

New Measurements of the Deuteron-to-Proton F_2 Structure-Function Ratio

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Nucleon structure functions, as measured in lepton-nucleon scattering, have historically provided a critical observable in the study of partonic dynamics within the nucleon. However, at very large parton momenta, it is both experimentally and theoretically challenging to extract parton distributions due to the probable onset of nonperturbative contributions and the unavailability of high-precision data at critical kinematics. Extraction of the neutron structure and the d quark distribution have been further challenging

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because of the necessity of applying nuclear corrections when utilizing scattering data from a deuteron target to extract the free neutron structure. However, a program of experiments has been carried out recently at the energy-upgraded Jefferson Lab electron accelerator aimed at significantly reducing the nuclear correction uncertainties on the d quark distribution function at large partonic momentum. This allows leveraging the vast body of deuterium data covering a large kinematic range to be utilized for d quark parton distribution function extraction. In this Letter, we present new data from experiment E12-10-002, carried out in Jefferson Lab Experimental Hall C, on the deuteron to proton cross section ratio at large Bjorken x . These results significantly improve the precision of existing data and provide a first look at the expected impact on quark distributions extracted from parton distribution function fits.

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Measurements of the nucleon F_2 structure function in inelastic lepton-nucleon scattering and the kinematic evolution of F_2 occupy a prominent place in the historical development and testing of the theory of the strong interaction, quantum chromodynamics (QCD) [1–3]. Such measurements have provided critical data in perturbative QCD (pQCD) fits used to extract quark and gluon distributions and in testing the universality of the pQCD evolution equations of these parton distribution functions (PDFs) [4–6]. While tremendous progress has been made in this endeavor over the last few decades, much is still left to be fully explored. One such example is the longitudinal momentum distribution of the down quarks when the nucleon’s momentum is predominantly carried by a single valence quark, or as $x \rightarrow 1$. Here, x is the Bjorken “scaling” variable, which can be interpreted as the fractional momentum of the nucleon carried by the struck quark. While there exist a number of effective theory predictions [5–9] for the ratio of the proton down to up quark distributions (d/u) at large x , additional experimental data are required to adequately test these. The last few years have seen the completion of three complementary experiments performed at Jefferson Lab utilizing the energy-upgraded CEBAF accelerator and aimed at extracting the neutron to proton F_2 ratio and providing access to d/u at large x . The first of these was the MARATHON [10] experiment in Hall A, which measured ratios of the inclusive structure function F_2 from the $A = 3$ mirror nuclei ${}^3\text{He}$ and ${}^3\text{H}$, as well as from the deuteron and proton. The second experiment was the BONuS12 [11] experiment in Hall B, which is a follow-up to the BONuS [12–14] experiment, but leveraging the doubling of the beam energy to 12 GeV to access larger x without entering the region of the nucleon resonances. Jefferson Lab (JLab) experiment E12-10-002 (this Letter) measured $H(e, e')$ and $D(e, e')$ inclusive cross sections with the aim of extracting the hydrogen and deuterium F_2 structure functions at large x and intermediate four-momentum transfer, Q^2 . The new high-precision data from this Letter, especially when coupled with new nuclear correction data from BONuS12 and MARATHON, will provide new insight into the up and down quark distributions within the nucleon.

The dataset was acquired in February–March of 2018 in Hall C. The experiment used the High Momentum Spectrometer (HMS), the SuperHMS (SHMS), and liquid cryogenic hydrogen and deuterium targets. The electron beam energy was 10.602 GeV, and the current varied between 30 and 65 μA . The experiment served as one of the commissioning experiments for the new or upgraded Hall C equipment associated with the JLab 12 GeV energy upgrade. The data were acquired in “scans” at a fixed spectrometer angle by varying the central momentum setting and alternating between the 10-cm-long hydrogen and deuterium targets. The results presented here stem from five different SHMS scans at (nominal) scattering angles of 21° , 25° , 29° , 33° , and 39° . The central momentum varied between 1.3 and 5.1 GeV/c. Additional scans were taken with the HMS at 21° and 59° . The 21° data were used as a cross-check between the well understood HMS and the newly constructed SHMS. The 59° data are still being analyzed and are not presented here. The kinematic coverage of this Letter, in Q^2 and x coordinates, is shown in Fig. 1; also displayed are the world data from SLAC (green triangles) and 6 GeV JLab (blue solid circles). Prior to this Letter, the invariant mass region of $W^2 < 3 \text{ GeV}^2$ (i.e., to the right of the solid curve) was poorly populated above a Q^2 of about 6 GeV^2 . The statistical uncertainties of this Letter, shown in the top panel of Fig. 1, are a vast improvement over the existing data.

