

Nuclear binding, correlations, and the A dependence of the EMC effectOmar Benhar^{1,*} and Alessandro Lovato^{2,3,4,5,†}¹*INFN, Sezione di Roma, 00185 Roma, Italy*²*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*³*Computational Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*⁴*INFN-TIFPA Trento Institute for Fundamental Physics and Applications, 38123 Povo, Italy*⁵*Instituto de Física Corpuscular (IFIC), Consejo Superior de Investigaciones Científicas (CSIC), and Universidad de Valencia, E-46980 Paterna, Valencia, Spain*

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The measurements of inclusive electron scattering from nuclear targets carried out at the Thomas Jefferson National Accelerator Facility in the mid 2000s have provided valuable novel information on the A dependence of the modifications of nuclear structure functions known as the EMC effect. We argue that these data are best described in terms of the scaling variable $\tilde{y}$, designed to take into account dynamical effects in interacting many-particle systems, and analyze the A dependence of the slope of the inclusive cross-section ratios, $R_A = (\sigma_A/A)/(\sigma_2/2)$, providing a measure of the size of the EMC effect in the region where nuclear binding plays a leading role. The results of our study clearly hint at a linear correlation between $dR_A(\tilde{y})/d\tilde{y}$ and the average nucleon removal energy $\langle E_A \rangle$. The role of correlation effects in the determination of $\langle E_A \rangle$ is highlighted.

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Introduction. The EMC effect—named after the European Muon Collaboration, and first reported at the beginning of the 1980s [1,2]—was the observation that the electromagnetic structure functions per nucleon of iron and deuterium, measured at CERN using a 280-GeV muon beam, displayed a surprising pattern of differences, clearly visible as deviations from unity in their ratio. More generally, the term EMC effect has come to refer to any departure from unity of the ratio R_A between the cross section per nucleon of a nucleus of mass number A and that of the deuteron, corresponding to $A = 2$.

A large set of data collected at CERN [3,4], SLAC [5], HERA [6,7], and Jefferson Lab [8–12] unambiguously confirmed that for values of the Bjorken scaling variable in the range $0.35 < x < 0.70$ R_A exhibits a nearly linear behavior and decreases from ≈ 1 to a minimum which, depending on A , can be as low as ≈ 0.8 . Such a large effect was totally unexpected, because the binding energy of nucleons in atomic nuclei is small—in fact, altogether negligible—compared to the large energy transfer associated with deep inelastic scattering (DIS) processes.

No definitive explanation has emerged, mainly because most existing theoretical approaches are inherently inadequate to provide a fully quantitative account of the data over the

whole range of x . The degree of understanding of the EMC effect—or lack thereof—has been brilliantly summarized by the authors of a paper published in the CERN Courier in 2013, entitled “The EMC Effect Still Puzzles after 30 Years” [13].

Many different models, extensively reviewed in, e.g., Refs. [14–17], have been proposed to explain the reduction of R_A at intermediate x . The role of nuclear binding has been often, although not always, taken into account, but the results of these studies generally suggest that the effect of binding alone is not large enough to describe the data (see, e.g., Refs. [18,19]).

In 2009, the interest in nuclear effects in DIS was reignited by the appearance of new data taken at Jefferson Lab—hereafter JLab—by the E03-103 Collaboration [8]. These authors carried out a detailed analysis of the A dependence of the EMC effect using inclusive cross sections measured by scattering a 5.766-GeV electron beam off ^2H , ^3He , ^4He , ^9Be , and ^{12}C . In order to minimize normalization uncertainties, the size of the effect was conveniently characterized by the slope of the cross-section ratio dR_A/dx in the linear region. The most striking outcome of this study was the observation of a significant departure of the data point corresponding to ^9Be from the linear dependence on the average nuclear density emerging from the fit of the SLAC data of Ref. [5]. According to Seely *et al.* [8], this anomaly may be explained considering that, because the nucleus of ^9Be consists of two tightly bound α particles and an additional neutron, the nucleon interacting with the beam particle is more likely found in a region of density significantly higher than the average beryllium density.

