Electrons for Neutrinos

Addressing Critical Neutrino-Nucleus Issues

A Run Group Proposal

Resubmission to Jefferson Lab PAC 46

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Abstract

The extraction of neutrino mixing parameters from neutrino oscillation experiments relies on the reconstruction of the incident neutrino energy and knowledge of the neutrino-nucleus interaction cross-section for various nuclei and incident neutrino energies. The energy reconstruction is done using the yield and kinematics of particles produced from neutrino interactions in nuclei. However, none of these energy reconstruction techniques have been tested experimentally using beams of known energy.

Because neutrinos and electrons are both leptons, they interact with nuclei in similar ways. We propose to measure electron scattering from a variety of targets at a range of beam energies in CLAS12 in order to test neutrino event selection and energy reconstruction techniques and to benchmark neutrino event generators. Event generators are critical inputs for analysis of neutrino oscillation and cross section experiments; providing data to test and improve those generators can significantly decrease the systematic uncertainties in neutrino experiments.

We request 25.5 days of beam time in Hall B to measure electron scattering at approximately 1.1, 2.2, 4.4, and 6.6 GeV from d, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, and ^{120}Sn targets. This time includes 1 day of calibration time on an H target and 5 days of overhead for target and energy changes (0.5 shift for each beam energy change and one shift for each liquid target change). The energies and targets span those used in major neutrino experiments, including MicroBooNE, MINERνA, NOνA, T2K, and the forthcoming ANNIE and DUNE.

This will provide enough data over a very wide range of energies and targets to help reduce one of the major uncertainties in current and especially next-generation neutrino oscillation experiments.

Letters of support from the major neutrino collaborations are attached to the end of this proposal.

This experiment was given C2 approval by PAC45. In this update we (a) combine this with a short range correlations proposal as a run group, (b) change the low energy (1.1 and 2.2 GeV) running to reversed-field to cover lower momentum transfer, (c)

significantly decrease the beam time requested by removing the 8.8 GeV running, (d) show comparisons between CLAS6 data and GENIE, the standard neutrino monte carlo event generator, and (e) show the potential impact of this data on the neutrino energy reconstruction and therefore on the neutrino oscillation parameters for the proposed DUNE experiment.

I. INTRODUCTION AND MOTIVATION

Neutrino oscillation, the subject of the 2015 Nobel Prize, can be studied by using accelerators to produce an intense source of one type of neutrino, and then searching for the disappearance of the produced neutrino species and/or the appearance of a different species at detectors hundreds of miles away, such as is done in the Tokai-to-Kamioka (T2K) and NOνA experiments. A future worldwide program, including the US-based Deep Underground Neutrino Experiment (DUNE) and/or the Hyper-Kamiokande (HK) experiment in Japan, will employ enormous detectors and unprecedented beam power to answer open questions about neutrinos and antineutrinos and about the standard model of particle physics. The importance of this is shown by its inclusion in both the Nuclear Science Advisory Committee's (NSAC's) Nuclear Physics 2015 Long Range Plan which states that "The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained", and the Particle Physics Project Prioritization Panel's (P5) 2014 Strategic Plan which lists "Pursue the physics associated with neutrino mass" as one of its five "intertwined science Drivers" for the field in the next decade [1].

In order to achieve the goals of current (2016-2026) and future (2026+) neutrino programs, unprecedented understanding of how neutrinos and antineutrinos interact with atomic nuclei is required. Neutrino-nucleus interactions are already a significant source of uncertainty for the current oscillation program at the level of 5–15%, as shown in Table I. Studies of the DUNE experiment show that as the uncertainty on the signal increases from 1% to 3%, the required exposure needed to discover CP violation doubles [2]. Improving the systematic uncertainty from the current 5–15% to the projected 1–3% is critical. Further improvements from 3% to 1% to the understanding of neutrino-nuclear uncertainties directly translate to reduced accelerator operation, time and cost of the experiment.

While neutrino oscillation experiments reduce their uncertainties by using identical detectors types for the near and far detectors, the incident neutrino flux can differ dramatically at the two detectors. For example, neutrino oscillations are expected to significantly change the projected DUNE ν_μ beam flux at the near and far detectors (see Fig. 1).

There are also concerns about how neutrino interactions are a potential source of bias in an oscillation experiment. Studies by the T2K collaboration, theory groups and phenome-

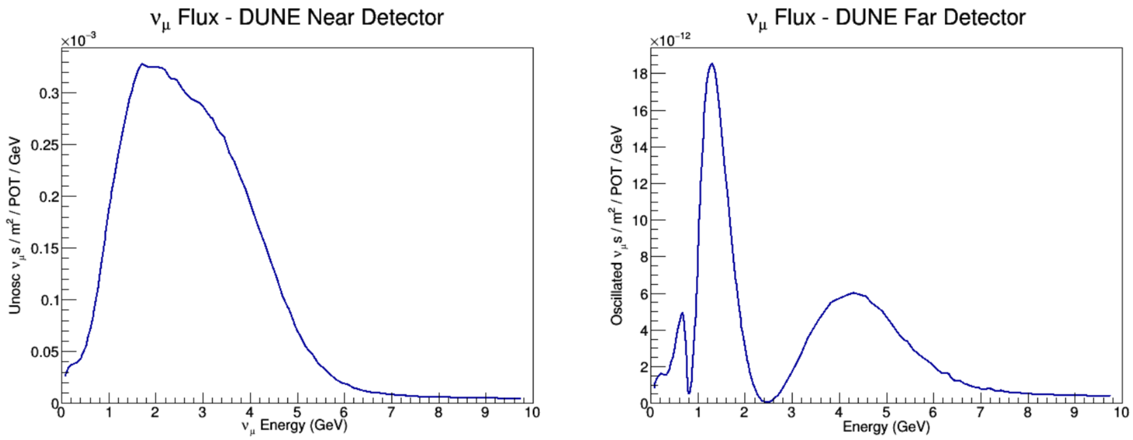

FIG. 1: The expected incident energy distribution of the DUNE ν_μ beam at the near detector (left) and the far detector (right).

nologists [3–11] indicate that if neutrino interactions are not modeled correctly, then the fitted values of the oscillation physics parameters can be significantly biased. Of particular concern are the amount and distribution of neutrons emitted in neutrino interactions, which is significant for neutrino-antineutrino comparisons used in CP violation studies. (For example, the typical charged current quasielastic [CCQE] neutrino interaction is $\nu n \rightarrow \mu^- p$ and the typical CCQE antineutrino interaction is $\bar{\nu} p \rightarrow \mu^+ n$. Thus CCQE neutrino interactions typically have a proton in the final state, but CCQE anti-neutrino interactions do not. Similar differences between neutrinos and anti-neutrinos will be seen in other CC reactions, such as resonance production.)

Neutrino experiments need to be able to reconstruct the incident neutrino energy precisely in order to interpret oscillation spectra [12]. Neutrino oscillation spectra are typically plotted versus E_ν, the reconstructed neutrino energy. The importance of this can be seen in Fig. 2, which shows the effects of energy reconstruction on the oscillation spectrum for DUNE. The difference between the two pairs of generated ("true") and reconstructed distributions are significant. These distortions could lead to very different reconstructed neutrino oscillation parameters.

The energy range of current neutrino sources are shown in Figure 3, with future sources, HK and DUNE, corresponding approximately to the T2K and MINERνA fluxes respectively. Measurements at 1 GeV are critical for the T2K and HK program which use carbon and

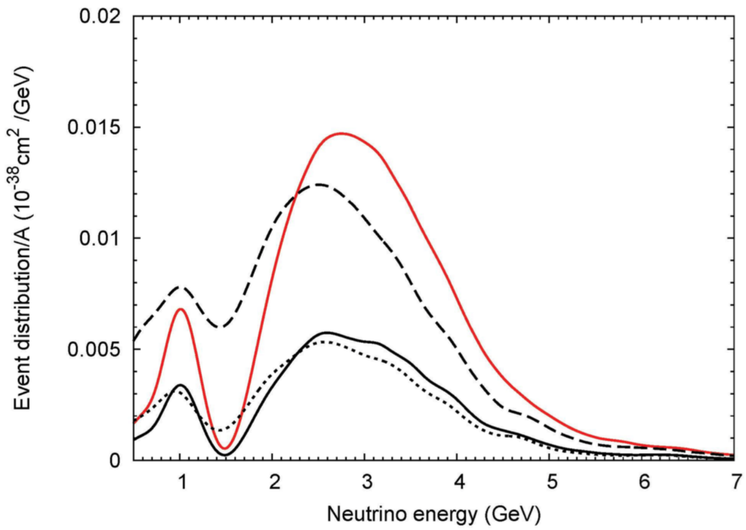

FIG. 2: Distribution of ν_e appearance events (normalized flux times cross section) per nucleon for DUNE vs. true (solid curve) and reconstructed (dashed curve) energy. The "true" events are generated using GIBUU and the energy is reconstructed from the detected electron, assuming QE kinematics (see Eq. 1). The upper two curves (solid red and dashed black) show the results obtained from an event sample with zero pions, the two lower curves are obtained from a sample with zero pions, one proton and X neutrons, showing the expected event distribution for electron appearance at DUNE. Figure 9 from Ref. [11].

water (oxygen) detectors, measurements from 1–2 GeV are important for the SBN Short Baseline Neutrino (argon) and NOνA (carbon) programs, and measurements spanning 1 to 10 GeV are crucial for the next generation DUNE (argon) experiment.

In addition to the flagship searches for CP violation, other neutrino physics programs will benefit from electron scattering data sets such as the ones described in this proposal. The ANNIE experiment on a gadolinum-doped water Cerenkov detector will do the first measurements of neutron yields from neutrino interactions; this experiment uses the Fermilab Booster neutrino beam used by MiniBooNE (1 GeV) flux. The Fermilab Booster neutrino beam is also used in searches for non-standard oscillations, including sterile neutrinos which are the focus of SBN Short Baseline Neutrino argon-based program at Fermilab [13].

This is a very active field of study. In addition to the regular Neutrino Interactions in Nuclei (NuInt) conferences, there are topical conferences such as the forthcoming July

total systematic uncertainty (neutrino interaction model)		
Experiment	ν_e CC	$\overline{\nu}_e$ CC
T2K	5.4% (>3.9%)	6.2% (>4.1%)
NOνA	17.6% (14.0%)	-

TABLE I: Fractional uncertainty (1σ) on the predicted rate of signal events (ν_e and $\overline{\nu}_e$ CC candidates) on the T2K and NOνA [14] experiments. The total systematic uncertainty on the signal is shown along with the fractional systematic uncertainty from the neutrino interaction model. The T2K numbers are from Table II in Ref [15], the neutrino interaction model uncertainties are estimated from the unconstrained cross section and final state interaction uncertainties.

