

Electrons for Neutrinos

Addressing Critical Neutrino-Nucleus Issues

Proposal to Jefferson Lab PAC 45

F. Hauenstein, C. Hyde, M. Khachatryan, S. Kuhn, L.B. Weinstein (co-spokesperson)
Old Dominion University, Norfolk VA

O. Hen (contact person), A Papadopoulou, A. Schmidt, E.P. Segarra, and R. Cruz Torres
Massachusetts Institute of Technology, Cambridge, MA

E.O. Cohen, M. Duer, and E. Piasetzky (co-spokesperson)
Tel-Aviv University, Tel Aviv, Israel

K. Mahn (co-spokesperson), J. Morrison, L. Pickering
Michigan State University, East Lansing, MI

D. Higinbotham, S. Stepanyan (co-spokesperson), S.A. Wood
Thomas Jefferson National Accelerator Facility, Newport News, VA

A. El Alaoui, Hayk Hakobian, T. Mineeva, J. Miller, W. Brooks
Universidad Tecnica Federico Santa Maria (UTFSM), Valparaiso, Chile

I. Balossino, L. Barion, G. Ciullo, M. Contalbrigo,
P. Lenisa, A. Movsisyan, and L.L. Pappalardo
INFN Ferrara and University of Ferrara, Ferrara, Italy

D. Watts and L. Zana
Edinburgh University, Edinburgh, Scotland

D. Ireland and D. Sokhan
Glasgow University, Glasgow, Scotland

M. Betancourt
Fermi National Accelerator Laboratory, Batavia, IL

T. Katori
Queen Mary University, London, Great Britain

M. Hattawy
Argonne National Laboratory, Argonne, IL

N. Kalantarians
Virginia Union University, Richmond, VA

and the CLAS12 Collaboration

(Dated: May 21, 2017)

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. Different detectors use different techniques. Water Cherenkov-detector based experiments, which cannot measure protons, create charged-current quasi-elastic (QE) enhanced event samples by rejecting pions and then estimate the neutrino energy based on only the measured lepton kinematic information. Calorimetric-detector experiments use a combination of leptonic and hadronic information. 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 41 days of beam time in Hall B to measure electron scattering at approximately 1, 2.2, 4.4, 6.6 and 8.8 GeV from H, ^4He , ^{12}C , ^{16}O , ^{40}Ar , and Pb targets. This time includes 1 day of calibration time on an H target and 3.5 days of overhead for target and energy changes. The energies and targets span those used in major neutrino experiments, including MicroBooNE, MINER ν A, NO ν A, 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.

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 $\text{NO}\nu\text{A}$ 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-

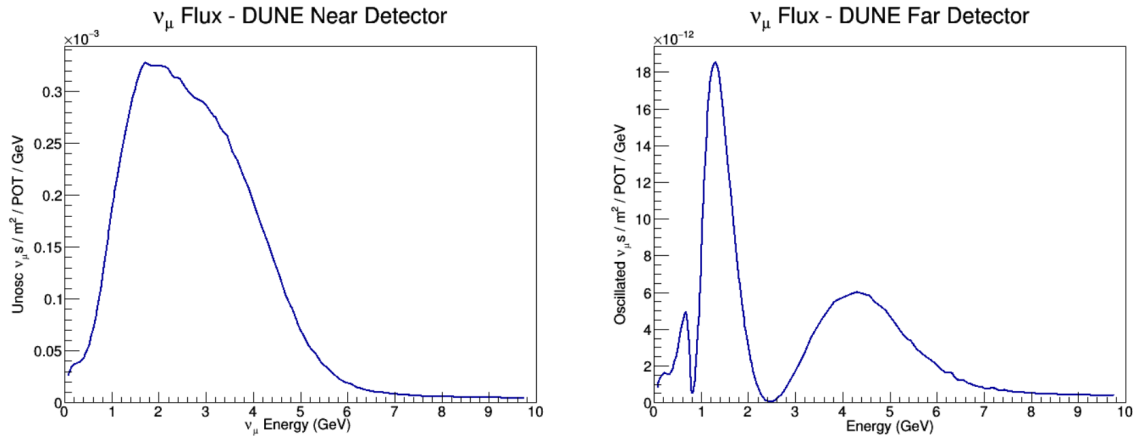


FIG. 1: The expected incident energy distribution of the DUNE ν_μ beam at the near detector (left) and the far detector (right).

nologists [3–10] 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. (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.)

