


















Evidence for Modified Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

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(Dated: December 29, 2023)

We extend the QCD Parton Model analysis using a factorized nuclear structure model incorporating individual nucleons and pairs of correlated nucleons. Our analysis of high-energy data from lepton Deep-Inelastic Scattering, Drell-Yan and W/Z production simultaneously extracts the universal effective distribution of quarks and gluons inside correlated nucleon pairs, and their nucleus-specific fractions. Such successful extraction of these universal distributions marks a significant advance in our understanding of nuclear structure properties connecting nucleon- and parton-level quantities.

Introduction: Subatomic systems, such as nucleons and atomic nuclei, and dense astrophysical matter, derive their properties from the many-body interactions between their constituent quarks and gluons which are described by the theory of Quantum Chromodynamics (QCD). The strongly coupled nature of QCD links the momentum distribution of quarks and gluons in these systems to their structure and emergent properties, such as mass and spin [1]. Therefore, it is crucial to understand the momentum distribution of quarks and gluons in nucleons and nuclei.

By analyzing high-energy collisions between leptons, nucleons, and nuclei, using a well-established QCD factorization formalism [2–4], parton distribution functions (PDFs) can be extracted for both nucleons and nuclei. These PDFs describe the fraction of total system momentum carried by different flavored quarks and gluons [5–7]. The nuclear PDFs (nPDFs) are observed to differ from the simple sum of their free proton and neutron PDFs, indicating a measurable role of nuclear dynamics that remains to be understood [8–13].

Compared to the nucleon PDFs, the nuclear PDFs are impacted by various nuclear effects due to the spatial distribution of nucleons in the nucleus (shadowing and anti-shadowing), their motion (Fermi-motion), and

strong interactions between nucleons affecting their internal parton structure [14, 15]. The standard global analyses (such as nCTEQ [8, 12, 16–19], EPPS [9, 20], nNNPDF [11, 21, 22], TUJU [10, 23], DSSZ [24], Khanpour et al. [25, 26]) extract parton densities inside the *full nucleus* using experimental data.

Here we propose to use the state-of-the-art knowledge of nuclear theory to guide the development of nuclear PDFs:

Nuclei are commonly described as a group of independent nucleons moving within an effective average mean field that leads to the population of atom-like nuclear shells [27]. In this picture, nuclear effects are modeled in the nPDFs by consistently modifying all nucleons under the effective influence of the nuclear mean-field. It is important to notice that this does not allow for a meaningful interpretation in terms of modified parton densities inside bound single nucleon states since they incorporate effects from many nucleon states present in the data.

Nuclear structure studies show that the formation of short-lived excitations, caused by strongly-interacting Short Range Correlated (SRC) nucleon pairs [28–31] are significant. While the abundance of SRC pairs differs among nuclei, they are predominantly proton-neutron pairs [28, 32–37] and have the same behavior in all nuclei [29, 30, 38–40]. Consequently, SRC pairs have universal properties across nuclei and typical separation energies of 15% – 30% of the nucleon mass, which is

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significantly higher than that of mean-field states [39–42]. The large energies and significant spatial overlaps of SRC pairs motivated various studies of the relation between SRC pairs and bound-nucleon structure [29].

This analysis studies nPDFs based on our understanding of high-resolution nuclear structure with SRCs. It allows for the first time to split the partonic structure inside nuclei into mean-field and SRC contributions and to extract information on nuclear structure from an analysis of the partonic content of nuclei. We try to take a model-agnostic approach by focusing on the broad-scale features common to modern high-resolution nuclear structure models, minimizing dependence on specific model details.

Short-Range Nuclear Structure: The fundamental quantity of nuclear structure that is relevant for our study is the nuclear spectral function $S_A(k, E)$ that defines the probability for finding a nucleon with momentum k and separation energy E in a nucleus with mass number A . We use a normalization convention of: $\int S_A(k, E)k^2dkdE \equiv 1$.

