Abstract—Long-baseline neutrino experiments require extensive understanding of heavy nuclei interactions to precisely measure neutrino oscillations. The proposed LDMX experiment can increase understanding of neutrino-nucleus scattering by studying analogous processes in electron-nucleus scattering through inclusive and (semi)exclusive cross sections from a precision tracker and electromagnetic and hadronic calorimeters. Using the GENIE neutrino event generator, I illustrate how electron scattering measurements in LDMX are sensitive to hadronic final state interactions (FSI) with measurements of the outgoing lepton and hadron kinematics, and highlight regions of the measurement phase space of interest for constraining FSI systematic uncertainties. Neutrons with kinetic energy in the 400-600 MeV and charged pions with kinetic energy in the 200-500 MeV range are particularly sensitive. We discuss how this study of electron nucleus scattering, using GENIE and LDMX, complements ongoing neutrino-nucleus scattering studies to better understand neutrinos interactions which will ultimately improve the sensitivity of neutrino experiments.

I. INTRODUCTION

Fueled by recent neutrino discoveries in the past half century, nuclear and particle physics have focused highly on understanding various unknown neutrino phenomena. Neutrinos represent the most abundant matter particle in the universe and were recently discovered to have mass through evidence of neutrino flavor oscillation, a divergence from the previously accepted Standard Model. Neutrinos could reveal why the universe is made of matter instead of antimatter. In order for this matter asymmetry to exist in the universe a particle must exhibit undiscovered CP violations, the difference between a matter and antimatter particle beyond opposite charge and parity. It is possible that neutrinos exhibit CP violations that could shed light on the asymmetry observed in our universe, and experiments are searching for these differences in neutrino and antineutrino oscillations. Neutrino oscillations are a phenomena where as neutrinos propagate through space the probability of measuring a specific flavor varies. If there is symmetry between matter and antimatter the probabilities of their oscillations should be the same, which recent experiments have shown may not be true [1].

Long baseline neutrino experiments, which attempt to improve our understanding of neutrino oscillations, rely on detectors to reconstruct the properties of neutrinos from their interactions with heavy nuclei. Differentiating between possible interaction models without knowing the initial neutrino energy (which is usually the case in neutrino beams) is extremely difficult, and leads to large uncertainties on oscillation measurements. However, electron nucleus interactions, where incoming electron energy and angle is always known, contain many analogous interaction processes, particularly final state interaction (FSI) processes where hadrons produced in neutrino interactions further interact within the nucleus. Ankowski et al. (ref) proposes applying the knowledge learned from probing different interaction model uncertainties, including from FSI, in electron nucleus scattering in the LDMX detector to neutrino nucleus scattering in order to better reconstruct and thus detect neutrinos during oscillation. In this study, we focus on modifying parameters in FSI models in electron-nucleus scattering, and then identify experimentally measurable quantities that could effectively constrain the model uncertainties.

II. BACKGROUND

A. Neutrino Nucleus and Electron Nucleus Interactions

Understanding neutrino nuclear interactions requires a model of neutrino nucleon interactions and nucleons in the nucleus. In the simplest form neutrino nucleus scattering is modeled by the sum of incoherent interactions between a neutrino and a free nucleon. However, this view ignores the more complex nuclear dynamics of initial nuclear state nucleon interactions and extra nuclear effects of momentum distribution and binding energy. The internal propagation of hadrons in a cascading effect, associated energy losses, and creation and absorption of mesons characterize the FSI of neutrino nucleus scattering [2].

Detectors rely on the outgoing nucleus particles for neutrino reconstruction, when incoming neutrino energy and sometimes angle is unknown. Misconstruction or missing of particles altogether can alter neutrino measurements. Furthermore, because detectors never see the internal nucleus interactions, translating the observed final particles from neutrino nucleus interactions to the initial neutrino interaction properties requires use of theoretical models, further complicating neutrino reconstruction and leading to large systematic uncertainties in experiments’ measurements. Different subprocesses of neutrino nucleus scattering include QEL (quasi-elastic), RES (resonant production), DIS (deep inelastic), and MEC
These processes typically occur with differing amounts of energy transfer between the incoming lepton and the nucleus, and so lead to different particles produced [3].