For example, 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 L/E_ν , where E_ν is the reconstructed neutrino energy (see Fig. 2).

The energy range of current neutrino sources are shown in Figure 3, with future sources, HK and DUNE, corresponding approximately to the T2K and MINER ν A fluxes respectively. Measurements at 1 GeV are critical for the T2K and HK program which use carbon and water (oxygen) detectors, measurements from 1–2 GeV are important for the SBN Short Baseline Neutrino (argon) and NO ν A (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

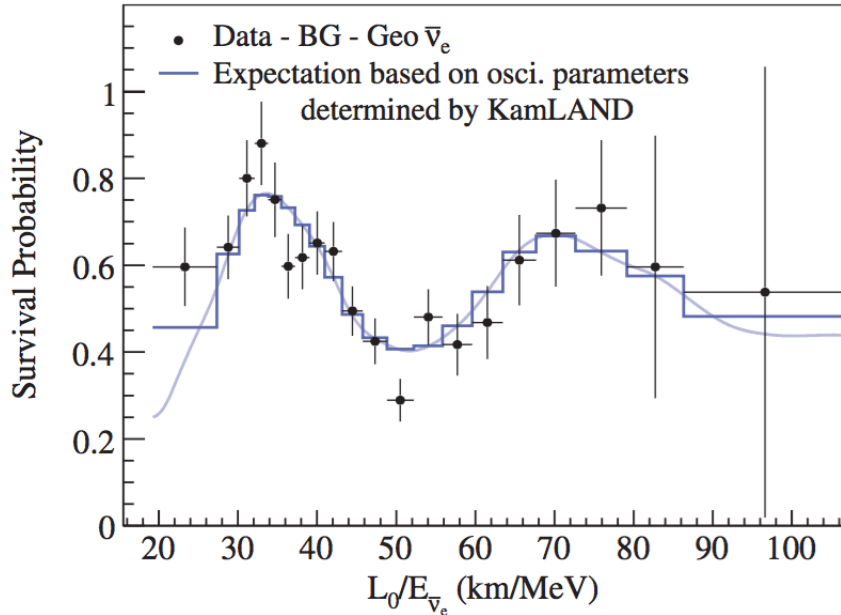


FIG. 2: Neutrino oscillation plot from KamLAND [11]. Note that the horizontal axis is distance divided by reconstructed neutrino energy.

total systematic uncertainty (neutrino interaction model)		
Experiment	ν_e CC	$\bar{\nu}_e$ CC
T2K	5.4% (>3.9%)	6.2% (>4.1%)
NO ν A	17.6% (14.0%)	-

TABLE I: Fractional uncertainty (1σ) on the predicted rate of signal events (ν_e and $\bar{\nu}_e$ CC candidates) on the T2K and NO ν A [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.

ANNIE experiment on a gadolinium-doped water Cherenkov 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 Nu-

