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Impact of the MARATHON data on F_{2n}/F_{2p} and off-shell effects in light nuclei

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The neutron structure function, F_{2n} , has historically been extracted from measurements of the deuteron structure function, which is limited by our understanding of the nuclear effects on the bound proton and neutron. The MARATHON collaboration recently extracted F_{2n} from the comparison of ^3H and ^3He targets, where the nuclear effects are larger but nearly identical, yielding a precise extraction of F_{2n}/F_{2p} . To ensure that this comparison is not biased by the specific model of nuclear effects used by MARATHON, we examine a range of models of the nuclear effects to obtain a more conservative, but more model-independent, extraction of F_{2n}/F_{2p} for comparison with deuteron extractions. Even with this approach, the results are precise enough to compare to deuteron extractions, providing new constraints on the nuclear effects in the deuteron and indicating the need for larger nuclear corrections than included in most models.

Deep inelastic scattering (DIS) from nucleons allows extraction of their structure functions which are used to constrain nuclear and nucleon parton distribution functions (pdfs) within global analyses. These pdfs depend on the fraction of the nucleon light-front momentum carried by the interacting quark, x , and the four-momentum transfer of the probe, Q^2 . A comparison of the proton and neutron structure functions, F_{2p} and F_{2n} , allows us to study the difference between the up- and down-quark contributions to the nucleon pdfs, since the proton represents a bound (uud) state and the neutron a (udd) state. While F_{2p} is precisely measured over a wide kinematic range, F_{2n} is less well known, especially at large values of Bjorken- x where the struck quark carries a large fraction of the neutron's longitudinal momentum. The lack of a free neutron target makes measurements of F_{2n} more challenging, and most methods of isolating scattering from the neutron introduce enhanced experimental uncertainties and model dependence in the extraction.

For many years, the standard way to extract F_{2n} was to measure the deuteron structure function, F_{2d} , subtract the proton contribution, and apply a model-dependent correction for the modification of the free nucleon structure functions due to binding, Fermi motion, and other effects [1–3]. Because $F_{2p} > F_{2n}$, especially at large x , the subtraction introduces a large enhancement in the experimental uncertainties. The model dependence of the nuclear corrections yields additional uncertainties that dominate at large x values. As such, the F_{2n} extractions have larger uncertainties than F_{2p} , and these uncertainties grow with x , especially above $x \approx 0.6$ [4, 5]

An alternative approach was proposed [6, 7] to compare the helion (h , ^3He nucleus) and triton (t , ^3H nucleus). These $A = 3$ mirror nuclei differ in that the number of protons and neutrons are swapped, and the expectation is that their structure should be nearly identical up to small differences associated with, for example, the isospin-symmetry breaking effects associated with the Coulomb interaction [8]. While the binding, smearing,

and off-shell effects will be larger in these $A = 3$ nuclei than in deuterium, the nuclear corrections should be nearly identical for the helion and triton, yielding a much smaller model dependence in the extraction of F_{2n}/F_{2p} [6, 7] from the F_{2h}/F_{2t} ratio.

The MARATHON experiment [9] provided precision measurements of F_{2h}/F_{2t} and extracted F_{2n}/F_{2p} using the Kulagin-Petti (KP) model [10, 11] to evaluate the size and uncertainties of the nuclear effects. The relative normalization of the F_{2h} and F_{2t} results was determined based on a comparison of the values of F_{2n}/F_{2p} extracted from h/t and d/p measurements, which depends on the nuclear effects in both cases. To avoid questions about whether this procedure may bias the comparison, we extract F_{2n}/F_{2p} using a range of nuclear models as a more conservative evaluation of the model dependence. We take a similar approach to normalizing the h/t ratios and then compare this more conservative, but less model dependent, result to extractions from worlds F_{2d}/F_{2p} data to constrain nuclear effects in the deuteron.

