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Electroweak and BSM Physics at the EIC

K.S. Kumar[1,a], A. Deshpande[1], J. Huang[2], S. Riordan[1], and Y.X. Zhao[1]

[1] *Department of Physics and Astronomy, Stony Brook University, NY 11794-3800, USA*
[2] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*

Abstract. We discuss the QCD and electroweak physics that becomes accessible by the analysis of semi-leptonic neutral weak amplitudes in polarized electron-light ion collisions at an EIC. Specifically, we discuss the reach for precise weak mixing angle measurements at much higher Q^2 than fixed target measurements, new neutral current spin-independent and -dependent interference structure functions, and searches for $e - \tau$ charged lepton flavor violation.

1 Introduction

The EIC offers a unique new combination of experimental probes given the high center-of-mass energy, high luminosity and the ability to polarize the electron and hadron beams. It is therefore natural to ask whether the envisioned machine parameters could enable new discoveries in the broad subfield of Fundamental Symmetries, which explores the origin and evolution of visible matter in the early universe. One aveune is studies of lepton-hadron electroweak interactions at progressively higher sensitivity. By comparing the measured interaction amplitudes with theoretical predictions within the framework of the Standard Model (SM) of strong, weak and electromagnetic interactions, insights are gained into the symmetries and interactions of matter in the universe at its earliest moments of existence, indirectly accessing energy scales similar to, and sometimes beyond the reach of, the highest energy accelerators currently operational.

Electroweak interaction studies at the EIC can also be used to probe novel aspects of nucleon structure via measurements of spin observables constructed from weak interaction amplitudes mediated by the W and Z bosons. Indeed, some parity-violating observables become accessible that have never before been measured.

In this article, we explore specific observables involving neutral current interactions that relate to the two broad physics themes discussed above.

2 Weak Neutral Currents at low Q^2

A comprehensive strategy to indirectly probe for new high energy dynamics via sensitive tests of electroweak interactions at the intensity frontier must also include precision measurements of flavor-diagonal weak neutral current interactions mediated by the Z^0 boson. For electron-hadron interactions at $Q^2 \ll M_Z^2$, weak neutral current amplitudes are accessed via parity violating asymmetries

[a] e-mail: krishna.kumar@stonybrook.edu

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A_{PV}, since pseudoscalar observables sensitive to weak-electromagnetic interference terms can be constructed from the product of vector and axial-vector electron and quark electroweak currents. The parity-violating part of the electron-hadron interaction at $Q^2 \ll M_Z^2$ can be given in terms of phenomenological couplings C_{ij}

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

with additional terms as required for the heavy quarks. Here C_{1j} (C_{2j}) gives the vector (axial-vector) coupling to the j^{th} quark.

Within the SM context, each coupling constant is precisely predicted since they are all functions of the weak mixing angle $\sin^2\theta_W$. Over the past two decades, the C_{1i}'s have been measured with steadily improving precision in table-top atomic parity violation experiments and in fixed target parity-violating electron scattering experiments, both in elastic scattering and deep inelastic scattering (DIS), most recently at Jefferson Laboratory (JLab) [1, 2]. Comparing these measurements to SM predictions has produced strong constraints on new high energy dynamics, such as limits on TeV-scale heavy Z' bosons and certain classes of interactions in supersymmetric theories, in a manner complementary to direct searches at colliders [3–6].

A unique feature of DIS A_{PV} measurements is the sensitivity to the C_{2i} coupling constants which involve the amplitudes with axial-vector quark currents. While the C_{2i}'s are kinematically accessible at large scattering angle measurements in fixed target elastic electron scattering, axial-hadronic radiative correction uncertainties cloud the interpretation of the measurements in terms of fundamental electroweak physics. Parity-violating DIS using ^{2}H is the only practical way to measure one combination accurately, namely $2C_{2u} - C_{2d}$. The first ever non-zero measurement of this combination was made recently at JLab [1], and a new experiment called SOLID has been proposed to improve on this measurement by nearly an order of magnitude [7]. Since there is no other way to make accurate measurements of axial-quark couplings, it is worth investigating whether one can make additional measurements at the EIC.