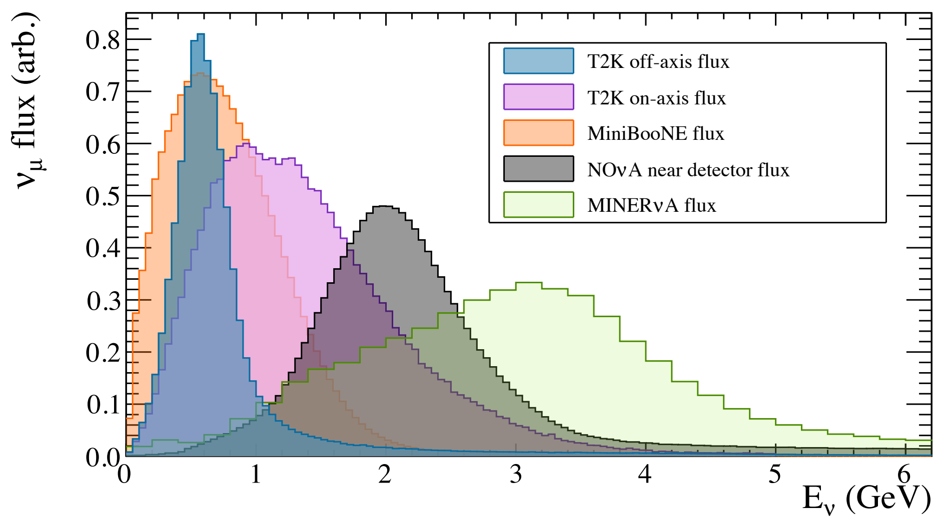

FIG. 3: Current neutrino sources, in arbitrary units, shown as a function of neutrino energy. The T2K off-axis flux is similar to what will be used for the future Hyper-Kamiokande experiment flux, and the MINERνA flux is similar to the future DUNE experiment flux.

2018 ECT* Trento workshop, the March 2018 NuPrint (Neutrino Cross Section Strategy Workshop), the April 2017 IPPP/NuSTEC topical meeting and the December 2016 INT workshop on neutrino-nucleus scattering. This proposal originated in discussions at the 2016 INT workshop where the need for improved electron scattering data over a wide kinematical phase-space for various reactions, nuclei and beam energies was highlighted.

II. LEPTON SCATTERING FROM NUCLEI

Electron and neutrino scattering from nuclei should be quite similar. Electrons interact by exchanging photons and interact via both longitudinal and vector currents. Neutrinos interact by exchanging W and Z bosons and interact via vector and axial currents. We are particularly interested in charge changing (CC) ν interactions where there is a charged lepton (usually a muon) in the final state.

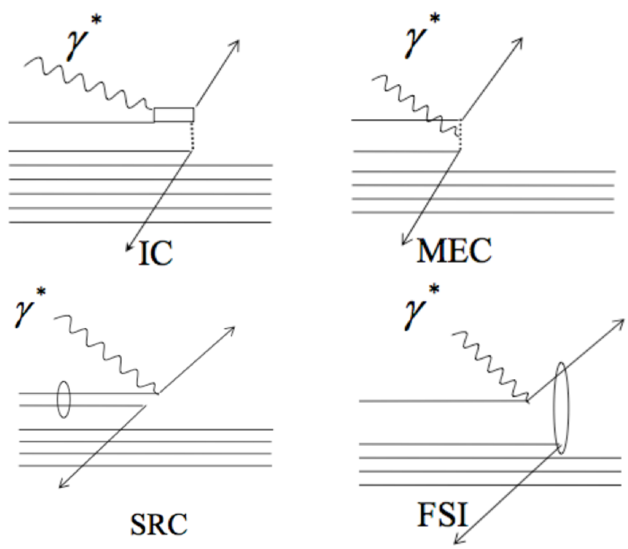

FIG. 4: Two body diagrams. (upper left) IC: the virtual photon is absorbed on a nucleon, exciting it to a Δ, which de-excites via $\Delta N \to NN$; (upper right) MEC: the virtual photon is absorbed on a meson being exchanged between two nucleons, resulting in the the knockout of both nucleons; (lower left) SRC: The virtual photon is absorbed on one nucleon of a short range correlated pair, resulting in the knockout of both nucleons; (lower right) FSI: the virtual photon is absorbed on one nucleon, which then rescatters.

Electrons interact with both one-body and two-body currents in the nucleus. One body currents mean that only one nucleon is involved in the interaction. Examples of this include quasi-elastic knockout and quasi-free Δ production. These give rise to the prominent (at low four-momentum transfer Q^2) quasielastic and Δ peaks. However, there are also several types of interactions that lead to two nucleons in the final state (see Fig. 4), including (1) isobar configurations (IC) where the electron excites a nucleon to a Δ and the Δ dexcites by interacting with a second nucleon ($\Delta N \to NN$), (2) meson exchange currents (MEC) where the virtual photon is absorbed on an exchanged meson leading to two-nucleon knockout, (3) short range correlations (SRC) where the electron knocks out one nucleon belonging to a short range correlated NN pair and the correlated partner nucleon is also ejected from the nucleus, and (4) final state interactions (FSI) where the knocked nucleon rescatters from a second nucleon. All of these processes lead to the same final state and therefore interfere with each other [16].

Because the photon is massless, its propagator has a factor of $1/Q^2$. This gives rise to the Mott cross section with its θ^{-4} dependence at small scattering angles. By contrast, the large W and Z masses give rise to constant propagators. To directly compare electron scattering results to neutrino results, one should weight the electron scattering events by $1/\sigma_{Mott}$. This effect also means that, for a given incident energy, electron scattering is concentrated at lower momentum transfer than neutrino scattering. Therefore, to get similar statistics over the full range of momentum transfers relevant for a particular neutrino energy, it is crucial to measure electron scattering at the same and higher energies.

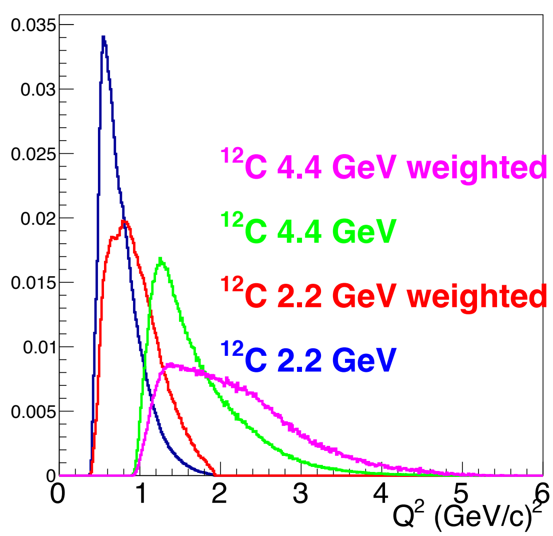

FIG. 5: The number of $^{12}\mathrm{C}(e,e')$ events with invariant mass $W < 2$ GeV for 2.2 and 4.4 GeV incident electron energy, normalized to the same area. The blue and green histograms show the number of 2.2 and 4.4 GeV events; the red and magenta show the same events, weighted by $1/\sigma_{Mott}$ to better reflect the expected distribution for neutrino events. The invariant mass cut is imposed to eliminate deep inelastic scattering events.

Fig. 5 shows the distribution of ${}^{12}\mathrm{C}(e,e')$ events (normalized to the same area) for 2.2 and 4.4 GeV electrons with and without the weighting by $1/\sigma_{Mott}$. The events are shown for invariant mass $W = [(m_p+\nu)^2 - \vec{q}^{\,2}]^{1/2} < 2$ GeV (where $\vec{q}$ and ν are the three-momentum and energy transfer) in order to eliminate DIS events. The weighted distribution has significantly fewer events at the lowest Q^2 and significantly more events at higher Q^2. To cover the Q^2 range of the 2.2-GeV weighted events, we need data at both 2.2 and 4.4 GeV. Similarly, to cover the the Q^2 range of the 4.4-GeV weighted events, we will need data at both 4.4 GeV and a higher energy.

III. NEUTRINO EVENT GENERATORS

Neutrino interactions are simulated using so-called "event generators" which provide a complete set of interaction processes on a wide range of target materials for an arbitrary neutrino beam energy. At the GeV-scale neutrino energies used by modern experiments, the neutrino can interact with the nucleus through a wide range of reaction channels. These include the quasielastic channel, the two-body channels shown in Fig. 4, resonance production leading to a pion in the final state, non-resonant pion production, deep inelastic scattering, etc. Generators provide the full kinematics of all particles exiting the nucleus in the output which is provided as input to a detector response model for simulation and event reconstruction.

Event generators are critical inputs in neutrino oscillation and cross section experiments. First, event generators easily simulate large numbers of neutrino interactions for the wide spectrum of neutrino energies and multiple target materials over a wide range of kinematics. Second, event generators are essential to calculate the efficiency of neutrino interactions. As it is impossible to simulate all possible combinations of leptons and hadrons out of a neutrino interaction, event generator output is used to seed the detector response simulation so acceptances and efficiencies can be calculated. This is especially important since neutrino detectors typically have 4π solid angles. Third, event generators also provide tools to estimate uncertainties on the neutrino interaction model. This is accomplished through the use of alternate models, or weighting schemes where an alternate model can be approximated with a thoughtful selection of weights to the existing simulation.

However, there are crucial assumptions inherent in generators and theoretical models which have implications for neutrino experiments. First, many of the models implemented in event generators do not include the most up to date theory understanding. Second, event generators, due to the needs of the experiments, are a combination of many different (possibly inconsistent) models. Such a Franken-model may not produce the correct total or differential cross section. Third, event generators are generally semiclassical (i.e., they work with cross sections, rather than amplitudes). This is a significant limitation since the nucleus is a quantum mechanical system and many of the interesting reaction mechanisms interfere strongly. Furthermore, they typically treat the primary interaction and final state interactions separately and incoherently. Mis-modelling, in the theory or the approximations in event generators, can lead to bias in extracted neutrino cross sections or oscillation parameters as discussed earlier.

In general, neutrino experiments cannot uniquely identify generator limitations. In neutrino experiments, the incident neutrino energy is unknown, so a given observable includes multiple reaction channels. Many modern neutrino detectors such as MicroBooNE, NOνA, MINERνA, and the proposed DUNE detectors can detect all final-state charged particles above a certain threshold and not just the scattered lepton. The hadronic state provides additional information with which to characterize neutrino interactions, but this does not resolve ambiguities between the FSI model or reaction channels, as seen by recent efforts on T2K [17].

Existing electron scattering data is insufficient for validation of the hadronic state in generators. Most generators have only been tested against inclusive (e, e') electron scattering data. Semi-inclusive (e.g., $(e, e'p)$ and $(e, e'\pi)$) data was mostly taken with small acceptance spectrometers at very specific kinematics. It is therefore important to provide electron scattering data with hadronic state information to test the different reaction channels in the event generators.

Testing neutrino event generators against a much wider range of electron scattering data will provide clear benefits even as deficiencies are exposed. The majority of models used for neutrino scattering can be run under an electron scattering configuration. This connection can be exploited to test and tune the models in event generators. Furthermore, the same parameters used to quantify agreement with electron scattering data can be provided to neutrino oscillation experiments, so that the impact of mis-modelling can be quantified and reduced. This will make electron scattering data a critical input to those physics programs.