Direct many-body calculations of $S_A(k, E)$ are computationally unfeasible for $A > 3$ nuclei. Therefore, we employ an established approximation where the spectral function is divided into two parts [30]:

$$S_A(k, E) = S_A^{\text{MF}}(k, E) + S_A^{\text{SRC}}(k, E) \quad , \quad (1)$$

with $S_A^{\text{MF}}(k, E)$ representing the single nucleons in a mean-field (MF), and $S_A^{\text{SRC}}(k, E)$ representing the spectral function of nucleons in SRC pairs.

The separation presented in Eq. (1) is rooted in the vastly different energy scales associated with the single-nucleon mean-field potential and the interaction energy inside SRC pairs. While mean-field nucleons have momenta and energy below nuclear Fermi momentum ($k_F \sim 250$ MeV/c) and Fermi energy $E_F \sim 35$ MeV, the strong pair-wise interaction energy inside SRC pairs leads to relative momenta of $300 \sim 800$ MeV/c and separation energies of $150 - 400$ MeV [39–42].

The high-energy scale associated with interactions in SRC pairs leads to a further factorization of their spectral function into a universal (nucleus independent) pair spectral function distribution, scaled by a (nucleus dependent) pair abundance factor [41]:

$$S_A^{\text{SRC}}(k, E) \approx \frac{Z}{A} C_A^p \times S_p^{\text{SRC}}(k, E) + \frac{N}{A} C_A^n \times S_n^{\text{SRC}}(k, E) \quad . \quad (2)$$

In the above approximation, we do consider all possible (pn) , (pp) , and (nn) nucleon-nucleon pairs even though this is not explicit in the notation.

Here C_A^N ($N=p, n$) are nucleus dependent constants that ‘count’ the fraction of nucleons in SRC pairs and $S_N^{\text{SRC}}(k, E)$ are universal (nucleus independent) pair distributions that are dominated by the strong nucleon-nucleon interaction at short-distance. Z and N are the total number of protons and neutrons

in the nucleus ($Z+N=A$). The universal pair spectral functions follow normalization conventions of $\int S_N^{\text{SRC}}(k, E)k^2dkdE \equiv 1$ ($N=p, n$) and therefore $\int S_A^{\text{MF}}(k, E)k^2dkdE = 1 - (ZC_A^p + NC_A^n)/A$.

Combining Eqs. (1) and (2) we obtain:

$$S_A(k, E) \approx S_A^{\text{MF}}(k, E) + \frac{Z}{A} C_A^p \times S_p^{\text{SRC}}(k, E) + \frac{N}{A} C_A^n \times S_n^{\text{SRC}}(k, E) \quad , \quad (3)$$

where we emphasize that the mean-field term $S_A^{\text{MF}}(k, E)$ captures low-energy, single nucleon dynamics and the SRC terms $C_A^N \times S_N^{\text{SRC}}(k, E)$ captures universal high-energy nucleon-pair dynamics.

We note that the approximation presented in Eq. (3) enjoys significant support [36, 39, 41, 43–46] by recent analyses of ab-initio many-body nuclear structure calculations and high-energy electro-induced nucleon knockout measurements. Furthermore, Eq. (1) can in principle be extended to also include three-nucleon correlation effects which are neglected in the context of this work.

SRC Motivated nuclear-PDFs: nPDFs are defined within perturbative QCD using the framework of collinear factorization [3, 47]. This framework allows the computation of cross-sections, $d\sigma_{AB \rightarrow X}$, for scattering of particles A, B into final state X as convolutions of perturbatively calculable parton-level short-distance cross-sections, $d\hat{\sigma}_{ij \rightarrow X}$, and non-perturbative PDFs, $f_{i(j)}$, where i and j sum over the partonic content of hadrons A and B , respectively.