The SHMS was a new spectrometer installed in Hall C to take advantage of the energy upgrade of the CEBAF accelerator to 12 GeV [18–20]. Its magnetic layout consists of a horizontal bender, three quadrupoles, and a dipole ($HQ\bar{Q}QD$). The maximum momentum is 11.0 GeV/c, the typical momentum acceptance is $\sim 10\%$ to 22% about the central momentum, and the solid angle is ~ 4.0 msr. The standard detector package includes a gas Cherenkov detector (filled with 1 atm of CO_2) and an electromagnetic calorimeter for particle identification (PID), two wire drift chambers for tracking and event reconstruction, and four hodoscope planes used in the event trigger. An additional heavy gas Cherenkov is present in the detector package but was not used in this analysis, as it is primarily used for hadron identification.

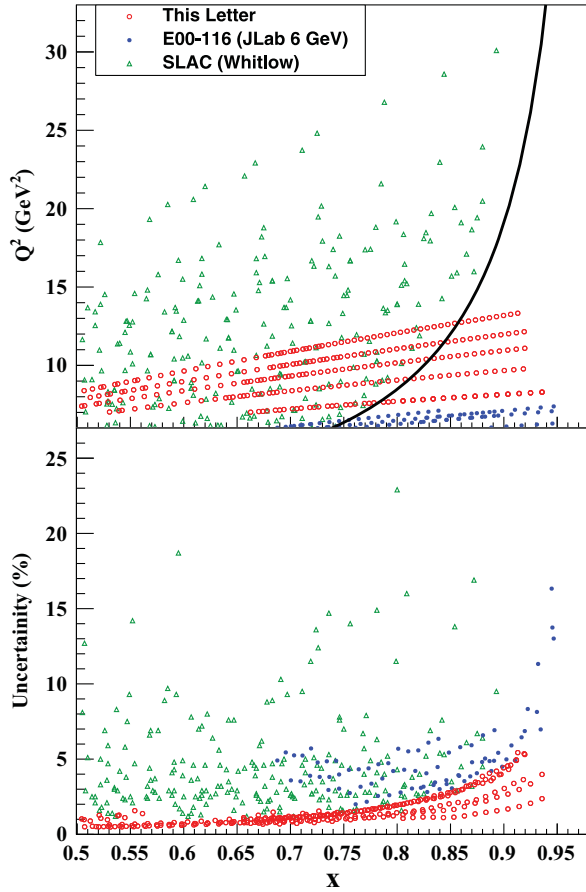


FIG. 1. The top panel shows the high- x kinematic coverage of this Letter (red circles) compared with the Whitlow reanalysis [15,16] of existing SLAC data (green triangles). The solid blue circles are from JLab’s 6 GeV experiment, E00-116 [17]. Only data where $x > 0.5$ and $Q^2 > 6$ are shown. The solid curve indicates $W^2 = 3 \text{ GeV}^2$, where W is the invariant mass of the produced hadronic system. The statistical uncertainty of the deuteron to hydrogen cross section ratio from these experiments is shown in the bottom panel.

In the one-photon exchange approximation, the differential cross section for inclusive electron scattering can be written as

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \frac{2MxF_2}{Q^2\varepsilon} \left(\frac{1 + \varepsilon R}{1 + R} \right), \quad (1)$$

where σ_{Mott} is the Mott cross section, M is the nucleon mass, Q^2 is the negative of the four-momentum transfer squared, R is the ratio of the longitudinal to transverse photoabsorption cross sections ($R = \sigma_L/\sigma_T$), and ε is the virtual photon polarization. The aim of this Letter is to obtain the F_2^D/F_2^H structure function ratio, as it presents several advantages theoretically as well as experimentally. By reporting a quantity involving deuterium rather than the “free” neutron, we avoid choosing a particular prescription for treating nuclear effects, allowing theory groups active in

this field to extract F_2^n using their own nuclear corrections. Furthermore, the σ_L/σ_T ratio is largely the same for hydrogen and deuterium [21]; thus, to first order, the F_2^D/F_2^H ratio is the same as the cross section ratio. The experimental advantage of reporting a cross section ratio is that several corrections to the yield cancel (e.g., detector efficiencies), and multiple systematic errors are reduced, such as the effective target length, dead time corrections, and spectrometer acceptance.

