DRAFT ***** Measurement of the EMC Effect of Tritium and Helium-3 by the JLab MARATHON Experiment ***** DRAFT

D. Abrams,[1] H. Albataineh,[2] B. S. Aljawrneh,[3] S. Alsalmi,[4,5] D. Androic,[6] K. Aniol,[7] W. Armstrong,[8] J. Arrington,[8,9] H. Atac,[10] T. Averett,[11] C. Ayerbe Gayoso,[11] X. Bai,[1] J. Bane,[12] S. Barcus,[11] A. Beck,[13] V. Bellini,[14] H. Bhatt,[15] D. Bhetuwal,[15] D. Biswas,[16] D. Blyth,[8] W. Boeglin,[17] D. Bulumulla,[18] J. Butler,[19] A. Camsonne,[19] M. Carmignotto,[19] J. Castellanos,[17] J.-P. Chen,[19] E. O. Cohen,[20] S. Covrig,[19] K. Craycraft,[11] R. Cruz-Torres,[13] B. Dongwi,[14] B. Duran,[10] D. Dutta,[15] N. Fomin,[12] E. Fuchey,[21] C. Gal,[1] T. N. Gautam,[16] S. Gilad,[13] K. Gnanvo,[1] T. Gogami,[22] J. Gomez,[19] C. Gu,[1] A. Habarakada,[16] T. Hague,[4] J.-O. Hansen,[19] M. Hattawy,[8] F. Hauenstein,[18] D. W. Higinbotham,[19] R. J. Holt,[8*] E. W. Hughes,[23] C. Hyde,[18] H. Ibrahim,[24] S. Jian,[1] S. Joosten,[10] A. Karki,[15] B. Karki,[25] A. T. Katramatou,[4] C. Keith,[19] C. Keppel,[19] M. Khachatryan,[18] V. Khachatryan,[26] A. Khanal,[17] A. Kievsky,[27] D. King,[28] P. M. King,[25] I. Korover,[29] S. A. Kulagin,[30] K. S. Kumar,[26] T. Kutz,[26] N. Lashley-Colthirst,[16] S. Li,[31] W. Li,[32] H. Liu,[23] S. Liuti,[1] N. Liyanage,[1] P. Markowitz,[17] R. E. McClellan,[19] D. Meekins,[19] S. Mey-Tal Beck,[13] Z.-E. Meziani,[10] R. Michaels,[19] M. Mihovilovic,[33,34,35] V. Nelyubin,[1] D. Nguyen,[1] Nuruzzaman,[36] M. Nycz,[4] R. Obrecht,[21] M. Olson,[37] V. F. Owen,[11] E. Pace,[38] B. Pandey,[16] V. Pandey,[39] M. Paolone,[10] A. Papadopoulou,[13] S. Park,[26] S. Paul,[11] G. G. Petratos,[4] R. Petti,[40] E. Piasetzky,[20] R. Pomatsalyuk,[41] S. Premathilake,[1] A. J. R. Puckett,[21] V. Punjabi,[42] R. D. Ransome,[36] M. N. H. Rashad,[18] P. E. Reimer,[8] S. Riordan,[8] J. Roche,[25] G. Salmè,[43] N. Santiesteban,[31] B. Sawatzky,[19] S. Scopetta,[44] A. Schmidt,[13] B. Schmookler,[13] J. Segal,[19] E. P. Segarra,[13] A. Shahinyan,[45] S. Širca,[33,34] N. Sparveris,[10] T. Su,[4,46] R. Suleiman,[19] H. Szumila-Vance,[19] A. S. Tadepalli,[36] L. Tang,[16,19] W. Tireman,[47] F. Tortorici,[14] G. M. Urciuoli,[43] B. Wojtsekhowski,[19] S. Wood,[19] Z. H. Ye,[8†] Z. Y. Ye,[48] and J. Zhang [26]