Introducing these nuclear quark and gluon distributions to the nuclear structure model of Eqs. (1) and (2) leads to an nPDF parametrization that is comprised of a linear combination of free-nucleon PDFs (representing the quasi-free nucleons), and SRC PDFs which describe the universal quark and gluon distributions inside an SRC pair:

$$f_i^A(x, Q) = \frac{Z}{A} \left[(1 - C_p^A) \times f_i^p(x, Q) + C_p^A \times f_i^{\text{SRC}p}(x, Q) \right] + \frac{N}{A} \left[(1 - C_n^A) \times f_i^n(x, Q) + C_n^A \times f_i^{\text{SRC}n}(x, Q) \right] \quad . \quad (4)$$

Here, $f_i^A(x, Q)$ is the nPDF of parton type i (gluon or quark flavors) in a nucleus with mass number A , carrying momentum fraction x at energy scale Q . $f_i^N(x, Q)$ and $f_i^{\text{SRC}N}(x, Q)$ are the PDFs of the free nucleon and of the modified nucleon in an SRC pair, respectively. Here we implicitly assume that $f_i^{\text{SRC}N}(x, Q)$ can be defined via a collinear factorization framework. Therefore, we apply the tools from perturbative QCD used for free nucleon PDFs to arrive at the physical predictions (*e.g.*, DGLAP evolution).

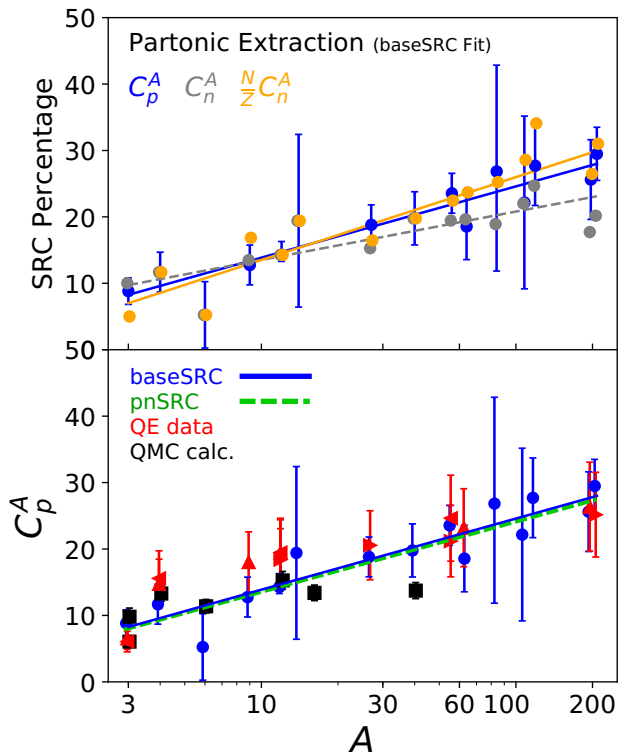


FIG. 1. (a) Comparison of nuclear structure parameters C_p^A , C_n^A , and $(N/Z)C_n^A$ values for the **baseSRC** fit. The solid lines represent logarithmic fits to the corresponding quantities. We show uncertainties only for the C_p^A , but errors for other quantities are of similar size. (b) Comparison of C_p^A values for the **baseSRC** fit and the SRC abundances extracted from quasi-elastic (QE) [48–50] data and nuclear Quantum Monte Carlo (QMC) [46] nuclear calculations. The logarithmic fits for **baseSRC** and **pnSRC** are also shown.

A key feature of this framework is that the nuclear structure dependence is fully encapsulated in the fraction of nucleons in SRC pairs C_A^N .

As we do not separate the individual effects of proton-proton, neutron-neutron and proton-neutron SRCs, Eq. (4) relates the modified structure of an average nucleon in an SRC pair, independent of its pair configuration.

We keep a model-independent approach as to the number of SRC pairs and their isospin structure. In fact, these nuclear structure parameters will be independently determined in our nPDF analysis for the first time (*cf.*, Fig. 1), and tested for consistency with independent results from specific nuclear structure studies.

We further note that Eq. (4) represents a natural evolution of previous studies that: (i) observed a linear correlation between measured SRC abundances and the modified structure of bound nucleons in the valence region (i.e., at high fractional-momentum $x \sim 0.3–0.7$), known as the EMC effect [51–53], and (ii) showed that this correlation can result from a universal modification of the valence region structure function of nucleons in

proton-neutron SRC pairs [50]. These studies were limited to the nucleon valence region ($x \sim 0.3–0.7$) and using lepton-nucleus Deep Inelastic Scattering (DIS) data with specific nuclear structure input for SRC abundances [50, 54]. As detailed below, here we study the fundamental nPDFs, extend the analysis to the full x range of 10^{-3} to 0.8, use a comprehensive data set on the parton structure of nuclei, and do not impose external inputs for nuclear structure parameters C_A^N . The latter is especially important as the independent extraction of C_A^N allows us to compare with known measured and calculated nuclear structure values to support, or challenge, the physical validity and interpretation of Eq. (4).