Experimentally, the deuteron to proton cross section ratio, $(\sigma_D/\sigma_H)_{\text{Exp}}$, is obtained using the Monte Carlo ratio method [22]

$$\left(\frac{\sigma_D}{\sigma_H} \right)_{\text{Exp}} = \frac{\mathcal{R}_D}{\mathcal{R}_H} \left(\frac{\sigma_D}{\sigma_H} \right)_{\text{Model}}, \quad (2)$$

where $\mathcal{R} = Y_{\text{Data}}/Y_{\text{MC}}$, Y_{Data} is the efficiency and background corrected charge normalized electron yield, Y_{MC} is the Monte Carlo yield obtained using a model cross section that is radiated using the Mo and Tsai formalism [23,24], and $(\sigma_D/\sigma_H)_{\text{Model}}$ is the same model cross section evaluated at the Born level. The yields were binned in W^2 and then converted to x . Electrons were selected by applying cuts to the gas Cherenkov and the energy deposited in the calorimeter normalized by the momentum of the track.

Corrections to Y_{Data} , along with their magnitudes relative to $(\sigma_D/\sigma_H)_{\text{Exp}}$ in the inelastic region ($W^2 > 3 \text{ GeV}^2$), include contributions from pion contamination (0.907–1.000), dead time (0.682–1.342), target density (0.989–0.998), tracking efficiency (0.987–1.000), trigger efficiency (1.000–1.004), and backgrounds from the target cell walls (1.033–1.060). Pions that pass the electron PID cuts were removed using a parametrization of the pion contamination as a function of the scattered electron energy, E' [25]. The computer dead time was found by comparing the number of triggers recorded in scalars to the number found in the data stream. The electronic dead time, due to events being lost at the trigger logic level, was measured by injecting a pulser of known frequency at the start of the trigger logic chain. These pulser events, identifiable via TDC information, were compared with the number of events recorded in the scalars. Tracking efficiency was calculated by taking the ratio of events with detected tracks to the number of events that passed PID, fiducial, and timing cuts. The trigger for this experiment required signals in three of the four hodoscope layers and a signal in either the gas Cherenkov or calorimeter. The trigger efficiency was $> 99\%$ and was determined by calculating the efficiency of the individual hodoscope planes. Backgrounds from the aluminum cell walls were subtracted from the cryogenic targets by utilizing “dummy” data taken on two aluminum targets placed at the same location as the cryogenic entrance and exit windows. A target density correction was applied to account for a local change in density due to heating from the electron beam.

A series of dedicated measurements at various currents up to 80 μA were performed, and the charge normalized yields were plotted vs beam current. The density reduction for the hydrogen (deuterium) target was $2.55 \pm 0.74(\%/100\mu\text{A})$ [$3.09 \pm 0.84(\%/100\mu\text{A})$]. For further details of the analysis, see Refs. [25–30].

Electrons produced by charge symmetric backgrounds, mainly from neutral pion production (e.g., $\pi^0 \rightarrow \gamma\gamma^* \rightarrow \gamma e^+e^-$), in which the photon decays into a positron and an electron, were included in the Monte Carlo yield. This background was measured by reversing the spectrometer's magnet polarity to measure the positron yield for both hydrogen and deuterium targets. The background was parametrized with a two parameter fit as a function of E' . Due to beam time constraints, positron data were acquired for only three of the five angular settings. To circumvent this limitation, the positron yield was parametrized as described in [31]. The parametrization was then used to extrapolate the positron yield to the kinematic settings where measurements were not available. For $x > 0.6$, the background contribution to the measured cross section was less than 1%, and it rose to 30% with decreasing x at the 39° angle setting. Additionally, the measured positron yield per nucleon was identical for both targets.

