SciPost Phys. Proc. 8, 098 (2022)

Simultaneous Extraction of Unpolarized PDFs and Nuclear Effects

C. Cocuzza[1⋆], A. Metz [1] and N. Sato [2]

1 Department of Physics, SERC, Temple University, Philadelphia, PA 19122, USA
2 Jefferson Lab, Newport News, Virginia 23606, USA

Jefferson Lab Angular Momentum (JAM) Collaboration

⋆ tug83224@temple.edu

Proceedings for the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects, Stony Brook University, New York, USA, 12-16 April 2021
doi:10.21468/SciPostPhysProc.8

Abstract

We present a new global QCD analysis of unpolarized parton distribution functions (PDFs) and nuclear effects including for the first time data from the SeaQuest and MARATHON experiments in addition to high-energy weak-boson-production data from the Tevatron and Large Hadron Collider. Simultaneously extracting the PDFs and nuclear effects, we examine the impact of the SeaQuest and MARATHON data on the light-quark sea asymmetry and the EMC ratios of deuterium, helium, and tritium.

Received 11-08-2021
Accepted 21-03-2022
Published 13-07-2022
doi:10.21468/SciPostPhysProc.8.098

1 Introduction

Over the past few decades, experiments from lepton-nucleon deep-inelastic scattering (DIS), Drell-Yan, and weak boson production have revealed much about the one-dimensional structure of the proton (p), encoded in PDFs. However, there are still gaps in our knowledge, particularly for the down quark (d) at large momentum fraction x and the asymmetry of up and down antiquarks ($\bar{u}$ and $\bar{d}$) above $x \approx 0.3$. Questions also remain concerning the nuclear effects within the light nuclei deuterium (D), helium (^{3}He), and tritium (^{3}H).

Recent experiments have attempted to provide insight on these questions. The MARATHON experiment at Jefferson Lab Hall A [1] measured DIS off of ^{3}He and ^{3}H targets in order to extract information on the ratio of down to up quarks d/u at high x as well as nuclear effects. These nuclear effects can be summed up by a non-trivial EMC ratio [2], which is defined as the ratio of the structure function F_2 for the nuclear target to the sum of F_2 for the constituent nucleons. The EMC ratio would be unity in the absence of nuclear effects. Meanwhile, the NuSea [3,4] and SeaQuest [5] experiments at Fermilab have measured the Drell-Yan process for proton and deuterium targets in order to extract information on the $\bar{d}/\bar{u}$ ratio at values of x up to 0.3 and 0.4, respectively.

We present an analysis using the JAM Monte Carlo global QCD framework including for the first time the latest measurements from SeaQuest and MARATHON , in addition to hadron-collider data from the Tevatron and LHC, and DIS data from fixed-target and collider experiments. With this data, we are able to extract the PDF ratios d/u and $\bar{d}/\bar{u}$ as well as the nuclear effects in $A = 2, 3$ nuclei [6, 7].

2 Methodology

Our theoretical framework is based on the JAM iterative Monte Carlo approach to QCD global analysis, which utilizes Bayesian inference sampling methodology that allows thorough exploration of the parameter space and robust error quantification. In this analysis, we parameterize the unpolarized PDFs at the input scale $\mu_0^2 = m_c^2$, with m_c the mass of the charm quark, using the standard form,

$$f(x, \mu_0^2) = N x^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\eta x), \tag{1}$$

where N, α, β, γ, and η are the parameters to be fit. We discriminate the valence and sea components through parameterizations for the quantities

$$u = u_v + \bar{u}, \quad d = d_v + \bar{d}, \quad \bar{u} = S_1 + \bar{u}_0, \quad \bar{d} = S_1 + \bar{d}_0, \quad s = S_2 + s_0, \quad \bar{s} = S_2 + \bar{s}_0, \tag{2}$$

where the dependence on x and μ_0^2 has been suppressed. The input distributions u_v, d_v, $\bar{u}_0$, $\bar{d}_0$, s_0, and $\bar{s}_0$, characterizing the quark distributions in the valence region, and the gluon PDF are parameterized individually as in Eq. (1). The S_1 and S_2 distributions describe the light and strange sea quarks, respectively, at low x by restricting the α in Eq. (1) so that the resulting distribution is more divergent than the valence PDFs. Furthermore, γ and η are free parameters for all distributions except s_0, $\bar{s}_0$, S_1, and S_2 where they are set to zero.