The same FSI processes occur in the analogous process of electron nucleus scattering. In electron scattering measurements, the incoming electron energy and angle can be measured, providing new information for understanding what initial incoming particle parameters result in different experimentally detectable FSI. This knowledge can then be readily applied to neutrino nucleus interactions because the hadronic interactions are relevant regardless of whether from electron or neutrino scattering.

**B. LDMX**

The proposed Light Dark Matter eXperiment (LDMX) [4] aims to detect light dark matter in the 0.5 MeV to 0.5 GeV range, a familiar mass range of protons and electrons. Incoming electrons from a 4 GeV beam scatter on a fixed Titanium target to produce low-mass dark matter. The experiment proposes efficient reconstruction of recoils and high-purity tagging of incoming electrons in a similar kinematic region of neutrino interactions in DUNE [5]. The experiment could provide (semi)exclusive cross section measurements and information on final state particles for electron nucleus scattering. A diagram of the proposed detector is shown in Fig. 2. The detector will include a recoil tracker in a magnet to precisely detect and measure charged particles produced in electron scattering interactions. It will also include an electromagnetic and hadronic calorimeter to further measure outgoing particle energies and allow sensitivity to neural particles (like neutrons and $\pi^0$).

**C. GENIE**

Because LDMX is still in the design study phase, we use the event generator GENIE [3] - a software library used to generate high energy physics interactions - to simulate electron nucleus interactions that would occur in the detector. GENIE uses Monte Carlo event generators and has the capacity to fully model both neutrino and electron scattering in analogous ways. We have GENIE (v3.0.6) model 4 GeV electrons impacting a titanium target to simulate the LDMX beam. To investigate differences in FSI, we use GENIE’s reweighting infrastructure [4] which is capable of propagating model uncertainties. Instead of repeatedly rerunning electron nucleus interactions under different FSI model parameters, the GENIE reweighting represents a numerical method to modify previously simulated events to match the effects of changing FSI parameters. We then use these reweighting utilities to study how measurements of the outgoing lepton and hadron kinematics under LDMX conditions are sensitive to different FSI parameters. Before in depth analysis of potential observables based on GENIE reweighting, I primarily checked that FSI weights only effected incoming lepton related quantities. We exposed a coding error in the GENIE Formation Zone weight. The weights significantly change the number of events as shown in Fig 3.

**D. Reduced Chi Squared**

Chi-squared: We use a chi-square metric with an assumed uncertainty of 1% to quantify differences between a central value (CV) model and FSI varied parameters. The FSI parameters are varied at level of $\pm 1\sigma$ uncertainty.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{0.01 * E_i}$$ (1)

Where the observed values, $O_i$ are the central values and the expected values, $E_i$ are $+1\sigma$ weight values. The degrees of freedom used are one less than the number of histogram bins.

$$\frac{\chi^2}{\text{dof}}$$ (2)
Therefore, a $\chi^2_{\text{dof}} > 1$ represents a promising observable for distinguishing between different FSI model parameters with LDMX.

III. EXPERIMENTAL METHODS

A. Overview

Python is used to create histograms of hadron and lepton kinematics from the GENIE simulated events of 4 GeV electrons impacting a titanium target. An unweighted central value (CV) is plotted against different FSI model parameters of $\pm 1\sigma$ uncertainty for different potential observables. The kinematics are tested for all, leading, or groups – all pions, neutrons and protons, kaons etc., for the possible outgoing particles: $e^-, k^+, k^-, k^-, p, n, \pi^+, \pi^-, \pi^0$ etc. The FSI model parameters of charge exchange, inelastic collisions, pion production and absorption for nucleon or pion are investigated. The chi squared statistic described above quantifies successful observable for probing the model parameters. A sampling of successful observable for various FSI parameters are shown below. Many different kinematics worked effectively for a single FSI parameter.

B. LDMX Detector Trigger and Acceptances

To model an inclusive electron scattering trigger, we require the outgoing electron $p_T$ greater than 400 MeV/c. We require outgoing hadron kinetic energy $> 60$ MeV and angle, $\theta < 40$ degrees to mimic detector acceptance. We use a chi-square metric with an assumed uncertainty of 1% to quantify differences between a central value (CV) model and FSI-varied models. The FSI models are varied at level of $\pm 1\sigma$ uncertainty.

