Letter of Interest: Heavy Flavors at the EIC

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The Electron-Ion Collider (EIC) Heavy Flavor Group is writing to express its interests in the future of high energy physics and the Snowmass 2021 planning process. We recognize the deep intellectual connections between particle and nuclear science and the rich collaborative opportunities that the EIC will bring in theory, computation, experiment, and detector technology [1]. We advocate for the inclusion of EIC science in the recommendations for the future of high energy physics in the US. Our primary interests align with the Energy Frontier of Snowmass 2021, with strong overlaps with the Theory and Computing Frontiers [2].

Open and hidden heavy-flavor production in deep-inelastic scattering needs a status review of the tools/theory to make precise predictions in the future EIC experiments. As heavy quarks introduce a new mass scale, the impact of flavor number schemes - fixed-flavor number (FFN) scheme and variable-flavor-number (VFN) scheme – on charm and bottom distributions has to be better understood [3,4].

Via neutral-current (NC) exchange in e+p/A collisions at the EIC, heavy flavor production can be used to probe the initial gluon distributions inside nucleon and nucleus. This can be used to constrain the gluon (nuclear) PDF especially in the large x_B region [5]. In the charged-current (CC) interaction channel with the scattered neutrino, heavy flavor and heavy flavor jet production offer the sensitivity to the strange quark sea [6]. The interpretation of data from these experiments may be complicated by a subtle interplay of effects arising from nuclear, target-mass, and other power-suppressed corrections, as well as potential contamination from target fragmentation. This requires a significance development in theory predictions and tools in order to extract valuable info (e.g. gluon and sea quark PDFs) from future data. One critical issue to be addressed is how to distinguish nPDF effects from other CNM effects through the analysis of future EIC data together with the data on heavy-flavor production at HERA and the LHC [7].

Many ambiguities remain regarding the possible role of heavy quarks - particularly charm - in hadronic and nuclear structure. A prime example of this is the issue of the nonperturbative or intrinsic charm contribution to the proton wave function [8,9]. Up-to-date, there is nearly a complete lack of measurements with direct sensitivity to nonperturbative charm in the nucleon. The ideal measurement would involve charm structure-function data in the high $x > 0.1$ and intermediate $Q \sim 10$ GeV region, which the EIC will be poised to extract with considerable precision. Similarly, the EIC will be well-positioned to not only constrain/isolate the presence of intrinsic charm but also to potentially determine its detailed origins in QCD. The EIC could shed light on this subject through a detailed exploration of the scale dependence of the nucleon's charm component. More broadly, there is a possible role to be played by charm-jet production in this area as well.

An exciting and cross-cutting field that must be further explored is the theory of QCD in dense environments. Comparative studies of light and heavy flavor meson, baryon and jet production on e+p and e+A collisions can shed light in the process of hadronization, the time scales involved and the magnitude of non-perturbative effects [10,11]. Modern effective field theories of QCD, such as soft-collinear effective theory, have allowed us to include effects of nuclear matter on the formation of parton showers and to combine those with heavy quark mass effects [12]. Theoretical developments in the past several years have shown that evolution in the nuclear medium can amplify the impact of charm and bottom mass on heavy flavor observables and can constrain the transport properties of large nuclei. This physics can be accessible in the forward proton/nucleus going direction [13].

The polarized e+p/A collisions at the future EIC will provide opportunities to further explore the nucleon/nucleus spin structure. Double spin asymmetry measurements of heavy flavor production will offer further constraints to the gluon polarization in addition to the measurements of jets. Compared to the quark transverse momentum distributions (TMDs), our knowledge of the gluon TMDs is much less advanced [14]. Heavy flavor production at the future EIC plays an irreplaceable role in probing gluon TMDs inside unpolarized and polarized nucleons. Processes like open or hidden heavy meson production are induced by photon-gluon fusion at the lowest order, and thus provide opportunities to measure the gluon TMDs. Measurements of charm hadron pairs will be of particular interest. Constraints to gluon Sivers asymmetry can be obtained through measurement of charm hadron pairs in polarized electron-proton collisions. Measurements of azimuthal distribution of the charm hadron pair momentum in unpolarized electron-proton collisions can be used to constrain linearly polarized gluon transverse momentum distributions. In the meantime, theoretical development in studying the QCD effects in these processes as well as their impact on the size of asymmetry will be carried out.

Quarkonia and exotic states are an important part of the EIC program. The clean DIS environment will help assess the robustness of the NRQCD framework and facilitate better constraints on the long-distance matrix elements and J/ψ and Υ production. It has been suggested that the Color Glass Condensate of QCD has universal properties common to nucleons and all nuclei. Study of heavy flavor production in e+A collisions at the EIC could provide access to the saturation regime [15]. The measurements are possible in two modes, exclusive and inclusive, and the energy range at EIC allows the study both productions of the charmonium and the bottomonium states, which increases the reliability of the searches. Bound heavy-quark states that are produced in e+A collisions at the EIC are also subject to disruption via interactions with partons inside the nucleus. Since these interactions are expected to depend on the size and binding energy of the state, measurements of quarkonia suppression at the EIC can provide information on the structure of the heavy quark states. This offers a new method to discriminate between compact tetra- and pentaquark versus hadronic molecule models of exotic quarkonia structure [16].

Heavy flavor physics at the EIC requires advances in detector development – an area of common interest for HEP and NP. The ability to reconstruct heavy flavor hadron decays with good signal significance is crucial for most of the proposed physics measurements. Micro vertexing and good momentum resolution, combined with low material budget are important requirements for this program. Collisions at the EIC are asymmetric and, while many of the heavy flavor decay daughters fall in the pseudorapidity region $|\eta| < 3$, the pattern of hadron production is skewed in the forward proton/nucleus going direction. The community is working on tracker designs including an all silicon detector [17] and a forward silicon tracker [13] optimized to extend forward rapidity coverage. Physics simulations are essential to back up these design efforts.

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