Note that extracting pdfs, rather than structure functions, requires disentangling additional effects: higher-twist contributions, target mass corrections, and effects beyond leading order. In this work we compare h/t and d/p extractions of F_{2n}/F_{2p} to assess structure function level conclusions while avoiding these additional complications. In the end, we also compare to pdf analyses that are addressing similar questions using both the structure function ratios and a variety of other data sets [12].

We begin by examining nuclear effects in the extraction of F_{2n}/F_{2p} from the measurements on light nuclei. In general, we define the nuclear corrections to be the ratio of the nuclear structure function to the sum of its constituent nucleons, $R_A = F_{2A}/(ZF_{2p} + NF_{2n})$. This includes both modification of the nucleon structure function for bound nucleons, and any other contributions that modify the nuclear structure functions.

Calculations of the deuteron structure function typically include the proton and neutron contributions, mod-

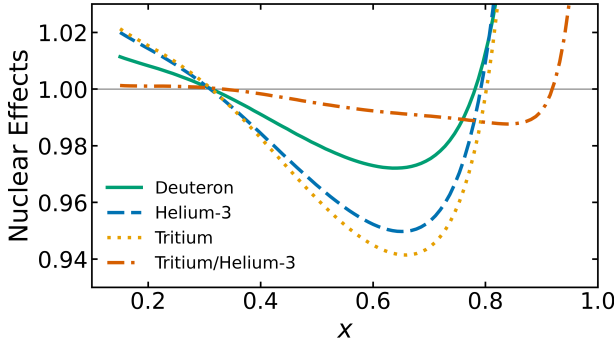


FIG. 1. The nuclear effects, $F_{2A}/(ZF_{2p} + NF_{2n})$, from the KP model [11] for ^2H (solid line), ^3He (dashed), ^3H (dotted), and the correction $\mathcal{R}_{th}$ (dash-dotted). The corrections to the h/t extraction are smaller than for the d/p case, and the larger effects and rapid x dependence occur at larger x values.

ified by smearing and binding, plus additional terms. Following Ref. [5], we take $F_{2d} = \bar{F}_{2p} + \bar{F}_{2n} + \delta F_{2d}$ where $\bar{F}_{2N} = S_N F_{2N}$ is the nucleon structure function contribution after smearing and binding, and δF_{2d} represents additional contributions. While S_N depends on both the convolution formalism and the free nucleon structure function, for a given calculation we can express it as a smearing function $S_N(x)$. We can then absorb the δF_{2d} contribution into the smearing function by taking $\Delta = \delta F_{2d}/F_{2d}$ and modify the smearing correction as $\tilde{S}_N = S_N/(1-\Delta)$. This allows us to express the deuteron structure function as $F_{2d} = \tilde{S}_p F_{2p} + \tilde{S}_n F_{2n}$, and yields the following expression for F_{2n}/F_{2p} as a function of F_{2d}/F_{2p} :

$$\frac{F_{2n}}{F_{2p}} = \frac{1}{\tilde{S}_n} \left(\frac{F_{2d}}{F_{2p}} - \tilde{S}_p \right). \quad (1)$$

Note that this equation corrects an error in Eq. (1) of Ref. [5], which included a factor of F_{2p} in the final term, which appeared in the equation but was not included in their analysis. The factor $\tilde{S}_N$ will depend on the convolution model, off-shell effects, and input structure functions. Ref. [5] evaluated $\tilde{S}_N$ for a range of different inputs to examine the sensitivity of F_{2n}/F_{2p} to the nuclear effects as a function of x .

In the MARATHON experiment [9], F_{2n}/F_{2p} was extracted using new and precise measurements of the F_{2h}/F_{2t} ratio for $0.195 < x < 0.825$. In this case, the nuclear effects are written out in terms of their impact on the helion and triton, rather than in terms of modified nucleons, with $R_h = F_{2h}/(2F_{2p} + F_{2n})$ and $R_t = F_{2t}/(F_{2p} + 2F_{2n})$. Taking $\mathcal{R}_{ht} = R_h/R_t$, we can extract F_{2n}/F_{2p} from F_{2h}/F_{2t} and a calculation of $\mathcal{R}_{ht}$:

$$\frac{F_{2n}}{F_{2p}} = \frac{2\mathcal{R}_{ht} - F_{2h}/F_{2t}}{2F_{2h}/F_{2t} - \mathcal{R}_{ht}}. \quad (2)$$