The uncertainties in the deuterium to hydrogen cross section ratio σ_D/σ_H , shown in Table I, are divided into two categories, uncorrelated point-to-point and correlated (see Supplementary Material [32] for more details). An overall normalization uncertainty of 1.1% due to uncertainty in the target density is included in the correlated error. The target density error includes uncertainties from the target temperature and pressure, measured length, thermal contraction, the equation of state used to calculate the density, and the target boiling correction. Additional point-to-point errors for target density are included to account for runs where the

TABLE I. The error budget for the cross section ratio σ_D/σ_H . The error after a cut of $W^2 > 3 \text{ GeV}^2$, which is a typical cut applied to eliminate the resonance region while performing PDF fits, is shown in parentheses.

Error	Point to point (%)	Correlated (%)
Statistical	0.5 – 5.4(2.9)	
Charge	0.1 – 0.6	
Target density	0.0 – 0.2	1.1
Live time		0.0 – 1.0
Model dependence		0.0 – 2.6(1.2)
Charge symmetric background		0.0 – 1.4
Acceptance		0.0 – 0.6(0.3)
Kinematic		0.0 – 0.4
Radiative corrections		0.5 – 0.7(0.6)
Pion contamination		0.1 – 0.3
Cherenkov efficiency		0.1
Total	0.6 – 5.4(2.9)	1.2 – 2.9(2.1)

boiling correction was far from the average due to higher or lower beam currents. A cross section model dependence error was assessed by altering the model fit parameters, thereby changing the $(\sigma_D/\sigma_H)_{\text{Model}}$ by as much as 10%. The change in $(\sigma_D/\sigma_H)_{\text{Exp}}$ was parametrized as a function of W^2 and used as the uncertainty. The most significant effects were observed at higher x values, where the resonance region causes rapid changes in the cross section. Binning in W^2 , as opposed to E' or x , was found to reduce this uncertainty due to the location of the resonance peaks being fixed. Errors from the radiative corrections include a contribution from both the model and the method. The model dependence was determined by scaling the various quasielastic contributions to the model. The error associated with the method (0.5%) was taken from [33]. A kinematic uncertainty was determined with Monte Carlo by individually varying the beam energy and central momentum of the spectrometer by $\pm 0.1\%$ and also by varying the spectrometer angle by $\pm 0.25 \text{ mr}$.

The results of this analysis are summarized in Figs. 2 and 3; the numerical values can be found in the tables included in Supplemental Material [32]. The σ_D/σ_H ratio is shown as a function of x for each of the SHMS spectrometer angles. The curves shown are predictions for F_2^D/F_2^H

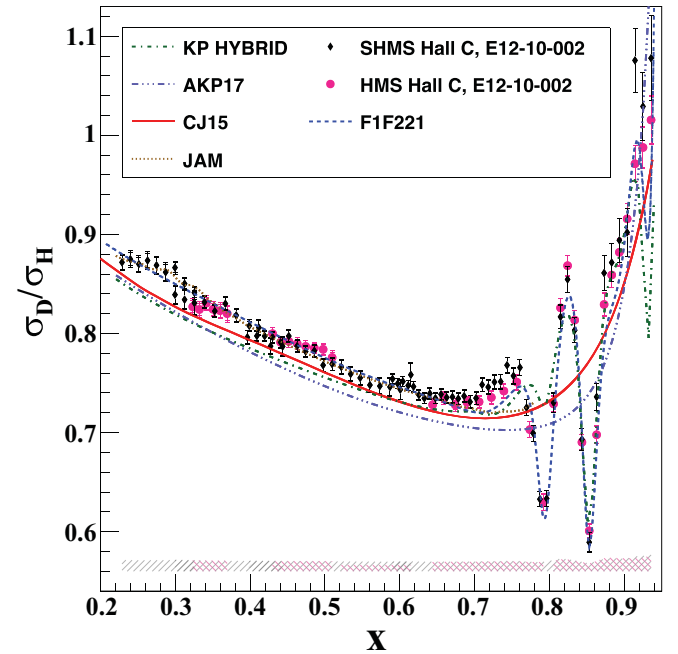


FIG. 2. The σ_D/σ_H ratio as a function of x for a spectrometer angle of 21° (Q^2 range from 3.39 to 8.25 GeV^2). To first order, the cross section ratio is equal to the F_2 structure function ratio. The error bars include uncorrelated systematic and statistical errors. The error bands include correlated systematic errors and an overall normalization uncertainty of 1.1% (see Table I). F1F221 (blue dashed line) is the model used in this analysis; the other curves are from different PDF fits (see text). Good agreement is observed between the HMS and SHMS spectrometers.