C. Kinetic Energy

The most significant sensitive particles occur in kinetic energy regions outside of detector acceptances. Neutrons represent very effective observables highlighting the importance of detecting them in LDMX.

D. Leading Kinetic Energy

The leading particle’s kinetic energy was plotted per event in order to removed multiplicity biases. Again, the most sensitive particles occur in regions below detector acceptances.

E. Multiplicity

Particle multiplicity represents one of the most effective measurable quantities in constraining FSI parameter uncertainties. More samples are necessary to validate these results.
Substantial differentiation between central value and weight FSI parameter can be seen through the $\cos(\theta)$ of the particles. The most sensitive particles to these parameter uncertainties require detectors to measure backwards angles.

The leading $\cos(\theta)$ further emphasizes the importance of detector angle acceptance to increase as these differences are not due to possible multiplicity biases when plotting the $\cos(\theta)$ of particles.

We also investigate hadron kinematics coupled with cuts on outgoing lepton kinematics or interaction type (qel, mec, res, dis). We find sensitivity to FSI parameters persists across different energy transfer, allowing for later constraint.

Promising observables were determined for FSI model parameters of charge exchange, absorption, inelastic collisions, for both pion and nucleon and pion production for pion. Strong differences between weight and unweight values for these parameters were observed with all necessary detector acceptances and triggering mechanisms taken into account. Neutrons with kinetic energy in the 400-600 MeV and charged pions with kinetic energy in the 200-500 MeV range are particularly sensitive. Lepton kinematics proved effective in further constraining pion parameters where large amounts of energy transfer is necessary for pion production (as the quasi-elastic and meson exchange current processes that are more dominant at low energy transfer do not produce pions in the initial state).

Various statistically successful observables were determined for charge exchange, absorption, inelastic collision and pion production. LDMX trigger and acceptance cuts greatly decreased differences in promising observables illustrating a necessity for a more detailed detector simulation to validate and expand on these differences. These study results use only ‘truth-level’ quantities, and therefore do not perfectly embody possible experimental limitations in kinematic measurements: more detailed measurement resolution and other effects should be considered in the future. Our chi squared analysis with the assumed uncertainty of 1% is only appropriate for a significant number of events and can produce artificial differences otherwise: while we took care to avoid making conclusions in areas of low statistics, more interaction statistics and a more sophisticated inclusion of measurement errors should be done in the future.

In further work we plan to continue constraining phase space through lepton kinematics in order to find the most effective region tailored to each FSI model parameter. Also, more complicated LDMX measurables like reconstructed transverse variables [8] could be even more effective. This study focuses on only exploring one FSI model’s uncertainties. Therefore, further probing of uncertainties of
different models for neutrino nucleus FSI, and additional models and uncertainties on the initial nuclear state and extra nuclear effect represent further facets of investigation. Further statistical evaluations of observables through chi squared parameter fitting or line fitting of a quadratic or exponential could advance the rudimentary method of chi squared goodness of fit testing done. Finally, an increased sample size can also increase generalizability and future success of results, and would allow for more detailed studies on rarer final states.

Using GENIE, we show how changes in FSI parameters in electron nucleus interactions impact the expected outgoing hadronic kinematics in the LDMX experiment. We identify observables that LDMX would be able to measure that are sensitive to current uncertainties in electron nucleus FSI. By making measurements in future LDMX data, we can constrain those uncertainties and similarly constrain the analogous uncertainties in neutrino nucleus FSI allowing for more accurate neutrino reconstruction. We find very promising observables through simple kinematics highlighting potential for LDMX to greatly advance understanding of FSI processes in electron nucleus scattering. These advancements are then applicable to neutrino nucleus scattering further advancing detector sensitivity and ultimately aiding understanding of the universe.

ACKNOWLEDGMENT

I would like to express my gratitude to my mentors, Shirley Li and Wesley Ketchum, for their patience, guidance and mentorship on my project and general future in physics. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

REFERENCES