Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment

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The ratio of the nucleon F_2 structure functions, F_2^n/F_2^p, is determined by the MARATHON experiment from measurements of deep inelastic scattering of electrons from ^{3}H and ^{3}He nuclei. The experiment was performed in the Hall A Facility of Jefferson Lab using two high-resolution spectrometers for electron detection, and a cryogenic target system which included a low-activity tritium cell. The data analysis used a novel technique exploiting the mirror symmetry of the two nuclei, which essentially eliminates many theoretical uncertainties in the extraction of the ratio. The results, which cover the Bjorken scaling variable range $0.19 < x < 0.83$, represent a significant improvement compared to previous SLAC and Jefferson Lab measurements for the ratio. They are compared to recent theoretical calculations and empirical determinations of the F_2^n/F_2^p ratio.

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This work reports on a novel measurement of a "textbook" [1] nuclear-particle physics observable, the ratio of the F_2 structure functions of the proton (p) and neutron (n), F_2^n/F_2^p, which provides fundamental information for the quark distributions of the two nucleons. Their structure functions, found from deep inelastic scattering (DIS) of electrons by protons and deuterons, have been of fundamental importance in establishing the internal quark structure of the nucleon [2], and for advancing our knowledge of the strong interaction in nature. First measurements occurred in a series of DIS experiments at the Stanford Linear Accelerator Center (SLAC) circa 1970 [3], which showed the existence of pointlike entities within the nucleons. Further studies of muon-nucleon and neutrino-nucleon DIS experiments at CERN [4–7] and Fermilab [8,9] established the quark-parton model (QPM) for the nucleon [10,11], and provided supporting evidence for the emerging theory of quantum chromodynamics (QCD) [12].

In this Letter we report the results of a measurement of F_2^n/F_2^p from electron DIS by the ^{3}He and ^{3}H mirror nuclei, which exploits their isospin symmetry [13,14], and allows us to significantly improve the accuracy of the ratio as compared to existing extractions from inclusive DIS measurements using ^{1}H and ^{2}H targets [15]. The cross section for electron-nucleon DIS is given, in the one-photon-exchange approximation, in terms of the structure functions $F_1(\nu, Q^2)$ and $F_2(\nu, Q^2)$ of the nucleon. In the lab frame and in natural units it reads [1]

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[\frac{F_2(\nu, Q^2)}{\nu} + \frac{2F_1(\nu, Q^2)}{M}\tan^2\left(\frac{\theta}{2}\right)\right], \quad (1)$$

where $\sigma_M = \{[4\alpha^2(E')^2]/(Q^4)\}\cos^2(\theta/2)$ is the Mott cross section, α is the fine-structure constant, E is the incident electron energy, E' and θ are the scattered electron energy and angle, $\nu = E - E'$ is the energy transfer, $Q^2 = 4EE'\sin^2(\theta/2)$ is the negative of the four-momentum transfer squared, and M is the nucleon mass. The invariant mass of the final hadronic state is $W = (M^2 + 2M\nu - Q^2)^{1/2}$.

The scattering process is mediated through the exchange of virtual photons. The cross section can also be written in terms of those for the absorption by the nucleon of longitudinally, σ_L, or transversely, σ_T, polarized photons. The functions F_1 and F_2 are related to the ratio $R = \sigma_L/\sigma_T$ as $F_1 = MF_2(\nu^2 + Q^2)/[Q^2\nu(1 + R)]$ [3]. All of the above formalism can also be applied to the case of DIS by a nucleus, with F_1 and F_2 becoming the structure functions of the nucleus in question. It should be noted that the ratio of DIS cross sections of different nuclear targets is equivalent to the ratio of their F_2 structure functions if R is the same for all nuclei. The latter has been confirmed experimentally within inherent experimental uncertainties [16].

The basic idea of the QPM [17,18] is to represent DIS as quasi-free scattering of electrons from the nucleon's partons or quarks, in a frame where it possesses infinite momentum. The nucleon's fractional momentum carried by the struck quark is then given by the Bjorken "scaling" variable, $x = Q^2/(2M\nu)$. In the limit where $\nu \to \infty$, $Q^2 \to \infty$ with x finite between 0 and 1, the structure functions become $F_1 = \frac{1}{2}\sum_i e_i^2 f_i(x)$ and $F_2 = x\sum_i e_i^2 f_i(x)$, where e_i is the fractional charge of quark type i, $f_i(x)dx$ is the probability that a quark of type i carries momentum in the range between x and $x + dx$, and the sum runs over all quark types. For the Gell-Mann–Zweig quarks, $F_2^p(x)$ becomes $F_2^p(x) = x[(4/9)U + (1/9)D + (1/9)S]$, and due to isospin symmetry, $F_2^n(x)$ becomes $F_2^n(x) = x[(1/9)U + (4/9)D + (1/9)S]$, where $U = u + \bar{u}$, $D = d + \bar{d}$, and $S = s + \bar{s}$, with bars denoting antiquarks [11].