Figure 1 shows the size of the nuclear effects for ^2H , ^3H , ^3He , and in the $^3\text{H}/^3\text{He}$ ratio [11]. For the $A = 3$

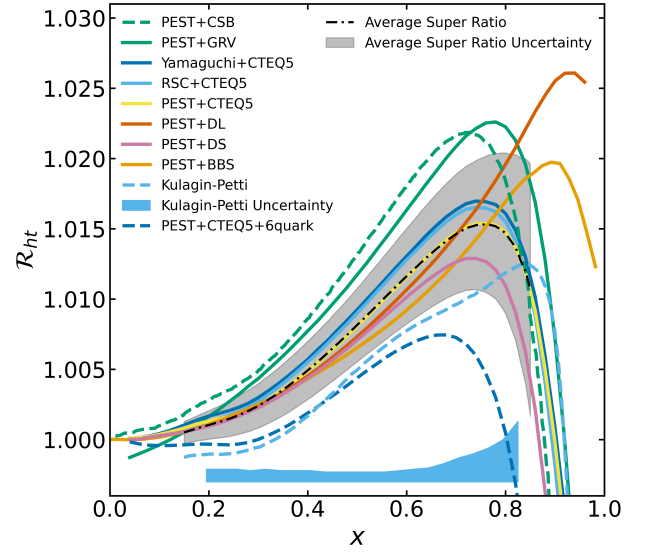


FIG. 2. Selected calculations of $\mathcal{R}_{ht}$ from Ref. [7] alongside the KP model [10, 11] that was used by the MARATHON experiment. Also shown is the average of all plotted models with a 1σ -rms band with a dash-dotted line. Models that include effects beyond smearing and off-shell effects are shown with dashed lines. The legend is ordered by descending values of the model evaluated at $x = 0.6$. The blue band shows the uncertainty from the KP model used in Ref. [9].

nuclei, the nuclear effects are significantly larger than for the deuteron extraction, as expected. Because the extraction from the h/t ratio depends only on the ratio of nuclear effects, $\mathcal{R}_{ht}$, the correction is significantly smaller than either case on their own. In addition, the rapid change in the x dependence, occurring at $x \approx 0.8$ for the deuteron or $A = 3$ nuclei is pushed out to $x > 0.9$ for $\mathcal{R}_{ht}$. This also yields much smaller uncertainties in the nuclear effects, as examined in Ref. [7], which examined a variety of models and concluded that the corrections were small with uncertainties at the $\lesssim 1\%$ level to $x = 0.8$. The MARATHON extraction [9] used the KP model [10, 11] along with the pdfs of [13] to calculate $\mathcal{R}_{ht}$. Again, the nuclear effects were found to be small in the ratio, as were the estimated uncertainties for this model: $< 0.1\%$ up to $x = 0.65$, growing to 0.43% at $x = 0.825$.

We repeat the MARATHON extraction of F_{2n}/F_{2p} by examining a range of models of $\mathcal{R}_{ht}$ to assess the model dependence of the extraction. For this study, we have chosen to use a subset of the $\mathcal{R}_{ht}$ calculations from Ref. [7] plus the KP model as used by the MARATHON experiment. The calculations in this reference vary by technique for calculating wave functions, choice of nuclear potential, choice of nucleon pdfs, and the inclusion of more exotic effects. The analysis presented here considers calculations that use wave functions calculated via the Faddeev equations, as they involve fewer approximations in the calculations. To best capture the variance