The data of Ref. [8], suggesting that the size of the EMC effect is driven by the *local*, rather than the *average*, nuclear

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density, imply in turn that short-range dynamics, responsible for the appearance of high-momentum nucleons which largely determine the nuclear structure functions at $x > 1$, may as well play a significant role at intermediate x [20,21]. Based on this conjecture, Fomin *et al.* [22] investigated the dependence of the slopes of the EMC ratios on a parameter dubbed R_{2N} , designed to provide a measure of the ratio between the probabilities of finding a nucleon belonging to a high momentum pair in a nucleus of mass number A and in the deuteron. A similar study aimed at determining the dependence of the slope on the average number of nucleons involved in local fluctuations of the nuclear density, measured by a parameter referred to as a_2 , has been performed by the authors of Ref. [9]. While supporting the local density interpretation proposed by Seely *et al.* [8], the results of this study do not rule out the alternative explanation of Refs. [20–22], advocating the role of high-momentum nucleon pairs. The results of a more recent analysis carried out by Arrington and Fomin [23] also led to the conclusion that the connection between the EMC effect and short-range correlations (SRCs)—with the ensuing appearance of a significant isospin dependence [24]—is still lacking a firm understanding.

Arrington *et al.* [9] also investigated a somewhat different explanation of the EMC effect. These authors analyzed the dependence of the slopes of the cross-section ratio on the average nucleon removal energy $\langle E_A \rangle$ and found a remarkable linear correlation. However, they did not pursue this observation further, nor did they discuss thoroughly the role of SRCs in the determination of $\langle E_A \rangle$.

In this Letter, aimed at extending and improving the pioneering study of Ref. [25], the A dependence of the EMC effect and the role of nuclear binding are analyzed using the scaling variable $\tilde{y}$ originally proposed in Ref. [26]. We emphasize that our methodology is both novel and effective, because (i) it suggests a simple and straightforward explanation of the EMC effect at intermediate $\tilde{y}$, and (ii) it sheds light on the direct connection between the size of the effect and a *well-defined* nuclear property, the average nucleon separation energy $\langle E_A \rangle$, the value of which can be computed to high accuracy using quantum Monte Carlo techniques.

Emergence of $\tilde{y}$ scaling. Consider a process whereby the probe particle is scattered by a many-body system at rest. At momentum transfer $\mathbf{q}$ such that $|\mathbf{q}| \gg d^{-1}$, with d being the average distance between target constituents, the impulse approximation regime sets in, and scattering off individual constituents—the mass and the momentum of which will be denoted m and $\mathbf{p}$, respectively—is the dominant reaction mechanism. The interaction with the probe triggers a transition of the target from the ground state to a final state $|F\rangle$ comprising the struck constituent, with momentum $\mathbf{p} + \mathbf{q}$, and the spectator system, left in the state $|\mathcal{R}\rangle$ with energy $E_{\mathcal{R}}$ and total momentum $-\mathbf{p}$. Assuming that final state interactions between the struck constituent and the recoiling spectator system will be negligible, the energy of the state $|F\rangle$ can be written in the form [26]

$$E_F = |\mathbf{q}| + p_{\parallel} + E_{\mathcal{R}} + \dots, \quad (1)$$

where $p_{\parallel}$ is the component of $\mathbf{p}$ parallel to the momentum transfer and the ellipsis represents terms of order $|\mathbf{q}|^{-1}$, which

are disregarded in the $|\mathbf{q}| \rightarrow \infty$ limit. As a consequence, conservation of energy in the scattering process requires an energy transfer,

$$\nu = |\mathbf{q}| + p_{\parallel} + E_{\mathcal{R}} - M, \quad (2)$$

with M being the target mass. Equation (2) implies that, in the kinematical region corresponding to large momentum transfer, the response of the target—which in general depends on *both* $\mathbf{q}$ and ν —becomes a function of the single variable

$$\tilde{y} = \nu - |\mathbf{q}|. \quad (3)$$

Note that in lepton scattering $Q^2 = |\mathbf{q}|^2 - \nu^2 > 0$, and $\tilde{y}$ turns out to be negative.

The above derivation shows that the occurrence of scaling results from the onset of a dominant reaction mechanism, independent of the underlying dynamics. A slightly different but conceptually equivalent implementation of the above procedure allows one to explain the observation of scaling in the variable y —perfectly analogous to $\tilde{y}$ of Eq. (3)—in reactions as different as neutron scattering by liquid helium [27] and quasielastic electron-nucleus scattering [28,29]. In all instances, the scaling variable is simply related to the component of the momentum of the struck constituent parallel to the momentum transfer in the target rest frame.

