.

The impact of the MARATHON data on the off-shell corrections δu and δd is shown in Fig. 3. In particular, whereas in the KP model [12, 13] the proton and neutron off-shell effects are set equal, in our analysis we allow flavor dependence of the effects to be determined from the global fit. Indeed, we find that while the $\delta u/u$ ratio

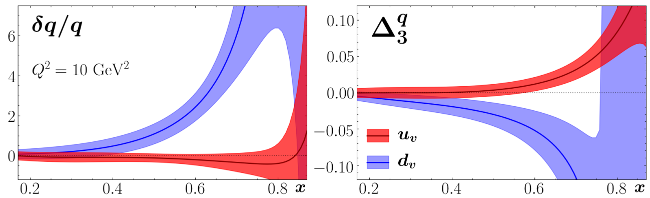

FIG. 3. Ratio of off-shell to on-shell PDFs $\delta q/q$ (left) and the difference between proton valence quarks in ^{3}He and ^{3}H normalized to the sum, Δ_3^q (right), for valence u (red bands) and d (blue bands) quarks, at $Q^2 = 10$ GeV^2.

is consistent with zero, for the d quark the $\delta d/d$ ratio is strongly enhanced at large values of x.

An even more direct way of quantifying this effect is to compare the PDFs in the proton bound in ^{3}He and in ^{3}H, defining the quantity

$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}}, \qquad (11)$$

which measures the strength of the isovector EMC effect for $q = u$ and d quarks. Since ^{3}He and ^{3}H are mirror nuclei, the ratio Δ_3^q would vanish if the nuclear corrections were purely isoscalar. Instead, the behavior in Fig. 3 indicates clear deviations from zero at $x \gtrsim 0.4$ in Δ_3^u and even more so in Δ_3^d. The fact that the Δ_3^q are nonzero and of opposite sign for u and d quarks strongly suggests the presence of an isovector component to the EMC effect.

Outlook — This is the first indication of an isovector effect in nuclear structure functions, and demonstrates the power of the MARATHON ^{3}He/^{3}H data, when combined with a global QCD analysis, to provide unique information on PDFs at large x and simultaneously on nuclear effects in $A = 2$ and $A = 3$ nuclei. Additional information on the nuclear EMC effects in ^{3}He and ^{3}H separately will come from ^{3}He/D and ^{3}H/D ratios measured by MARATHON , which are expected to be analyzed in the near future.

Beyond constraints on neutron structure, and the d/u PDF ratio at large x, will come from the BONuS experiment at Jefferson Lab, which tags spectator protons in semi-inclusive DIS from the deuteron. Future data on DIS from asymmetric nuclei may also provide further information on the isospin dependence of nuclear effects on structure functions.

Acknowledgments — We thank A. Accardi, P. C. Barry, I. Fernando and Y. Zhou for helpful discussions and communications. This work was supported by the U.S. Department of Energy Contract No. DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates Jefferson Lab, and the National Science Foundation under grant number PHY-1516088. The work of C.C. and A.M. was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, within the framework of the TMD Topical Collaboration, and by Temple University (C.C.). The work of A.W.T. was supported by the University of Adelaide and by the Australian Research Council through the Discovery Project DP180100497.

[1] P. Jimenez-Delgado, W. Melnitchouk and J. F. Owens, J. Phys. G **40**, 093102 (2013).
[2] J. J. Ethier and E. R. Nocera, Ann. Rev. Nucl. Part. Sci. **70**, 43 (2020).
[3] W. Melnitchouk and A. W. Thomas, Phys. Lett. B **377**, 11 (1996).
[4] S. Kuhlmann, J. Huston, J. Morfin, F. I. Olness, J. Pumplin, J. F. Owens, W.-K. Tung and J. J. Whitmore, Phys. Lett. B **476**, 291 (2000).
[5] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, and N. Sato, Phys. Rev. D **93**, 114017 (2016).
[6] S. I. Alekhin, S. A. Kulagin and R. Petti, Phys. Rev. D **96**, 054005 (2017).
[7] N. Baillie *et al.*, Phys. Rev. Lett. **108**, 142001 (2012).
[8] S. Tkachenko *et al.*, Phys. Rev. C **89**, 045206 (2014).
[9] L. T. Brady, A. Accardi, W. Melnitchouk and J. F. Owens, JHEP **06**, 019 (2012).
[10] I. R. Afnan, F. R. P. Bissey, J. Gomez, A. T. Katramatou, W. Melnitchouk, G. G. Petratos and A. W. Thomas, Phys. Lett. B **493**, 36 (2000).
[11] I. R. Afnan, F. R. P. Bissey, J. Gomez, A. T. Katramatou, S. Liuti, W. Melnitchouk, G. G. Petratos and A. W. Thomas, Phys. Rev. C **68**, 035201 (2003).
[12] D. Abrams *et al.*, arXiv:2104.05850 [hep-ex]
[13] S. A. Kulagin and R. Petti, Nucl. Phys. **A765**, 126 (2006).
[14] N. Sato, C. Andres, J. J. Ethier, and W. Melnitchouk, Phys. Rev. D **101**, 074020 (2020).
[15] E. Moffat, W. Melnitchouk, T. Rogers and N. Sato, arXiv:2101.04664 [hep-ph].
[16] N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier and A. Accardi, Phys. Rev. D **93**, 074005 (2016).
[17] J. C. Collins, D. E. Soper and G. F. Sterman, Adv. Ser. Direct. High Energy Phys. **5**, 1 (1989).
[18] M. A. G. Aivazis, F. I. Olness and W.-K. Tung, Phys. Rev. D **50**, 3085 (1994).
[19] E. Moffat, T. C. Rogers, W. Melnitchouk, N. Sato and F. Steffens, Phys. Rev. D **99**, 096008 (2019).
[20] W. Melnitchouk, A. W. Schreiber and A. W. Thomas, Phys. Rev. D **49**, 1183 (1994).
[21] W. Melnitchouk, A. W. Schreiber and A. W. Thomas, Phys. Lett. B **335**, 11 (1994).
[22] S. A. Kulagin, G. Piller and W. Weise, Phys. Rev. C **50**, 1154 (1994).
[23] S. A. Kulagin, W. Melnitchouk, G. Piller and W. Weise, Phys. Rev. C **52**, 932 (1995).
[24] P. J. Ehlers, A. Accardi, L. T. Brady and W. Melnitchouk, Phys. Rev. D **90**, 014010 (2014).
[25] A. J. Tropiano, J. J. Ethier, W. Melnitchouk and N. Sato, Phys. Rev. C **99**, 035201 (2019).
[26] J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009).
[27] J. T. Londergan, J. C. Peng and A. W. Thomas, Rev. Mod. Phys. **82**, 2009 (2010).
[28] H. Mineo, W. Bentz, N. Ishii, A. W. Thomas and