The F_2 positivity dictates that F_2^n/F_2^p is bounded for all values of x: $(1/4) \le F_2^n/F_2^p \le 4$, a relationship known as the Nachtmann inequality [19]. This relationship was verified in the pioneering SLAC experiments E49a and E49b circa 1970 [15], which found that the ratio approaches unity at $x = 0$ and approximately 1/4 at $x = 1$. The SLAC findings showed that at low x the three quark-antiquark distributions are equal, dominated by sea quarks, and that at large x the u (d) quark distribution dominates in the proton (neutron). These findings were surprising as the expectation, at the time, from SU(6) symmetry was that F_2^n/F_2^p should be equal to 2/3 for all x. The behavior of the ratio at $x = 1$ was justified by the diquark model of Close [20], and Regge phenomenology, initiated by Feynman [21]. In Close's diquark model, the diquark configuration with spin 1 is suppressed relative to that with spin 0. The phenomenological suppression of the d quark distribution, which results from the F_2^n/F_2^p value of 1/4 at $x = 1$, can be understood in the quark model of Isgur [22] in terms of the color-magnetic hyperfine interaction between quarks, which is also responsible for the $N - \Delta$ mass splitting. It should be noted that perturbative QCD arguments [23] and a treatment based on quark-counting rules [24] suggest that the F_2^n/F_2^p ratio should have the larger value of 3/7 at $x = 1$.

The original considerations of the F_2^n/F_2^p magnitude were called into question in the 1990s when a re-examination of the subject by Whitlow *et al.* [25], who, using the original SLAC data [15] and a plausible model of the EMC effect in which the deuteron, medium and heavy nuclei scale with nuclear density [26], found a strong sensitivity in the determination of the ratio at large x. The EMC effect, discovered at CERN [27] and quantified precisely at SLAC [28], is the difference from unity in the per-nucleon DIS cross section ratios of heavy nuclei to deuterium as a function of x, and is usually perceived to characterize the modification of the nucleon structure functions in nuclear matter. The above strong sensitivity was subsequently confirmed in a relativistic reanalysis of the SLAC data, which assumes the presence of minimal binding effects in the deuteron [29]. In Ref. [25], it also became evident that the F_2^n/F_2^p ratio was very sensitive to the choice of the nucleon-nucleon (N-N) potential model governing the structure of the deuteron (d), later confirmed in Refs. [30,31]. The large uncertainty in the extraction of the F_2^n/F_2^p ratio at large x calls into question the presumption that F_2^n/F_2^p and D/U tend to 1/4 and zero, respectively, as x approaches 1.

These difficulties in the F_2^n/F_2^p determination can be remedied using a method proposed by Afnan *et al.* [13,14], which determines the F_2^n/F_2^p ratio from DIS measurements on ^{3}H (triton) and ^{3}He (helion), exploiting the isospin symmetry and similarities of these two nuclei. In the absence of Coulomb interactions and for an isospin symmetric world, the properties of a proton (neutron) bound in the ^{3}He nucleus should be identical to that of a neutron (proton) bound in the ^{3}H nucleus. Defining the EMC-type ratios for the F_2 structure functions of helion (h) and triton (t) by $R_h = F_2^h/(2F_2^p + F_2^n)$ and $R_t = F_2^t/(F_2^p + 2F_2^n)$, one can write the "superratio" of these ratios as $\mathcal{R}_{ht} = R_h/R_t$, which directly yields the F_2^n/F_2^p ratio as

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h/F_2^t}{2F_2^h/F_2^t - \mathcal{R}_{ht}}. \tag{2}$$

