Hadronic Tomography at the EIC and the Energy Frontier

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The future program of the High-Luminosity LHC (HL-LHC) [1] is premised on the realization of next-generation sensitivity to a wide variety of both standard model (SM) and beyond standard model (BSM) processes. The success of this program in stringently testing the SM and performing impactful measurements at the TeV-scale is critically dependent upon improvements to modern knowledge of the internal structure of hadrons. The future Electron-Ion Collider (EIC) [2] will undertake a dedicated program to measure the *multidimensional* structure of the nucleon, lighter mesons, and light to heavy nuclei. This program [2] represents an effort to map the comprehensive *tomography* of the proton and other QCD bound states, with the goal of answering fundamental questions at the heart of QCD, including the origin of hadronic mass and spin. Doing so will entail extensive measurement of observables related to the transverse-momentum dependent parton distributions (TMDs) and generalized parton distributions (GPDs) and, ultimately, of the unintegrated Wigner distributions, $W(x, \vec{b}_T, \vec{k}_T)$, from which TMDs and GPDs may be projected; for instance, the unpolarized parton distribution function (PDF), $f(x)$, and corresponding TMD distribution, $f(x, \vec{k}_T)$ can be *schematically* obtained as

$$f(x) = \int d^2\vec{k}_T f(x, \vec{k}_T) = \int d^2\vec{k}_T d^2\vec{b}_T\, W(x, \vec{b}_T, \vec{k}_T) \ . \tag{1}$$

The relation in Eq. (1) is the subject of extensive, ongoing theoretical and phenomenological research, and, as such, will be one of the themes of collaboration between the EIC- and LHC-focused communities expressed in this LoI. As single-dimensional quantities like parton distribution functions (PDFs) and form factors can be obtained from such relations, EIC tomography measurements will widely benefit the broad range of high-energy physics topics at hadron colliders, for which SM predictions depend upon, and are often critically limited by, such information. We note that determinations of PDFs (and related quantities) in QCD global analyses with SM assumptions can be extended to combined fits involving BSM higher-dimensional operators in SMEFT; this important subject and its connection to the EIC are discussed in a companion LoI, Ref. [3].

There are numerous instances in which precision QCD and hadronic structure studies at the EIC will impact activities at the Energy Frontier. In this LoI, we highlight a *representative* but *inexhaustive* list of these issues before describing some of the future developments needed to capitalize on the EIC science program in this regard.

- **High-energy QCD.** By measuring a range of interactions up to $\sqrt{s} = 140\,\text{GeV}$ in comparatively clean ep/eA DIS processes, the EIC will probe fundamental aspects of QCD that are otherwise challenging to disentangle via hadronic collisions alone. These include the DIS production and dynamics of heavy quarks and QCD jets (discussed at length in companion LoIs — Refs. [4, 5], respectively). In turn, such processes in the

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unpolarized case offer an array of complementary channels to inclusive neutral- and charged-current structure function measurements. When taken together, these data can drive future QCD global analyses by providing a comprehensive flavor separation of (un)polarized PDFs and enhancing precision determinations of QCD sector SM quantities, including α_s and the heavy-quark masses (see Refs. [6–8]).

- **Gluonic structure of the proton and Higgs phenomenology.** Searches for deviations from the SM in the Higgs sector are limited by knowledge of quantities like the unpolarized gluon PDF and the gluon-gluon parton luminosity, $\mathcal{L}_{gg}$, which are relevant for the dominant $gg \to h$ fusion channel. The EIC will pursue a dedicated program to constrain the gluonic structure of the proton, including the PDF down to $x \sim 10^{-4}$, with strong sensitivity to the Higgs cross section.

- **QED interaction of the partons and photon parton density.** The advent of high-precision measurements at hadron colliders necessitates the systematic and consistent inclusion of electroweak (EW) corrections for many processes under study. For instance, the appearance of photonic initial-state collinear divergences naturally leads to a treatment analogous to the one adopted in QCD for their factorization and reabsorption in the physical PDFs; similarly, a photon density in the proton must be taken into account. A precise determination of the photon density over an extended range of partonic x and its interplay with quark-gluon degrees-of-freedom will be informed by the broad range of observables available at the EIC. Ultimately, an upgraded fitting framework will be needed to exploit this potential: a systematic collection of partonic matrix elements with NLO-EW effects as well as control over the scale dependence of the resulting PDFs with a combined N^{3}LO (QCD) + NLO (QED) accuracy.