[1] *University of Virginia, Charlottesville, Virginia 22904, USA*
[2] *Texas A & M University, Kingsville, Texas 78363, USA*
[3] *North Carolina A & T State University, Greensboro, North Carolina 27411, USA*
[4] *Kent State University, Kent, Ohio 44240, USA*
[5] *King Saud University, Riyadh 11451, Kingdom of Saudi Arabia*
[6] *University of Zagreb, 10000 Zagreb, Croatia*
[7] *California State University, Los Angeles, California 90032, USA*
[8] *Argonne National Laboratory, Lemont, Illinois 60439, USA*
[9] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[10] *Temple University, Philadelphia, Pennsylvania 19122, USA*
[11] *William & Mary, Williamsburg, Virginia 23187, USA*
[12] *University of Tennessee, Knoxville, Tennessee 37996, USA*
[13] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[14] *Istituto Nazionale di Fisica Nucleare, Sezione di Catania, 95123 Catania, Italy*
[15] *Mississippi State University, Mississipi State, Mississipi 39762, USA*
[16] *Hampton University, Hampton, Virginia 23669, USA*
[17] *Florida International University, Miami, Florida 33199, USA*
[18] *Old Dominion University, Norfolk, Virginia 23529, USA*
[19] *Jefferson Lab, Newport News, Virginia 23606, USA*
[20] *School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[21] *University of Connecticut, Storrs, Connecticut 06269, USA*
[22] *Tohoku University, Sendai 980-8576, Japan*
[23] *Columbia University, New York, New York 10027, USA*
[24] *Cairo University, Cairo, Giza 12613 Egypt*
[25] *Ohio University, Athens, Ohio 45701, USA*
[26] *Stony Brook, State University of New York, New York 11794, USA*
[27] *Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, 56127 Pisa, Italy*
[28] *Syracuse University, Syracuse, New York 13244, USA*
[29] *Nuclear Research Center-Negev, Beer-Sheva 84190, Israel*
[30] *Institute for Nuclear Research of the Russian Academy of Sciences, 117312 Moscow, Russia*
[31] *University of New Hampshire, Durham, New Hampshire 03824, USA*
[32] *University of Regina, Regina, Saskatchewan S4S 0A2, Canada*
[33] *Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana 1000, Slovenia*
[34] *Jožef Stefan Institute, Ljubljana, Slovenia*
[35] *Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz 55122, Germany*
[36] *Rutgers, The State University of New Jersey, Piscataway, New Jersey 08855, USA*

[37] *Saint Norbert College, De Pere, Wisconsin 54115, USA*
[38] *University of Rome Tor Vergata and INFN, Sezione di Roma Tor Vergata, 00133 Rome, Italy*
[39] *Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*
[40] *University of South Carolina, Columbia, South Carolina 29208, USA*
[41] *Institute of Physics and Technology, 61108 Kharkov, Ukraine*
[42] *Norfolk State University, Norfolk, Virginia 23504, USA*
[43] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Rome, Italy*
[44] *University of Perugia and INFN, Sezione di Perugia, 06123 Perugia, Italy*
[45] *Yerevan Physics Institute, Yerevan 375036, Armenia*
[46] *Shandong Institute of Advanced Technology, Jinan, Shandong 250100, China*
[47] *Northern Michigan University, Marquette, Michigan 49855, USA and*
[48] *University of Illinois-Chicago, Chicago, Illinois 60607, USA*

(Dated: July 8, 2022)

The Jefferson Lab Hall A Tritium Collaboration

To be submitted for publication

Measurements of the EMC effect for the tritium and helium-3 nuclei are reported. The data were obtained by the MARATHON Jefferson Lab experiment which performed deep inelastic scattering of electrons from deuterium and the three-body nuclei, using a cryogenic gas target system and the Hall A High Resolution Spectrometers. The data cover the Bjorken x range from 0.19 to 0.83, corresponding to a squared four-momentum transfer Q^2 range from 2.7 to 11.9 $(\mathrm{GeV}/c)^2$. MARATHON reports the first precision measurement of the EMC effect of tritium. The MARATHON results on the three-body EMC effect are consistent with the trends of the heavier nuclei. They are compared to available measurements from DESY-HERMES and JLab-Hall C experiments as well as with a few-body theoretical predictions.

PACS numbers: 13.60.-r, 14.65.-q, 21.45.+v, 21.60.+v, 25.30.-c, 27.10.+h

The European Muon Collaboration (EMC) discovered a significant suppression of the deep inelastic scattering (DIS) cross section for iron per one bound nucleon (or the structure function F_2) with respect to that of deuterium for the Bjorken scaling variable x from 0.3 to 0.7, corresponding to the quark-valence region [1]. This variable is defined in the lab frame as $x = Q^2/[2M(E-E')]$ where M is the nucleon mass, and E and E' are the incident and scattered lepton energies in the scattering from the nucleus. This effect, named *EMC effect*, was confirmed by a reanalysis of older SLAC data [2], and by various experiments with electron and muon beams [3–6]. Nuclear effects are commonly studied using the ratio $R_A = \sigma^A/\sigma^d$ of cross sections for scattering off a nucleus A and deuterium d, normalized per one nucleon. In the valence quark region $0.3 < x < 0.6$, R_A is approximately a linear function of x with negligible Q^2 dependence. The slope $\mathrm{d}R_A/\mathrm{d}x$ in this region depends on the nuclear target and its value increases with the nuclear mass number A. Nuclear effects on R_A have also been studied in other kinematical regions (for a review of data and models see Refs. [7–11]).

