Snowmass 2021 Letter of Intent: EW and BSM physics at EIC

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I. INTRODUCTION

In this LOI for the Snowmass planning process, we briefly outline prospects and topics of study related to Electroweak (EW) and Beyond the SM (BSM) physics at the future EIC deep inelastic scattering (DIS) facility. Much of the focus of the EIC has been on QCD and nuclear processes. However, the EIC offers both unique and complementary opportunities to probe EW and BSM physics with high precision. This LOI outlines a number of studies that are ongoing or that will be extended and/or finalised during the Snowmass process. We also very much welcome further participation and contributions.

II. ELECTRO-WEAK AND BSM PHYSICS AT EIC

A. *PDF fits and flavour decomposition:*

Both neutral and charged [1] current measurements will be crucial in disentagling the flavour decomposition of the proton. These measurements will be included in global QCD analysis fits to extract the proton parton distribution functions (PDFs). A detailed description can be found in a parallel Letter of Intent [2]

In addition, charm production in charged current deep inelastic scattering offers the unique opportunity to probe directly the strangeness content of the nucleon in the high-x region. It is expected to result in $\mathcal{O}(1000)$ events in $100\,\mathrm{fb}^{-1}$ of integrated luminosity after charm tagging [3], [4].

B. *Parity violation:*

The high luminosity, high center-of-mass energy and polarized beams allow the EIC to make complementary measurements in the Fundamental Symmetries subfield. A whole series of observables rely on measurements of parity violating asymmetries in DIS:

$$A_{PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}. \tag{1}$$

Since both beams are polarized, parity violating measurements as described in equation 1 can be obtained for polarized electrons or polarized protons (by summing over the polarization of the other beam) [5]. The A^e_{PV} allows access to unpolarized structure functions, especially the interference structure functions $F^{\gamma Z}_{1,3}$. On the other hand, A^h_{PV} would access $g^{\gamma Z}_{1,5}$ and put significant constraints on the polarized strangeness inside the proton.

Beyond the structure function information, the A^e_{PV} measurement on the deuteron beam would allow an extraction of the weak mixing angle with little PDF uncertainty. Furthermore, initial studies indicate that with very well contrainted PDFs one could verify the running of the weak mixing angle with the proton beam as well. Both of these measurements will be in a kinematic region below the Z-pole where very little data exists.

Finally, comparisons of A^e_{PV} measurements on heavy nuclei available at the EIC with the deuteron result, could shed some light on the EMC effect with a weak mediator. The feasibility of these measurements are going to be investigated.

C. *Weak Neutral Current Couplings*

In the $Q^2 \ll M_Z^2$ limit, the weak neutral current contribution to DIS can be parameterized in terms of contact interactions

$$\begin{aligned}\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_{\ell,q} \Big[& C_{1q}\ \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\ \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q \\ & + C_{3q}\ \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \Big],\end{aligned} \tag{2}$$

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where the C_{iq} denote the weak neutral current couplings. A comparison of the measured values of the C_{iq} couplings with the SM predictions can be used to set limits on the new physics scale Λ. Furthermore, the C_{1q} and C_{2q} couplings are functions of the weak mixing angle θ_W and the wide kinematic range of the EIC allows for precision tests of the $\overline{\mathrm{MS}}$-running [5] of $\sin^2\theta_W(\mu)$ below the Z-pole, in the previously unexplored range of 10 GeV $< \mu <$ 70 GeV. Such tests could probe "Dark Parity Violation" [6], mediated by a light hidden sector dark-Z boson that communicates with the SM through kinetic mixing with mass $m_{Z_d} \sim$ 20 GeV.