The F_2^n/F_2^p ratio found from this Eq. (2) depends on the ratio of the EMC effects in ^{3}He and ^{3}H. Since the neutron and proton distributions in the $A = 3$ nuclei are similar, the ratio can be calculated reliably with the expectation that $\mathcal{R}_{ht} \simeq 1$ [14,32], once F_2^h/F_2^t is measured experimentally. The seeming dependence of the process on the F_2^n/F_2^p input is actually artificial. In practice, one can employ an iterative procedure to eliminate this dependence altogether. Namely, after extracting F_2^n/F_2^p from the data using some calculated $\mathcal{R}_{ht}$, the extracted F_2^n/F_2^p can then be used to compute a new $\mathcal{R}_{ht}$, which is then used to extract a more accurate value of F_2^n/F_2^p. This procedure is iterated until convergence is achieved and a self-consistent solution for the extracted F_2^n/F_2^p is obtained. The convergence of the procedure was confirmed in Refs. [32,33].

The above technique was used in the Jefferson Lab (JLab) MARATHON experiment [33] (initiated in 1999 [34]), which took data in 2018 using the Electron Accelerator and Hall A Facilities of the Lab. Electrons scattered from light nuclei were detected in the Left and Right High Resolution Spectrometers (LHRS and RHRS) of the Hall [35]. The beam energy was fixed at 10.59 GeV, and its current ranged from 14.6 to 22.5 μA. The experiment detected DIS events using a cryogenic gaseous target system [36]. The LHRS was operated at a momentum of 3.1 GeV/c with angles between 16.81° and 33.55°. The RHRS was operated at a single setting of 2.9 GeV/c and 36.12°.

The target system consisted of four high-pressure cells, of length 25.0 cm and diameter 1.27 cm, containing ^{3}He, ^{3}H, ^{2}H, and ^{1}H gases. The four cells were filled at temperatures of 294.3, 296.3, 296.1, 297.4 K, and pressures of 17.19, 13.82, 35.02, 35.02 atm, resulting in densities (determined from data-supported virial models [37]) of 2.129 ± 0.021, 3.400 ± 0.010, 5.686 ± 0.022, and 2.832 ± 0.011 kg/m^3, respectively. The target assembly also contained an empty cell and a "dummy target" consisting of two Al foils separated by 25.0 cm, which were used to measure the contribution to the scattered electron yields from the Al end caps of the cells. The 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). This cycling amounted to 0.7% of the allocated experiment time.

Scattered particles were detected in the HRSs using two planes of scintillators for event triggering, two drift chambers for particle tracking, and a gas threshold Čerenkov counter and a lead-glass calorimeter for particle identification. Particles were identified as electrons on the basis of (i) a minimal pulse height in the Čerenkov counter, and (ii) the energy deposited in the calorimeter, consistent with the momentum as determined from the drift chamber track using the spectrometers' optical properties. The detector efficiencies for both spectrometers were found to be stable and independent of the gas target used. Details on the Hall A Facility, beam line, and detector instrumentation as used in MARATHON, including calibrations, are given in Refs. [38–43].

All events properly identified as electrons originating from the gas (of atomic mass A) inside each target cell were binned by Bjorken x, resulting in the formation of an electron yield $Y(x)$ defined as

$$Y(x) = \frac{N_{e'}}{N_e(\rho/A)_t L_t} C_{\rm cor}, \tag{3}$$

where $N_{e'}$ is the number of scattered electrons, N_e is the number of incident beam electrons, ρ_t is the density of the gas target, L_t is the selected gas target length [18.0 (22.5) cm at the smallest (largest) angle], and $C_{\rm cor} = C_{\rm det} C_{\rm cdt} C_{\rm den} C_{\rm tec} C_{\rm psp} C_{\rm rad} C_{\rm cde} C_{\rm bin} C_{\rm dth}$. Here, $C_{\rm det}$ is the correction for trigger and detector inefficiency, $C_{\rm cdt}$ is the computer dead-time correction (1.001 to 1.065), $C_{\rm den}$ is a correction to the target density due to beam heating effects (1.066 to 1.125), $C_{\rm tec}$ is a correction for falsely reconstructed events originating from the target cell end caps (0.973 to 0.998), $C_{\rm psp}$ is a correction for events originating from pair symmetric processes (0.986 to 0.999), $C_{\rm rad}$ is a correction for radiative effects (0.826 to 1.173), $C_{\rm cde}$ is a correction for Coulomb distortion effects (0.997 to 1.000), $C_{\rm bin}$ is a bin-centering correction (0.995 to 1.001), and $C_{\rm dth}$ is a correction for the beta decay of tritons to helions, applicable only to the tritium yield [0.997 (0.989) at the beginning (end) of the experiment]. A cross section model by Kulagin and Petti (K-P), based on the works of Refs. [44–46], was adopted [47] for the bin-centering correction, and the Coulomb correction (which used the Q^2-effective approximation as outlined in Ref. [48]).