In the infinite momentum frame, the Bjorken variable x has the meaning of the fraction of the target nucleon's momentum carried by quarks. Momentum conservation suggests that if the valence quark fraction is suppressed in nuclei then the corresponding lower-x fraction should be enhanced. Quite a few models have been suggested to explain the redistribution of missing valence light-cone momentum in nuclei between bound nucleons and non-nucleon degrees of freedom in nuclei such as nuclear pions, nucleon resonances, multi-quark clusters and also considering the change of the quark-gluon confinement scale in nuclear environment (for a review see [7–11]). It is known since the 1970s that smearing the nucleon structure function with the nuclear momentum distribution (due to Fermi motion) results in an enhancement of the nuclear structure functions at high x [12, 13]. The EMC data [1] showed a striking deviation from the expectations on the Fermi motion effect [13]. A revision of the Fermi motion correction to include the effect of the nuclear binding allows a reduction of the discrepancy between calculations and data [14]. Further refinements and quantitative studies of the Fermi motion and nuclear binding effect with a realistic nuclear spectral function including a high-momentum component, can explain about half of the observed EMC effect at its maximum value around $x \sim 0.7$ [15–17], somewhat underestimating the value of the slope $\mathrm{d}R_A/\mathrm{d}x$ at $x = 0.4$. Since bound nucleons are off-mass-shell due to the nuclear binding, their invariant mass squared is, for kinematic reasons, $p^2 = p_0^2 - \boldsymbol{p}^2 < M^2$. This off-shell effect results in a nuclear modification to the structure of the bound nucleons, after averaging with the nuclear energy-momentum

---

*Present address: Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA.

†Present address: Department of Physics, Tsinghua University, Beijing 100084, China.

distribution [18]. In the theoretical model of Ref. [17] this effect is addressed in terms of a dimensionless function $\delta f(x)$ describing the relative off-shell correction to the nucleon F_2 structure function. There, it was shown that the EMC effect can be described with a high accuracy over the complete kinematic region covered by existing data using the same $\delta f(x)$ function for bound protons and neutrons. Predictions based on this assumption were verified with a broad range of data from a variety of high-energy processes [19–21]. The further study of a possible isospin dependence [20, 22] of this correction requires the use of nuclei with a large neutron or proton excess like ^{3}H and ^{3}He. Nuclear modifications of various types of the bound nucleon structure in the valence quark region are also present in a number of different models [23–25]. Other nuclear effects, such as corrections from meson-exchange currents and the propagation of the hadronic (quark-gluon) component of the virtual intermediate photon in the nuclear environment are relevant in the small x region [7–9, 26].

A crucial step in understanding the origin of the EMC effect is a comparison of realistic calculations of the structure functions of the lightest nuclei, deuterium ^{2}H, helium-3 ^{3}He (h) and tritium ^{3}H (t), with precision measurements. In this Letter we report the measurement of the EMC effect of the $A = 3$ mirror nuclei in the MARATHON Jefferson Lab (JLab) experiment [27], which previously determined the ratio of the proton (p) and neutron (n) F_2 structure functions, F_2^n/F_2^p, from DIS measurements off tritons (t) and helions (h) [28]. MARATHON used the Continuous Electron Beam Accelerator and the Hall A Facility of JLab.

Electrons scattered from d, h, and t particles in high-pressure gas target cells in a cryogenic target system [30], cooled to a temperature of 40 K, were detected in the Left and Right High Resolution Spectrometers (HRS) of the Hall [29]. The incident-beam energy was fixed at 10.59 GeV, and the beam current ranged from 14.6 to 22.5μA. The Left HRS was operated at a fixed momentum of 3.1 GeV/c, placed at angles between 16.81° and 33.55°. The Right HRS was operated at a single setting of 2.9 GeV/c and 36.12°. In each HRS system electrons were detected using two planes of scintillators for event triggering, a pair of drift chambers for particle track reconstruction, and a gas threshold Čerenkov counter and a lead-glass calorimeter for particle identification. The target cells were cycled many times in the beam for each kinematic setting in order to minimize effects of possible drifts of the beam diagnostic or other instrumentation (*e.g.* the beam current monitors). Essential information for the experimental apparatus has been provided in Ref. [28]. Additional detailed information on the Hall A spectrometer Facility, and the associated beam instrumentation with calibrations, as used in MARATHON are given in Refs. [31–36].

All events properly identified as electrons originating from the gas inside each target cell were binned by Bjorken x, resulting in the formation of an electron yield, equal to the number of scattered eletrons for each bin divided by the number of incident beam electrons and of gas target nuclei per unit area, as described in Ref. [28]. The ratio of the yields for two targets is equivalent to the ratio of their cross sections, because the identical lengths of the target cells cancel out in the latter ratio. The overall electron detection efficiency, close to unity (~ 0.985), was found to be independent of target cell at all kinematics, so it cancels out in the ratios of the yields. Several multiplicative correction factors were applied to the individual target yields. The correction for i) computer dead-time ranged from 1.001 to 1.065, ii) target density change due to beam heating effects from 1.066 to 1.112, iii) falsely-reconstructed events originating from the endcaps from 0.973 to 0.998, iv) events originating from pair symmetric processes from 0.986 to 0.999, v) radiative effects from 0.853 to 1.167, vi) beta decay of tritons to helions (applicable only to the tritium yield) [0.997 (0.989) at the beginning (end) of the experiment], vii) Coulomb distortion effects (0.997 to 1.000), viii) bin-centering adjustment (0.995 to 1.001). In the above, the ranges refer to the ^{3}He, ^{3}H, and ^{2}H gas yields. A cross section model from Refs. [17, 19] was adopted for the Coulomb correction (which used the Q^2-effective approximation as outlined in Ref. [37]), and for the bin-centering correction.