The authors of Ref. [26] argued that DIS of electrons by protons may also be described using the formalism of many-body theory. The results of their analysis offer compelling evidence that the proton structure functions extracted from measured cross sections corresponding to $|\mathbf{q}| \gtrsim 5$ GeV exhibit a striking scaling behavior when plotted as a function of $\tilde{y}$. This outcome does not, in fact, come as a surprise, because the same data have long been shown to scale in the Nachtmann variable ξ [30], which reduces to $\xi = -\tilde{y}/m_N$ —with m_N being the nucleon mass [31]—in the target rest frame. Moreover, because in the $m_N^2/Q^2 \rightarrow 0$ limit ξ reduces to the Bjorken scaling variable x , $\tilde{y}$ scaling turns out to be related to x scaling as well. It should be kept in mind, however, that the closeness of their numerical values by no means implies that x and $\tilde{y}$ represent the same physical quantity or that analyzing the x dependence and the $\tilde{y}$ dependence of the data provides the same information.

To see why $\tilde{y}$ is best suited to study the EMC effect, consider that the scale of nuclear effects in lepton-nucleus scattering is set by the amount of energy deposited in the $(A-1)$ -nucleon spectator system, $\delta\nu$, which in turn determines the energy transfer to the struck nucleon. It can be easily shown that, in the limit of small $|\mathbf{p}|/m_N$, $\delta\nu \approx \langle E_A \rangle$, with $\langle E_A \rangle$ being the average energy needed to remove a nucleon from the target nucleus (see, e.g., Ref. [29]). The simple relation between $\tilde{y}$ and the energy transfer entails that, compared to that of the deuteron, the structure function per nucleon of a nucleus of mass A is shifted towards larger values of $\tilde{y}$ by an amount $\approx [\langle E_A \rangle - \langle E_2 \rangle] > 0$, and the cross section ratio at intermediate $\tilde{y}$ turns out to fall below unity [26].

The emergence of the EMC effect from the analysis of the $\tilde{y}$ dependence of the nuclear structure functions is illustrated in Fig. 1. The shift arising from the different nucleon removal energies can be clearly observed by comparing the measured

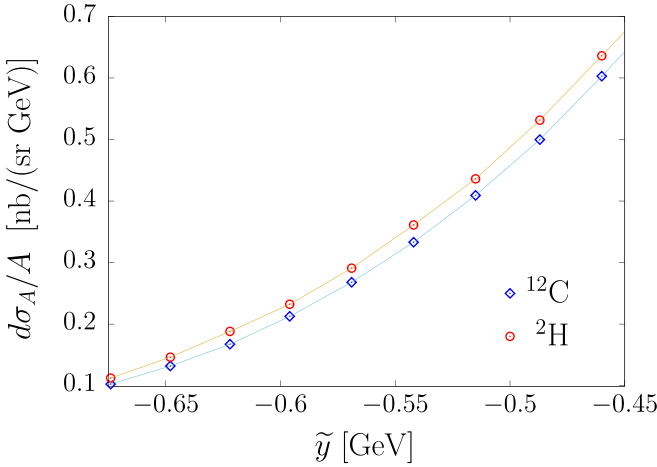


FIG. 1. Inclusive cross section per nucleon of ^2H (circles) and ^{12}C (diamonds) at $E_e = 5.766$ GeV and $\theta_e = 40^\circ$. The JLab data, originally reported by the E03-103 and E02-019 Collaborations in Refs. [8,22], are taken from the compilation of Ref. [32]. Error bars are not visible on the scale of the plot; the lines connecting the data points are meant to guide the eye.

inclusive cross sections per nucleon of ^2H and ^{12}C in the region $-0.7 < \tilde{y} < -0.45$ GeV, in which $R_A(\tilde{y}) < 1$ (see Fig. 2 below).

The pattern appearing in Fig. 1 provides the basis of the present study, in which the slopes of the EMC ratios are obtained from their dependence on the scaling variable $\tilde{y}$. For the sake of illustration, the ratio $R_A(\tilde{y})$ corresponding to $A = 12$ is displayed in Fig. 2. Note that, although the cross sections of Fig. 1 exhibit similar shapes when plotted as a function of x , in this case the more involved relation between the Bjorken variable and the energy transfer prevents a clear-cut identification of binding as the primary driver of the EMC effect at intermediate values of the scaling variable.