As the DIS coherence length scales as $1/x$, it is more natural to associate higher- x phenomena with short-range nuclear physics than very low- x ($x \sim 10^{-2}–10^{-3}$) phenomena. Low- x reactions are sensitive to the number of nucleons the virtual photon propagates through, given by the nuclear thickness function [14]:

$$T^{(2)}(b) = \int dz_1 \int dz_2 \rho^{(2)}(b_1=b, z_1; b_2=b, z_2), \quad (5)$$

where $\rho^{(2)}$ is the two-nucleon density defining the probability for finding two nucleons with transverse and longitudinal positions b and z . For mean-field models, we can assume $\rho^{(2)}$ approximately factorizes into $\sim \rho(b_1, z_1)\rho(b_2, z_2)$. Studies show the SRC pairs significantly impact the two-nucleon density leading to a typical correction of [55, 56]

$$\rho^{(2)}(b_1, z_1; b_2, z_2) \approx \rho(b_1, z_1)\rho(b_2, z_2) \{1 + C(|z_1 - z_2|)\}, \quad (6)$$

where the correlation function $C(|z_1 - z_2|)$ is sensitive to the number of nucleons in SRC pairs, i.e. C_A^N . Therefore, the SRC-induced correlation in the nuclear density can impact the calculated nuclear thickness functions and thereby low- x phenomena.

As with the modeling of high- x Fermi-motion effects, accounting for low- x behavior in the present SRC model is an effective way to capture dynamics that is sensitive to the abundance of SRC pairs. It does not mean to imply that the measured behavior at low- x stems only from the modification of the structure of nucleons in SRC pairs.

Analysis and Results: The analysis utilized the full set of available world data on nuclear lepton DIS, Drell-Yan processes, and W and Z boson production (see the Supplementary Material for data-set details). The corresponding theory predictions were obtained in collinear factorization with the parton-level cross-sections calculated at the next-to-leading order (NLO) of QCD. The DIS data primarily constrain the u and d quark and anti-quark distributions, whereas the W and Z boson production data from LHC proton-lead collisions also constrain strange quark and gluon distributions down to lower momentum fractions of $x \sim 10^{-3}$.

χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
traditional	0.85	0.97	0.88	0.72	1408	0.85
baseSRC	0.84	0.75	1.11	0.41	1300	0.80
pnSRC	0.85	0.84	1.14	0.49	1350	0.82
N_{data}	1136	92	120	336	1684	

TABLE I. The partial χ^2/N_{data} values for the data subsets; the number of data points (N_{data}) for each process are listed in the bottom row. The **traditional** fit has 19 shape and 3 W/Z normalization parameters. The **baseSRC** and **pnSRC** fits have 21 shape, 3 W/Z normalization, and 30 and 19 SRC parameters, respectively. In total there are 1684 data points after cuts.

Energy scale dependence is accounted for using the DGLAP evolution equation, which also helps constrain the gluon distribution through the Q -dependence of DIS data. Parton number and momentum sum rules are ensured to be separately satisfied for $f_i^{p(n)}(x, Q)$ and $f_i^{\text{SRC}p(n)}(x, Q)$, and are therefore also satisfied for their linear combination in Eq. (4) independently of the values of C_p^A and C_n^A .