The PDFs are evolved using the DGLAP evolution equation, and the renormalization group equation (RGE) is solved numerically for the strong coupling α_S at two loops making use of the boundary condition $\alpha_S(M_Z) = 0.118$. The boundary conditions for the RGE are parameterized at the scale μ_0^2 and inferred from data. The evolution equations are solved using the zero-mass variable-flavor-number scheme with splitting kernels evaluated at $\mathcal{O}(\alpha_S^2)$. The values of the heavy-quark mass thresholds for the evolution of the PDFs and α_S are taken from the PDG values $m_c = 1.28$ GeV and $m_b = 4.18$ GeV in the $\overline{\text{MS}}$ scheme [8]. All hard-scattering kernels are expanded to NLO in the strong coupling, with the NLO expressions for Drell-Yan and W-lepton production taken from [9] and [10], respectively.

For a nuclear target, nuclear effects such as binding, Fermi motion, and off-shell effects become relevant at $x \gtrsim 0.2$. In the weak-binding approximation, appropriate for light nuclei, nuclear PDFs can be expressed in terms of convolutions of light-cone momentum distributions of nucleons inside nuclei and nucleon PDFs [11, 12]. The off-shell effects, which take into account the fact that a nucleon of mass M and 4-momentum k in a nucleus typically has $k^2 \neq M^2$, can be parameterized in a similar manner using off-shell light-cone momentum distributions [7].

3 Quality of Fit

In addition to the new MARATHON data and SeaQuest data we fit also 2694 data points for the structure function F_2 measured in fixed-target DIS experiments on p and D targets as well as 1185 data points on reduced neutral and charged-current proton DIS cross sections, all with

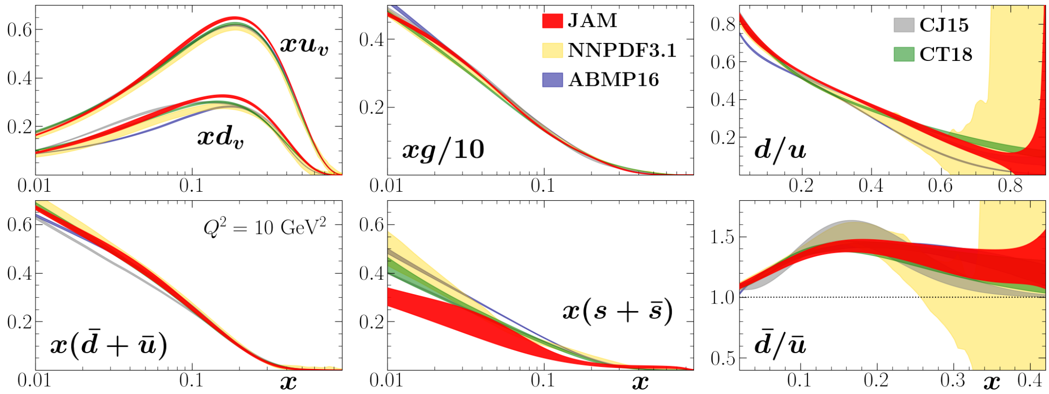

Figure 1: Comparison of the JAM PDFs (red bands) with the results from NNPDF3.1 [13] (gold), ABMP16 [14] (blue), CJ15 [16] (cyan), and CT18 [15] (gray) at the scale $Q^2 = 10$ GeV^2. All bands represent 1σ uncertainty and all results are at NLO. Note that the gluon PDF has been divided by 10.

the kinematic constraints $W^2 > 3.0$ GeV^2 and $Q^2 > m_c^2$. We fit also 199 Drell-Yan data points from NuSea [3,4], 97 data points on $W^\pm$ asymmetries, 56 data points on reconstructed Z/γ^* cross sections, and 200 data points on jet production.

The quality of our analysis is summarized by the global average $\chi^2/N_{\rm dat} = 1.10$ for a total of 4466 data points, with a $\chi^2/N_{\rm dat}$ of 1.10 for DIS, 1.20 for Drell-Yan, 0.94 for W/Z boson production, and 1.09 for jet production. For the MARATHON experiment, we find a $\chi^2/N_{\rm dat}$ of 0.99 for the measurement of the D/p structure function ratio and 0.67 for the measurement of the ^{3}He/^{3}H ratio, with the latter improving significantly with the inclusion of off-shell corrections. For the SeaQuest experiment, we find a $\chi^2/N_{\rm dat}$ of 1.10, along with some tension with the NuSea data for $x \gtrsim 0.2$, as has been seen in previous analyses [5].