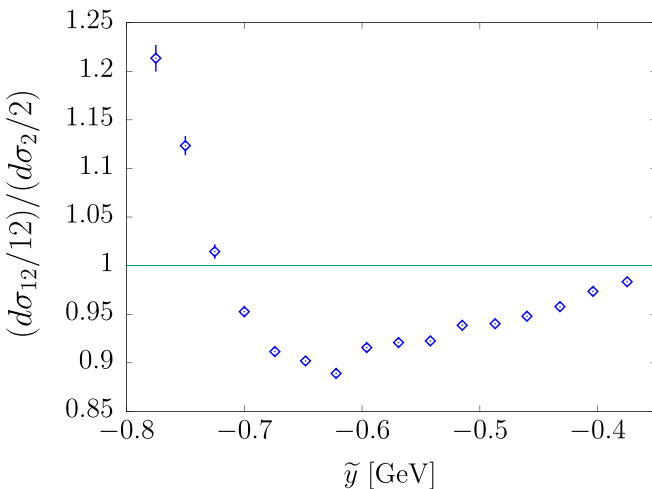


FIG. 2. Ratio of the inclusive cross section per nucleon of ^2H and ^{12}C at $E_e = 5.766$ GeV and $\theta_e = 40^\circ$ reported in Refs. [8,22] and compiled in Ref. [32]. The data are displayed as a function of the scaling variable $\tilde{y}$ of Eq. (3).

The correlation of the slopes with the nucleon removal energy has been investigated using values of $\langle E_A \rangle$ obtained from state-of-the-art quantum many-body calculations based on realistic models of nuclear dynamics as described in the following.

Determination of $\langle E_A \rangle$. Removing a nucleon of momentum $\mathbf{p}$ from a nucleus of mass number A leaves the residual $(A - 1)$ -nucleon system in a state $|\mathcal{R}\rangle$ which is not, in general, an eigenstate of the Hamiltonian. Its energy—given by $E_{\mathcal{R}} \approx M_{\mathcal{R}} = M_A - m_N + E_A$ in the $\mathbf{p}^2/M_{\mathcal{R}}^2 \rightarrow 0$ limit—is distributed according to the nuclear spectral function, which describes the probability to find a nucleon with removal energy E_A [33,34]. Electron-nucleus scattering experiments have provided convincing evidence that SRCs in the target ground state, leading to the excitation of two-particle–two-hole states, are associated with the appearance of high-energy contributions, pushing $\langle E_A \rangle$ much beyond the predictions of the nuclear shell model [29].

In principle, $\langle E_A \rangle$ should be obtained from the target spectral function, the determination of which involves nontrivial difficulties. The available models are mostly based on a combination of electron-nucleus scattering data and results of theoretical nuclear matter calculations [35,36]. While being adequate to describe a large set of measured inclusive cross sections, however, the spectral functions obtained from this approach are limited by both the kinematic range and precision of the input data and the complexity of many-body calculations involving continuum states.

More precise estimates of the average nucleon removal energy can be derived from the Galitskii-Migdal-Koltun sum rule [37,38], allowing one to write $\langle E_A \rangle$ in terms of ground-state expectation values which can be accurately computed using quantum Monte Carlo (QMC) techniques. For realistic Hamiltonian models, which include a potential describing irreducible three-nucleon ($3N$) interactions, the resulting expression is

$$\langle E_A \rangle = \frac{1}{A} \left[\frac{A-2}{A-1} \langle T \rangle - \langle V_{3N} \rangle - 2\mathcal{E}_A \right], \quad (4)$$

where $\mathcal{E}_A = \langle H \rangle$, $\langle T \rangle$, and $\langle V_{3N} \rangle$ denote the expectation values of the full nuclear Hamiltonian, the kinetic energy operator, and the $3N$ potential. The factor $(A - 2)/(A - 1)$ takes into account the kinetic energy associated with the center-of-mass motion of the recoiling nucleus.

For all nuclei with mass number $A \leq 12$ we have computed $\mathcal{E}_A$, $\langle T \rangle$, and $\langle V_{3N} \rangle$ within the Green's function Monte Carlo (GFMC) scheme [39]. The results corresponding to a Hamiltonian comprising the Argonne v_{18} [40] and Illinois-7 [41] two- and three-nucleon potentials, respectively, are listed in Table I together with the associated values of $\langle E_A \rangle$. We also report ^{40}Ca results, obtained from the cluster variational Monte Carlo (CVMC) method [42] using the Argonne v_{18} and the Urbana IX [43] interactions. It should be noted, however, that CVMC calculations are known to underestimate the ground-state energy of ^{40}Ca . To gauge the impact of this deficiency on our analysis we have reevaluated $\langle E_A \rangle$ replacing the CVMC ground-state energy with the experimental value, while keeping the kinetic energy and V_{3N} expectation values unchanged. The resulting removal energy of ^{40}Ca is given

TABLE I. Ground-state expectation values per nucleon and associated removal energies obtained from Eq. (4). The results corresponding to $A \leq 12$ have been obtained from GFMC calculations using the Argonne v_{18} and Illinois-7 potentials; for ^{40}Ca the energies have been computed using the CVMC approach and replacing the Illinois-7 potential with the Urbana IX model. The bottom line reports values of $\langle E_A \rangle$ corrected to take into account the uncertainty associated with the variational method; see text for details. All energies are in MeV.