The free nucleon PDFs $f_i^{p(n)}(x, Q)$ are fixed to the distributions determined in Ref. [8] via global analysis of nucleon structure observables. The SRC nucleon PDFs $f_i^{\text{SRC}p(n)}(x, Q)$ use the same functional form as $f_i^{p(n)}(x, Q)$ with 21 shape parameters that are fit herein. We perform two independent analyses where i) C_p^A and C_n^A are allowed to vary freely, and ii) where we assume proton-neutron SRC dominance, i.e. $C_p^A = \frac{N}{Z} \times C_n^A \equiv C_A$. We refer to these fits as the **baseSRC** and **pnSRC** fits respectively. For comparison we also repeated the traditional (mean-field like) analysis of Ref. [12] using the same dataset used herein, which we refer to as the **traditional** fit.

The resulting fit quality in terms of its χ^2 for each SRC fit and for the **traditional** fit are listed in Table I for each data type separately, and for all data combined. As can be seen, the SRC fit using Eq. (1) results in overall χ^2 values comparable and even better than the **traditional** fit. All data are well reproduced for the full range of the data, corresponding to an x range of about 10^{-3} to 0.75.

Figure 1 shows the extracted C_p^A and C_n^A coefficients as determined by the global **baseSRC**. The coefficients show logarithmic growth with the nuclear mass number A , starting from $\sim 5\%$ for helium-3 and reaching $\sim 20\%$ for lead. As shown in Fig. 1-b), the **baseSRC** and **pnSRC** fits give similar results with the **baseSRC** fit preferring a similar number of SRC protons and neutrons, even for heavy neutron-rich nuclei. This dynamics is consistent with the observation of pn -dominance, previously determined from nuclear structure studies [28, 32]. Therefore, the **baseSRC** and **pnSRC** consistency is a first indication of consistency between quark-gluon level analysis and nuclear structure studies.

Focusing on the lower panel, Figure 1 also shows

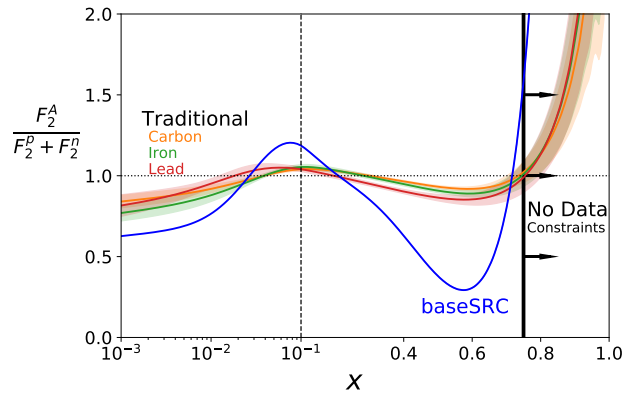


FIG. 2. Ratio of F_2^A structure functions compared to the scaled sum computed with free-proton PDFs at Q^2 of 10 GeV^2 using nCTEQ15 proton PDFs. The numerator is computed for different nuclei (Carbon, Iron, Lead) from the **traditional** fit, and the SRC distributions are extracted from the **baseSRC** fit. The logarithmic-linear x -axis scale highlights both the EMC and the shadowing regions.

the extracted C_p^A coefficients are consistent with previous, independent, extractions from both nuclear structure calculations [46] and quasi-elastic electron scattering measurements [48–50]. As the nuclear structure calculations assume point-like nucleons, and the measurements are done at energies that only probe nucleons (and not their substructure), they are both insensitive to the nucleon nPDFs.

Therefore, we report here the first direct extraction of nuclear structure information from parton level observables in an nPDF data analysis that is fully consistent with independent nuclear structure extractions.

Finally, looking at the nucleon structure itself, Fig. 2 shows the extracted isoscalar nucleon (i.e. proton + neutron) F_2 structure function ratio for nucleons in SRC pairs relative to free nucleons. Results shown are obtained from the **baseSRC** fit. The extraction is done for the summed proton plus neutron structure function, that our analysis is most directly sensitive to. For comparison, we also show the average proton and neutron modifications as determined by the **traditional** fit for carbon, iron, and lead. Direct measurements of the ratio $F_2^A/(F_2^p + F_2^n)$ exist for the low A deuteron and triton measurements [57, 58] that are not shown here. Extending the current analysis to lighter nuclear, including the mirror nuclei ^3H and ^3He , are planned for future study.