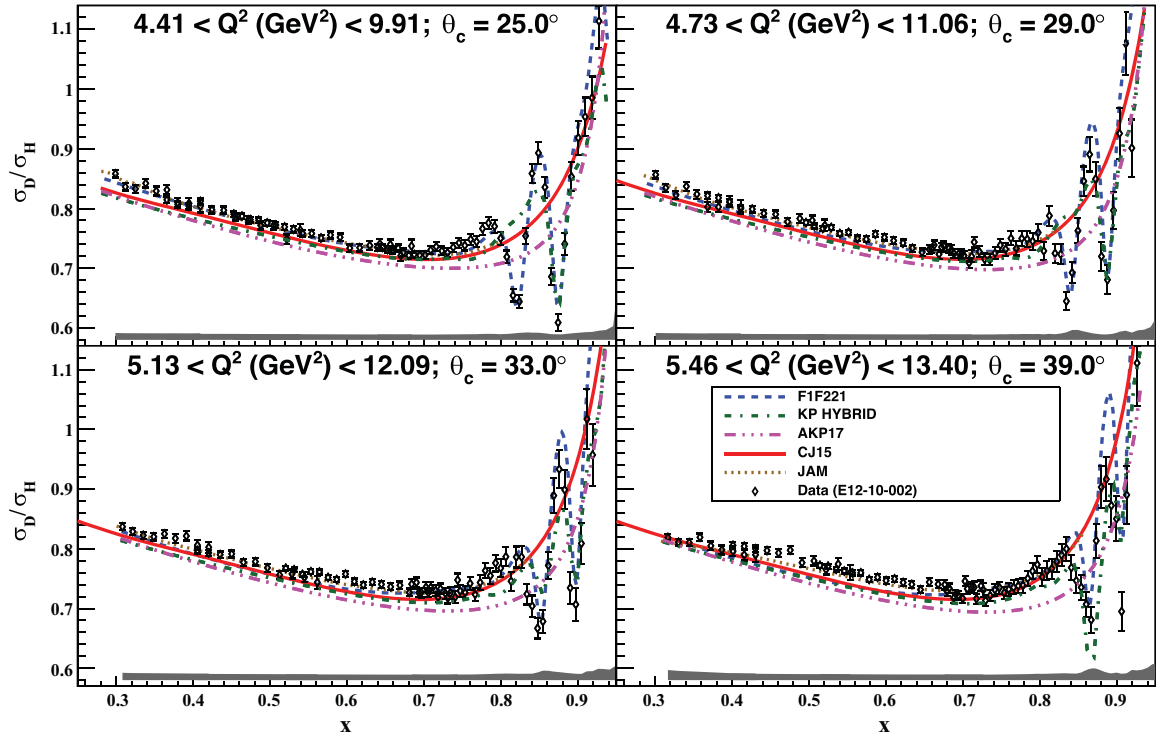


FIG. 3. The cross section ratio, σ_D/σ_H , as a function of x for SHMS spectrometer angles of 25°, 29°, 33°, and 39°. To first order, the cross section ratio is equal to the F_2 structure function ratio. The Q^2 range of each setting is indicated in each panel.

obtained using four available models evaluated at the same kinematics as the data: CJ15 [9] (solid red line), AKP17 [7] (dot-dot-dot-dashed violet line), KP Hybrid [8] (dot-dashed line) and JAM [34,35] (dotted brown line). The model used to extract the cross section is F1F221 (dashed blue line), which is an improved fit to world data [36]. None of the models shown includes the data from this analysis.

As a representative example of the theoretical impact of this experimental result, the dataset from this Letter [32] was evaluated with the CJ15 QCD analysis [9] framework, which deploys state-of-the-art deuteron nuclear corrections. This next-to-leading-order analysis utilizes data from a variety of high energy scattering processes, including deep inelastic scattering, weak boson and jet production, and Drell-Yan. A fitted normalization factor of -2.1% was determined in order for the dataset to agree with the CJ model [37], slightly larger than the total x dependent correlated error of 1.3% – 2.1% shown in Table I. Furthermore, this experiment ran in parallel with E12-10-007 (a measurement of the EMC effect), which observed a 2.0% normalization difference from previous EMC measurements [38]. The direction of this normalization difference is consistent with that found in the CJ15 study. The fitted PDFs with and without this experiment were compared at the central value as well as the size of uncertainties. For consistency, the error band for each fit was calculated at 90% confidence level [39]. Figure 4 depicts the d/u ratio, a fundamental quantity and testing