Target	2.2 GeV (e,e')	2.2 GeV $(e,e'p)$	4.4 GeV (e,e')	4.4 GeV $(e,e'p)$
^{3}He	24.5	9.3	4.1	1.5
^{4}He	46.3	17.3	8.0	2.8
C	30.0	11.0	4.8	1.5
Fe	1.4	0.5	0.4	0.1

TABLE II: Available number of e2a good events in millions. "Good" events are those passing electron and proton particle ID, vertex, fiducial, and invariant mass $W < 2$ GeV cuts. The invariant mass cut is imposed to eliminate deep inelastic scattering events.

IV. PREVIOUS RESULTS

There have been several specific efforts by electron scattering labs to measure cross sections of interest for the neutrino community. In the early 2000s, JLab measured inclusive electron scattering, $A(e,e')$, cross sections on p, d, ^{12}C, Al and Fe targets at 1.2 GeV at 13, 16, 19, 22 and 28° to help guide neutrino experiments. They measured over a wide range of energy loss and separated the longitudinal and transverse response functions. This was an extension to experiments E04-001 and E02-109. Final cross sections are expected this year.

In 2016 JLab measured ^{40}Ar and ^{48}Ti$(e,e'p)$ in Hall A in order to measure their spectral functions [18]. These measurements focused on kinematic regions dominated by single-nucleon knockout and attempted to avoid regions dominated by two-nucleon currents and final state interactions.

Some data already exists on nuclear targets with the CLAS6 detector. We have started reanalyzing the data on 2.2, and 4.4 GeV electron beams incident on ^{3}He, ^{4}He, ^{12}C and Fe targets from the e2a data set (see Table II). There is a little data at 1.1 GeV on ^{3}He and ^{12}C from the e2a data set. There is also 4.4 GeV data on ^{3}He and Fe from the e2b data set and 5 GeV data on ^{12}C, Fe and Pb targets from the eg2 data set. Results from the preliminary analysis of the e2a data is presented below.

In addition, the CLAS12 hadronization and color transparency experiments will take 11 GeV data on ^{12}C, Pb and one or two other targets. This data can also be analyzed for purposes of understanding neutrino interactions.

A. Analysis of CLAS6 data

We have started analyzing 2.2 and 4.4 GeV e2a data from ^{3}He, ^{4}He, ^{12}C, and Fe targets in order to understand the quality of the neutrino QE event selection algorithms and energy reconstruction techniques.

We considered two commonly used energy reconstruction algorithms. If we use only the lepton kinematic information, then

$$E_\nu = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)} \tag{1}$$

where $\epsilon \approx 20$ MeV is the average binding energy, M is the nucleon mass, and the subscript l refers to the outgoing lepton. In the case of charged-current quasi-elastic (CC-QE) neutrino scattering, the outgoing lepton is a muon and its mass cannot be neglected. In the case of electron scattering, the outgoing lepton is an electron and $m_l \approx 0$. This technique is typically used with Cerenkov-type detectors, such as T2K.

If we consider events with a scattered electron and a proton but zero pions, then we can write that

$$E_{tot} = E_e + T_p + \epsilon \tag{2}$$

where E_e is the scattered electron energy, T_p is the proton kinetic energy, and $\epsilon \approx 20$ MeV is the average binding energy. Note that we can also calculate $E_{tot} = p_e^z + p_p^z$. This avoids the ambiguities introduced by the binding energy, but is broadened by the fermi momentum of the nucleons and is significantly less precise than the total energy method. This total energy technique is typically used in calorimetric-type detectors such as NOνA, MINERνA, MicroBooNE, and DUNE.

If we detect both the electron and a proton, then we can also calculate the perpendicular momentum of the electron plus proton, and use that to help identify QE events,

$$p_{perp}^{tot} = |\vec{p}_\perp^{\,e} + \vec{p}_\perp^{\,p}| \quad . \tag{3}$$

We started with e2a $(e, e'p)$ events. We applied the standard CLAS e2a momentum corrections, vertex corrections, particle ID cuts, and fiducial cuts. We weighted each of the events by $1/\sigma_{Mott}$ to remove the effects of the virtual-photon propagator and to better compare to neutrino data. In analogy with neutrino experiment analyses, we then selected events with no detected charged pions and with zero photons detected in the EC (from

π^0 decay) in order to enhance the "QE" signal. For each event with one detected pion, we calculated the acceptance of that pion in order to estimate the number of events with undetected pions so that we could subtract those events from the total.

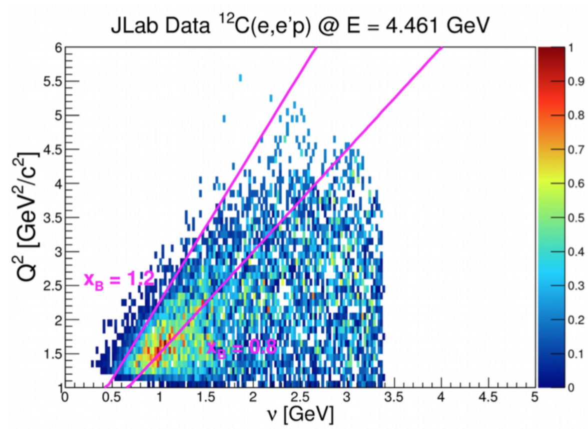

FIG. 6: (left) PRELIMINARY. The momentum transfer squared vs the energy transfer for 4.46 GeV C(e,e'p) events, after subtracting for undetected pions. The magenta lines show the approximate range of the QE peak $0.8 \leq x_B \leq 1.2$.

Even with the zero-pion enhanced-QE event sample, many of the events are clearly non-quasielastic. This can be seen in Fig. 6, which shows the momentum vs energy transfer distribution of 4.46 GeV C(e,e'p) events. Many of the events are outside the QE region, shown by the lines at $x_B = Q^2/2m\nu = 0.8$ and 1.2. The peak of the QE region is at $x_B = 1$.

Fig. 7 shows the reconstructed energy using Eq. 1 for 2.2 GeV electrons on C for all events, for events with no detected pions, and for events with no detected pions and subtracted for undetected charged pions. The subtracted spectrum shows a very broad peak at the electron beam energy. Fig. 7 also shows the reconstructed energy plotted versus the $(e, e'p)$ perpendicular momentum, $p_\perp^{tot} = |\vec{p}_\perp^{\,e} + \vec{p}_\perp^{\,p}|$. The events that reconstruct to the correct beam energy are almost all located at $p_\perp < 250$ MeV/c.

In order to reconstruct a true zero-pion spectrum, we estimated the contribution of the undetected pions by extrapolating from the angular acceptance of the detected pions event by event and subtracted this estimated contribution from the data. The distribution of reconstructed beam energies for events with one detected pion and for events with one undetected pion are shown in Fig. 8. The pion acceptance is approximately 50%. The background is now significantly decreased but there are still a very significant number of events that do not reconstruct to the beam energy, even in this zero-pion data set (see Fig. 7

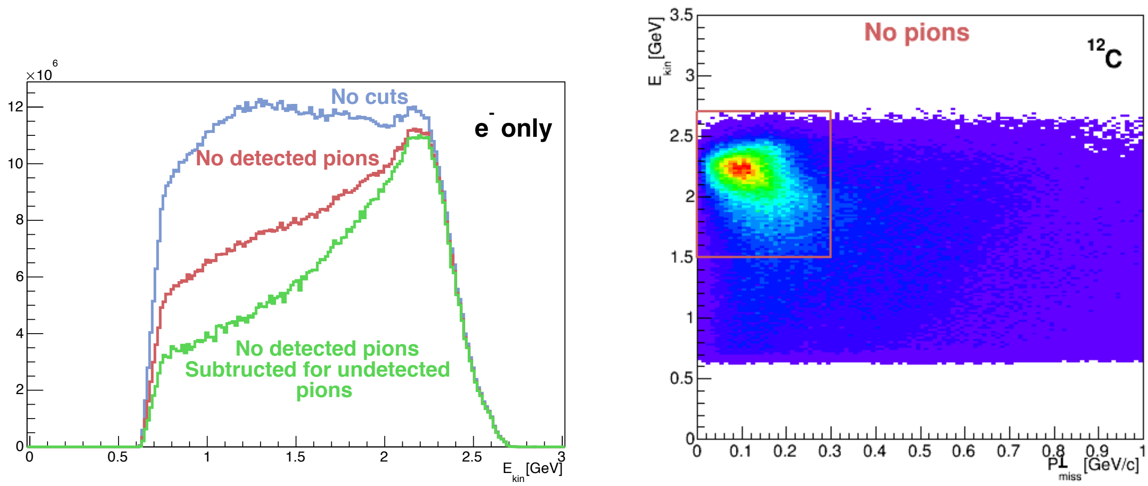

FIG. 7: (left) PRELIMINARY. The weighted number of events plotted versus the reconstructed incident electron energy using just the scattered electron kinematics for 2.2 GeV C$(e, e'p)$ events with (blue) no cuts, (red) no detected charged pions and (green) subtracted for undetected detected charged pions. The events are weighted by $1/\sigma_{Mott}$ to more closely resemble the angular distribution of a neutrino reaction; (right) the reconstructed energy with no detected charged pions plotted vs the $(e, e'p)$ perpendicular momentum, $p_\perp^{tot} = |\vec{p}_\perp^{\,e} + \vec{p}_\perp^{\,p}|$. The events which reconstruct to the correct beam energy almost all have $p_\perp < 0.25$ GeV/c.

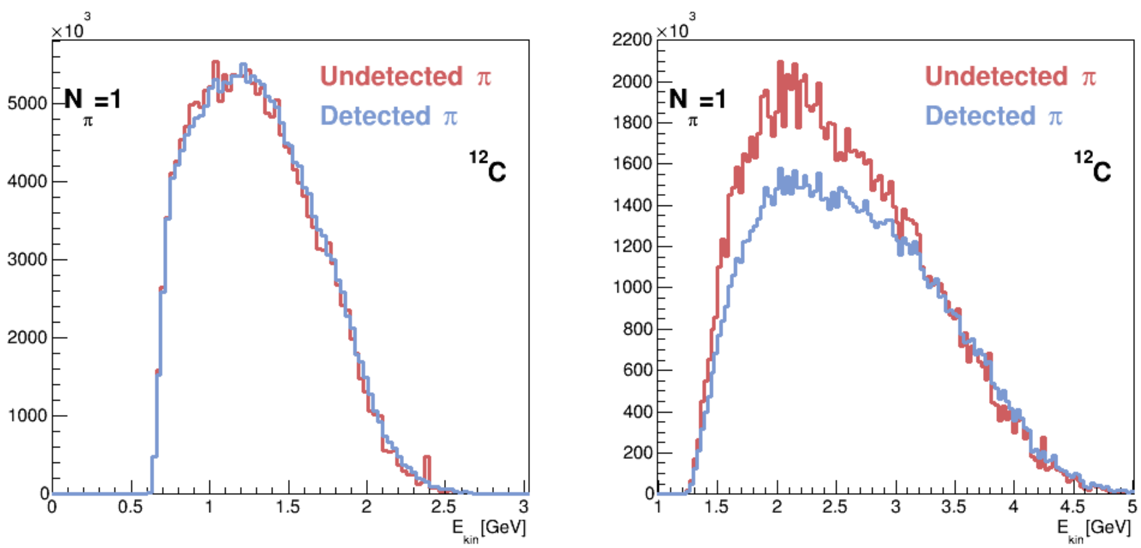

FIG. 8: (left) PRELIMINARY. The ^{12}C reconstructed incident electron energy using just the scattered electron kinematics for events with one detected pion (blue) and for events with one undetected pion (red) for (left) 2.26 GeV and (right) 4.46 GeV data.

left).