As can be seen in Fig. 2, the SRC and **traditional** cases both result in qualitatively similar deviations from the free-nucleon structure, with the SRC showing generally larger modification than even lead (Pb) in the **traditional** case, as expected. The amount by which the SRC modification is larger than the **traditional** case however varies significantly with x . At very low- x , below $2 - 3 \times 10^{-2}$, we observe only a

slightly increased suppression for the SRC case. At intermediate- x of $2 - 3 \times 10^{-2}$ to 2×10^{-1} we observe a more pronounced difference between the SRC and **traditional** enhancements. Furthermore, at high- x value, above ~ 0.6 , the difference is most pronounced. Part of this enhanced high- x effect can be understood to result from the effects of Fermi-motion that are known to grow with x and are included in our approach inside the modification function and therefore leads to the appearance of enhanced modification effects at high- x [59].

When we combine the elements of Fig. 2 to construct the nPDFs, we find that the valence nPDFs for the **traditional** and SRC fits are identical, within uncertainties. This highlights the fact that the nPDFs are truly constrained by the data, despite the differing parameterizations.

Conclusions: We have performed the first-ever global QCD analysis of nuclear PDFs using a framework based on concepts from SRC nuclear models. It leads to similar, or better, data description as compared to the traditional parameterization, and enables a meaningful physical interpretation of the fit. The incorporated data include the high-energy DIS, DY, and electroweak boson production commonly used in nPDF fits. The analysis determines both the standard “average” nuclear PDFs (that can be compared with traditional nPDF fits), as well as a universal distribution of partons in SRC nucleon pairs and the fractions of such SRC pairs.

This analysis represents a direct extraction of nuclear structure information from experimental observables directly probing quark-gluon nuclei dynamics. The fact that the obtained fractions of SRC pairs agree with their previous extractions from the low-energy quasielastic data establishes a direct link between high-energy partonic properties and lower-energy nuclear physics. It thus presents a significant advance in our quest to understand atomic nuclei in terms of QCD. Furthermore, the extracted distributions of partons in SRC pairs can be directly tested using measurements of tagged processes at the Jefferson Lab accelerator and the future Electron-Ion Collider.

This new nPDF set can also potentially impact the analysis of heavy-ion measurements that require a combination of a nuclear PDFs, together with initial

state nuclear matter effects [60–62]. Whereas traditional approaches thus far assign the same nPDF to all nucleons in the calculated initial-state distributions, the SRC approach allows additional flexibility. With the SRC PDFs, we can i) follow the traditional approach and simply use averaged distributions, or ii) we can construct a more complex initial-state nucleon distribution using a combination of the free PDF and SRC-modified PDF to each nucleon depending on its correlation state. Furthermore, it is noteworthy that the SRC parameterization (in which the dependence of A and x is factorized) produces an excellent description of the data; the conceptual simplicity of this parameterization is striking.

ACKNOWLEDGMENTS

We are grateful to Jeff Owens and Efrain Segarra for valuable discussion. The work at WWU Münster was funded by the DFG through the Research Training Group 2149 “Strong and Weak Interactions—from Hadrons to Dark Matter” and the SFB 1225 “Isoquant,” project-id 273811115. The research of P. D. was funded as a part of the Center of Excellence in Quark Matter of the Academy of Finland (project 346326). M.K. thanks the School of Physics at the University of New South Wales in Sydney, Australia for its hospitality and financial support through the Gordon Godfrey visitors program. A.K. is grateful for the support of Narodowe Centrum Nauki under grant no. 2019/34/E/ST2/00186. The work of C.K. was supported by the U.S. DoE contract DE-AC05-06OR23177, under which Jefferson Science Associates LLC manages and operates Jefferson Lab. J.G.M. has been supported by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. DoE. F.O. was supported by the U.S. DoE under Grant No. DE-SC0010129, and the DOE Nuclear Physics, within the Saturated Glue (SURGE) Topical Theory Collaboration. RR is supported by the Polska Akademia Nauk (grant agreement PAN.BFD.S.BDN. 613.022.2021-PASIFIC 1, POPSICLE). This work has received funding from the European Union’s Horizon 2020 research and innovation program under the Skłodowska-Curie grant agreement No. 847639 and from the Polish Ministry of Education and Science. The work of I.S. was supported by the French CNRS via the IN2P3 project GLUE@NLO.