While different quark flavor combinations of the C_{1q} coefficients are relatively well constrained [7], [8], [9], the C_{2q} couplings are not as well-known due to their relatively small values in the SM. The C_{1q} and C_{2q} couplings can be accessed via the parity violating deep inelastic scattering asymmetry in Eq. (1), using a deuteron target. The EIC can extract the combination $2C_{2u} - C_{2d}$ at the few percent level, significantly improving on the recent [10], [11] result $2C_{2u} - C_{2d} = -0.145 \pm 0.068$ at $Q^2 = 0$. Its high luminosity and wide kinematic range allows for better separation of contributions arising from the C_{1q} couplings and hadronic effects through higher twist and sea quark contributions. The C_{2q} couplings probe the Leptophobic Z' scenario [12], [13] which is difficult to constrain at the LHC due to large QCD dijet backgrounds.

A high-intensity positron beam would provide a unique opportunity to improve upon the large uncertainty [14] in the C_{3q} couplings through a measurement of the asymmetry between electron and positron deep inelastic scattering off an isoscalar target [15]. It would be the first such extraction of the C_{3q} couplings using electron and positron beams.

D. Charged Lepton Flavor Violation:

The discovery of neutrino oscillations imply charged lepton flavor violation (CLFV) in the SM, although highly suppressed due to the small neutrino masses. However, many beyond the SM scenarios predict significantly higher CLFV rates [16]. While CLFV between the first two generations are tightly constrained, the EIC can play an important role in the search for charged lepton flavor violating process $eN \to \tau X$ and improve on HERA limits [17], [18]. Such a CLFV process could be mediated by the tree-level exchange of Leptoquarks (LQ) [19], [20]. The wide kinematic range of the EIC allows scalar and vector LQs to be distinguished, through a difference in the y-dependence of the corresponding cross sections. Polarized lepton beams can distinguish between left-handed and right-handed LQs. Positron and electron beams can be used to distinguish between F=0 and |F|=2 LQ channels respectively, where F=L+3B is the fermion number. Proton versus deuteron nuclear targets can be used to distinguish between LQs with different electroweak quantum numbers. In the model-independent approach, constraints on different LQ states translate into constraints on higher dimension CLFV operators. Lepton number violation can be also induced by the heavy neutral leptons (HNLs). The exploration of the HNLs at the EIC is detailed in a parallel Letter of Intent [21].

E. Testing the charged current chiral structure:

The chiral structure of electroweak interactions allows only left-handed electrons and right-handed positrons to couple to the W-boson. Thus, the SM predicts a linear dependence on the lepton beam polarization for the charged current processes $e^{\pm} + p \to \overset{(-)}{\nu}_e + X$. Precision measurements of the polarization dependence can test the chiral structure of the charged current interactions. A right-handed W-boson (W_R), arising in Left-Right Symmetric models with spontaneous symmetry breaking $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \to SU(2)_L \otimes U(1)_Y$, could lead to a deviation from a linear lepton beam polarization dependence. The higher luminosity and degree of lepton beam polarization at the EIC can allow for modest improvements [22] over the HERA [23] limits on the W_R-boson mass, M_R. While the Tevatron and the LHC have already set more stringent limits on M_R, in the TeV range, by looking for deviations in the transverse mass distribution of the Drell-Yan process $pp \to W \to l\nu_l$, the observed distribution is sensitive to a time-like charged boson and in general can be affected by physics involving different chiral and flavor structures. Thus, the EIC measurements could be complementary to LHC limits.

F. Complementarity of EIC and LHC probes of the SMEFT:

The SM of particle physics has so far been successful in describing all observed laboratory phenomena. No appreciable deviation from SM predictions has been conclusively observed. Given this situation it is increasingly important to understand how indirect signatures of new physics can be probed and constrained by the available data. This effort will help guide future searches for new physics by suggesting in what channels measurable deviations from SM predictions may occur given the current bounds.

The SM effective field theory (SMEFT) provides a convenient theoretical framework for investigating indirect signatures of heavy new physics without associated new particles at low energies. Considerable effort has been devoted to performing global analyses of the availabe data within the SMEFT and other frameworks. An issue that arises in such global fits is the appearance of flat directions that occur when the available experimental measurements cannot disentangle the contributions from different EFT operators.