One example of the importance of achieving sensitive constraints on the C_{2i} couplings is a heavy Z′ boson (predicted in many SM extensions), which could introduce an additional amplitude and induce a deviation in the measured C_{2i} couplings [8, 9]. A remarkable feature of this amplitude is the fact it is sensitive to the Z′ boson even in the case that it might not couple to leptons (so-called lepto-phobic Z′). The limits on the existence of such bosons from other precision weak neutral current measurements as well as from colliders is very weak because all signatures require non-zero lepton-Z′ couplings. Note that this amplitude cannot contribute to any tree-level amplitudes nor amplitudes involving the C_{1i} couplings at the quantum loop level. The projected uncertainty from the JLab measurements will be sensitive to a lepto-phobic Z′ with a mass $\sim$ 150 GeV, significantly better than the current limit from indirect searches when there is no significant Z-Z′ mixing.

The JLab extraction will rely on a simultaneous fit of electroweak couplings, higher-twist effects and violation of charge symmetry to a series of A_{PV} measurements in narrow x and Q^2 bins. It is highly motivated to find ways to improve the sensitivity to the C_{2i} couplings further, given its unique sensitivity for TeV-scale dynamics such as the aforementioned Z′ bosons. Apart from statistical reach, the EIC measurements will have the added advantage of being at significantly higher range of Q^2 so that higher-twist effects should be totally negligible.

In the next section, we explore how well we can measure semi-leptonic weak neutral current couplings at the EIC in a more general framework that explores new parity-violating observables comprehensively.

3 Electroweak Physics at the EIC

3.1 Neutral Current Structure Functions

One can write down the most general hadronic tensor lepton-nucleon DIS under the assumption of CP-symmetry including the spin of both the lepton and hadron. For purely electromagnetic scattering at leading twist and without parity-violation, there are four structure functions F_1^γ, F_2^γ, g_1^γ and g_2^γ. With the addition of the neutral weak interaction and parity-violation but with the additional assumption of the Callan-Gross relation, one can now access the interference structure functions $F_1^{\gamma Z}$, $F_3^{\gamma Z}$, $g_1^{\gamma Z}$ and $g_5^{\gamma Z}$ [10–13]. Charged weak interactions can be similarly analyzed and indeed the observables at the EIC from which various W-exchange structure functions can be extracted have been studied [14]. We have begun the analysis required to carry out a similar analysis for weak-electromagnetic interference neutral current structure functions, as discussed below.

3.1.1 Predicted Asymmetries

The DJANGOH generator can be used to simulate DIS lepton-proton (nuclei) scattering with QED and QCD radiative effects treated at at next-to-leading order [15]; this has already been used for the EIC charged current study mentioned above [14]. The R-L asymmetry for inclusive scattering of longitudinal polarized electrons off unpolarized hadrons can be written as (neglecting the pure Z-exchange amplitude):

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\Big[g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^\gamma}\Big]. \tag{1}$$

Here, g_V^e and g_A^e are the vector and axial-vector couplings of the electron to the Z^0 boson. The (+)-(-) asymmetry [1] for inclusive scattering of an unpolarized electron beam on longitudinally polarized hadron can be written as:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\Big[g_V^e \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^\gamma}\Big], \tag{2}$$

$$g_A^e = -0.5, \quad g_V^e = -0.5 + 2\sin^2\theta_W, \tag{3}$$

$$Y_- = 2y - y^2, \quad Y_+ = y^2 - 2y + 2. \tag{4}$$

In the quark-parton model, the structure functions can be written as linear combinations of the unpolarized and polarized parton distribution functions (pdfs). The nice feature of the interference structure functions is that they carry different weights for u-type and d-type quarks as compared to the purely electromagnetic structure functions and therefore it will help in 6-flavor global fits trying to unfold the individual unpolarized and polarized pdfs.