The corrections to the h/d and t/d cross section ratios from each effect listed above become minimal, and in some cases, so do the associated systematic uncertainties. For example, the radiative effect correction ranges from 1.000 to 1.004 and 1.006 to 1.012, respectively. The dominant point-to-point systematic uncertainties for the yield ratios are those from the beam-heating gas target density changes [$\pm(0.1\% - 0.5\%)$], the radiative correction [$\pm(0.25\% - 0.45\%)$], and the choice of spectrometer acceptance limits ($\pm 0.2\%$). The total point-to-point uncertainty ranged from $\pm 0.46\%$ to $\pm 0.49\%$ for the h/d cross section ratio, and $\pm 0.34\%$ to $\pm 0.47\%$ for the t/d ratio. Details on the determination of the yields, and all associated corrections and uncertainties, can be found in Refs. [32–36].

The experiment also collected DIS data for the proton, in the x range from 0.19 to 0.37, for normalization purposes. The resulting σ_d/σ_p ratio measured by MARATHON is in excellent agreement with the *reference* measurements of the seminal SLAC-E49b and E87 experiments [38], as shown in Ref. [28]. The d/p data from MARATHON allowed an accurate determination of the $R_{np} = \sigma^n/\sigma^p$ ratio from the relation [19, 39] $R_{np} = (\sigma^d/\sigma^p)/R_d - 1$, where $R_d = \sigma^d/(\sigma^p + \sigma^n)$.

In the extraction of R_{np} from the MARATHON ^{3}He and ^{3}H data, it was realized [28] that the σ_h/σ_t ratio had to be normalized by a factor of 1.025, a result of requiring the equality of the R_{np} values extracted from σ_h/σ_t and σ_d/σ_p in the vicinity of $x = 0.3$. In this work we follow the same approach by requiring that the R_{np} value extracted individually from σ_t/σ_d and σ_h/σ_d be equal to that extracted from σ_d/σ_p in the vicinity of $x = 0.3$, where nuclear corrections are minimal. We define the EMC-type ratios for the cross sections of ^{3}He (h) and ^{3}H (t) as $R_h = \sigma^h/(2\sigma^p + \sigma^n)$ and $R_t = \sigma^t/(\sigma^p + 2\sigma^n)$, respectively. Then, the double ratios $\mathcal{R}_{hd} = R_h/R_d$ and $\mathcal{R}_{td} = R_t/R_d$ allow us to determine R_{np} in two separate ways:

$$R_{np} = \frac{2\mathcal{R}_{hd}(\sigma^d/\sigma^h) - 1}{1 - \mathcal{R}_{hd}(\sigma^d/\sigma^h)} = \frac{\mathcal{R}_{td}(\sigma^d/\sigma^t) - 1}{1 - 2\mathcal{R}_{td}(\sigma^d/\sigma^t)}, \qquad (1)$$

once the ratios σ^h/σ^d and σ^t/σ^d have been measured experimentally, and the ratios $\mathcal{R}_{hd}$ and $\mathcal{R}_{td}$ have been theoretically calculated with a reliable model.

Predictions for the R_d, $\mathcal{R}_{hd}$, and $\mathcal{R}_{td}$ ratios were obtained prior to the analysis of the MARATHON data from the theoretical model of kulagin and Petti (K-P) [17, 19], which provides a good description of the EMC effect for all known targets (for a review see Ref. [26]). This model includes a number of nuclear effects out of which the major correction for the relevant kinematics comes from the smearing effect with the nuclear energy-momentum distribution, described in terms of the nuclear spectral function, together with an off-shell correction to the bound nucleon cross sections [17]. The underlying nucleon structure functions come from a global QCD analysis [40], which was performed up to NNLO approximation in the strong coupling constant including target mass corrections [41] as well as those due to higher-twist effects. For the spectral functions of the ^{3}H and ^{3}He nuclei, the results of Ref. [39] have been used, while for the ^{2}H the wave function of AV18 nucleon-nucleon interaction [42] was applied. In order to evaluate theoretical uncertainties, the ^{3}He spectral function of Ref. [43] and the ^{2}H wave function of Ref. [44] was used. Reasonable variations of the high-momentum part of the nucleon momentum distribution in ^{3}H and ^{3}He were considered, and uncertainties in the off-shell correction of Ref. [17], as well as in the nucleon structure functions of Ref. [40], were accounted for [45].

The comparison of R_{np} as extracted from the measured σ_h/σ_d, σ_t/σ_d, and σ_d/σ_p ratios was done at $x = 0.31$, where nuclear corrections are not expected to contribute to isoscalar nuclear ratios like $\mathcal{R}_{hd}$, $\mathcal{R}_{td}$, and R_d. This expectation is based on the experimental data for $A \geq 3$ nuclei [3–6] in the range $0.25 \leq x \leq 0.35$, taking into account the quoted normalization uncertainties therein. This approach is also in line with the results of Refs. [19, 46, 47]. The K-P model predicts a value of 1.000, 1.000, and 1.000 at $x = 0.31$ for $\mathcal{R}_{hd}$, $\mathcal{R}_{td}$, and R_d, with uncertainties of $\pm 0.38\%$, $\pm 0.42\%$ and $\pm 0.20\%$, respectively. The values of σ_d/σ_p, σ_h/σ_d, and σ_t/σ_d at $x = 0.31$ were determined by weighted fits to the MARATHON data, which included statistical and point-to-point uncertainties added in quadrature.