When forming ratios of electron yields from different targets, which are equivalent to cross section ratios, the target length L_t and the correction $C_{\rm det}$ cancel out. In general, the corrections to the *ratios* from each effect become minimal, and in some cases, so do the associated systematic uncertainties. For example, the radiative effect correction, ranges from 0.997 (at the highest x) to 1.015 (at the lowest x) for the h/t cross section ratio. The dominant point-to-point systematic uncertainties for the yield ratios are those from the beam-heating 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 $\pm 0.4\%$ to $\pm 1.0\%$ ($\pm 0.3\%$ to $\pm 0.5\%$) for the d/p (h/t) cross section ratio. Details on the determination of the yields, and all corrections and uncertainties, can be found in Refs. [39–43].

The experiment also collected DIS data for the proton and deuteron over the x range from 0.19 to 0.37 for the purpose of finding F_2^n/F_2^p from the σ_d/σ_p ratio in the vicinity of $x = 0.3$, where it is known that nuclear effects (beyond additivity) are minimal in the latter ratio [44,46], and comparing it with F_2^n/F_2^p found using DIS by the triton and helion. The measured values of σ_d/σ_p are given, together with associated uncertainties, in Table I of the Supplemental Material [49]. The $\sigma_d/\sigma_p = F_2^d/F_2^p$ values, plotted in Fig. 1, are compared to reference measurements from the seminal SLAC E49b and E87 experiments [50], performed with similar beam energies. It is evident from Fig. 1 that the JLab and SLAC data are in excellent mutual agreement. Given $\mathcal{R}_d = F_2^d/(F_2^p + F_2^n)$, the F_2^n/F_2^p ratio is calculated as $F_2^n/F_2^p = (F_2^d/F_2^p)/\mathcal{R}_d - 1$ [32,45]. The $\mathcal{R}_d$ ratio used in the MARATHON F_2^d/F_2^p data analysis is from the K-P model based on Refs. [44,45]. The results of this model are, in the vicinity of $x = 0.3$, in excellent agreement with determinations using data from the JLab BoNuS [51]

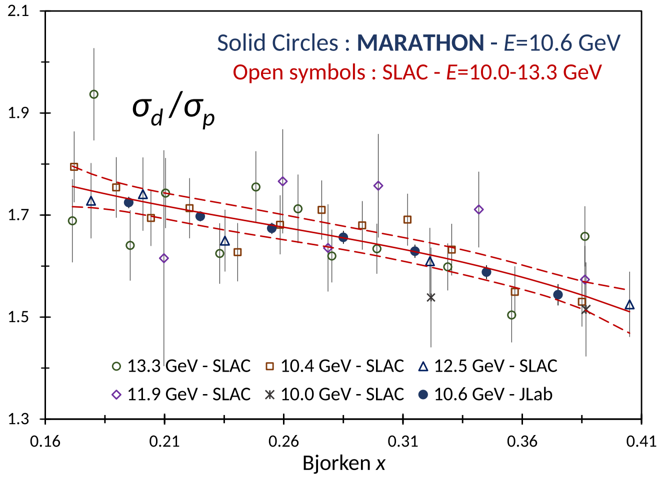

FIG. 1. The σ_d/σ_p DIS ratio versus the Bjorken x from the JLab MARATHON experiment. Also shown are seminal SLAC data [50] in the same kinematic region as MARATHON (see text). All error bars include statistical and random point-to-point uncertainties, added in quadrature. The solid line is a fit to the SLAC data. The dashed lines represent the one-sigma uncertainty of the fit. The overall normalization error is $\pm 0.55\%$ and $\pm 1.1\%$ for the MARATHON and SLAC data, respectively.

and SLAC E139 [28] experiments, and two distinct calculations based on studies of data from DIS off nuclei, described in Refs. [46] (using nuclei with $A \geq 4$) and [52] (using nuclei with $A \geq 3$).