The data in each (x, Q^2) bin can be binned in kinematic variable y and then be fitted to a slope and intercept to cleanly extract $F_1^{\gamma Z}$, $F_3^{\gamma Z}$ (or $g_1^{\gamma Z}$, $g_5^{\gamma Z}$) structure functions. Electron-proton collisions were used to do the projections for the structure functions, while electron-deuteron collisions were used for $\sin^2\theta_W$ projections (since structure function uncertainties cancel for ^{2}H). The projections have taken into account the radiative corrections. Bin migration due to radiative effects was also taken into account with an unfolding technique. The cuts were $Q^2 > 1$ GeV^2, $W_h > 2$ GeV, $y > 0.1$ for structure function studies, with $Q^2 < 6400$ GeV^2 and $x > 0.2$ in addition for $\sin^2\theta_W$ projections. All

[1] The electron direction is designated as the spin (+) direction.

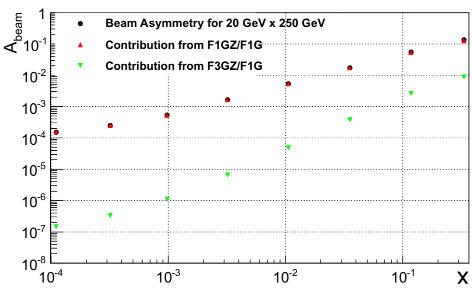

Figure 1. The right-left asymmetry for 20 GeV polarized electrons on 250 GeV unpolarized protons.

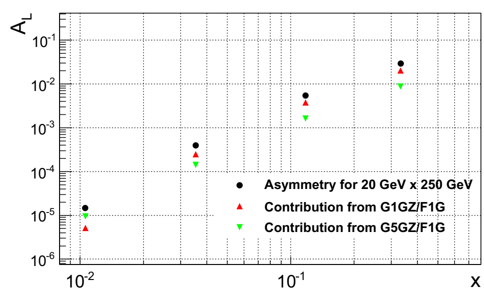

Figure 2. The right-left asymmetry for 20 GeV unpolarized electrons on 250 GeV polarized protons.

the projections were assuming integrated luminosity as 100 fb^{-1} (per nucleon for e-D collisions) and beam (target) polarization as 80 %. We studied four different energy configurations for the electron and hadron energies: 10 GeV x 100 GeV, 10 GeV x 250 GeV, 20 GeV x 250 GeV and 20 GeV x 325 GeV.

Figure 1 and Fig. 2 show the asymmetries as a function of x for the 20 x 250 case for the case of flipping the electron beam and hadron beam helicities respectively. An interesting feature is the fact that while the electron beam asymmetry is mostly sensitive to $F_1^{\gamma Z}$, the hadron beam asymmetry has significant contribution from both $g_1^{\gamma Z}$ and $g_5^{\gamma Z}$.

3.2 The Weak Mixing Angle

The observable with the best sensitivity to cleanly measure coupling constants without significant theoretical uncertainty is A_{beam} in e–^{2}H collisions, averaging over the hadron polarization. From the extracted interference structure function ratios, clean separation of two linear combination of couplings namely $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$ becomes feasible as a function of Q^2. For this first study, we show the extracted measurement of the weak mixing angle at the appropriate values of Q for three different beam energy scenarios, as shown in Fig. 3 for an integrated luminosity of 400 fb^{-1} per nucleon.

Such projected errors might turn out to be very important when the EIC turns on depending on the outcome of other future measurements indicated in Fig. 3. For example, it is quite possible that the dark matter in the universe has weak couplings to ordinary matter via dark photons, a subject of great current interest. If such dark photons have a small admixture with the Z^0 boson, it is possible that the theoretical prediction shown in Fig. 3 is modified [16]; depending on the mass of the dark boson, this deviation could begin to occur at the Q range accessed by the EIC measurements.

The next steps are to see if the projected errors can be improved by studying electron-proton collisions using different luminosities. In this case, structure function uncertainties might become important. However, it is possible that these uncertainties are small enough at high x so that the required precision can be obtained with significantly lower luminosity and without the requirement of a deuteron beam.