K. Yazaki, Nucl. Phys. **A735**, 482 (2004).
[29] I. C. Cloët, W. Bentz and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009).
[30] M. Lacombe, B. Loiseau, R. Vinh Mau, J. Cote, P. Pires and R. de Tourreil, Phys. Lett. B **101**, 139 (1981).
[31] A. Kievsky, E. Pace, G. Salme and M. Viviani, Phys. Rev. C **56**, 64 (1997).
[32] R. B. Wiringa, V. G. J. Stoks and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[33] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).
[34] F. Gross and A. Stadler, Phys. Rev. C **78**, 014005 (2008).
[35] F. Gross and A. Stadler, Phys. Rev. C **82**, 034004 (2010).
[36] R. W. Schulze and P. U. Sauer, Phys. Rev. C **48**, 38 (1993).
[37] A. C. Benvenuti *et al.*, Phys. Lett. B **223**, 485 (1989); *ibid.* B **237**, 592 (1990).
[38] M. Arneodo *et al.*, Nucl. Phys. **B483**, 3 (1997).
[39] M. Arneodo *et al.*, Nucl. Phys. **B487**, 3 (1997).
[40] L. W. Whitlow *et al.*, Phys. Lett. B **282**, 475 (1992).
[41] S. P. Malace *et al.*, Phys. Rev. C **80**, 035207 (2009).
[42] H. Abramowicz *et al.*, Eur. Phys. J. C **75**, 580 (2015).
[43] E. A. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998); J. Webb, Ph.D. Thesis, New Mexico State University (2002), arXiv:hep-ex/0301031.
[44] T. Aaltonen *et al.*, Phys. Rev. Lett. **102**, 181801 (2009).
[45] V. M. Abazov *et al.*, Phys. Rev. Lett. **112**, 151803 (2014); *ibid.* **114**, 049901 (2015).
[46] T. Aaltonen *et al.*, Phys. Lett. B **692**, 232 (2010).
[47] V. M. Abazov *et al.*, Phys. Rev. D **76**, 012003 (2007).
[48] D. Acosta *et al.*, Phys. Rev. D **71**, 051104(R) (2005).
[49] V. M. Abazov *et al.*, Phys. Rev. D **91**, 032007 (2015).
[50] V. M. Abazov *et al.*, Phys. Rev. D **88**, 091102 (2013).
[51] V. Khachatryan *et al.*, Eur. Phys. J. C **76**, 469 (2016).
[52] S. Chatrchyan *et al.*, Phys. Rev. D **90**, 032004 (2014).
[53] S. Chatrchyan *et al.*, Phys. Rev. Lett. **109**, 111806 (2012).
[54] S. Chatrchyan *et al.*, JHEP **04**, 050 (2011).
[55] G. Aad *et al.*, Eur. Phys. J. C **79**, 760 (2019).
[56] M. Aaboud *et al.*, Eur. Phys. J. C **77**, 367 (2017).
[57] G. Aad *et al.*, Phys. Rev. D **85**, 072004 (2012).
[58] V. M. Abazovet al., Phys. Rev. Lett. **101**, 062001 (2008).
[59] A. Abulenciaet al., Phys. Rev. D **75**, 092006 (2007) [erratum: Phys. Rev. D75, 119901(2007)].
[60] B. I. Abelevet al., Phys. Rev. Lett. **97**, 252001 (2006).