The results of the extraction of R_{np} from the σ^d/σ^p data are, in the vicinity of $x = 0.3$, in excellent agreement with the corresponding results of JLab BoNuS [46] and SLAC-E139 [3]. The predictions of Ref. [17] on R_d are also in very good agreement with the independent analyses of Refs. [25, 48].

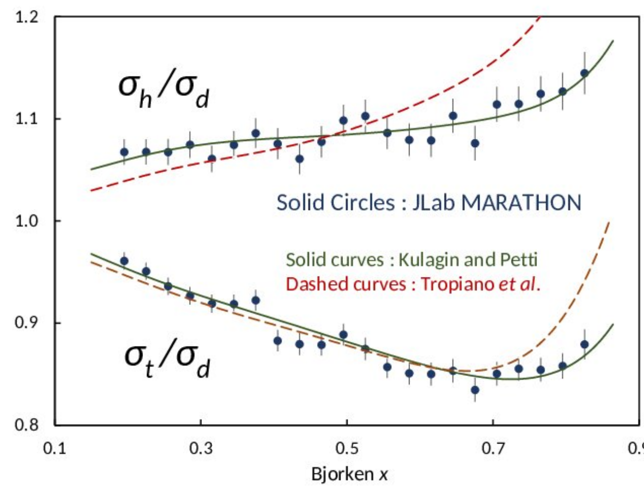

FIG. 1: The MARATHON results on the ^{3}He/^{2}H and ^{3}H/^{2}H ratio of the DIS cross sections vs. Bjorken x. The error bars include statistical and point-to-point systematics uncertainties. The solid line is the prediction of the model [19], the dashed curve is the result of Ref. [22]

In order to match the σ^n/σ^p values found using the three different sets of nuclei, the σ_h/σ_d and σ_t/σ_d ratios at $x = 0.31$ had to be normalized by a multiplicative factor of 1.021±0.005 and 0.996±0.005 respectively. These two factors are perfectly consistent with the normalization factor of 1.025±0.007 of the σ_h/σ_t ratio, as determined similarly in Ref. [28]. All values for the σ_h/σ_d and σ_t/σ_d ratios reported and further used in this work have been normalized using these factors. The normalized ratios' values are given in Tables 1 and 2 of the online Supplemental File, together with associated uncertainties, and plotted in Fig. 1. As a matter of convention, which will be followed for the remainder of this work, the ratios have been adjusted so that the cross sections are per nucleon.

The data are compared to the theoretical predictions of the K-P model [17, 19, 45] and Ref. [22] (TEMS). Both K-P and TEMS predictions are based on a nuclear convolution approach [17, 19, 49], but they involve different assumptions. K-P uses the proton and neutron structure functions from a global QCD fit [40] and the relative off-shell correction from Ref. [17]. TEMS employs the results of an analysis [50] with the off-shell effect adjusted from a fit to JLab Hall C data [6], allowing for different off-shell modifications for bound protons and neutrons. The MARATHON data are in excellent agreement with the K-P prediction over the entire measured range of x, as quantified by a χ^2 per degree of freedom of 1.0.

The average of σ_h/σ_d and σ_t/σ_d provides a model-independent determination of the average isoscalar EMC effects of three-body mirror nuclei ^{3}He and ^{3}H. The resulting isoscalar ratio $(\sigma_h + \sigma_t)/(2\sigma_d)$ values and associated uncertainties are listed in Table 3 of the online Supplemental file, and plotted in Fig. 2 along with sta-

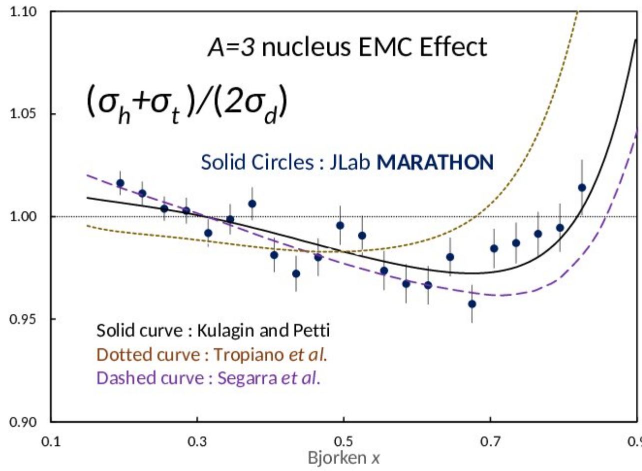

FIG. 2: The EMC effect in a isoscalar combination ^{3}He$+^3$H of the cross sections vs. Bjorken x. The error bars include statistical and point-to-point systematics uncertainties. The solid line is the prediction of the model [19], the dotted and the dashed curves are the results from Ref. [22] and Ref. [25], respectively.