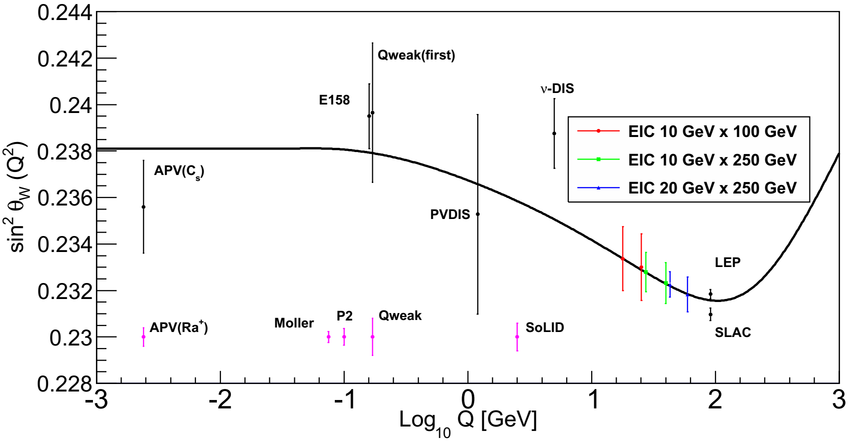

Figure 3. The projected errors on the weak mixing angle are shown at the appropriate average Q values for the case of 400 fb^{-1} per nucleon in e-^{2}H collisions for 3 different beam energy combinations. Also shown are other projected determinations at lower Q anticipated over the next decade.

3.3 Polarized Quark Distributions

From the hadron spin-flip asymmetries, polarized structure functions measurements can be extracted. It can be seen from Figs. 4 and 5 that for an integrated luminosity of 100 fb^{-1}, significant new constraints on the interference structure functions become feasible at $x > 0.1$. The next steps are combine these constraints with the γ and W structure functions and determine whether the new constraints from the inteference structure functions alleviates the need to use semi-inclusive scattering to accomplish a clean 6-flavor separation of the parton distribution functions including polarization.

4 Charged Lepton Flavor Violation

With the discovery of neutrino oscillations, it is natural to ask whether lepton flavor non-conservation can be observed in *charged* lepton interactions. Speculative new theories of the early universe that predict Majorana neutrinos often also predict observable rates of charged lepton flavor violation (CLFV). The most sensitive CLFV searches to date have come from searches for the neutrinoless conversion of stopped muons to electrons in nuclei, searches for the rare decay of a free muon to an electron and photon, and searches for the rare decay of a kaon to an electron and muon. The limits from these processes, though extremely sensitive, all involve the $e \leftrightarrow \mu$ transition. Speculative CLFV theories can predict enhanced rates for $e \leftrightarrow \tau$ transitions.

In lepton-hadron interactions, one could search for the rare cases where an electron converts to a muon or tau lepton, or a muon converts to a tau lepton. The only successful such searches for $e \to \tau$ transitions have been carried out at the HERA electron-hadron collider experiments ZEUS and H1. The CLFV process could be mediated by a hypothesized new heavy boson known as a leptoquark, which carries both lepton and baryon quantum numbers and appears naturally in many SM extensions such as Grand Unified Theories, supersymmetry, and compositeness and technicolor models (for a concise review, see [17]). The most recent published search by H1 finds no evidence for CLFV $e \to \tau$