- **TMDs for precision electroweak physics.** The W-boson mass, M_W, is an important testbed for the SM in the EW sector, being potentially sensitive to oblique, propagator-level corrections due to insertions of hypothetical BSM degrees-of-freedom. Like the Higgs cross section, determinations of M_W are limited by nucleon structure uncertainties that the EIC stands to improve. Currently, the best determinations of M_W come from global EW fits (with $\delta[M_W] = 8$ MeV), but precise extractions have also been obtained by fitting the transverse mass and transverse-momentum distributions of the decaying leptons in proton-proton collisions at ATLAS and in proton-antiproton collisions at D0 and CDF (currently, achieving $\delta[M_W] = 19$ MeV), for which PDF uncertainties are a limitation. In the latter approach, an additional nonperturbative effect from the flavor dependence of the intrinsic transverse momenta of the partons entering the collision has a statistically significant impact on the extracted values of the $W^\pm$ masses [9, 10], inducing shifts in M_W comparable to those associated with PDF variations. By improving knowledge of TMD PDFs as well as TMD fragmentation functions and hadronization processes through precise measurements of unintegrated SIDIS multiplicities, the EIC will enhance the accuracy of M_W extracted from hadron collider data and EW/BSM phenomenology generally [3].

  Resolution of nuclear structure. Although hadron colliders like the LHC primarily examine proton-proton events, in many cases there remains an indirect dependence on nuclear-scattering information — entering, for instance, via PDFs constrained with nuclear data. The treatment of nuclear DIS, however, involves various ambiguities associated with corrections due to the nuclear environment. While, the EIC will help to dissect nuclear-medium effects on various tomographic distributions, it will also measure hadronic structure with high precision in a way that avoids excessive dependence on nuclear targets through combinations of EW currents and other dedicated processes.

  In a complementary direction, ultra-peripheral photonuclear collisions at hadron colliders [11] are also sensitive to the internal structure of both the proton and of nuclei. Coherent photoproduction of vector mesons and other final states is sensitive to the internal structure of the target; the Fourier transform of $d\sigma/dt$ gives access to the transverse density distribution — essentially the GPD for nuclei. In the Good-Walker paradigm, $d\sigma/dt$ for incoherent photoproduction is sensitive to event-by-event internal fluctuations of the target structure, notably including gluonic hot spots [12]. These studies will also be pursued with increased precision at the EIC [2], where they will provide synergies with corresponding DIS measurements.

Leveraging the full breadth of the $\mathcal{O}(1\,\mathrm{ab}^{-1})$ data set expected from the EIC will require a combination of theoretical, computational, and experimental advances. We identify and briefly describe several leading examples below.

Next-generation perturbative QCD developments. In order to facilitate the unambiguous extraction and interpretation of multi-dimensional distributions, it will be necessary to further develop the QCD factorization theorems which allow the separation of soft, nonperturbative matrix elements from hard partonic sub-processes. Extension to higher orders in perturbative QCD will also be necessary for higher precision. The delineation of leading, twist-2 from higher-twist matrix elements will be enabled by high-precision EIC data, and the accompanying theory must be developed to extract higher-twist effects. These developments can be expected to benefit the understanding of multi-parton interactions at hadron colliders as well as QCD processes like jet-p_T broadening in nuclear scattering.

Phenomenological studies of TMDs/GPDs. With the advent of the EIC, systematic studies of observables sensitive to quark-gluon dynamics and hadronization like J/ψ production will become feasible, offering unique opportunities to deepen knowledge, including of the gluon TMDs — particularly at low x. Given the need for flexible models suited for phenomenology, common frameworks for all T-even and T-odd gluon TMDs at twist-2 must be produced as in Ref. [13], which calculated a spectator model for the parent nucleon, encoding effective small-x effects through BFKL resummation. Reliable models are important inputs for the generation of pseudodata allowing the identification of key processes at the EIC sensitive to the details of gluon dynamics. Additionally, TMD fits based on Drell-Yan data are now available at N^3LL accuracy [14, 15], and the flavor dependence of the intrinsic-k_T has been recently included in numerical codes widely used at LHC experiments [16]. Ensuring that TMD improvements from the EIC complement analogous measurements at hadron colliders will depend upon the continued development of this work. Similar arguments apply to modeling and simulation of the nucleon GPDs, providing novel insights into the spatial distribution of quark-gluon degrees-of-freedom.

New directions in continuum strong QCD. To capitalize on a new era of experiments like the EIC and HL-LHC, sound predictions for all parton distributions are necessary. Existing calculations of meson distribution functions (valence, glue and sea) [17, 18] will be extended to GPDs, delivering pressure and mass distributions; similarly, to the nucleon. TMD studies bring an additional complication: namely, TMD extraction from data requires knowledge of fragmentation functions (FFs), for which realistic calculations are limited. The future of momentum imaging depends critically on progress with the calculation of FFs; hence, this will be an effort focus. Links will be forged between experiment, phenomenology and lattice.

Connections to lattice QCD. Recent progress in lattice QCD has led to many exciting possibilities, including the direct lattice calculation of collinear PDFs (unpolarized as well as the helicity and transversity distributions) and extension to GPDs [19]. Synergies with QCD global analyses in the EIC era will require further theoretical refinements. Opportunities include studies of the gluonic structure of the proton and of light nuclei, in which a synthesis of EIC measurements and lattice calculations may enlighten a range of issues including the double helicity flip gluon structure functions of light nuclei and the gluon PDFs, GPDs (including the D-term, pressure and shear), and TMDs of the proton and light nuclei.