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SUPPLEMENTARY MATERIAL

The Data: For this analysis we used data from nuclear DIS (including JLab), Drell-Yan (DY), and high-mass W/Z production. These are the same data as used in the nCTEQ15HIX analysis of Ref. [12] with the addition of the LHC W/Z production data from proton-lead collisions used in the nCTEQ15WZ [16] analysis. As with nCTEQ15HIX, we choose kinematic selection cuts of $Q > 1.3$ GeV and $W > 1.7$ GeV for DIS data. These cuts are relaxed as compared to the usual requirements ($Q > 2$ GeV and $W > 3.5$ GeV) enforced in previous nCTEQ nPDF analyses, which allows us to include more of the high- x data in particular data from JLab experiments.

The Fits: For our fit to the nuclear data, we fix the proton PDFs $f_{i/p}(x, Q)$ to the nCTEQ15 proton distributions [8]. We have also explored other proton sets from different groups, e.g. [7, 63–65] and obtained comparable results.

The **traditional** fit uses the same parametrization and open parameters as the nCTEQ15HIX analysis. We parameterize the SRC PDFs using a similar form as in

both nCTEQ15 and nCTEQ15HIX:

$$x f_i^{SRC}(x, Q_0) = p_0 x^{p_1} (1-x)^{p_2} e^{p_3 x} (1+e^{p_4 x})^{p_5}, \quad (7)$$

$$\frac{\bar{d}^{SRC}}{\bar{u}^{SRC}}(x, Q_0) = p_0 x^{p_1} (1-x)^{p_2} + (1+p_3 x)(1-x)^{p_4}.$$

Specifically, we parameterize the following flavor combinations: $\{u_v, d_v, (\bar{u}+\bar{d}), (\bar{d}/\bar{u}), (s+\bar{s}), g\}$ and 21 shape parameters: $\{p_{1\dots 5}^{u_v}, p_{1,2,3}^{d_v}, p_{1,2,3}^{\bar{u}+\bar{d}}, p_{0\dots 5}^g, p_{0,1,2}^{s+\bar{s}}, p_5^{\bar{d}/\bar{u}}\}$.

Additionally, for each non-isoscalar nucleus we fit the C_p^A and C_n^A coefficients from Eq. (4) which count the fractions of protons and neutrons in the SRC pairs. For isoscalar nuclei we set $C_p^A = C_n^A$. The data used in our analysis covers 18 nuclear targets: $\{^2\text{H}, ^3\text{He}, ^4\text{He}, ^6\text{Li}, ^9\text{Be}_{\text{iso}}, ^{12}\text{C}, ^{14}\text{N}, ^{27}\text{Al}, ^{40}\text{Ca}, ^{56}\text{Fe}, ^{64}\text{Cu}, ^{84}\text{Kr}, ^{108}\text{Ag}, ^{119}\text{Sn}, ^{131}\text{Xe}, ^{184}\text{W}, ^{197}\text{Au}, ^{208}\text{Pb}\}$ with 6 of them: $\{^2\text{H}, ^4\text{He}, ^6\text{Li}, ^9\text{Be}_{\text{iso}}, ^{12}\text{C}, ^{40}\text{Ca}\}$, being isoscalar (or isoscalar corrected). This yields a total of 30 parameters controlling the SRC fractions for the **baseSRC** fit, and 19 for the **pnSRC** fit. For very weakly constrained nuclei (^{131}Xe , ^{184}W) we include additional bounds on $C_{p(n)}^A$ coefficients. In the **pnSRC** fit we also keep the C_p^A and C_n^A free for ^3He .

For our analysis we use the nCTEQ++ framework which has a modular structure and links to a variety of external tools, including a modified version of HOPPET [66] (extended to accommodate grids of multiple nuclei), APPLgrid [67], and MCFM [68]. Additionally, we have used FEWZ [69] for benchmarking our W/Z calculations, and xFitter [70] for various cross checks.