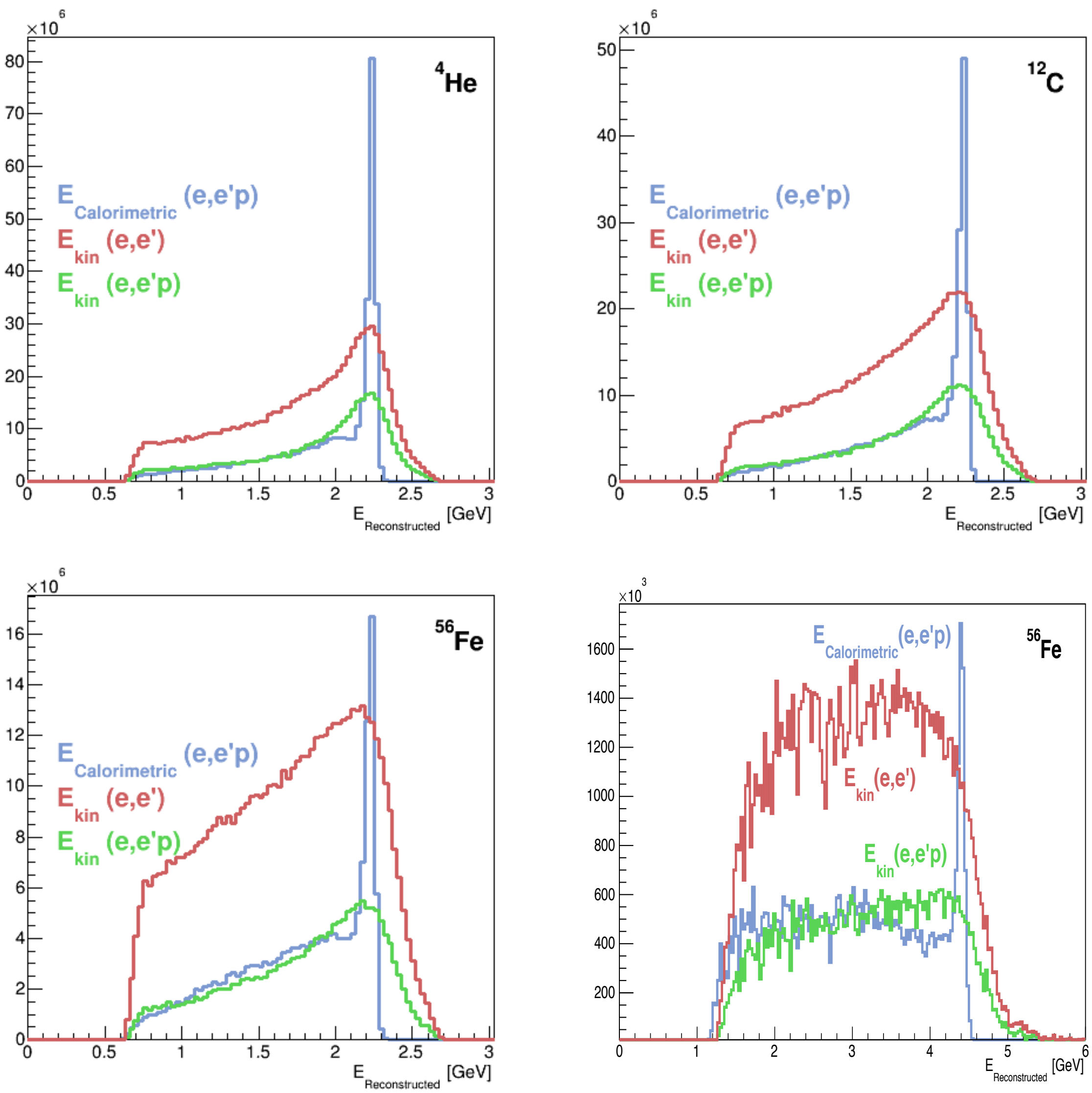

FIG. 9: PRELIMINARY. The pion-subtracted reconstructed incident energy (blue) for $(e, e'p)$ events using $E_{tot} = E_e + T_p + \epsilon$ (Eq. 2), (red) for (e, e') events using Eq. 1 and (green) for $(e, e'p)$ events using Eq. 1. (upper left) 2.26 GeV ^{4}He events; (upper right) 2.26 GeV ^{12}C events; (lower left) 2.26 GeV ^{56}Fe events, and (lower right) 4.46 GeV ^{56}Fe events. The horizontal axis is the reconstructed energy in GeV. The events are weighted by $1/\sigma_{Mott}$ to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

The resolution of the reconstructed energy spectrum improves dramatically when we include information about the detected proton. Fig. 9 shows that the calorimetric energy reconstruction is sharply peaked at the beam energy. However, only a minority of even these zero-pion events reconstruct to the beam energy. The low energy "tail" is the same for both energy reconstruction methods. Requiring a proton in the final state (i.e., comparing kinematic energy reconstruction for (e, e') and $(e, e'p)$ events) reduces the background significantly, but also reduces the number of events. Fig. 9 also shows that the statistical precision for 4.46 GeV is dramatically worse than at 2.26 GeV.

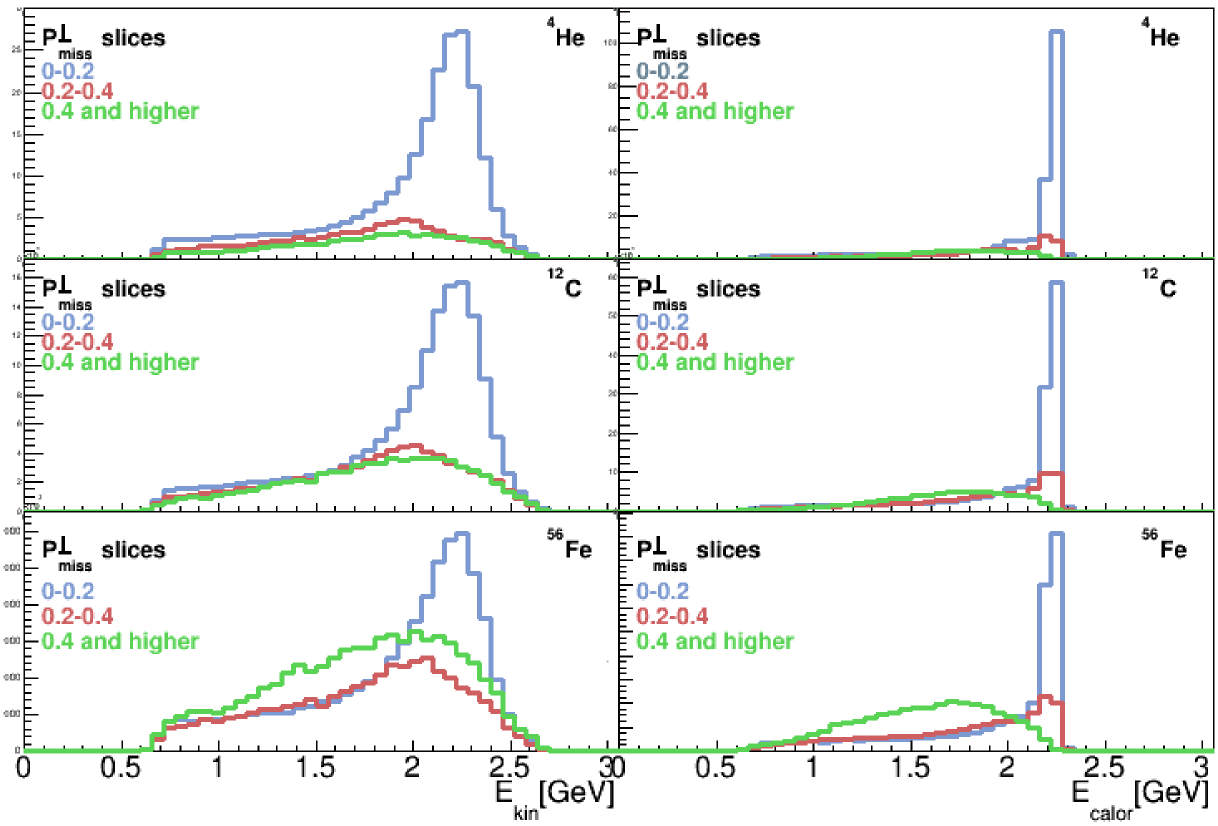

FIG. 10: PRELIMINARY. The pion-subtracted reconstructed $(e, e'p)$ incident electron energy using (left) just the lepton information of Eq. 1 and (right) the total energy of Eq. 2 for different $p_\perp$ slices. (top) ^{4}He; (middle) ^{12}C; and (bottom) ^{56}Fe. The events are weighted by $1/\sigma_{Mott}$ to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

The background fraction (i.e., the fraction of events that do not reconstruct to the beam energy) increases dramatically from ^{4}He to ^{56}Fe and from 2.2 to 4.4 GeV electrons (see Fig. 9). It is difficult to determine the dividing line between background and non-background events when using just the lepton information. There is a broad peak located at the beam energy with a wide tail extending to lower energies. However, the separation between the background and non-background events is very clear in the total energy distribution (which includes the proton information too); there is a narrow peak at the beam energy and a broad slowly decreasing background that extends to lower energies. This background is also

	2.2 GeV		4.4 GeV	
Target	$E_{kin}(e,e')$	$E_{cal}(e,e'p)$	$E_{kin}(e,e')$	$E_{cal}(e,e'p)$
^{4}He	0.23	0.46	0.21	0.34
C	0.20	0.39	0.16	0.27
Fe	0.16	0.26	0.11	0.14

TABLE III: Fraction of events reconstructed to within 5% of the beam energy at 2.26 and 4.46 GeV for the lepton-only method (E_{kin}) and for the electron energy plus proton energy method (E_{cal}).

Energy (GeV)	C	Fe
1.75–2	0.119±0.001	0.141±0.004
1.5–1.75	0.094±0.001	0.127±0.002
1.25–1.5	0.064±0.001	0.104±0.002
1–1.25	0.037±0.001	0.074±0.002
0.75–1	0.020±0.001	0.037±0.001

TABLE IV: Fraction of events reconstructed in different energy bins with $p_\perp > 0.2$ GeV/c for 2.26 GeV electrons for the electron energy plus proton energy method (E_{cal}).

significantly larger in ^{56}Fe than ^{4}He.

The effect of this background can be seen in the probability that the electron energy can be reconstructed within 5% of the beam energy for different energies and targets, see Table III. The reconstruction probability ranges from 11% to 46%. This "feed-down" of the beam energy can dramatically skew reconstructed neutrino oscillation parameters if it is not properly modeled.