AI for proton tomography. Advances in computation involving new possibilities in machine learning, artificial intelligence, and other Big Data methods will assist the unfolding of the nucleon's multidimensional structure from large EIC data sets. These advances must be accompanied by progress in developing next-generation Monte Carlo event-generator frameworks to assist the realistic simulation of (SI)DIS cross sections with dependence on TMD PDFs and other unintegrated distributions.

[1] "High-Luminosity Large Hadron Collider (HL-LHC) : Preliminary Design Report," (2015), 10.5170/CERN-2015-005.

[2] A. Accardi *et al.*, "Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all," Eur. Phys. J. A **52**, 268 (2016), arXiv:1212.1701 [nucl-ex].

[3] Y. Furletova *et al.*, "EW and BSM physics at EIC," (2020), a Letter of Interest submitted to the Snowmass 2021 Energy Frontier.

[4] I. Vitev *et al.*, "Heavy Flavors at the EIC," (2020), a Letter of Interest submitted to the Snowmass 2021 Energy Frontier.

[5] M. Arratia *et al.*, "Jet Physics at the Electron Ion Collider," (2020), a Letter of Interest submitted to the Snowmass 2021 Energy Frontier.

[6] C. Bauer *et al.*, "QCD and precision physics," (2020), a Letter of Interest submitted to the Snowmass 2021 Theory Frontier.

[7] P. Nadolsky *et al.*, "Toward the N3LO accuracy of parton distribution functions," (2020), a Letter of Interest submitted to the Snowmass 2021 Energy Frontier.

[8] S. Forte and M. Vos, "Precise measurements of heavy-quark masses," (2020), a Letter of Interest for the Snowmass 2021 Theory Frontier.

[9] Alessandro Bacchetta, Giuseppe Bozzi, Marco Radici, Mathias Ritzmann, and Andrea Signori, "Effect of Flavor-Dependent Partonic Transverse Momentum on the Determination of the W Boson Mass in Hadronic Collisions," Phys. Lett. B **788**, 542–545 (2019), arXiv:1807.02101 [hep-ph].

[10] Giuseppe Bozzi and Andrea Signori, "Nonperturbative Uncertainties on the Transverse Momentum Distribution of Electroweak Bosons and on the Determination of the W Boson Mass at the LHC," Adv. High Energy Phys. **2019**, 2526897 (2019), arXiv:1901.01162 [hep-ph].

[11] S. R. Klein, D. T. Takaki, *et al.*, "New opportunities at the photon energy frontier," (2020), a Letter of Interest for the Snowmass 2021 Energy Frontier.

[12] Spencer R. Klein and Heikki Mäntysaari, "Imaging the nucleus with high-energy photons," Nature Rev. Phys. **1**, 662–674 (2019), arXiv:1910.10858 [hep-ex].

[13] Alessandro Bacchetta, Francesco Giovanni Celiberto, Marco Radici, and Pieter Taels, "Transverse-momentum-dependent gluon distribution functions in a spectator model," Eur. Phys. J. C **80**, 733 (2020), arXiv:2005.02288 [hep-ph].

[14] Ignazio Scimemi and Alexey Vladimirov, "Non-perturbative structure of semi-inclusive deep-inelastic and Drell-Yan scattering at small transverse momentum," JHEP **06**, 137 (2020), arXiv:1912.06532 [hep-ph].

[15] Alessandro Bacchetta, Valerio Bertone, Chiara Bissolotti, Giuseppe Bozzi, Filippo Delcarro, Fulvio Piacenza, and Marco Radici, "Transverse-momentum-dependent parton distributions up to N^3LL from Drell-Yan data," JHEP **07**, 117 (2020), arXiv:1912.07550 [hep-ph].

[16] Stefano Camarda *et al.*, "DYTurbo: fast predictions for Drell–Yan processes," Eur. Phys. J. C **80**, 251 (2020), [Erratum: Eur.Phys.J.C 80, 440 (2020)], arXiv:1910.07049 [hep-ph].

[17] Minghui Ding, Khépani Raya, Daniele Binosi, Lei Chang, Craig D Roberts, and Sebastian M. Schmidt, "Symmetry, symmetry breaking, and pion parton distributions," Phys. Rev. D **101**, 054014 (2020), arXiv:1905.05208 [nucl-th].

[18] Zhu-Fang Cui, Minghui Ding, Fei Gao, Khépani Raya, Daniele Binosi, Lei Chang, Craig D Roberts, Jose Rodríguez-Quintero, and Sebastian M Schmidt, "Kaon parton distributions: revealing Higgs modulation of emergent mass," (2020), arXiv:2006.14075 [hep-ph].

[19] C. Monahan, L. Del Debbio, H.-W. Lin, and K. Orginos, "Towards global fits of three-dimensional hadron structure from lattice QCD," (2020), a Letter of Interest for the Snowmass 2021 Theory, Energy, and Computational Frontiers.