Nucleus	$\mathcal{E}_A/A$	$\langle T \rangle/A$	$\langle V_{3N} \rangle/A$	$\langle E_A \rangle$
^2H	-1.113	9.905	0.000	2.225
^3He	-2.573	16.967	-0.367	13.997
^4He	-7.105	28.000	-1.550	34.427
^9Be	-6.433	31.333	-1.978	42.261
^{10}B	-6.470	33.900	-2.550	45.623
^{11}B	-6.691	33.545	-2.282	45.855
^{12}C	-7.775	36.417	-2.933	51.589
^{40}Ca	-4.920	30.970	-0.230	40.246
	-8.520	30.970	-0.230	47.446

in the bottom line of Table I. The validity of our procedure is supported by a comparison between the average removal energy of ^{16}O obtained from the CVMC method and the one computed using the highly accurate auxiliary-field diffusion Monte Carlo (AFDMC) method [44]; see Supplemental Material [45] for details of the CVMC/FHNC validation and the χEFT removal-energy analysis, including Refs. [46–50].

Data analysis and results. The slopes of the EMC ratios corresponding to the JLab data reported in Refs. [8,9,11] have been obtained from the inclusive cross sections of ^2H , ^3He , ^4He , ^9Be , and ^{12}C compiled in Ref. [32]. Our analysis covers the same kinematic region studied by the authors of Ref. [8], corresponding to $0.35 < x < 0.7$. For non-isospin symmetric nuclei, the effect of neutron excess has been taken into account using the procedure described in Ref. [11]. The EMC ratios of ^9Be , ^{10}B , ^{11}B , and ^{12}C recently reported by Karki *et al.* [12]—obtained from measurements performed in JLab Hall C using a 10.6-GeV electron beam—have been also included in our study. On the other hand, the data collected in Hall B by the CLAS Collaboration [10] were not available to us in a form suitable to consider their dependence on $\tilde{y}$.

Finally, we have analyzed the Q^2 -averaged EMC ratios of ^4He , ^9Be , ^{12}C , and ^{40}Ca reported by the SLAC E139 experiment [5], as well as the one corresponding to isospin-symmetric nuclear matter (SNM) at equilibrium density, obtained by the authors of Ref. [51] performing an $A \rightarrow \infty$ extrapolation based on the inclusive cross sections of ^4He , ^{12}C , ^{27}Al , ^{56}Fe , and ^{197}Au measured at SLAC [52].

The results of our work are summarized in Fig. 3, displaying the slopes of the EMC ratios obtained from the data collected by JLab experiments E03-103 [11] and E12-10-008 [12] and SLAC experiment E139 [5]. For clarity, the E139 and E03-103 points corresponding to $A = 4, 9$, and 12 are offset by ± 0.8 MeV, respectively. The nuclear matter result, represented by the square, has been obtained from the EMC ratio reported in Ref. [51]. The horizontal error bars associated

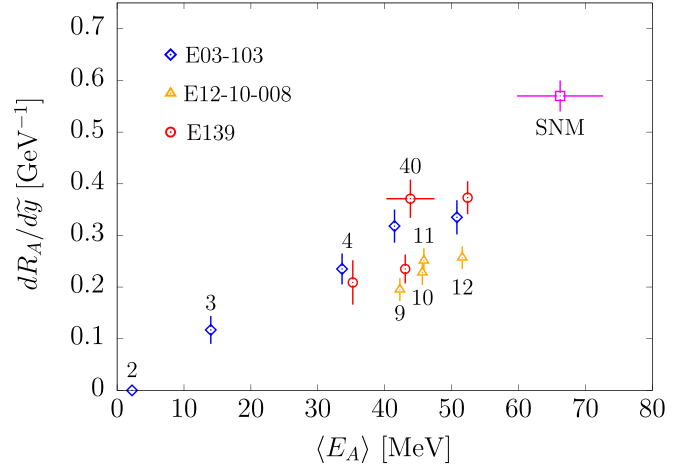


FIG. 3. Slopes of the EMC ratios in the $\tilde{y}$ region corresponding to $0.35 < x < 0.7$. The results, labeled according to the target mass number A , have been obtained from data collected by the E03-103 and E12-10-008 experiments at JLab and the E139 experiment at SLAC. For clarity, the E139 and E03-103 points corresponding to $A = 4, 9$, and 12 are offset by ± 0.8 MeV, respectively. The nuclear matter result, represented by the square, has been obtained from the EMC ratio reported in Ref. [51].