Since we want to quantify this energy "feed-down", Tables IV and V show the uncertainties in the energy reconstruction spectrum for different bins in the reconstructed energy for 2.26 and 4.46 GeV electrons for $p_\perp > 0.2$ GeV/c. The $p_\perp$ cut increases the relative fraction of events in each reconstructed energy bin, but does not affect the relative uncertainty. Relative uncertainties at 2.26 GeV are very small, but uncertainties at 4.46 GeV are significantly larger, ranging from 3 to 10% in each bin. These tables are integrated over the entire momentum transfer range.

Energy (GeV)	C	Fe
1.5–2	0.071±0.007	0.112±0.007
2–2.5	0.065±0.008	0.132±0.006
2.5–3	0.082±0.007	0.141±0.005
3–3.5	0.119±0.006	0.143±0.004
3.5–4	0.122±0.004	0.110±0.003

TABLE V: Fraction of events reconstructed in different energy bins with $p_\perp > 0.2$ GeV/c for 4.26 GeV electrons for the electron energy plus proton energy method (E_{cal}).

Fig. 10 shows the reconstructed energy of Eqs. 1 and 2 for ^{4}He, ^{12}C and ^{56}Fe at 2.2 GeV cut on different bands of perpendicular momentum (Eq. 3). For $p_\perp < 0.2$ GeV/c, almost all events reconstruct to the beam energy, except for a small tail that contains a large contribution from radiative effects. However, at $0.2 \le p_\perp \le 0.4$, a much smaller fraction of the events reconstruct to the beam energy and at $0.4 \le p_\perp$ none of the events reconstruct to the beam energy. This is presumably due to the effects of non-QE reaction mechanisms, such as MEC, IC, FSI, etc.

Describing data like this for a wide variety of targets and beam energies will be a stringent test of the event generators.

B. Comparison to Neutrino Event Generators

We compared our data to two neutrino event generators, GENIE and GIBUU. We used the electron version of GENIE, which incorporates quasielastic scattering, 2particle-2hole interactions (which are intended to include the effects of SRC and MEC), and final state interactions. We are working on including resonance production and radiative effects.

Because electron-GENIE does not yet incorporate resonance production, we restricted our comparison to zero-pion $(e, e'p)$ events on the quasielastic peak, $0.8 \le x_B \le 1.2$ (see Fig. 11).

Despite restricting the event sample in this way, there is still a remarkable difference between data and GENIE. Fig. 12 shows the 4.46 GeV perpendicular momentum spectrum for data and for GENIE for C and for Fe. Both data and GENIE show a peak at $p_\perp \approx 0.1$

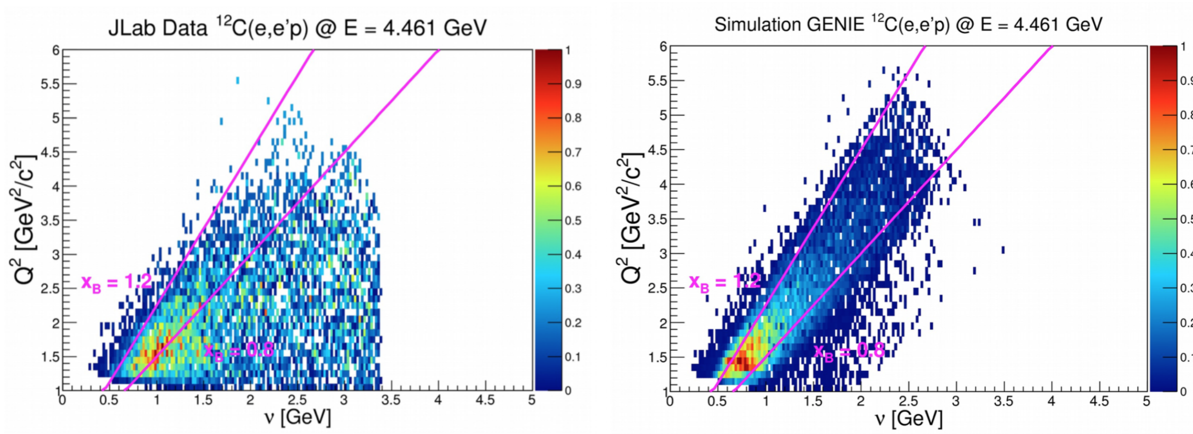

FIG. 11: (left) PRELIMINARY. The momentum transfer squared vs the energy transfer for 4.46 GeV C(e,e'p) events. The magenta lines show the approximate range of the QE peak $0.8 \leq x_B \leq 1.2$. (left) data, after subtracting for undetected pions; (right) GENIE.

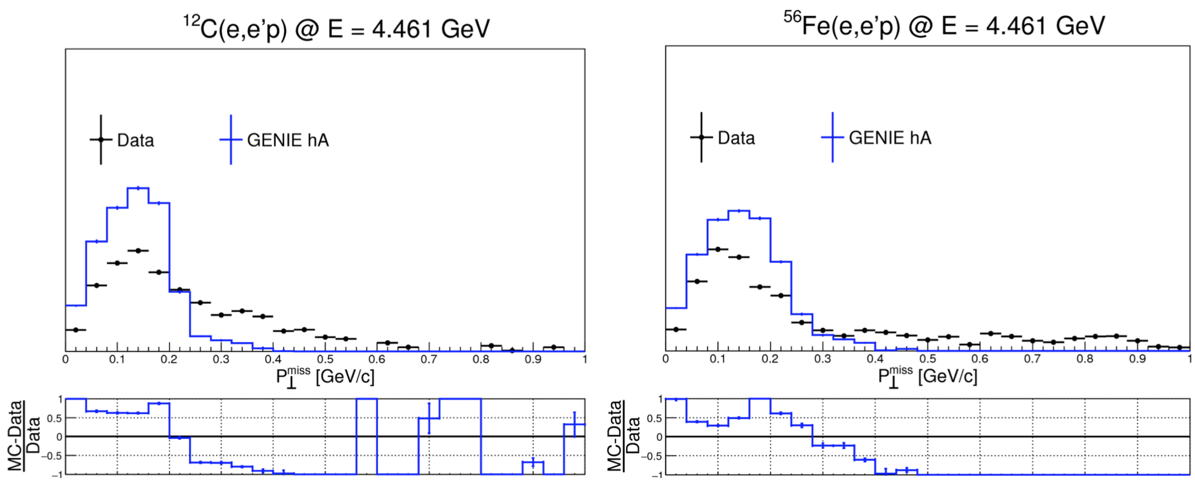

FIG. 12: (left) PRELIMINARY. The $p_\perp$ distribution of zero-pion QE ($0.8 \leq x_B \leq 1.2$) $(e, e'p)$ events for data (black points) and for GENIE (blue histogram) and the ratio (GENIE minus data divided by data) [bottom] for 4.46 GeV electrons. (left) Carbon and (right) Iron.

GeV/c. However, while the GENIE distribution has a small tail extending to $p_\perp \approx 0.4$ GeV/c, the data has a very large tail extending out to almost 1 GeV/c. This large tail is completely undescribed by GENIE.

There are various different models of FSI incorporated in GENIE that give slightly different results. GENIE hA is the current nominal standard, Fig. 13 shows the 2.26 GeV Carbon perpendicular momentum spectrum for data and for GENIE for different FSI models in GENIE. However, none of the FSI models describes the data at all well.

As can be seen in Fig. 14, there is a large difference between the reconstructed $(e, e'p)$

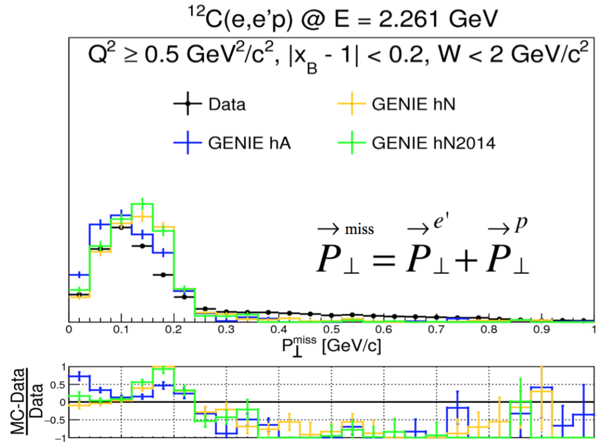

FIG. 13: (left) PRELIMINARY. The $p_\perp$ distribution of zero-pion QE ($0.8 \leq x_B \leq 1.2$) $(e, e'p)$ events for data (black points) and for GENIE with various FSI models (blue, green and yellow histograms) and the ratio (GENIE minus data divided by data) [bottom] for 2.26 GeV electrons and a Carbon target.

energy for data and for GENIE. The low $p_\perp$ events reconstruct well for both data sets, although the data has a long tail extending to small reconstructed energy that is probably partially due to electron radiation. However, the medium and large $p_\perp$ events reconstruct to incorrect beam energies and GENIE completely fails to reproduce these distributions.

The failure of GENIE to describe the reconstructed energy spectrum for the very restricted QE data set with zero pions and $0.8 \leq x_B \leq 1.2$ is remarkable. It shows that GENIE fails dramatically, even in the region where it should be most accurate.

C. The need for a systematic study

The existing CLAS6 data presented in this proposal is very instructive in showing the large potential of large acceptance electron scattering data to help address crucial neutrino-nucleus interaction issues. However, the data set is insufficient to perform the systematic study required to have high-impact on next generation of high-precision neutrino oscillation experiments. The existing data is largely limited to 2.2 and 4.4 GeV incident electron energy on ^{3}He, ^{4}He and ^{12}C nuclei with additional data for 5 GeV electrons on C, Al, Fe, and Pb targets. As explained below, this partial coverage of beam energies and target nuclei prevents the execution of the required detailed systematic study.