The flat directions that appear when studying 2-lepton, 2-quark four-fermion operators and how the EIC can play a crucial role in resolving them, will be investigated. Although the naive expectation is that these operators are well-probed by high invariant-mass Drell-Yan distributions at the LHC, only a very limited number of combinations of Wilson coefficients can be probed by such measurements. The ability to polarize both electron and proton beams at an EIC allows for probes of Wilson coefficient combinations not accessible at the LHC [24]. Combined fits of LHC and projected EIC data lead to much stronger constraints than either experiment alone. Polarized positron beams could provide even further discrimination between SMEFT operators, as discussed in Section II-C of this LOI.

G. Heavy photons:

The high energy and luminosity at the EIC offers interesting opportunities for heavy photon and “dark" Z' searches, by providing kinematics equivalent to a multi-TeV lepton beam on a fixed proton or heavier target. This could well complement searches at other moderate- or low-energy luminosity-frontier facilities such as BDX [25] or LDMX [26]. The level of complementarity has not been assessed fully yet, and investigations into this topic are in their early stages. For example, it might become possible to drastically improve probing the parameter space in models with new force mediators with leptonic couplings. In the nuclear rest frame, radiative production off the lepton beam, $e + X \to e + X + A' \to e + X + l\bar{l}$, tends to produce the A' with a substantial fraction of the beam energy. Compared to a hypothetical fixed-target experiment at the same center of mass energy, electron-going final states have significantly lower boost and hence wider opening angles in the laboratory frame, allowing access to kinematics that are otherwise difficult to capture. At the same time, the EIC environment, which aims at very detailed (and comparably “clean") measurements of the hadronic final state, may allow testing models with leptophobic mediator couplings in detail.

H. Lorentz- and CPT-violating effects:

Lorentz and CPT symmetry are among the most well established symmetries in physics. However, many BSM theories admit regimes where one or both of these symmetries can be spontaneously broken. Low-energy tests of Lorentz and CPT symmetry can be performed using the effective field theory framework known as the Standard-Model Extension (SME). To date, SME operators describing Lorentz- and CPT-violating effects on QCD degrees of freedom have been largely unconstrained. Recent studies suggest differential cross section measurements at the EIC will allow for precision tests of Lorentz and CPT symmetry in the quark sector [27], [28]. Data for unpolarized inclusive deep inelastic scattering at 100 fb^{-1} luminosity can increase bounds on quark sector coefficients by two orders of magnitude over data taken at HERA. Symmetry violations would be visible as variations in the cross section as a function of sidereal time. Additional processes, including those with polarization effects, charged-current exchange, and QCD corrections, have the ability with the EIC to place first constraints on a number of completely unexplored effects stemming from Lorentz and CPT violation.

REFERENCES

[1] Elke C. Aschenauer, Thomas Burton, Till Martini, Hubert Spiesberger, and Marco Stratmann. Prospects for Charged Current Deep-Inelastic Scattering off Polarized Nucleons at a Future Electron-Ion Collider. *Phys. Rev. D*, 88:114025, 2013.

[2] S. Fazio, T.J. Hobbs, A. Prokudin, A. Vicini, et al. Hadronic tomography at the EIC and the energy frontier. *Letter of Interest submitted to the Snowmass 2021 Energy Frontier*, 2020.

[3] Miguel Arratia, Yulia Furletova, T.J. Hobbs, Fredrick Olness, and Stephen J. Sekula. Charm jets as a probe for strangeness at the future Electron-Ion Collider.

[4] I. Vitev, X. Dong, S. Sekula, et al. Heavy flavors at the EIC. *Letter of Interest submitted to the Snowmass 2021 Energy Frontier*, 2020.

[5] Y. X. Zhao, A. Deshpande, J. Huang, K. S. Kumar, and S. Riordan. Neutral-current weak interactions at an EIC. *The European Physical Journal A*, 53(3), Mar 2017.