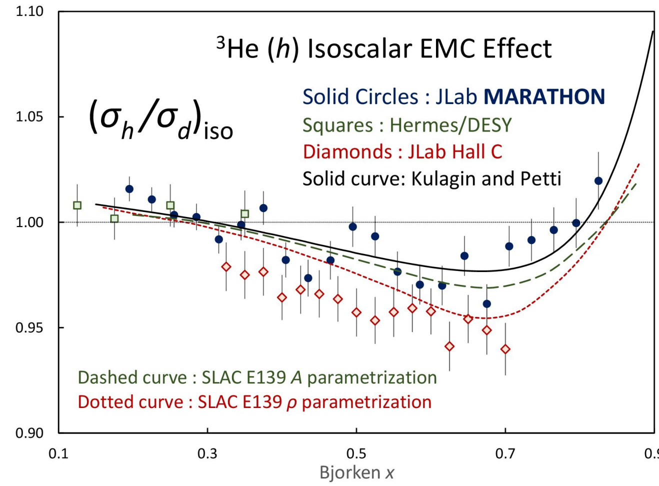

FIG. 3: The ^{3}He/^{2}H cross section ratio from the MARATHON experiment corrected for isoscalarity vs. Bjorken x. The error bars include statistical and point-to-point systematics uncertainties. Also shown are the results from DESY-Hermes [5] and JLab-Hall C [6] experiments. The solid line is the prediction of the model [19], while the dashed (dotted) curve is based on the parameterization by SLAC-E139 [3] in terms of the nuclear mass number A (nuclear charge density ρ).

tistical and point-to-point systematic uncertainties added in quadrature. Also shown are the predictions of K-P [19, 45], TEMS [22] and Segarra *et al.* [25].

To obtain the isoscalar EMC effect separately for the ^{3}He and ^{3}H nuclei, the ratios σ_t/σ_d and σ_h/σ_d should be corrected for the neutron (proton) excess. This is achieved by applying a factor

$$F_{\rm IS} = \frac{A(1+R_{np})}{2[Z+(A-Z)R_{np}]}, \quad (2)$$

where (Z, A) is (2,3) and (1,3) for ^{3}He and ^{3}H, respectively. The $R_{np} = \sigma^n/\sigma^p$ values used in Eq.(2) come directly from the MARATHON data [28], resulting in the smallest possible associated uncertainty. The values of the correction are given in Tables 4 and 5 of the online Supplemental File. Using MARATHON-extracted R_{np} in Eq.(2) allows us to cast the isoscalar ratios as follows:

$$(\sigma_h/\sigma_d)_{\rm IS} = \tfrac{1}{2}\left[\sigma_h/\sigma_d + \mathcal{R}_{ht}(\sigma_t/\sigma_d)\right], \quad (3)$$

$$(\sigma_t/\sigma_d)_{\rm IS} = \tfrac{1}{2}\left[\sigma_t/\sigma_d + (\sigma_h/\sigma_d)/\mathcal{R}_{ht}\right], \quad (4)$$

where $\mathcal{R}_{ht} = R_h/R_t$ is the ratio of ^{3}He (R_h) and ^{3}H (R_t) isoscalar ratios ("super-ratio") for which we use the K-P model prediction [19, 28]. The values of $\mathcal{R}_{ht}$ for MARATHON kinematics together with estimated theory uncertainty are listed in [28] showing that $\mathcal{R}_{ht}$ is well below 1% for most points with a maximal value reaching 1.25%. Note that $(\sigma_h/\sigma_t)_{\rm IS} = \mathcal{R}_{ht}$ and in the limit $\mathcal{R}_{ht} = 1$ we have identical individual isoscalar EMC-effect for ^{3}H and ^{3}He.

The measured values of $(\sigma_h/\sigma_d)_{\rm IS}$ and $(\sigma_t/\sigma_d)_{\rm IS}$ of the individual EMC effects of the two $A = 3$ nuclei are given in Tables 4 and 5 of the online Supplemental file, together with associated uncertainties, and plotted in Figs. 3 and 4. Since the ratios σ_h/σ_d and σ_t/σ_d are correlated, the uncertainties of the $A = 3$, ^{3}H and ^{3}He EMC effects have been determined by a Monte Carlo simulation, where it has been estimated that one half of both the point-to-point and overall scale uncertainties are correlated. Shown in the Figures are the predictions of K-P model [19, 45]. Also shown are the results from SLAC-E139 parametrizations of the EMC effect, in terms of the nuclear charge density ρ and $\ln(A)$ [3]. The MARATHON data are in gross disagreement with the charge density parametrization, but in a good agreement with the mass number parametrization. Also shown in Fig. 3 are data from the JLab Hall C E03-013 experiment with $W^2 \geq 3.0$ (GeV/c)^2 [6], and from the DESY-Hermes experiment [5] as listed in Ref. [51]. It is evident from Fig. 3 that the MARATHON data tie very well with the DESY-Hermes data but not with the JLab Hall C data.