The lepton (electron or neutrino) interaction is determined by the energy and momentum

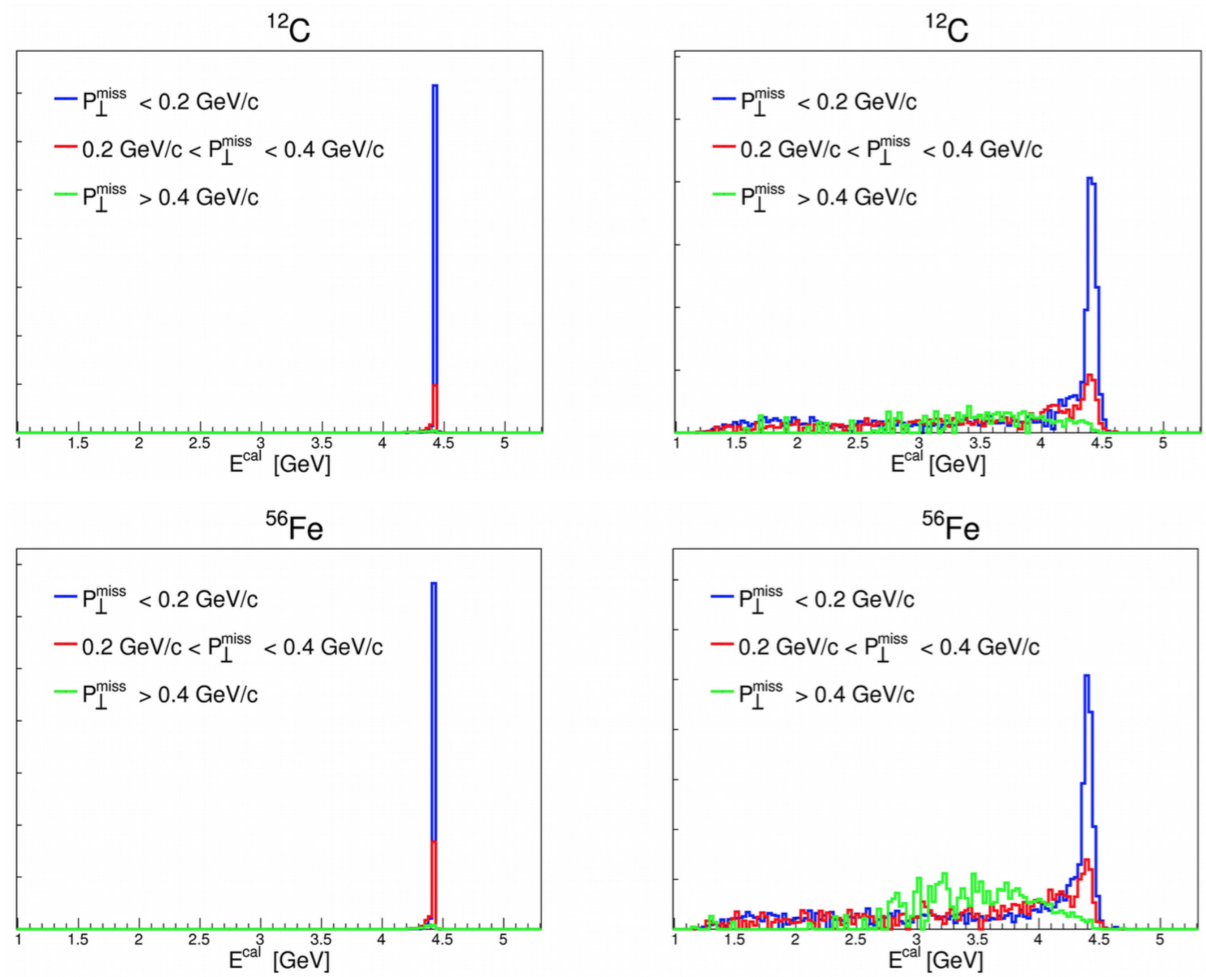

FIG. 14: (left) PRELIMINARY. The calorimetric reconstructed energy distribution of zero-pion QE ($0.8 \leq x_B \leq 1.2$) $(e, e'p)$ events for GENIE (left) and data (right) for Carbon (top) and Iron (bottom), for different regions in $p_\perp$ (blue: $p_\perp \leq 0.2$ GeV/c, red: $0.2 \leq p_\perp \leq 0.4$ GeV/c and green: $p_\perp \geq 0.4$ GeV/c).

transfers of the reaction. The electron-nucleus cross-section decreases dramatically with Q^2 whereas the neutrino-nucleus cross-section decreases much more slowly due to the large mass of the exchanged W boson. Therefore, to cover a comparable momentum transfer range to that obtained in neutrino scattering, higher energy electron beams are required (especially for the proposed DUNE experiment). It should also be noted that while current and future neutrino oscillation experiments use primarily C, O and ^{40}Ar nuclei, to constrain models of hadronic FSI requires data on both lighter and heavier nuclei. Without obtaining data on a nuclear mass range that is wider than that spanned by neutrino experiments, and at comparable momentum transfers, one can not ensure proper modeling of FSIs, multiplicity distributions and more. The beam-energies and target nuclei chosen for the current proposal are expected to provide an electron-scattering data-base over a wide enough phase-space in kinematical coverage and target nuclei to perform the systematic study required to maximize our impact on the next generation of neutrino oscillation analyses.

The latest NuPrint workshop requested multi-dimensional studies, in order to explore multi-particle correlations, such as proton-pion, and proton-neutron.

D. Projected impact on neutrino uncertainties

A preliminary analysis of the 6 GeV data shows the potential impact on Dune oscillation analyses. We used the 2.26 GeV ^{56}Fe reconstructed energy spectrum for zero-pion $(e, e'p)$ events. We assumed that the fractional energy feed-down was energy independent (i.e., that the probability of reconstructing an event to, e.g., 85% of the incident energy, was independent of the incident energy) and therefore used this spectrum for *all* incident energies. We compared the energy feed down for our data with the energy feed down from neutrino events with the DUNE Far Detector energy spectrum as simulated with GENIE and NEUT for CC zero-pion neutrino events. Fig. 15 (left) shows the fractional energy feeddown for 2.26 GeV zero-pion Fe$(e, e'p)$ events and for GENIE and NEUT CC zero-pion neutrino events.

GENIE shows a significantly larger energy feed down than NEUT (i.e., the total energy reconstructed in the detector is much smaller for GENIE events than for NEUT events), probably due to their differing predictions of final state neutrons. Measuring final state neutrons in CLAS will help resolve this difference between GENIE and NEUT. (We note that the DUNE near detector will have significant challenges to measure neutrons, so while the near detector has some sensitivity to different generator models, the different flux at the near and far detectors makes extrapolation from the near detector reliant on model assumptions.) The Fe$(e, e'p)$ data shows a much larger energy feed down than either the GENIE or NEUT results. Part of this difference could be due to the difference between neutral current electron scattering and charged current neutrino scattering.

We took the expected DUNE Far Detector neutrino flux and simulated the events using GENIE. We then reconstructed the neutrino energy spectrum using the GENIE, NEUT, and 2.26 GeV Fe data energy feed down spectra from Fig. 15 (left). Fig. 15 (right) shows the results. There is a small but significant difference in the reconstructed energy spectrum

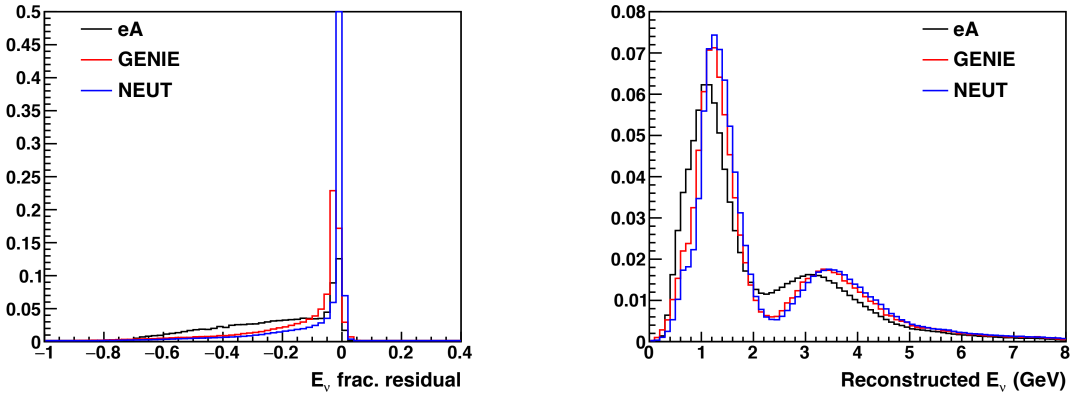

FIG. 15: PRELIMINARY: (left) The fractional energy reconstruction ("feed down") for (black) 2.26 GeV ^{56}Fe zero-pion $(e, e'p)$ events, and CC zero-pion neutrino events simulated with (red) GENIE and (blue) NEUT. (right) the reconstructed incident neutrino energy spectra for the DUNE far detector with oscillation included, simulated with GENIE and reconstructed with (black) $(e, e'p)$ data, (red) GENIE, and (blue) NEUT. Both data and simulation are cut on $Q^2 > 0.5$ GeV^2.

between GENIE and NEUT and a much larger and very significant difference between the measured $(e, e'p)$ data and the two neutrino monte carlos.

Much more work needs to be done to quantify these differences. We need to upgrade the electron version of GENIE to include all of the reaction mechanisms so we can compare electron scattering data to electron scattering MC (rather than to neutrino MC) and we need data at more beam energies so we can parametrize the energy feed down spectrum and not just use a single incident electron energy.

This is the first preliminary attempt to directly quantify the impact of this proposal on oscillation analyses. However, there is very strong support for this proposal among the neutrino experimental community (see the attached letters of support at the end of this proposal), as they expect that this data will have a significant impact on their programs as it improves reliability of the models. Many studies have shown that incorrect multinucleon process models can bias neutrino oscillation results, but a similar effect is possible in other channels. An incomplete list of studies are Ref. [4–10, 19]. The flux integrated nature of near detector and neutrino nuclear scattering data alone is insufficient to probe all parameters in the model.

One other example of how this proposal will impact current and future experiments is with semi-inclusive neutron measurements. The difference between neutrino and antineutrino oscillation is used to infer CP violation (dCP). As a result, differences between neutrinos and antineutrinos in the interaction model must be understood in great detail. Because in charged current interactions $\nu \rightarrow \mu^-$ and $\bar{\nu} \rightarrow \mu^+$, antineutrino interactions have more neutrons in the final state than neutrino interactions. One of the most troubling challenges to tackle experimentally is the identification of neutrons in neutrino interactions. Unidentified neutrons carry away energy from the interaction, which creates a bias in the energy estimation in oscillation experiments. The beam in neutrino mode typically has about 5–10% anti-neutrinos and the beam in anti-neutrino mode typically has $\approx 30\%$ neutrinos, making knowledge of the neutron contribution to the neutrino and anti-neutrino interactions even more important.

V. THE PROPOSED MEASUREMENT

We propose to extend these electron scattering measurements to a wider range of nuclei and beam energies in order to perform a systematic study of neutrino energy reconstruction techniques and to provide data to dramatically improve neutrino event generators. Modern neutrino detectors contain large amounts of ^{12}C, ^{16}O and ^{40}Ar. Carbon is the primary nuclear constituent of scintillator, oxygen is the primary nuclear constituent of water Cerenkov counters, and the proposed DUNE detectors will be liquid-Argon Time Projection Chambers. By spanning a range of nuclei both heavier and lighter than the ^{12}C, ^{16}O and ^{40}Ar of typical neutrino detectors, we can help significantly constrain the A dependence of the event generator physics models. We plan to measure scattering on ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, and Sn.

We plan to measure both ^{12}C and ^{16}O at the lower energies of interest to the Accelerator Neutrino Neutron Interaction Experiment (ANNIE), Tokai to Kamioka (T2K), and forthcoming HyperKamiokande (HK) experiments. The T2K near detector uses both scintillator (i.e., largely carbon) and water. Both ANNIE and the T2K far detector (Super-Kamiokande) use water Cerenkov counters to detect neutrinos. CLAS12 data on both ^{12}C and ^{16}O at the energies relevant to T2K will provide a crucial complementary test of the models needed to compare their near and far detector data sets. The CLAS data will also be useful for combining the results of the T2K and NOνA (liquid scintillator [i.e., carbon-based]) experiments.