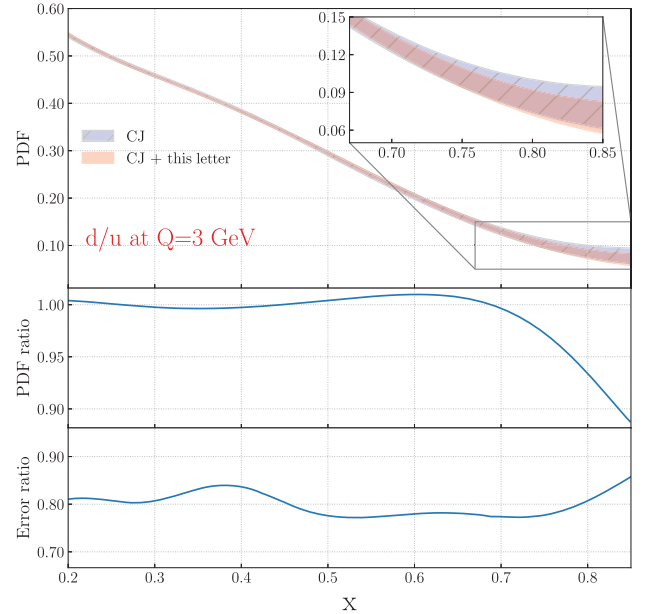


FIG. 4. Top: the d/u ratio for the proton from CJ15 (blue) and when this Letter is included in the dataset used in CJ15 (red). Middle: The relative change in the d/u PDF central value; the shift at $x > 0.7$ is due to the previous lack of deuteron data at high x . Bottom: the reduction in the d/u PDF relative uncertainty. The inclusion of the data from this Letter results in a roughly 20% reduction in the uncertainty. While a typical cut of $W^2 > 3.0 \text{ GeV}^2$ is used to eliminate the resonance region in the CJ15 framework, a cut of $W^2 > 3.5 \text{ GeV}^2$ was applied to the new dataset.

ground for multiple pQCD predictions regarding nucleon structure. The fitted d/u PDF before and after inclusion of these data is shown, where the significant reduction in the uncertainties demonstrates the importance of high-precision data in PDF extractions. Not only did the inclusion of this Letter reduce the relative error by approximately 20% across the entire x range, but it also shifted the d/u central value at large x by as much as 10%. Furthermore, these data provide additional constraints on the parameters used in higher twist corrections, the individual d and u quark distributions, and the target mass corrections used in these fits.

It should be noted that, on average, the ratio of deuterium to hydrogen cross section from this Letter and from MARATHON [40] differs by as much as 4.3% or 2σ where the datasets overlap in the x range of 0.2 – 0.3, with this Letter being above the MARATHON result. However, in a recent QCD analysis [41], a normalization factor of +1.9% was required to get the MARATHON d/p data to agree with the existing data. If this normalization is applied together with the normalization factor found in the above CJ15 study, the two datasets agree within 0.3%. All the aforementioned data agree with the previously available SLAC data, which have large uncertainties [15].

In summary, high-precision inclusive measurements on hydrogen and deuterium were performed for Q^2 from 3.4 to 13.4 GeV² and x from 0.3 to 0.93. Inclusion of this dataset with one PDF fitting framework resulted in a 20% uncertainty reduction in the proton d/u, and when combined with the MARATHON and BONuS12 results, will have a significant impact on understanding PDFs in the valence regime. It can be used, moreover, for quark-hadron duality studies, spin-flavor symmetry breaking, and constraints on nuclear corrections. The results of this Letter will also be beneficial for the future EIC and DUNE [42] experimental programs. DUNE will benefit from higher-precision neutrino oscillation Monte Carlos, and the EIC can have higher-precision cross section predictions, where structure function information at large x feeds down through perturbative Q^2 evolution to lower x and higher values of Q^2 . Moreover, the combination of precision PDFs at high x and low Q^2 with low x and high Q will allow for critical studies of the onset of nonperturbative effects and inter-nucleon bindings.

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- the deuteron to proton from this Letter as shown in Figs. 2 and 3. Identical dataset as Supplemental 1 but with additional columns to list the individual uncertainties.
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