4 Results for PDFs and Nuclear Effects

The results for the PDFs are shown in Fig. 1. Most notably, we see that the $\bar{d}/\bar{u}$ ratio is larger than one up to $x \approx 0.4$; a consequence of the inclusion of the SeaQuest data in our analysis that brings our results in agreement with those from CT18 and ABMP16 but in slight disagreement with those from NNPDF3.1 and CJ15. The inclusion of the SeaQuest data significantly reduces the errors on the $\bar{d}/\bar{u}$ ratio, up to around 50% for $x \gtrsim 0.3$. For the d/u ratio our result agrees with CJ15 and is consistent with NNPDF3.1, but disagreements are seen with CT18 and especially ABMP16. In the valence sector the resulting PDFs are generally slightly larger compared to other groups and, correlated with this result, we find a relatively suppressed strange distribution.

Figure 2 shows the result for the EMC ratio $R(D) = F_2^D/(F_2^p + F_2^n)$ as well as that for the super ratio $\mathcal{R} = R(^3\text{He})/R(^3\text{H})$, where $R(^3\text{He}) = F_2^{^3\text{He}}/(2F_2^p + F_2^n)$ and $R(^3\text{H}) = F_2^{^3\text{H}}/(F_2^p + 2F_2^n)$. The fact that $R(D)$ differs from one throughout most of the shown x-range demonstrates the strength of the nuclear effects within deuterium. For $R(D)$ our results are generally close to the CJ15 result for $x \lesssim 0.4$, while some discrepancy exists for larger values of x. Good agreement with the AKP17 result is observed in a narrow range around $x \approx 0.6$ and at very high x only. Notably, while the KP model [18] predicts $R(D) = \mathcal{R} = 1$ at $x = 0.31$, our result for $R(D)$ is not consistent with this prediction. Furthermore, at high x our result for $\mathcal{R}$ is also inconsistent with the KP model. While the inclusion of the MARATHON data drastically reduces

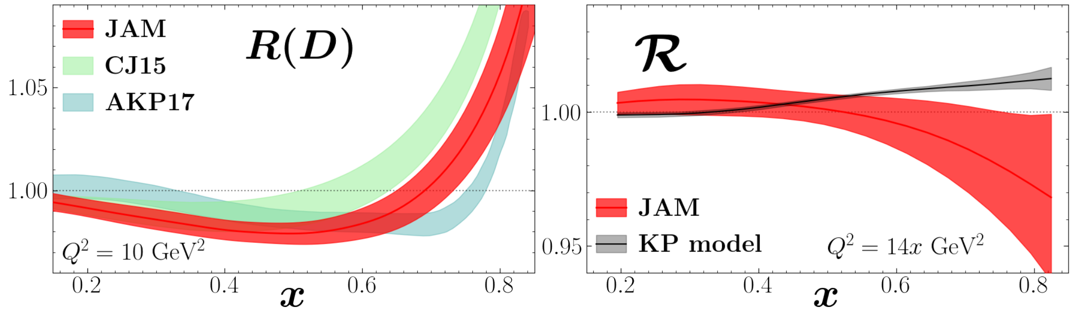

Figure 2: Results from this analysis (red bands) for the deuteron EMC ratio $R(D)$ at $Q^2 = 10$ GeV^2 (left) and the super-ratio $\mathcal{R}$ at the MARATHON kinematics $Q^2 = 14x$ GeV^2 (right). The deuteron EMC ratio $R(D)$ is also compared with that from CJ15 [16] (green band) and AKP17 [17] (light blue band). The super ratio $\mathcal{R}$ is compared with the KP model [18] (gray band).

the uncertainty on $\mathcal{R}$ across the entire range of x, from 50% at high x to 70% at low x, the resulting errors are still much larger than those from the KP model, suggesting that the latter may be underestimated.

5 Conclusions

We have presented the resulting PDFs and EMC ratios of a global QCD analysis including for the first time data from the SeaQuest and MARATHON experiments. The inclusion of the SeaQuest data causes some slight tension with the NuSea data, but reduces the uncertainty of the $\bar{d}/\bar{u}$ ratio by roughly 50% at high x and reveals that the ratio must remain larger than one up to $x \approx 0.4$. The MARATHON data drastically decreases the uncertainties on the super ratio $\mathcal{R}$. To some extent, our results for the EMC ratios disagree with those from the KP model. In particular, we find $R(D) < 1$ at $x = 0.31$.

In the future, combining this analysis with semi-inclusive DIS data could provide even more information on the $\bar{d}/\bar{u}$ ratio. Additional information on the nuclear EMC effects in ^{3}He and ^{3}H separately will come from $^3\text{He}/D$ and $^3\text{H}/D$ ratios measured by MARATHON , which are expected to be analyzed in the near future. Beyond this, constraints on neutron structure, and the d/u PDF ratio at large x, will come from the BONuS experiment at Jefferson Lab, which tags spectator protons in semi-inclusive DIS from the deuteron.

