# Bridging Theory and Experiment at the Electron-Ion Collider

Alessandro Bacchetta, Wim Cosyn, Felix Ringer, and Anna Stasto

(Dated: June 30, 2023)

## SCIENTIFIC JUSTIFICATION

This workshop aims to address and discuss specific outstanding questions that currently exist within the electron-ion collider (EIC) community that require input from theory. Answers to these questions can be critical to successful completion of the next steps in the EIC project (finalization of detector design) or are desired before the actual start of EIC operations.

The EIC will be the next US-based nuclear physics facility, to be constructed at Brookhaven National Lab with a projected start of operations in the early 2030s. The EIC was launched as an official DOE project at the end of 2019 and has recently been awarded critical decision 1 (CD1) status in 2021. The community around the EIC is organized in the EIC user group (EICUG) which currently counts 1390 members across 275 institutions spread over the entire globe. At the moment the community is working towards project milestones CD2 and 3 (projected in 2025), which correspond to approval of the preliminary design of the project including baseline scope, cost and schedule (CD2), and approval of start of construction (CD3).

The EIC will produce high-luminosity collisions of beams of (polarized) electrons and protons/ions at large center of mass energies (20-140 GeV) and will be the first collider of its kind. There is the possibility to have two interaction regions (IR) where each IR can house a general-purpose detector. The DOE project funds the construction of one IR and detector, around which the ePIC collaboration was recently formed [1]. The ePIC collaboration already counts around 600 scientists. It is recognized by the community that a second, complementary, detector is essential to fully exploit the science potential of the EIC and to carry out the necessary cross checks of relevant measurements [2]. The effort to work towards the realization of a second detector, which should follow the completion of the first one within a few years, is being led within the EICUG by a second detector working group.

Some of the key physics topics that the EIC will address are:

- Performing a three-dimensional tomography of the nucleon through measurements in (semi-)inclusive deep inelastic scattering and hard exclusive processes. This happens through the extraction of precision partonic distribution functions (PDFs), from collinear PDFs to transverse momentum dependent (TMD) distributions and generalized parton distributions (GPDs). These studies can help unravel the different quark and gluon contributions to global properties of the nucleon such as its spin and mass.
- Precision measurements of nuclear PDFs (including diffractive PDFs).
- Determination of gluon saturation regime at low Bjorken $x$. Here key channels of interest are coherent and incoherent diffraction in $eA$ scattering.
- Studies of QCD in nuclear systems: Nuclear medium modifications of PDFs (shadowing, EMC-like effects) and fragmentation functions. Studies of the short-range nature of the nuclear force and nuclear short-range corelations. Studies of hadronization in the medium (hard probes).
- Novel aspects of jet physics complementing studies at RHIC and the LHC.
- $XYZ$ meson spectroscopy.
- Study of electroweak physics and searches for new physics beyond Standard Model.

To successfully run this program once the EIC starts operations, the community has been carrying out extensive studies and simulations that inform the design of the EIC detector(s) and interaction region (IR). The recent status was summarized in the EIC Yellow report [3]. These dedicated studies are ongoing and require input from the experimental, accelerator and theoretical communities. This needs to happen now so that the best possible detector(s) can be designed and theoretical frameworks can be developed to carry out the studies that we envision at the EIC. During these studies, various physics questions arise that require specific and timely theoretical input. These questions are often not on the radar of the theoretical community, or require the need for a dedicated theoretical study that feeds into decisions with regard to the detector design.

Those reasons led to the formation of the Theoretical Working Group (WG) within the EICUG at the end of 2021. Its four conveners are the organizers of the proposed workshop. The WG has been soliciting input from the EIC community on topics that require attention from the theory community and organized several online meetings where these topics have been discussed. These meetings are held ad hoc and typically include a couple of presentations and a discussion session, with meetings lasting an hour or two in total. They are summarized on the wiki page of the theory WG [4]. While these meetings serve their purpose, and online meetings have the advantage of being accessible to all, the advantage of a dedicated in-person workshop cannot be overstated.

The workshop will cover several topics/questions which leads to an audience with a broader scope than the more topically focused online meetings. There is the possibility for extended discussions across the whole week, and the opportunity to meet in smaller groups throughout the workshop which naturally leads to new collaborations. The meeting can also address questions with regard to the possible second detector and complementarity with the ePIC detector. There is the opportunity to have a more specific goal of the meeting such as drafting a list of high-priority topics that need to be addressed by the theoretical community in the years before the EIC starts operations, which can serve as a guide for the immediate future.

Some examples of physics topics that we want to address at the meeting are:

### Diffraction

Diffractive events are characterized by the *rapidity gap*, a region in the detector void of any activity. At electron-proton collider HERA, about $10\%$ of all events were diffractive. The diffraction is very sensitive to the partonic structure of the target at low values of Bjorken $x$, and thus may play an important role in the studies and searches for the onset of parton saturation. Exclusive diffraction, for example in the elastic production of vector mesons, with the momentum transfer dependence can be used to map the spatial distribution of gluons in protons and nuclei. Diffractive processes in which the target breaks up, may be used on the other hand to study the fluctuations in the spatial distribution of partons. Note, however, that there are currently challenges to this picture [5]. This was a topic of one of our recent meetings and can be further addressed at the workshop.