It is customary to extract from EMC effect measurements, the slope of $(\sigma_A/\sigma_d)_{\rm IS}$ in the x range between 0.3 and 0.7, assuming that the effect follows there an approximate linear behavior. A linear fit to the MARATHON data including statistical and random systematic uncertainties results in the values of -0.085 ± 0.037 and -0.10 ± 0.04 for ^{3}He and ^{3}H, respectively. The ^{3}He slope value is similar to the -0.085 ± 0.027 one by JLab E03-013 experiment [6], although it uses different isoscalarity

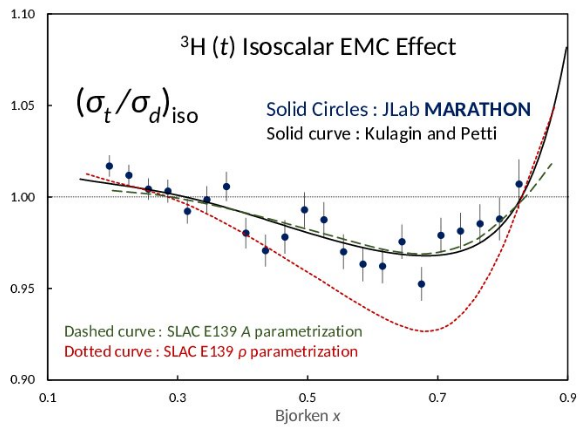

FIG. 4: The ^{3}H/^{2}H cross section ratio from the MARATHON experiment corrected for isoscalarity vs. Bjorken x. The error bars include statistical and point-to-point systematics uncertainties. The solid line is the prediction of the model [19], while the dashed (dotted) curve show the A (ρ)-dependent SLAC-E139 parameterization [3].

correction factor values than MARATHON.

In summary, the MARATHON experiment has provided a precise measurement of the EMC effect for the three-body nuclei ^{3}He and ^{3}H individually, as well as for their isoscalar combination, in the range of Bjorken x from 0.19 to 0.83 in the DIS regime with $W > 1.8$ GeV and $Q^2 \geq 2.73$ (GeV/c)^2. The results indicate that the $A = 3$ EMC effects do not scale with the nuclear charge density, while they are consistent with the A-dependent SLAC-E139 fit results performed for $A \geq 4$ nuclei [3]. The MARATHON data are in agreement with theoretical predictions in which nuclear corrections are originated by the energy-momentum distribution of bound nucleons together with an off-shell modification of their internal structure [17, 19], but they do not provide evidence for a sizable isovector EMC effect component as argued in Ref. [22]. Also, the MARATHON data for $x < 0.7$ are consistent with a parameterization of the EMC effect in terms of the fraction of the nuclear high-momentum component generated by short-range correlations [25].

We acknowledge the outstanding support of the staff of the Accelerator Division and Hall A Facility of JLab, and work of the staff of the Savannah River Tritium Enterprises and the JLab Target Group. We thank Drs. M. E. Christy and Y. Kolomensky for useful discussions on the optical properties of the HRS systems, and the interpretation of the data, respectively. We are grateful to Dr. W. Melnitchouk for his contributions to the development of the MARATHON proposal, and to Dr. A. W. Thomas for many valuable discussions on and support of the MARATHON project since its inception. This material is based upon work supported by the U.S. Department of Energy (DOE), Office of Science, Office of Nuclear Physics under contracts DE-AC05-06OR23177 and DE-AC02-06CH11357. This work was also supported by DOE contract DE-AC02-05CH11231, DOE award DE-SC0016577, DOE award DE-SC0010073, National Science Foundation awards NSF-PHY-1405814 and NSF-PHY-1714809, the Kent State University Research Council, the Pazy Foundation and the Israeli Science Foundation under grants 136/12 and 1334/16, and the Italian Institute of Nuclear Physics.