We need to cover a wider range of incident beam energies than the neutrino experiments in order to cover a similar range in momentum transfer (Q^2). Because the photon is massless, electron scattering is very forward peaked and thus concentrated at relatively low Q^2. Because the W and Z bosons are so massive, neutrino scattering is far more isotropic and therefore samples a much wider range of Q^2 at the same incident energy (Fig. 5). We plan to measure at 1.1, 2.2, 4.4, and 6.6 GeV incident energies, spanning the range of beam energies and especially momentum transfers covered in neutrino measurements.

The low energy (1.1 and 2.2 GeV) measurements will be at reversed CLAS field in order to extend our measurements to lower Q^2 to better match some of the low energy neutrino measurements such as T2K.

We will take advantage of the large acceptance of the CLAS12 detector to use detected hadrons (primarily pions and protons) to identify and isolate specific channels with contributions from specific reaction mechanisms. We plan to focus on and identify QE scattering and quasi-free resonance production events, as well as identifying events from more complicated processes. We will compare our measured yields to those predicted by the standard neutrino event generators. We will also test energy reconstruction algorithms for the wide range of beam energies, targets, and reaction channels/event topologies.

In addition, we will use the enhanced CLAS12 neutron detection capabilities to identify events with energetic neutrons. CLAS12 will have much better neutron detection capabilities than CLAS6, due to the extra layers of the forward electromagnetic calorimeter (the preshower detector) and to the central neutron detector. These energetic neutrons are typically not detected in neutrino experiments, even in hermetic detectors such as MicroBooNE and MINERνA, leading to misidentification of the incident neutrino energy. This effect is especially important for the CP violation studies discussed in the previous section. The results will also be compared to neutron measurements at MINERνA and NOνA.

We plan to spend 4 hours at each beam energy on a hydrogen target for calibration purposes, especially to measure the resolution and efficiency of neutron detection through the H$(e, e'\pi^+)n$, and H$(e, e'\pi^+\pi^+\pi^-)n$ reactions.

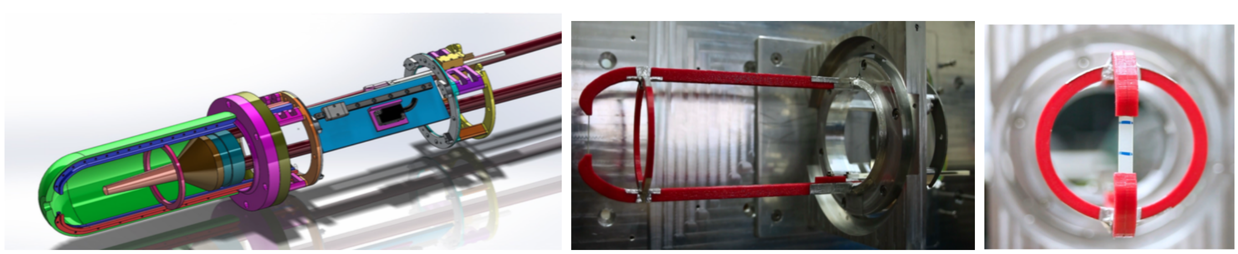

FIG. 16: The CLAS12 target system under development at UTFSM. (left) a drawing of the system showing the target vacuum enclosure (green), the tapering liquid target cell (copper), and the upper (blue) and lower (red) supports for the solid target tape; (middle) the prototype solid target system with the upper and lower supports (red). The tape with the solid targets passes between the upper and lower supports at the far left; (right) end view looking upstream at the tape with the solid targets.

We need one piece of equipment beyond the baseline. We plan to use a new CLAS12 liquid and solid target system under development by W. Brooks, H. Hakobyan and I. Vega at the Universidad Tecnica Federico Santa Maria (UTFSM) for the approved experiment E12-06-117. This system has a small (several-cm) liquid target cell followed by solid targets on a moveable “tape” system. See Fig. 16. The target system is already fully designed and key components have been tested. It can be ready for use in 2019.

The Saclay cryotarget is currently configured to handle liquids from H to ^{4}He. We will need software modifications to the cryotarget to handle oxygen and argon, with their much higher boiling points.

We plan to generate yield maps and cross sections for different types of events (zero pion, zero pion one proton, one pion, etc) that can be compared to the results of neutrino event generators run through the CLAS12 monte carlo. This will significantly reduce the uncertainty inherent in creating cross sections for these types of events.

CLAS12 should be able to run at a luminosity of $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} for nuclear targets, about 10 times greater than CLAS6. The data shown in Fig. 10 each represent about 5 days of beam time at a luminosity of 10^{34} cm^{-2}s^{-1} and therefore correspond to about 0.5 days of CLAS12 beam time.

We project that we will need significantly more statistics than were acquired using CLAS6 at 4.46 GeV in order to study the neutron channels and to subdivide the data into five different bins in Q^2 at each beam energy and into different reaction channels (e.g., $(e, e'p)$, $(e, e'pp)$, $(e, e'p\pi)$, $(e, e'pn)$, etc.). Using the entire existing 4.46 GeV ^{12}C data set, the relative uncertainty is about 10% in the fraction of events in a 0.5 GeV reconstructed energy bin. If we subdivide the data set into five Q^2 bins, this uncertainty will more than double.

Therefore, we request 0.5 days for each target and beam energy combination at 1.1 GeV where the cross sections are largest, increasing to 2 days at each beam energy and target at 6.6 GeV due to the decreased cross section at higher energies. This will approximately double the statistics of the CLAS6 data, with an even greater improvement in the neutron channels. We will adjust the beam current and target thicknesses to attain the desired luminosity.

Due to the inadequacies of nuclear models spanning all of the reaction channels energies and targets, scaling our expected statistics from the measured CLAS6 data is a far more reliable method of estimating the beam time needed than performing detailed simulations.

Although C has already been measured in CLAS6 at the lower energies, it is important to measure both ^{12}C and ^{16}O with the exact same beam energies and detectors in order to provide meaningful comparison data for ANNIE and T2K. Similarly, in order to reduce systematic uncertainties in comparing data sets and to take advantage of the improved

Energy (GeV)	^{4}He	^{12}C	^{16}O	^{40}Ar	Sn	Total
1	0.5	0.5	0.5	0.5	0.5	2.5
2.2	1	1	1	1	1	5
4.4	1	1	0	1	1	4
6.6	2	2	0	2	2	8
Total (days)	4.5	4.5	1.5	4.5	4.5	19.5

TABLE VI: Beam time requested for each beam energy and target (days). This does not include 28 hours of overhead per beam energy (5 days total) for energy and target changes plus 1 day for calibration with hydrogen.

capabilities of CLAS12, we are requesting time to remeasure ^{4}He at 2.2 and 4.4 GeV.

We expect that pass changes will take 4 hours (according to Arne), solid target changes will take a few minutes, and liquid target changes will take 8 hours (according to Bob Miller). Thus, we request another 28 hours of overhead per beam energy for beam energy and target changes for a total of 5 days.

Our total request is for 25.5 days, including 19.5 days of data taking, 1 day of calibration, and 5 days of beam energy and target changes.

This experiment will not be sensitive to the exact beam energies and can easily adapt the specific energies used to the requirements of the accelerator and scheduling.

A. Run group proposal with "Exclusive Studies of Short Range Correlations in Nuclei"

This proposed experiment can run along with the "Exclusive Studies of Short Range Correlations in Nuclei" proposal as run group, using the CLAS12 detector in its standard configuration. By running these experiments together, targets, beam time, and calibrations can be shared in addition to the complementary nature of the physics to be studied. These experiments will take data at common beam energies of 4.4 and 6.6 GeV on several of the same targets. They will overlap on a total of 9 days at 4.4 and 6.6 GeV. The information obtained in both experiments is useful for understanding detector-related efficiencies and reconstruction effects, as well as contributions from FSIs and other reaction mechanisms that are important for of both analyses. The Short-Range Correlations in Nuclei proposal will expand the nuclear mass range over a wide phase space in kinematical coverage which will directly improve the data we take in the Electron for Neutrinos proposal.

VI. SUMMARY

Neutrino experiments are one of the priorities of the Particle Physics Project Prioritization Panel's 2014 Strategic Plan. In order to achieve the goals of these experiments, we will need to dramatically improve our understanding of how neutrinos and anti-neutrinos interact with matter.

Because neutrinos and electrons are both leptons, they interact with nuclei in similar ways. We propose to measure electron scattering from a variety of targets at a range of beam energies in CLAS12 in order to test neutrino event selection and energy reconstruction techniques and to benchmark neutrino event generators. Event generators are critical inputs in neutrino oscillation and cross section experiments; providing data to test and improve those generators can significantly decrease the systematic uncertainties in neutrino experiments.

We request 19.5 days of beam time in Hall B to measure electron scattering at 1, 2.2, 4.4, and 6.6 GeV from ^{4}He, ^{12}C, ^{16}O, ^{40}Ar, and Sn targets plus 1 day of calibration time on an H target and 5 days of overhead for energy and target changes. These energies and targets span those used in major neutrino experiments, including MicroBooNE, MINERνA, NOνA, T2K, and the forthcoming HK, ANNIE and DUNE.

This will provide enough data over a very wide range of energies and targets to help reduce one of the major uncertainties in current and especially next-generation neutrino oscillation experiments. Letters of support from the major neutrino collaborations are attached to the end of this proposal.

This data will enable the first tests of neutrino energy reconstruction with actual data (rather than with simulations that do not capture all of the underlying nuclear physics). Electron scattering data has never been analyzed in the same way as neutrino data with the goal of really understanding how well we can predict incoming neutrino energies, a crucial variable in the analysis and interpretation of neutrino oscillation data.

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May 19, 2017

Jefferson Lab Program Advisory Committee
12000 Jefferson Avenue
Newport News, VA 23606

Subject: Electrons for Neutrinos Addressing Critical Neutrino-Nucleus Issues Proposal to Jefferson Lab PAC 45 - DRAFT

Dear Jefferson Lab Program Advisory Committee,

We are writing in support of the proposal "*Electrons for Neutrinos: Addressing Neutrino-Nucleus Issues*" that is being submitted to the Jefferson Lab PAC. This work specifically targets the measurement of electron scattering on a variety of nuclei and beam energies relevant for current and upcoming neutrino experiments. The fact that this data is being collected in a 4π detector will additionally allow exploration of a variety of final state kinematics and facilitate direct comparison with neutrino scattering measurements.

The incident neutrino energy is an important parameter in the analysis of neutrino oscillations. It has never before been tested with data how well the incoming neutrino beam energy can be reproduced in neutrino-nucleus interactions. This data will allow such a test given that the incoming electron beam energy is known and the analysis of this data will be carried out in a way similar to techniques employed in the analysis of neutrino data. These results will be of value to multiple neutrino experiments that use nuclei as neutrino targets and will provide important input to both the short and long-baseline neutrino programs at Fermilab.

We hope that you review this proposal favorably.