of the calculations, we attempt to factorize the contributions to the nuclear effects. Each nuclear potential is paired with the CTEQ5 pdfs and then each pdf set is paired with the PEST potential. This technique was chosen to mitigate any bias introduced from selecting any particular potential or pdf set, as the CTEQ5 (PEST) calculations are near the average of the results from different pdfs (potentials). These selected calculations are shown in Fig. 2 alongside the KP model. Also shown is the average of the calculations and the 1σ root mean square (rms) uncertainty band that we use to quantify the model uncertainty of the $\mathcal{R}_{ht}$ calculations. In figure 2, dashed lines are used to indicate calculations that introduce effects beyond smearing and off-shell effects, e.g. contributions from six-quark bags, charge-symmetry violation, or higher-twist contributions that do not cancel in the h/t ratios. Not surprisingly, these increase the rms scatter of the models, and to be conservative we take the full set of models shown in evaluating the uncertainty band used in our analysis. If we were to focus only on more conventional effects, the rms of the distribution would be lower by 30–60% over the MARATHON data range.

The MARATHON collaboration found that their d/p cross section ratios were consistent with previous SLAC [14] data. A $(2.5 \pm 0.7)\%$ renormalization was applied to the h/t ratios so that the F_{2n}/F_{2p} values extracted from h/t were in agreement with those extracted from d/p at $x = 0.31$. This procedure has the drawback that it relies on the KP model for both the h/t and the d/p nuclear effects. One might be concerned that this goes against the idea of minimizing the model dependence by avoiding corrections to the deuteron, although the corrections for deuterium at low x have smaller uncertainties than at larger x values.

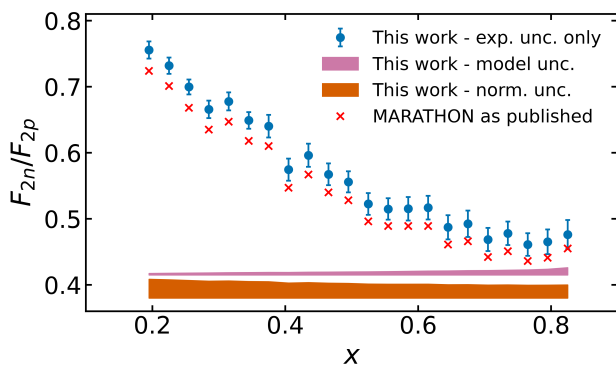


FIG. 3. F_{2n}/F_{2p} from this analysis, compared to the original extraction [9]. The error bars include statistical and point-to-point systematic uncertainties. The model uncertainty is the impact of the 1σ uncertainty on $\mathcal{R}_{ht}$ and the normalization band shows the correlated shift associated with the 1.25% normalization uncertainty in F_{2h}/F_{2t} .

While MARATHON found that a $(2.5 \pm 0.7)\%$ change

in the nominal h/t target thickness ratio was needed, this is somewhat larger than the nominal 1.1% normalization uncertainty from the measurement of the target thicknesses [15–17]. A separate global pdf analysis [12] also found that a much smaller correction of $(0.7 \pm 0.6)\%$ provided the best consistency with world’s data given their model of the nuclear effects. These disagreements indicate that the normalization procedure has a significant model dependence. In this work, we take a conservative approach by applying a renormalization correction of $(1.25 \pm 1.25)\%$ including both the target thickness uncertainty and other systematic uncertainties that may impact the overall normalization of the ratio. Note that the radiative corrections applied were based on the more up-to-date formalism of Ref. [18], and so do not suffer from the systematic issues observed in other recent extractions of the EMC effect [19]. This uncertainty was chosen so that the one-sigma range is sufficient to include the nominal target thickness measurements, the MARATHON renormalization adjustment, and the independent evaluation of Ref. [12]. This approach increases the total uncertainty, but does not significantly limit the sensitivity to nuclear effects in the comparison of h/t and d/p measurements, as will be demonstrated in the comparison of our updated extraction to other n/p extractions.