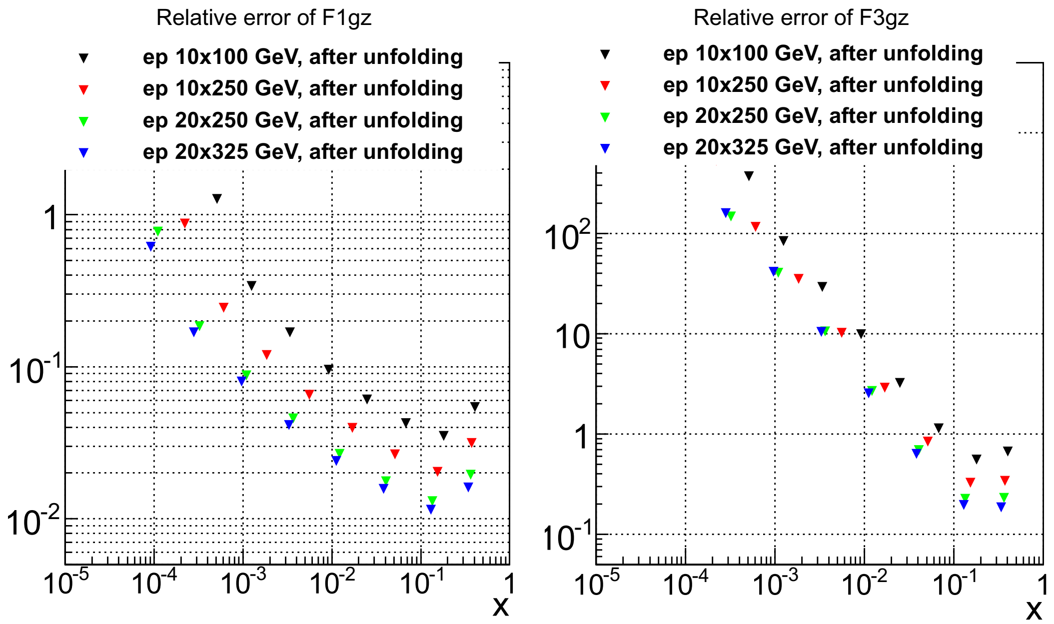

Figure 4. The projected fractional errors on $F_1^{\gamma Z}$ (left) and $F_3^{\gamma Z}$ from A_{beam} measurements using $e-p$ collisions with an integrated luminosity of 100 fb^{-1}.

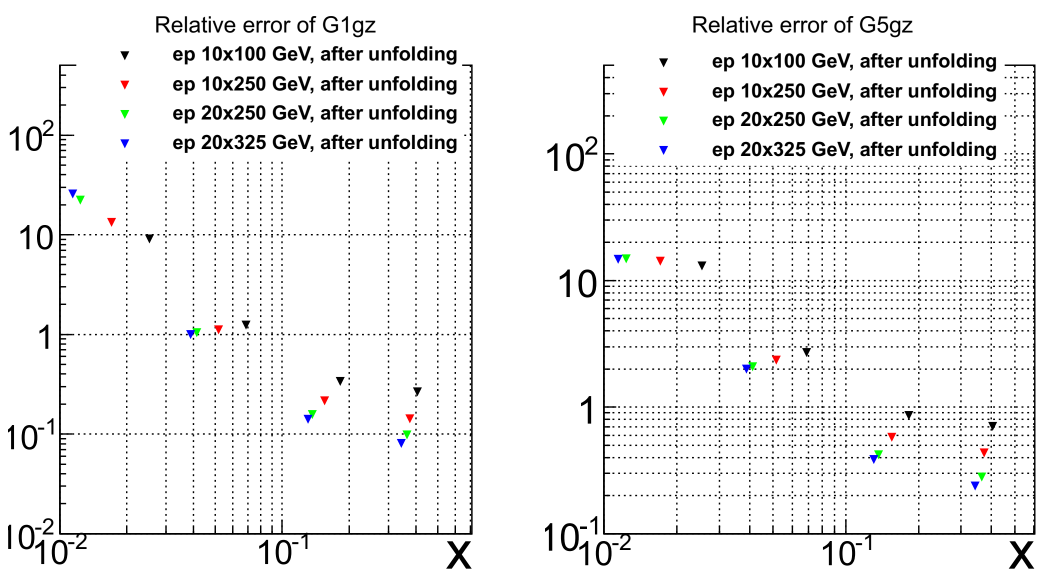

Figure 5. The projected fractional errors on $g_1^{\gamma Z}$ (left) and $g_5^{\gamma Z}$ from A_L measurements using $e-p$ collisions with an integrated luminosity of 100 fb^{-1}.

transitions [18], which can in turn be converted to a limit on the mass and the couplings of leptoquarks in specific SM extensions.

A high energy, high luminosity EIC, with 100 to 1000 times the accumulated luminosity of HERA experiments would allow a large increase in sensitivity. A recent study has shown that an EIC with 90 GeV center-of-mass energy could surpass the current limits with an integrated luminosity of 10fb^{-1} [19]. The study also showed that the EIC could compete or surpass the updated leptoquark limits from rare CLFV tau decays for a subset of quark flavor-diagonal couplings. Once the neutral current structure function study is completed, it is planned to carry out full detector simulations and carry out a feasibility study of how to select high energy *tau*-jets in the EIC detector, exploiting both jet reconstruction variables as well as vertex reconstruction to identify displaced vertices.

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