Sincerely,

Joseph Lykken

Attachment: Neutrino Proposal 2017

Fermilab

Deborah Harris
MINERvA Department Leader
Neutrino Division
630.840.4545
dharris@fnal.gov

May 16, 2017

Jefferson Laboratory Physics Advisory Committee

Dear JLAB Physics Advisory Committee,

We are writing in support of the new proposal to study electron scattering on He, C, O, Ar, and Pb using electron energies of 1.1 through 8.8 GeV with the CLAS12 Spectrometer, "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues".

The discovery of neutrino mass and mixing has inspired a new generation of neutrino oscillation experiments, that imposes stringent new requirements on our understanding of the impact of the nuclear environment on neutrino scattering. These same neutrino oscillation experiments have also given rise to intense neutrino beams, which in turn have allowed for a dedicated neutrino scattering experiment. The MINERvA experiment's goal is to measure and compare neutrino scattering cross sections on different nuclei using neutrinos in the few GeV range. We are writing on behalf of that collaboration to say that we very much encourage the electron scattering measurements coming from the Electrons for Neutrinos proposal, since they are key to help shed light on these interactions.

To model neutrino interactions at oscillation experiments, many different effects must be parameterized and measured. At the moment, neutrino experiments have to disentangle uncertainties related to both vector and axial currents, and to the impact of the nuclear environment. While some of these, such as the axial vector component of the neutrino-nucleon cross section, are best measured by neutrino experiments such as MINERvA, several other effects can be precisely measured in electron scattering experiments. The Electrons for Neutrinos data will substantially improve the reach of MINERvA by constraining models of the vector current and impact of the nuclear environment, thus allowing us to use the full power of the MINERvA data to measure effects specific to neutrino scattering.

Although near detectors are planned for all long-baseline oscillation experiments, they simply are not enough to constrain the models needed for the high precision predictions for the far detector. Part of the reason for this is that due to the large mixing angles, the far detector spectra are substantially different from the near detector spectra. The next goals in the field are associated with precise comparisons of electron neutrino to antineutrino appearance. One has simply to look at T2K's recent oscillation papers to understand how much oscillation experiments rely on external cross section measurements. This reliance will only increase as accelerator-based oscillation experiments become systematically dominated over the next decade.

Having a systematic electron scattering data-base with various final states obtained on a wide range of nuclei and beam-energies will significantly constrain our neutrino event generators will also allow MINERvA itself to make better measurements: we do our best to predict backgrounds using our own data but we too must extrapolate, in our case from other kinematic regions, and the better that extrapolation is the better our measurements will be.

Please contact us if you have any additional questions about how these data will support MINERvA's physics program.

Sincerely,

Laura Fields

Deborah Harris

MINERvA Spokespeople
on behalf of the MINERvA Collaboration

Prof Tsuyoshi Nakaya
Kyoto University
Dr Morgan O. Wascko
Imperial College London

Prof Jim Napolitano
Chair, Jefferson Lab Program Advisory Committee

cc: Prof Or Hen, Prof Kendall Mahn, Prof Larry Weinstein

Monday, 15 May 2017

Dear Prof. Napolitano:

We are writing in support of the new proposal to study electron scattering on He, C, O, Ar, and Pb using electron energies of 1.1 through 6.6 GeV with the CLAS12 Spectrometer, "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues".

Neutrino oscillation experiments require the ability to reconstruct the neutrino's initial energy. However, neutrino beams are inherently wide-band in energy with respect to the nuclear effects that drive the systematic uncertainties of neutrino oscillation analyses; this complicates the task of neutrino energy reconstruction for oscillation experiments.

Electron-scattering experiments, on the other hand, can precisely determine the initial energy of electron beams, providing a laboratory for studying the same hadronic scattering effects that complicate the reconstruction of neutrino energy for T2K. Thus, these data would help us validate our neutrino interaction model in a new way.

Because of the large potential benefits to the T2K neutrino-interactions and oscillation physics programme, we strongly support this proposal.

Best regards,

T. Nakaya and M. Wascko
T2K Spokespersons

Kamioka Observatory, ICRR, The University of Tokyo

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THE UNIVERSITY OF TOKYO

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Institute for Cosmic Ray Research
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October 9, 2016

May 12th 2017

Dear Jefferson Lab Program Advisory Committee,

I am writing to express the support of the Hyper-Kamiokande proto-collaboration for the "Electrons for Neutrinos: Addressing Critical Neutrino Nucleus Issues" experiment being proposed to the Jefferson Lab PAC.

The field of neutrino oscillations studies is undergoing a major transition as we move from first 'observations' to high precision quantification of oscillation parameters and searches for new physics. Future experiments like Hyper-Kamiokande will have massive data sets with 2% statistical uncertainty.

One of the main sources of systematic uncertainties in neutrino oscillation analyses are neutrino-nucleus cross sections. The use of wide-energy neutrino beams, combined with the vector-axial nature of the neutrino interaction, makes reducing and quantifying this uncertainty a considerable challenge. The use of near and far detectors significantly helps mitigate this situation. However as neutrinos oscillate between the two detectors, their energy spectra can be very different which leads to a systematical uncertainty that is still significant. In addition to the beam neutrino and antineutrino source, Hyper-Kamiokande will also use atmospheric neutrinos. Therefore, our knowledge of neutrino-nucleus cross sections, specifically for the various reaction channels in the 1--10 GeV region, needs to be significantly improved. The multinucleon emission channel is particularly problematic as the models have a large amount of uncertainty associated to them. The multiplicity of protons and neutron emission is also of high interest as the current generation experiment, Super-Kamiokande, will undergo gadolinium doping to enable neutron tagging.

Data gathered in the proposed JLab experiment will be particularly helpful in calibrating neutrino event generators, incident neutrino energy reconstruction algorithms and quantifying the remaining systematical uncertainties. The use of the large-acceptance, open trigger, CLAS spectrometer with its multiple particle detection capabilities is a unique feature of this proposal that makes it of particular interest for neutrino experiments. The detection of neutrons is quite interesting. I therefore endorse this proposal and hope it will be approved.

We are particularly interested in the 1 and 2 GeV data on O targets, the target material of the Hyper-Kamiokande experiment, but I note that data at multiple energies and targets is important to validate the entire model.

Sincerely,

Masato Shiozawa

Masato SHIOZAWA
The University of Tokyo
Project leader of the Hyper-Kamiokande

Prof. Mark Messier
Indiana University
Dr. Peter Shanahan
Fermilab

May 19, 2017

Prof. Jim Napolitano
Chair, Jefferson Lab Program Advisory Committee

Cc: Prof. Or Hen, Prof. Kendall Mahn, Prof. Larry Weinstein

Dear Prof. Napolitano,

We are writing to express our support for proposal P45 "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues''.

For long-baseline neutrino experiments such as NOvA, the precision with which neutrino cross-sections and the topologies of their final states are modeled can limit our ability to understand the neutrino rates we observe in our near detector. While most of this uncertainty cancels when comparing near and far detectors for neutrino oscillation measurements, important uncertainties remain and the collaboration invests considerable analysis effort to understand the observed differences between simulation and data in near detector. In addition to reducing this effort and the final uncertainty in oscillation measurements associated with neutrino interaction modeling, external constraints from electron scattering as may be provided by P45 also stand to enhance the efficiency and power of neutrino interaction studies using data from our near detector.

The NOvA detectors are largely composed of carbon and the neutrino energy spectrum peaks at 2 GeV; thus the planned P45 program of nuclei and energies is well matched to our experimental conditions.

Sincerely,

Mark Messier and Peter Shanahan

Co-spokespersons for the NOvA Collaboration

Prof. Bonnie Fleming
Yale University
Dr. Geralyn (Sam) Zeller
Fermilab

May 18, 2017

Dear Jefferson Lab Program Advisory Committee,

On behalf of the MicroBooNE collaboration, we are writing to you in strong support of the proposal "*Electrons for Neutrinos: Addressing Neutrino-Nucleus Issues*" that has been submitted to the Jefferson Lab PAC. MicroBooNE is currently operating a 170 ton liquid argon TPC that is studying short-baseline neutrino physics at Fermilab. Given the dearth of existing electron scattering data on argon and the need to improve our understanding of neutrino-argon interactions, we see a clear and urgent need for these proposed measurements. We are particularly interested in understanding with this data how well we can constrain the incoming (unknown) neutrino energy in MicroBooNE. This is a measurement that has not been done before with electron scattering data and has the potential to significantly advance our understanding of the complex nuclear effects impacting our neutrino measurements.

The future liquid argon-based neutrino program, including MicroBooNE, will be immediate beneficiaries of this important data. We hope that you review this proposal favorably.

Sincerely,

Bonnie Fleming
Geralyn (Sam) Zeller
MicroBooNE Spokespeople

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May 18, 2017

Dear Jefferson Lab Program Advisory Committee,

We are writing in support of the new proposal "Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issues" that aims to study electron scattering on different target nuclei at a range of energies.

Neutrino oscillation measurements, like those produced in IceCube's DeepCore array, are reliant on robust predictions of neutrino-nucleus cross sections. The use of wide-energy neutrino beams, combined with the vector-axial nature of the neutrino interaction, makes reducing and quantifying this uncertainty a considerable challenge. Electron-scattering experiments, on the other hand, may precisely determine the initial energy of electron beams, providing a laboratory for studying the same hadronic scattering effects that complicate the reconstruction of neutrino energy. These measurements, in particular those to be obtained in the proposed Jefferson Lab experiment at higher energies, are expected to be especially beneficial in testing the suite of models currently used on the IceCube experiment for oscillation physics.

Sincerely,

Darren R Grant
IceCube Collaboration Spokesperson
Canada Research Chair in Astroparticle Physics

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Prof. Matthew J Wetstein
Iowa State University
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May 11, 2017

Dear Jefferson Lab Program Advisory Committee,

We are writing to express the support of the ANNIE collaboration for the "Electrons for Neutrinos: Addressing Critical Neutrino Nucleus Issues" experiment being proposed to the Jefferson Lab PAC.

The field of neutrino oscillations studies is undergoing a major transition as we move from first 'observations' to high precision quantification of oscillation parameters and searches for new physics. One of the main sources of systematic uncertainties in neutrino oscillation analyses are neutrino-nucleus cross sections. The use of wide-energy neutrino beams, combined with the vector-axial nature of the neutrino interaction, makes reducing and quantifying this uncertainty a considerable challenge. Of a particular challenge is the production and simulation of neutrons out of neutrino interactions, where the missing energy can lead to a bias in the neutrino energy. The ANNIE experiment will make the first measurements on water of neutron yields. However, the hadronic models available in neutrino event generators are not well tested.

Data gathered in the proposed JLab experiment will be particularly helpful in calibrating neutrino event generators, incident neutrino energy reconstruction algorithms and quantifying the remaining systematical uncertainties. The use of the large-acceptance, open trigger, CLAS spectrometer with its measurement of neutrons are a unique feature of this proposal.
We therefore endorse this proposal and hope it will be approved.

We are particularly interested in the 1 and 2 GeV data on O targets which are relevant to the ANNIE energy spectrum peaked at 700 MeV.

Yours sincerely,

Matthew Wetstein

Mayly Sanchez

(on behalf of the ANNIE collaboration)