Using the average value of the $\mathcal{R}_{ht}$ calculations in Fig. 2 and applying the 1.25% normalization factor to the measured h/t ratio yields a modified extraction of F_{2n}/F_{2p} , shown in Fig. 3 and in Table 1 of the Supplemental Materials [20]. In this figure, the points include the experimental uncertainties, while the bands indicate the model dependence from the $\mathcal{R}_{ht}$ uncertainty shown in Fig. 2 and the 1.25% normalization uncertainty. Despite the large differences between the $\mathcal{R}_{ht}$ calculations, it is clear that the uncertainties are dominated by the experimental data and the normalization uncertainties. While the h/t normalization has a significant contribution to the final uncertainty and modifies the extracted F_{2n}/F_{2p} , it has minimal impact on its shape. Compared to the original result [9], it increases F_{2n}/F_{2p} by about 0.025 with a slightly smaller effect at large x . Because F_{2n}/F_{2p} shifts up but has a slightly faster falloff with x , the modified h/t normalization has a reduced impact on extrapolation to $x = 1$ [21, 22].

Even with the more conservative estimation of model dependence, this extraction of F_{2n}/F_{2p} has significantly smaller uncertainty than those based on d/p measurements. Figure 4 shows F_{2n}/F_{2p} from this analysis alongside the range extracted from d/p extractions using models with and without off-shell effects [5]. The off-shell effects increase the extracted F_{2n}/F_{2p} value, with the highest edge of this range corresponding to larger deuteron off-shell effects.

The $A = 3$ results are in good agreement with d/p extractions at low x , and the assumed uncertainty on the

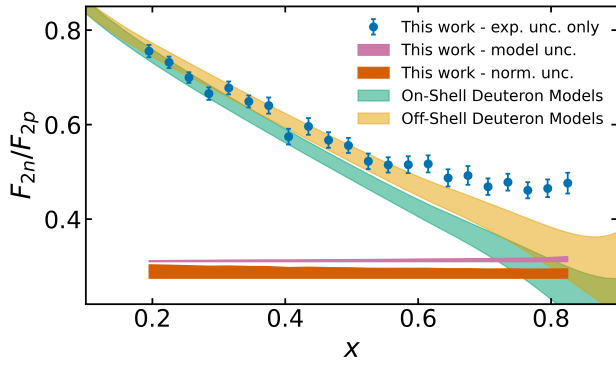


FIG. 4. Comparison of this work (circles) and F_{2n}/F_{2p} extractions from d/p measurements with (top band) and without (bottom band) the inclusion of off-shell effects [5].

normalization factor is sufficient to cover the full range of deuteron extractions in this region. The extracted F_{2n}/F_{2p} values show a significant difference at larger x values, where the nuclear effects are large. Note that while an increase in the h/t normalization factor could reconcile the extractions for $x > 0.6$, it would require a 4σ shift to be consistent with the upper edge of the deuteron off-shell extractions. This would resolve the high- x discrepancy but would reduce F_{2n}/F_{2p} by almost 0.1 in the low- x region, causing a more significant disagreement with the d/p extractions in the region where the nuclear uncertainties are believed to be smallest.

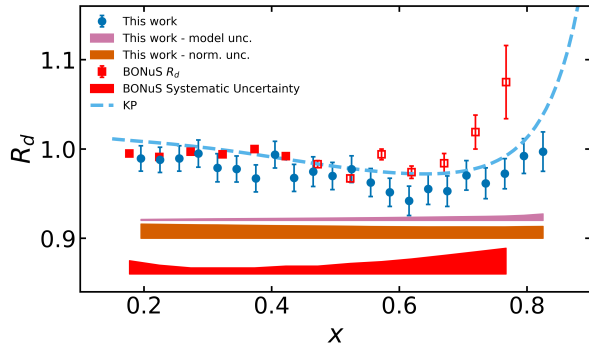


FIG. 5. R_d extracted from the comparison of F_{2n}/F_{2p} from the h/t measurement discussed here and a compilation of world's d/p measurements [1]. Filled points indicate kinematics with large invariant mass ($W^2 > 3 \text{ GeV}^2$), for which we expect to see behavior consistent with DIS [23].