The focus of MARATHON was to study DIS from helion and triton in order to extract F_2^n/F_2^p in the range $0.19 < x < 0.83$ using the measured $\sigma_h/\sigma_t = F_2^h/F_2^t$ ratio and model-calculated values of the superratio $\mathcal{R}_{ht}$. The latter values come from the K-P model [45,46], which provides a global description of the EMC effect for all known targets (for a review see Ref. [53]). The 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 F_2 [46]. The underlying nucleon structure functions come from the global QCD analysis of Ref. [54], which was performed up to NNLO approximation in the strong coupling constant including target mass corrections [55] 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. [32] have been used. In order to evaluate theoretical uncertainties, the ^{3}He spectral function of Ref. [56] 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. [46], as well as in the nucleon structure functions, were accounted for. The maximum resulting uncertainty in $\mathcal{R}_{ht}$ is estimated to be up to $\pm 0.4\%$ (at $x = 0.8$), contributing minimally to the total uncertainty in the final F_2^n/F_2^p values. The K-P calculations were performed prior to the analysis of the MARATHON data.

The comparison of F_2^n/F_2^p as extracted from σ_h/σ_t and σ_d/σ_p was done at $x = 0.31$, where nuclear corrections contribute negligibly to EMC-type ratios like $\mathcal{R}_d$ and $\mathcal{R}_{ht}$, as $\sigma_A/A = \sigma_d/2$ [57] (determined by the $A \geq 3$ data of Refs. [28,58,59] and taking into account the quoted normalization uncertainties therein). The K-P models used, predicted a value of 1.000 at $x = 0.31$ for both $\mathcal{R}_{ht}$ and $\mathcal{R}_d$ with uncertainties of $\pm 0.1\%$ and $\pm 0.2\%$, respectively. The recent work of Ref. [52], based on a global analysis of nuclear DIS data where the EMC effect is accounted for through nucleon short-range correlations, found $\mathcal{R}_{ht}(x = 0.31) = 1.001$, with a similar uncertainty. The values of σ_d/σ_p and σ_h/σ_t at $x = 0.31$ were determined by weighted fits to the MARATHON data, which included statistical and point-to-point uncertainties added in quadrature. In order to match the F_2^n/F_2^p values found using the two different sets of nuclei, the σ_h/σ_t ratio at $x = 0.31$ had to be normalized by a multiplicative factor of 1.025 ± 0.007. Consequently, all reported values of σ_h/σ_t have been normalized upwards by 2.5%. The origin of this necessary normalization is attributed to probable inaccuracies in the determination of the nominal densities of the ^{3}H and ^{3}He gas targets.

The normalized σ_h/σ_t values are given in Table II of the Supplemental Material [49], together with associated uncertainties. The F_2^n/F_2^p values are given in Table III of Ref. [49], together with associated uncertainties. Shown also in Table III [49] are the $\mathcal{R}_{ht}$ superratio values used to find F_2^n/F_2^p. The $\mathcal{R}_{ht}$ uncertainty was incorporated in quadrature with the point-to-point F_2^n/F_2^p uncertainty. Figure 2 shows the MARATHON F_2^n/F_2^p results, along

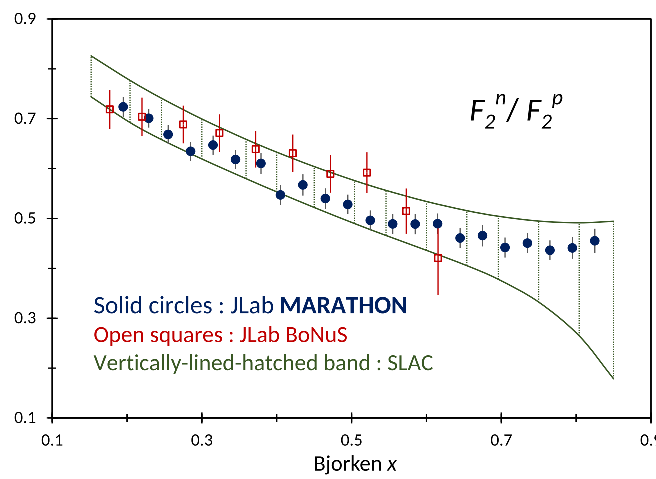

FIG. 2. The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [60], and a band based on the fit of the SLAC data as provided in Ref. [50], for the MARATHON kinematics $[Q^2 = 14 \cdot x\,(\mathrm{GeV}/c)^2]$ (see text). All three experimental datasets include statistical, point to point systematic, and normalization uncertainties.