Acknowledgements

We thank Jake Ethier and Wally Melnitchouk for the fruitful collaboration on the work in [6,7], which forms the basis for this contribution. Similarly, we thank Thia Keppel, Hanjie Liu, and Anthony Thomas for their work in [7]. We thank Felix Ringer and Werner Vogelsang for the code used for calculating the W-lepton cross sections. We thank P. C. Barry and Y. Zhou for helpful discussions. This work was supported by the U.S. Department of Energy Contract No. DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates Jefferson Lab, and the National Science Foundation under grant number PHY-1516088. The work of C.C. and A.M. was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, within the framework of the TMD Topical Collaboration, and by Temple University (C.C.). The work of N.S. was supported by the DOE, Office of Science, Office of Nuclear

Physics in the Early Career Program.

References

[1] D. Abrams et al., *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*, arXiv:2104.05850.

[2] J. J. Aubert et al., *The ratio of the nucleon structure functions F_2^n for iron and deuterium*, Phys. Lett. B **123**, 275 (1983), doi:10.1016/0370-2693(83)90437-9.

[3] E. A. Hawker et al., *Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea*, Phys. Rev. Lett. **80**, 3715 (1998), doi:10.1103/PhysRevLett.80.3715.

[4] R. S. Towell et al., *Improved measurement of the anti-d / anti-u asymmetry in the nucleon sea*, Phys. Rev. D **64**, 052002 (2001), doi:10.1103/PhysRevD.64.052002.

[5] J. Dove et al., *The asymmetry of antimatter in the proton*, Nature **590**, 561 (2021), doi:10.1038/s41586-021-03282-z.

[6] C. Cocuzza, W. Melnitchouk, A. Metz, and N. Sato, *Bayesian Monte Carlo extraction of the sea asymmetry*, Phys. Rev. D **104**, 074031 (2021), doi:10.1103/PhysRevD.104.074031.

[7] C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato and A. W. Thomas, *Isovector EMC Effect from Global QCD Analysis with MARATHON Data*, Phys. Rev. Lett. **127**, 242001 (2021), doi:10.1103/PhysRevLett.127.242001.

[8] M. Tanabashi et al., *Review of Particle Physics*, Phys. Rev. D **98**, 030001 (2018), doi:10.1103/PhysRevD.98.030001.

[9] T. Becher, M. Neubert and G. Xu, *Dynamical threshold enhancement and resummation in Drell-Yan production*, J. High Energy Phys. **07**, 030 (2008), doi:10.1088/1126-6708/2008/07/030.

[10] F. Ringer and W. Vogelsang, *Single-spin asymmetries inWboson production at next-to-leading order*, Phys. Rev. D **91**, 094033 (2015), doi:10.1103/PhysRevD.91.094033.

[11] S. A. Kulagin, G. Piller and W. Weise, *Shadowing, binding, and off-shell effects in nuclear deep-inelastic scattering*, Phys. Rev. C **50**, 1154 (1994), doi:10.1103/PhysRevC.50.1154.

[12] S. A. Kulagin, W. Melnitchouk, G. Piller and W. Weise, *Spin-dependent nuclear structure functions: General approach with application to the deuteron*, Phys. Rev. C **52**, 932 (1995), doi:10.1103/PhysRevC.52.932.

[13] R. D. Ball et al., *Parton distributions from high-precision collider data*, Eur. Phys. J. C **77**, 663 (2017), doi:10.1140/epjc/s10052-017-5199-5.

[14] S. Alekhin, J. Blümlein, S. Moch and R. Plačakytė, *Parton distribution functions, α_s, and heavy-quark masses for LHC Run II*, Phys. Rev. D **96**, 014011 (2017), doi:10.1103/PhysRevD.96.014011.

[15] T.-J. Hou et al., *New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC*, Phys. Rev. D **103**, 014013 (2021), doi:10.1103/PhysRevD.103.014013.

[16] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens and N. Sato, *Constraints on large-x parton distributions from new weak boson production and deep-inelastic scattering data*, Phys. Rev. D **93**, 114017 (2016), doi:10.1103/PhysRevD.93.114017.

[17] S. I. Alekhin, S. A. Kulagin and R. Petti, *Nuclear effects in the deuteron and constraints on the d/u ratio*, Phys. Rev. D **96**, 054005 (2017), doi:10.1103/PhysRevD.96.054005.

[18] S. A. Kulagin and R. Petti, *Global study of nuclear structure functions*, Nucl. Phys. A **765**, 126 (2006), doi:10.1016/j.nuclphysa.2005.10.011.