This discrepancy suggests that nuclear effects, beyond those included in the calculations examined here, are needed to yield consistent extractions. The simplest explanation would be larger off-shell effects in the deuteron, which would increase F_{2n}/F_{2p} above the top of the yellow band in Fig. 4. If we assume that the discrepancy is caused by the larger corrections for the d/p extraction, with our more conservative uncertainties properly

capturing the model dependence for the h/t extraction, we can use the MARATHON F_{2n}/F_{2p} plus the measured F_{2d}/F_{2p} ratios to extract the nuclear correction, $R_d = F_{2d}/(F_{2p} + F_{2n})$. Figure 5 shows our extraction of R_d , the analog of the EMC effect for the deuteron, using the d/p data from Refs. [1] along with the KP calculation and an extraction by the BONuS experiment [24]). The agreement with the BONuS extraction is good in the region where both data sets are at large W^2 , while the BONuS extraction begins to differ for data at much lower W^2 values. Even if the source of nuclear effects is the same for DIS and resonance region data at large x , the impact of nuclear effects, e.g. due to Fermi motion, will have a different effect as the cross section is very different where there is large resonance structure.

It is also possible that some more exotic effect significantly modifies the d/p extraction, or even the h/t extraction, at large x . One such possibility is the inclusion of isospin-dependent nuclear corrections [12, 25–27]. While most calculations yield different nuclear corrections for protons and neutrons due to conventional effects, e.g. the impact of Fermi motion on F_{2p} and F_{2n} , due to the faster falloff of F_{2n} at large x , the calculations included in this analysis do not include any explicit isospin-dependent nuclear corrections beyond those that arise from the difference between the proton and neutron distributions in the $A=3$ nuclei. Complementary to this work, global pdf analyses have made efforts to reconcile the F_{2n}/F_{2p} extraction from deuteron and $A=3$ nuclei by including parameterized flavor-dependent off-shell and/or higher-twist effects, as suggested to be important by the CJ collaboration [28]. Results from the JAM collaboration [12] claimed a large flavor-dependent off-shell effect, while a separate study [29] reported that, with their additive higher-twist parameterization that described the MARATHON data well, the observed off-shell function difference between proton and neutron is consistent with zero. The latter result is consistent with the off-shell deuteron models in Fig. 4 and still deviates from the $A=3$ extractions at large x .

This work and similar pdf analyses clearly demonstrate that the MARATHON data provide the first opportunity to perform significant studies of the isospin dependence. The benefit of working at the structure function level is that our conclusions depend only on the consistency of the structure function data and associated nuclear corrections. This makes the interpretation more straightforward than global pdf analyses which are sensitive to tension between a range of different experimental data sets as well as the theory connecting the pdfs to these more complicated observables. The limitation of our approach is that we do not separate the contribution of the pdfs from other QCD effects such as target mass corrections [30, 31] and higher twist effects [2]. Because of this, we cannot probe the interplay between isospin-dependent off-shell effects and higher-twist effects, suggested to be

important in the CJ global QCD analysis [28]. The fact that the conclusions of the pdf analyses depend on assumptions made indicates that we still don't have sufficient knowledge to extract the isospin dependence of nuclear effects in a model-independent fashion, but demonstrate the potential to constrain nuclear effects, including isospin dependence, by comparing precise data on few-body nuclei.

In conclusion, we have presented an updated extraction of F_{2n}/F_{2p} from the MARATHON data using a more conservative analysis aimed at minimizing the model dependence of the extracted ratio. While the uncertainties are larger than the original analysis [9], they are still a significant improvement over extractions based on d/p measurements. Our results are in good agreement with extractions based on d/p [5] up to $x \approx 0.6$, while at larger x values, our results are significantly higher.

Because of the larger model dependence in the extraction from d/p measurements, it is natural to conclude that this difference indicates the presence of larger nuclear effects for the deuteron; either larger off-shell corrections or other effects beyond binding and Fermi motion. Another possibility [12] is that isospin-dependent off-shell or higher-twist effects change the h/t extraction while cancelling, at least in part, in the deuteron extraction. In this case, it is possible to have cancellation between proton and neutron corrections such that the impact is larger in the h/t extraction than for d/p , but the general conclusion remains: corrections beyond those included in most nuclear models appear to be necessary.