with the removal energies of ^{40}Ca and SNM account for the uncertainty arising from the variational determination of $\langle E_A \rangle$ discussed above. In the case of SNM, the ground-state energy per nucleon obtained by the authors of Ref. [53] using the variational approach and the formalism of correlated basis functions (CBF) turns out to be $\mathcal{E}_0/A = -10.07 \pm 0.82$ MeV, to be compared with the empirical value $\mathcal{E}_0/A \simeq -16$ MeV. The removal energies obtained from Eq. (4) combining the calculated and empirical values of $\mathcal{E}_0$ with the expectation values $\langle T \rangle/A$ and $\langle V_{3N} \rangle/A$ reported in Ref. [53] are $\langle E_{\text{SNM}} \rangle = 60.3$ and 72.2 MeV, respectively. It is remarkable that the average removal energy of SNM calculated from the spectral function of Ref. [33], computed in CBF perturbation theory, is within less than 3% of the one obtained from Eq. (4) using the results of Ref. [53].

Overall, the pattern observed in Fig. 3 clearly hints at a linear relationship between the slopes of the EMC ratios and the average nucleon removal energies, although the results obtained from the E12-10-008 data turn out to lie somewhat below those corresponding to the other experiments. This discrepancy, which also emerged from the standard analysis of Karki *et al.* [12], is, in fact, more visible in our results. To understand this feature, consider that, in general, the deviation between the slopes obtained by analyzing the dependence of R_A on x and $\tilde{y}$ is a decreasing function of Q^2 . In the present study, the effect of the $x \rightarrow \tilde{y}$ transformation is largest for the E03-103 data, and the corresponding slopes turn out to be enhanced by a noticeable amount.

It should be kept in mind, however, that, even in the regime in which of $\tilde{y} \approx -m_N x$ and the slopes of the EMC ratios are little affected by the transformation, the scaling variables $\tilde{y}$ and x have a profoundly different physical interpretation.

Conclusions. The general picture emerging from our study appears to be consistent with the prediction of a linear dependence of the EMC effect on the average nucleon removal energy, thereby supporting the validity of the description of nuclear DIS data in terms of the scaling variable $\tilde{y}$ derived in Ref. [26]. The identification of $\langle E_A \rangle$ as the primary factor determining the EMC ratio at intermediate $\tilde{y}$ is also strengthened by the measurements reported in Ref. [12], showing that the ^{10}B and ^{11}B ratios are consistent within experimental error. This observation simply reflects the fact that the corresponding removal energies, listed in Table I, only differ by half of a percent.

It should be emphasized that the approach employed in our analysis contributes to clarify the somewhat elusive role of SRCs. Semi-inclusive electron-nucleus scattering experiments have long established that high-momentum nucleons belonging to strongly correlated pairs have large removal energies, originating from excitation of the recoiling spectator system to continuum states [54–56]. These data demonstrate that SRCs significantly affect the average nucleon removal energy, which in turn determines the size of the EMC effect.

A quantitative assessment of the dependence of $\langle E_A \rangle$ on SRC can be obtained by considering the case of SNM at equilibrium density. The result of a direct calculation, performed using the spectral function of Ref. [33], shows that the strength located at momenta larger than the Fermi momentum $p_F \approx 260$ MeV—which would vanish identically in the absence of ground-state correlations—contributes 37% of the average removal energy.

Finally it is noteworthy that the linear dependence of the EMC effect on $\langle E_A \rangle$ illustrated in Fig. 3 is, in fact, largely

independent of the microscopic description of nuclear dynamics. On the other hand, nuclear dynamics determines the size of the effect, measured by the slope of the EMC ratio. The results obtained by repeating our analysis with an alternative Hamiltonian model, based on chiral effective field theory (χ EFT), are reported as Supplemental Material [45].

The results reported in this Letter show that the analysis based on the variable $\tilde{y}$ —which, unlike the Bjorken variable x , has a straightforward physical interpretation in the rest frame of the target nucleus—provides a largely model-independent explanation of both the origin and the A dependence of the EMC effect in the kinematic region in which nuclear binding plays a leading role.

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Data availability. The data that support the findings of this article are openly available [5,12,32].

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