with data from the JLab BoNuS experiment [60] for $W \geq 1.84\ \mathrm{GeV}/c^2$, evolved to the Q^2 of MARATHON [25], and results from early SLAC measurements with $W \geq 1.84\ \mathrm{GeV}/c^2$ [15,50]. The SLAC results are presented as a band, the width of which at high x is dominated primarily by uncertainties due to the choice of the N-N potential used for the evaluation of the deuteron wave function [25,30,31]. The MARATHON data are in good agreement with the BoNuS data, and fall well within the SLAC results band. The highest x points are consistent with F_2^n/F_2^p tending to a value between 0.4 and 0.5 at $x = 1$. This is consistent with the predictions of perturbative QCD and quark counting rules (for which this ratio is $3/7$ at $x = 1$), and with a recent prediction [61] that treats strong interactions using the Dyson-Schwinger equations, where diquark correlations in the nucleons are consequences of dynamical chiral symmetry breaking (for which the nucleon F_2 ratio lies, at $x = 1$, between 0.4 and 0.5). It is also consistent with a covariant quark-diquark model which also predicts that this ratio should be $3/7$ at $x = 1$ [62].

The MARATHON F_2^n/F_2^p values are in excellent agreement, as quantified by a χ^2 per degree of freedom (df) of 0.8, with those predicted by K-P, which were used in the determination of $\mathcal{R}_{ht}$. For this reason, an iterative procedure, as described earlier, was not necessary. A comparison between the MARATHON F_2^n/F_2^p results and the K-P prediction is shown in Fig. 3. Shown also in Fig. 3 are the σ_t/σ_h MARATHON values compared with the K-P prediction. The predicted σ_t/σ_h values by K-P, which were also used in the determination of $\mathcal{R}_{ht}$, are in excellent agreement with the MARATHON data, as quantified by a χ^2/df of 0.8. Also shown in Fig. 3 is the nuclear DIS determination of F_2^n/F_2^p by Segarra *et al.* [52], the latest calculation for F_2^n/F_2^p by the CTEQ-JLab (CJ) Collaboration [63], and a recent prediction for σ_t/σ_h by Tropiano *et al.* [64], which includes isovector components in the off-shell effects for the bound nucleons in the $A = 3$ nuclei, resulting in different corrections for the proton and neutron.

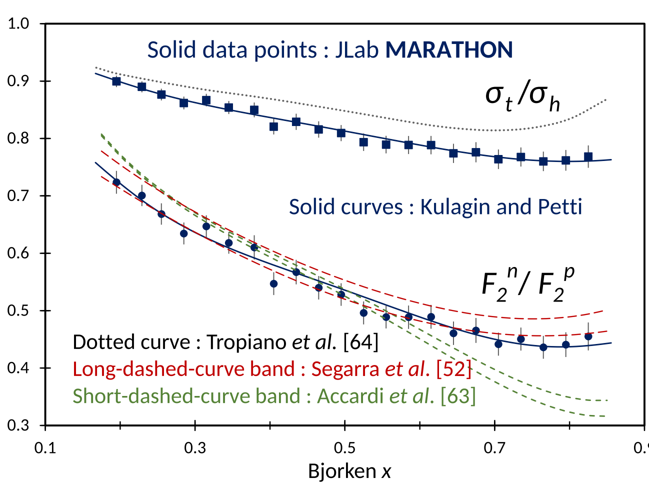

FIG. 3. The DIS σ_t/σ_h and the F_2^n/F_2^p ratios from the MARATHON experiment, plotted versus the Bjorken x, compared to the theoretical predictions of Kulagin and Petti, and of Refs. [52,63,64] (see text). The error bars include overall systematic uncertainties. All curves correspond to the MARATHON kinematics.

In summary, the MARATHON experiment has provided a precise determination of the nucleon F_2^n/F_2^p ratio from electron DIS by the $A = 3$ mirror nuclei. The analysis is based on a novel data-driven approach minimizing model corrections and drastically reducing theoretical uncertainties with respect to other conventional extractions of the ratio. The results are expected to improve our knowledge of the nucleon parton distributions, and to be used in algorithms which fit [44,63,65] hadronic data to properly determine, taking into account their Q^2 variation, the essentially unknown $(u + \bar{u})/(d + \bar{d})$ ratio at large Bjorken x, which is relevant for the interpretation of high-energy collider data. They will also provide unique input for the study of the partonic structure of the few-body nuclear systems.

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