One such option is the contribution of isospin-dependent nuclear corrections which would imply a flavor-dependent EMC effect, a topic that has received significant attention recently. The non-trivial correlation between the nuclear effects [32] and the presence of short-range correlations (SRCs) [33] in light nuclei, combined with dominance of np-SRCs [34] suggests a mechanism for isospin-dependent nuclear effects [26, 35]. This has been examined in more detail in recent analyses [27, 36], demonstrating the correlation has potential sensitivity to the question of flavor dependence, but not yet providing evidence for or against this. The sensitivity will be improved with the addition of EMC and SRC measurements for a range of new targets [37, 38], while parity-violating electron scattering in a non-isoscalar target such as ^{48}Ca can provide a clean and precise measurement of such flavor dependence [39–41].

Future JLab measurements will provide additional constraints on both the nuclear effects in the deuteron and on the possibility of isospin- or flavor-dependent nuclear corrections [42]. Measurements of scattering from the neutron in deuterium with a tagged spectator proton provide another way to extract F_{2n}/F_{2p} with reduced (and very different) model dependence [43, 44], and have also been used to extract nuclear effects in the deuteron [24]. The BONuS12 experiment [45] has made such tagged mea-

surements in CLAS12, which should significantly improve the precision and the coverage at large x . Parity violating electron-proton DIS scattering in SoLID [40, 41] can provide a model-independent extraction by using the flavor sensitivity of the weak probe, rather than using nuclear targets, to isolate the d/u quark ratio.

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- [1] J. Arrington, F. Coester, R. J. Holt, and T. S. H. Lee, *J. Phys. G* **36**, 025005 (2009).
 - [2] A. Accardi, M. E. Christy, C. E. Keppel, W. Melnitchouk, P. Monaghan, J. G. Morfin, and J. F. Owens, *Phys. Rev. D* **81**, 034016 (2010).
 - [3] S. Li, A. Accardi, I. P. Fernando, C. E. Keppel, W. Melnitchouk, P. Monaghan, G. Niculescu, M. I. Niculescu, and J. F. Owens, arXiv:2309.16851 (2023).
 - [4] A. Accardi, W. Melnitchouk, J. F. Owens, M. E. Christy, C. E. Keppel, L. Zhu, and J. G. Morfin, *Phys. Rev. D* **84**, 014008 (2011).
 - [5] J. Arrington, J. G. Rubin, and W. Melnitchouk, *Phys. Rev. Lett.* **108**, 252001 (2012).
 - [6] 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).
 - [7] 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).
 - [8] R. Wiringa, R. Schiavilla, S. C. Pieper, and J. Carlson, *Phys. Rev. C* **89**, 024305 (2014).
 - [9] D. Abrams *et al.* (Jefferson Lab Hall A Tritium), *Phys. Rev. Lett.* **128**, 132003 (2022).
 - [10] S. A. Kulagin and R. Petti, *Nucl. Phys. A* **765**, 126 (2006).
 - [11] S. A. Kulagin and R. Petti, *Phys. Rev. C* **82**, 054614 (2010).
 - [12] C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato, and A. W. Thomas (Jefferson Lab Angular Momentum (JAM)), *Phys. Rev. Lett.* **127**, 242001 (2021).
 - [13] S. I. Alekhin, S. A. Kulagin, and R. Petti, *Phys. Rev. D* **96**, 054005 (2017).
 - [14] A. Bodek *et al.*, *Phys. Rev. D* **20**, 1471 (1979).
 - [15] S. Li *et al.*, *Nature* **609**, 41 (2022).
 - [16] J. Arrington, R. Cruz-Torres, T. J. Hague, L. Kurbany, S. Li, D. Meekins, and N. Santiesteban, *Eur. Phys. J. A* **59**, 188 (2023).
 - [17] S. N. Santiesteban *et al.*, arXiv:2304.13770 (2023).
 - [18] S. Dasu *et al.*, *Phys. Rev. D* **49**, 5641 (1994).
 - [19] S. Moran, M. Arratia, J. Arrington, D. Gaskell, and B. Schmookler, *Phys. Rev. C* **110**, 025202 (2024), arXiv:2402.17147 [nucl-ex].
 - [20] See Supplemental Material at [URL will be inserted by publisher] for $\mathcal{R}_{ht}$ and extracted F_{2n}/F_{2p} values and textual descriptions of figures.