EIC can measure with high precision the inclusive diffractive structure function both on protons and on nuclei, the latter for the first time. Using these measurements the ratio of diffractive cross sections in protons and nuclei could be constructed. There are predictions from various approaches which significantly differ as to the magnitude of this ratio. In particular this ratio would provide a very sensitive test of the onset of parton saturation. Beyond the inclusive diffraction there are number of exclusive processes in diffraction which have been proposed to be studied at the EIC. One of them is elastic diffractive vector meson production. This process could be measured on protons as well as on nuclei as a function of the momentum transfer dependence The Fourier transform of this cross section allows for the extraction of the profile in the impact parameter. The crucial condition for this measurement is that the target stays intact. In the case of nuclei one refers to this process as the *coherent* diffraction, as opposed to the incoherent process in which the nucleus may break up. The latter process results in a harder momentum transfer dependence and completely dominates the coherent production at large $-t$. Thus it becomes an experimental challenge to separate coherent and incoherent production properly. This challenge has been a topic of study already during the Yellow Report and several of our ad hoc meetings, but still warrants attention from both the theory and experimental sides. There are still unresolved questions as to mechanisms that can modify the position and magnitude of the diffractive dips in the coherent signal, one example being Coulomb distortion of the electron which can be theoretically modeled. Also the extraction of the coherent signal which is done by vetoing the incoherent contributions comes with specific experimental challenges that benefit from theory input.

### Polarized Bethe-Heitler process

For collider experiments, precise knowledge of the integrated luminosity is essential to determine cross section measurements. To achieve this, traditionally the Bethe-Heitler process has been used in kinematics where the emitted photon is nearly collinear to the incident beams [6]. It is the process of choice as it is theoretically well known and has a very large cross section. The EIC will operate polarized beams, thus luminosity measurements need to measure the polarized Bethe Heitler process, which requires accurate theoretical knowledge of its cross section. It turns out that while a theoretical framework exists [7], there is no implementations that can be directly used by the EIC community and the calculations also warrant a revisit for EIC kinematics.

### Radiative Corrections

Accounting for radiative QED corrections at the EIC will be critical for precision comparisons to QCD calculations and the extraction of relevant nonperturbative quantities. Several complementary and/or competing approaches have been proposed in the literature. For example, traditionally, parton shower event generators are used to account for radiative corrections [8, 9]. In this case, QED radiative corrections are included in the experimental analysis. Numerical results can be found in the work by Badelek et al. [10]. Recently, an alternative approach has been proposed by Liu et al. [11]. Here radiative corrections are accounted for on the theory side. These studies may have a direct impact on the experimental design and data taking. Within this workshop, we aim to bring together the different communities and facilitate an open exchange that will greatly benefit the experimental work in the upcoming years.

### Addressing broader community questions

Besides dedicated questions from the community, we also aim to address broader topics that have been raised recently. This includes for example the interpretation of the EIC data in terms of non-perturbative QCD objects (unpolarized PDFs, polarized

PDFs, nuclear PDFs, (nuclear) fragmentation functions) and the need to build a comprehensive global analysis framework for all these objects including also TMDs and GPDs. While this is a longer-term effort, a dedicated workshop where the experimentalists can provide input can help to guide future theoretical efforts. Related to this aspect, the question has been raised how lattice QCD can best assist the experiments related to the 3D tomography of the proton at EIC. Recent progress in lattice allows reliable calculations of the parton distribution functions for a moderate range of $x$, and has also shown the potential to calculate generalized parton distributions and transverse-momentum-dependent distributions. These aspects are also closely related to global analyses mentioned above and the use of new machine learning tools at the EIC.

In addition to the topics mentioned here, it is to be expected that any new significant questions or issues that arise in the time leading up to the potential workshop would also be incorporated in its program.

---

[1] "ePIC collaboration web page," `https://wiki.bnl.gov/EPIC/index.php?title=Collaboration` (2023), accessed: 2023-06-30.
[2] EICUG, "Maximizing the scientific output of the eic," (2022).
[3] R. Abdul Khalek *et al.*, Nucl. Phys. A **1026**, 122447 (2022), arXiv:2103.05419 [physics.ins-det].
[4] "EIC Theory Working Group wiki page," `https://wiki.bnl.gov/eicug/index.php?title=Theory` (2023), accessed: 2023-06-30.
[5] S. R. Klein, Phys. Rev. C **107**, 055203 (2023), arXiv:2301.01408 [hep-ph].
[6] M. Helbich, Y. Ning, S. Paganis, Z. Ren, W. B. Schmidke, F. Sciulli, U. Schneekloth, C. Buttner, A. Caldwell, and J. Sutiak, Nucl. Instrum. Meth. A **565**, 572 (2006), arXiv:physics/0512153.
[7] A. Afanasev, I. Akushevich, and N. Merenkov, Phys. Rev. D **64**, 113009 (2001), arXiv:hep-ph/0102086.
[8] L. W. Mo and Y.-S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).
[9] A. A. Akhundov, D. Y. Bardin, and N. M. Shumeiko, Sov. J. Nucl. Phys. **44**, 988 (1986).
[10] B. Badelek, D. Y. Bardin, K. Kurek, and C. Scholz, Z. Phys. C **66**, 591 (1995), arXiv:hep-ph/9403238.
[11] T. Liu, W. Melnitchouk, J.-W. Qiu, and N. Sato, JHEP **11**, 157 (2021), arXiv:2108.13371 [hep-ph].
[12] P. Achenbach *et al.*, (2023), arXiv:2303.02579 [hep-ph].