[6] Hooman Davoudiasl, Hye-Sung Lee, and William J. Marciano. Muong-2, rare kaon decays, and parity violation from dark bosons. *Physical Review D*, 89(9), May 2014.

[7] C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. E. Wieman. Measurement of parity nonconservation and an anapole moment in Cesium. *Science*, 275(5307):1759–1763, 1997.

[8] D. Androic and et al. First determination of the weak charge of the proton. *Physical Review Letters*, 111(14), Oct 2013.

[9] D. Androić et al. Precision measurement of the weak charge of the proton. *Nature*, 557(7704):207–211, 2018.

[10] D. Wang et al. Measurement of parity violation in electron–quark scattering. *Nature*, 506(7486):67–70, 2014.

[11] D. Wang et al. Measurement of Parity-Violating Asymmetry in Electron-Deuteron Inelastic Scattering. *Phys. Rev. C*, 91(4):045506, 2015.

[12] Matthew R. Buckley and Michael J. Ramsey-Musolf. Precision probes of a leptophobic Z' boson. *Phys. Lett. B*, 712:261–265, 2012.

[13] Martín González-Alonso and Michael J. Ramsey-Musolf. Leptophobic Z' boson and parity-violating eD scattering. *Physical Review D*, 87(5), Mar 2013.

[14] A. Argento and et al. Electroweak asymmetry in deep inelastic muon-nucleon scattering. *Physics Letters B*, 120(1):245 – 250, 1983.

[15] A. Accardi and et al. e$^+$@ JLAB White paper: An experimental program with positron beams at jefferson lab, 2020.

[16] M. Tanabashi et al. Particle data group. *Phys. Rev.*, D 98:030001, 2018.

[17] S. Chekanov and et al. Search for lepton-flavor violation at HERA. *The European Physical Journal C*, 44(4):463–479, Dec 2005.

[18] A. Aktas and et al. Search for lepton flavour violation in ep collisions at HERA. *The European Physical Journal C*, 52(4):833–847, Oct 2007.

[19] W. Buchmüller, R. Rückl, and D. Wyler. Leptoquarks in lepton-quark collisions. *Physics Letters B*, 191(4):442 – 448, 1987.

[20] Matthew Gonderinger and Michael J. Ramsey-Musolf. Electron-to-tau lepton flavor violation at the Electron-Ion Collider. *Journal of High Energy Physics*, 2010(11), Nov 2010.

[21] B. Batell, T. Ghosh, T. Han, and K Xie. BSM physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons. *Letter of Interest submitted to the Snowmass 2021 Energy Frontier*, 2020.

[22] Yulia Furletova and Sonny Mantry. Using polarized positrons to probe physics beyond the standard model. *AIP Conf. Proc.*, 1970(1):030005, 2018.

[23] A. Aktas, V. Andreev, T. Anthonis, B. Antunovic, S. Aplin, A. Asmone, A. Astvatsatourov, A. Babaev, S. Backovic, J. Bähr, and et al. First measurement of charged current cross sections at HERA with longitudinally polarised positrons. *Physics Letters B*, 634(2-3):173–179, Mar 2006.

[24] Radja Boughezal, Frank Petriello, and Daniel Wiegand. Removing flat directions in standard model EFT fits: How polarized electron-ion collider data can complement the LHC. *Physical Review D*, 101(11), Jun 2020.

[25] M. Battaglieri et al. Dark matter search in a Beam-Dump eXperiment (BDX) at jefferson lab – 2018 update to pr12-16-001. Oct 2019.

[26] Torsten Åkesson et al. Light Dark Matter eXperiment (LDMX), 2018.

[27] Enrico Lunghi and Nathan Sherrill. Lorentz violation and the electron-ion collider. *Phys. Rev. D*, 98(11):115018, 2018.

[28] V. Alan Kostelecký, Enrico Lunghi, Nathan Sherrill, and A.R. Vieira. Lorentz and CPT Violation in Partons. *JHEP*, 04:143, 2020.