- [21] Z.-F. Cui, F. Gao, D. Binosi, L. Chang, C. D. Roberts, and S. M. Schmidt, *Chin. Phys. Lett.* **39**, 041401 (2022).
- [22] H. Valenty, J. R. West, F. Benmokhtar, D. W. Higinbotham, A. Parker, and E. Seroka, *Phys. Rev. C* **107**, 065203 (2023).
- [23] J. Arrington, R. Ent, C. E. Keppel, J. Mammey, and I. Niculescu, *Phys. Rev. C* **73**, 035205 (2006).
- [24] K. A. Griffioen *et al.*, *Phys. Rev. C* **92**, 015211 (2015).
- [25] M. M. Sargsian *et al.*, *J. Phys.* **G29**, R1 (2003).
- [26] J. Arrington, *EPJ Web Conf.* **113**, 01011 (2016).
- [27] J. Arrington and N. Fomin, *Phys. Rev. Lett.* **123**, 042501 (2019).
- [28] A. Accardi, J. Owens, S. Park, and X. Jing, Light sea and valence quarks in the cj22 global pdf analysis, DIS2023 (2023).
- [29] S. I. Alekhin, S. A. Kulagin, and R. Petti, *Phys. Rev. D* **107**, L051506 (2023).
- [30] O. Nachtmann, *Nucl. Phys. B* **63**, 237 (1973).
- [31] H. Georgi and H. D. Politzer, *Phys. Rev. D* **14**, 1829 (1976).
- [32] J. Seely *et al.*, *Phys. Rev. Lett.* **103**, 202301 (2009).
- [33] N. Fomin *et al.*, *Phys. Rev. Lett.* **108**, 092502 (2012).
- [34] J. Arrington, N. Fomin, and A. Schmidt, *Annual Review of Nuclear and Particle Science* **72**, 307 (2022).
- [35] J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell, and P. Solvignon, *Phys. Rev. C* **86**, 065204 (2012).
- [36] B. Schmookler *et al.* (CLAS), *Nature* **566**, 354 (2019).
- [37] J. Arrington, D. Day, and N. Fomin, spokespersons, Jefferson lab experiment E12-06-105 (2006).
- [38] J. Arrington, A. Daniel, N. Fomin, and D. Gaskell, spokespersons, Jefferson lab experiment E12-10-008 (2010).
- [39] I. C. Cloet, W. Bentz, and A. W. Thomas, *Phys. Rev. Lett.* **109**, 182301 (2012).
- [40] J. Arrington *et al.* (Jefferson Lab SoLID), *J. Phys. G* **50**, 110501 (2023).
- [41] R. Beminiwattha, J. Arrington, and D. J. Gaskell, *Eur. Phys. J. A* **59**, 194 (2023).
- [42] J. Arrington *et al.*, *Prog. Part. Nucl. Phys.* **127**, 103985 (2022).
- [43] N. Baillie *et al.* (CLAS), *Phys. Rev. Lett.* **108**, 142001 (2012), [Erratum: *Phys. Rev. Lett.* **108**, 199902 (2012)].
- [44] S. Tkachenko *et al.* (CLAS), *Phys. Rev. C* **89**, 045206 (2014), [Addendum: *Phys. Rev. C* **90**, 059901 (2014)].
- [45] S. Kuhn, S. Bueltmann, M. Christy, K. Griffioen, C. Keppel, and W. Melnitchouk, spokespersons, Jefferson lab experiment E12-06-113 (2006).