Probing Nuclear Structure with Future Colliders

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Improved knowledge of the nucleon structure is a crucial pathway toward a deeper understanding of the fundamental nature of the QCD interaction, and will enable important future discoveries. The experimental facilities proposed for the next decade offer a tremendous opportunity to advance the precision of our theoretical predictions to unprecedented levels. In this report we briefly highlight some of the recently developed tools and techniques which, together with data from these new colliders, have the potential to revolutionize our understanding of the QCD theory in the next decade.

Introduction: The recent discovery of the Higgs boson at the Large Hadron Collider (LHC) was a remarkable endeavour which culminated in the 2013 Nobel Prize. As we look ahead to the next decade, a number of new facilities on the horizon will provide new insights about fundamental microscopic phenomena. This includes the high-luminosity upgrade of the LHC, (HL-LHC), a proposed electron ring for the LHC (LHeC), a proposed electron-ion collider (EIC), and a proposed Electron-Ion Collider (EIC).

For all these facilities, the route to new discoveries will be high-precision comparisons between theory and data that can validate the features of the Standard Model and search for discrepancies which may signal undiscovered phenomena. These comparisons between data and theory rely crucially on the Parton Distribution Functions (PDFs) which connect the theoretical quarks and gluons with experimental observations. Unfortunately, the PDFs are often the limiting factor in these comparisons. Thus, our ability to fully characterize the Higgs boson and constrain physics Beyond the Standard Model (BSM) ultimately comes down to how accurately we determine the underlying PDFs. If you cannot distinguish signal from background, you cannot make discoveries.

In this brief report, we will examine how new data and new tools might facilitate these discoveries.

Nuclear PDFs: Although the fits to the proton PDFs have been quite successful, it is crucial to extend the framework to consider the nuclear degrees of freedom. For

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A Large Hadron electron Collider at CERN [http://lhec.web.cern.ch/]
bElectron-Ion Collider (EIC) User Group [http://www.eicug.org/]
The articles cited here are limited due to space; please also see references therein.
example, the neutrino-induced Deeply Inelastic Scattering (DIS) process provides essential information for PDF flavor differentiation. In Fig. 1 we display a comparison of recent nuclear PDFs with uncertainties. While there has been impressive progress in recent years constraining the nPDFs, there is certainly room for improvement, especially compared to the proton PDF efforts; the new experimental facilities (including LBNF) will provide important new PDF constraints which in turn will constrain potential BSM signals.

**PDF Sensitivity & PDFSense**

In order to quickly and efficiently determine the potential impact of new data sets on the PDFs and other observables, we introduce a generalization of the PDF-mediated correlations called the sensitivity $S_f$. This is a combination of the correlation coefficient and the residuals (data minus theory scaled by the uncertainty) of the PDF uncertainty, and it identifies those experimental data points that tightly constrain the PDFs. We find the sensitivity is useful for identifying regions of the $\{x, Q^2\}$ kinematic plane in which the PDFs are particularly constrained by physical observables. The details of the sensitivity can be found in Ref. 3 and the implementation is available in the public package PDFSense.

In Fig. 2 we display the sensitivities $S_f$ for the LHeC, HL-LHC, and EIC using pseudodata sets for a sample PDF flavor, $d(x, Q)$, c.f., Ref. 5. We observe the LHeC shows strong sensitivity in both the very high- and low-$x$ regions, while the HL-LHC covers the intermediate-$x$ region out to very large $Q^2$, and the EIC complements these in the high-to-medium-$x$ region at lower $Q^2$ values. The combination of these measurements can provide very strong constraints on the various PDF flavors across the broad $\{x, Q^2\}$ kinematic plane.

[https://metapdf.hepforge.org/PDFSense/](https://metapdf.hepforge.org/PDFSense/)
Fig. 2. Future HEP experiments such as the LHeC, HL-LHC, and EIC can have substantial PDF sensitivity $S_f$ as shown here for the $d(x, \mu)$ distribution computed according to the conventions in Refs. 3 and 5.

In Fig. 3, we plot the sensitivity of EIC pseudodata to the 14 TeV LHC Higgs production cross section, $\sigma_H$. The constraints that a medium-energy machine like an EIC would place on Higgs phenomenology stem from the predominance of the $gg \to H$ fusion channel at the LHC, and the sensitivity of the DIS data to the gluon via QCD evolution, which then connects the high-$x$ and low-$Q$ gluon PDF probed by the EIC to the lower-$x$ and high-$Q$ PDF of the LHC. The sensitivity of the EIC pseudodata generally surpasses that of the fixed-target experiments that currently dominate the constraints on high-$x$ PDFs. Therefore, the EIC will strongly constrain the PDF dependence of HEP observables at moderate to large-$x$, including several in the Higgs and electroweak sectors, like $M_W$ and $\sin(2\theta_W)$.

**PDFs from lattice QCD:** Additional information on PDFs may also come from lattice QCD calculations which generally compute the Mellin moments of PDFs, as illustrated in Fig. 4 where we display the sensitivity, $S_f$, of the first moment for the strange quark. Despite additional data from HERA and LHC, it is interesting to note that some of the strongest sensitivities come from the fixed-target neutrino DIS experiments (CCFR, NuTeV) in the high-$x$ and low-$Q$ region. At present, the strange PDF still has relatively large PDF uncertainties, and this can limit the precision of “standard candle” benchmark process such as $W/Z$ production; hence, additional constraints from lattice QCD would be welcome.

**Borrowing from Machine Learning:** Finally, in Fig. 5, we display a distribution of residuals using a t-distributed Stochastic Neighbor Embedding (t-SNE) which is a machine-learning algorithm for visualization of high-dimensional data. In this case, we have taken the 56-dimensions of the PDF uncertainty eigenvectors and reduced this to a 3D projection of the 4000+ data points considered for the CT18 fit. The algorithm identifies points with similar characteristics and groups these together. We have color coded the points for the DIS, Drell-Yan, and Jets+tt sets. In this case, the fact that the algorithm has grouped similar experiments together suggests that such machine-learning techniques can help us identify subtle relations that may not be apparent via other methods.
Conclusions: We have highlighted a few of the tools and techniques that will allow us to most effectively capitalize on the wealth of new data from these proposed colliders to advance our knowledge of the structure of the nucleon, the associated nuclear PDFs, and the underlying QCD theory. Additionally, these tools demonstrate how each of these experimental facilities occupies a unique place in the kinematical parameter space. As such, these complementary data sets will provide us with unprecedented understanding of strong interaction physics, and provide the key for many new discoveries.

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