[1] J. J. Aubert *et al.* [EMC], Phys. Lett. **B123**, 275 (1983).
[2] A. Bodek *et al.*, Phys. Rev. Lett. **50**, 1431 (1983); A. Bodek *et al.*, Phys. Rev. Lett. **51**, 534 (1983).
[3] R. G. Arnold *et al.* [SLAC-E139], Phys. Rev. Lett. **52**, 727 (1984); J. Gomez *et al.*, Phys. Rev. D **49**, 4348 (1994).
[4] P. Amaudruz *et al.* [NMC], Nucl. Phys. B **441**, 3 (1995).
[5] K. Ackerstaff *et al.* [HERMES], Phys. Lett. B **475**, 386 (2000) [erratum: Phys. Lett. B **567**, 339 (2003)].
[6] J. Seely *et al.* [JLab E03103], Phys. Rev. Lett. **103**, 202301 (2009); J. Arrington *et al.*, Phys. Rev. **C104**, 065203 (2021).
[7] M. Arneodo, Phys. Rept. **240**, 301 (1994).
[8] D. F. Geesaman, K. Saito, and A. W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).
[9] P. R. Norton, Rept. Prog. Phys. **66**, 1253 (2003).
[10] Simone Malace, David Gaskell, Douglas W. Higinbotham, and Ian C. Cloet, Int. Journal Mod. Phys. **E23**, 1430013 (2014).
[11] O. Hen, G. A. Miller, E. Piasetzky, and L. B. Weinstein, Rev. Mod. Phys. **89**, 045002 (2017).
[12] G. B. West, Ann. Phys. **74**, 464, (1972); W. B. Atwood and G. B. West, Phys. Rev. D **7**, 773 (1973);
[13] A. Bodek and J. L. Ritchie, Phys. Rev. D **23**, 1070 (1981).
[14] S. V. Akulinichev, S. A. Kulagin, and G. M. Vagradov, Phys. Lett. B **158**, 485 (1985); S. V. Akulinichev *et al.*, Phys. Rev. Lett. **55**, 2239 (1985).
[15] S. A. Kulagin, Nucl. Phys. A **500**, 653 (1989).
[16] C. Ciofi Degli Atti and S. Liuti, Phys. Lett. B **225**, 215 (1989).
[17] S. A. Kulagin and R. Petti, Nucl. Phys. **A765**, 126 (2006).
[18] S. A. Kulagin, G. Piller, and W. Weise, Phys. Rev. C **50**, 1154 (1994).
[19] S. A. Kulagin and R. Petti, Phys. Rev. **C82**, 054614 (2010).
[20] S. A. Kulagin and R. Petti, Phys. Rev. C **90**, 045204 (2014).
[21] P. Ru, S. A. Kulagin, R. Petti and B. W. Zhang, Phys. Rev. D **94**, 113013 (2016).
[22] A. J. Tropiano *et al.*, Phys. Rev. C **99**, 035201 (2019)
[23] L. L. Frankfurt and M. I. Strikman, Nucl. Phys. B **250**, 143 (1985).
[24] I. C. Cloet, W. Bentz, and A. W. Thomas, Phys. Lett. B **642**, 210-217 (2006).
[25] E. P. Segarra *et al.*. Phys. Rev. Lett. 124, 092002 (2020).
[26] S. A. Kulagin, EPJ Web Conf. **138**, 01006 (2017).
[27] G. G. Petratos *et al.*, JLab PR12-10-103 **MARATHON**

Proposal: **M**e**A**_surement of the_ F_2^n/F_2^p, d/u **RA**_tios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the_ **T**_ritium and_ **H**_elium Mirr_**O**_r_ **N**_uclei_, 2010.
[28] D. Abrams *et al.*, Jefferson Lab Hall A Tritium Collaboration, Phys. Rev. Lett. **128**, 132003 (2022).
[29] J. Alcorn *et al.*, Nucl. Instrum. Methods **A522**, 294 (2004).
[30] R. J. Holt *et al.*, *Conceptual Design of a Tritium Gas Target for JLab* (JLab report), May 2010; D. Meekins, *Hall A Tritium Target*, (JLab report), November 2018.
[31] J. Bane, Ph.D. Thesis, University of Tennessee, 2019.
[32] T. Hague, Ph.D. Thesis, Kent State University, 2020.
[33] T. Kutz, Ph.D. Thesis, Stony Brook University, 2019.
[34] H. Liu, Ph.D. Thesis, Columbia University, 2020.
[35] M. Nycz, Ph.D. Thesis, Kent State University, 2020.
[36] T. Su, Ph.D. Thesis, Kent State University, 2020.
[37] Herbert Uberall, *Electron Scattering from Complex Nuclei*, Academic Press (1971).
[38] A. Bodek *et al.* (SLAC-E49-E87), Phys. Rev. **D20**, 1471 (1979).
[39] E. Pace, G. Salme, S. Scopetta, and A. Kievsky, Phys. Rev. **C64**, 055203 (2001).
[40] S. Alekhin, S. A. Kulagin, and R. Petti, AIP Conf. Proc. **967**, 215 (2007).
[41] H. Georgi, H. D. Politzer, Phys. Rev. **D14**, 1829 (1976).
[42] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995); S. Veerasamy and W. N. Polyzou, Phys. Rev. C **84**, 034003 (2011).
[43] R. W. Schulze and P. U. Sauer, Phys. Rev. **C48**, 38 (1993).
[44] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).
[45] Sergey Kulagin and Roberto Petti, private communication, 2018.
[46] K. A. Griffioen *el.*, Phys. Rev. **C92**, 015211 (2015).
[47] L. B. Weinstein *et al.*, Phys. Rev. Lett. **106**, 052301 (2011).
[48] S. I. Alekhin, S. A. Kulagin, and R. Petti, Phys. Rev. **D96**, 054005 (2017).
[49] S. A. Kulagin and W. Melnitchouk, Phys. Rev. C **78**, 065203 (2008).
[50] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, and N. Sato, Phys. Rev. D **93**, 114017 (2016).
[51] Erica Garutti, Ph.D. Thesis, University of Amsterdam, 2003.