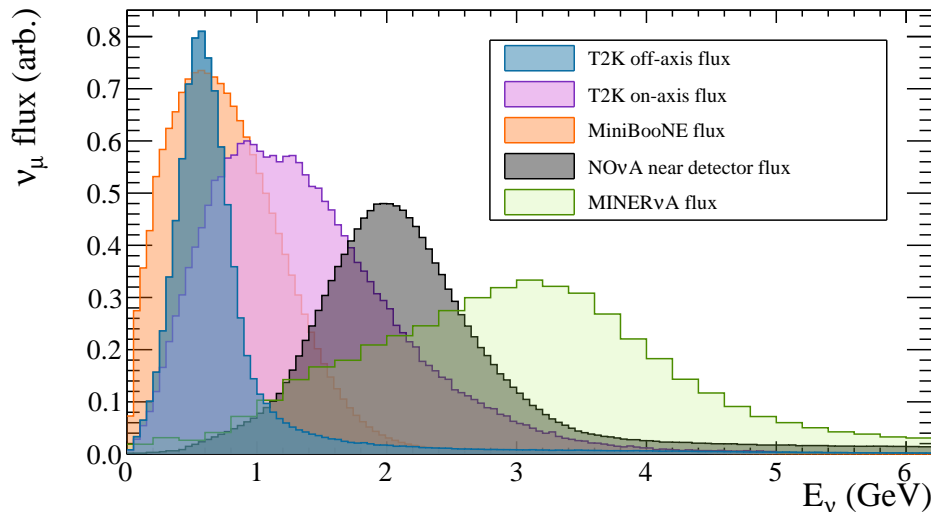


FIG. 3: Current neutrino sources, in arbitrary units, shown as a function of neutrino energy. The T2K off-axis flux is similar to what will be used for the future Hyper-Kamiokande experiment flux, and the MINER ν A flux is similar to the future DUNE experiment flux.

clei (NuInt) conferences, there are topical conferences such as the April 2017 IPPP/NuSTEC topical meeting and the December 2016 INT workshop on neutrino-nucleus scattering. This proposal is largely the result of the discussions at the recent 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.

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 Delta production. These give rise to the prominent (at

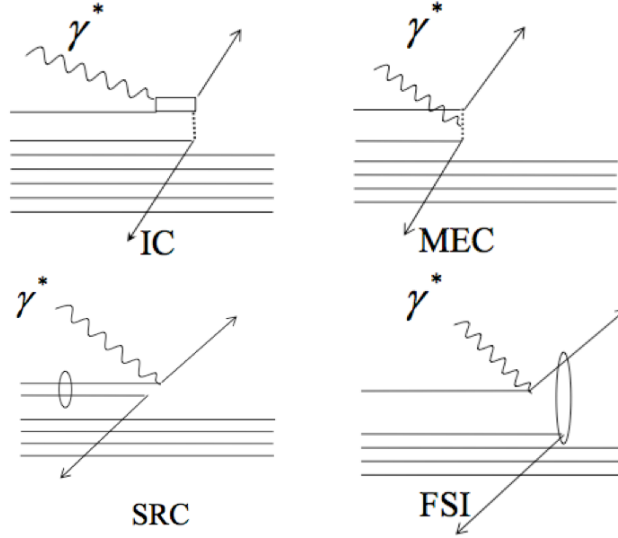


FIG. 4: Two body diagrams. (upper left) IC: the virtual photon is absorbed on a nucleon, exciting it to a Δ , which de-excites via $\Delta N \rightarrow NN$; (upper right) MEC: the virtual photon is absorbed on a meson being exchanged between two nucleons, resulting in the the knockout of both nucleons;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

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 deexcites by interacting with a second nucleon ($\Delta N \rightarrow NN$), (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.

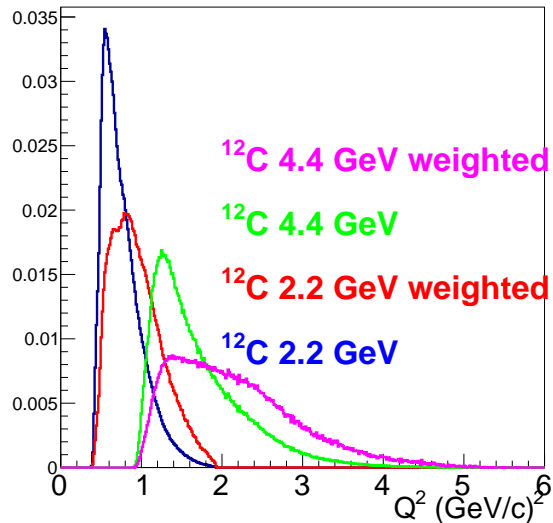


FIG. 5: The number of $^{12}\text{C}(e, e')$ events with invariant mass $W < 2$ GeV for 2.2 and 4.4 GeV incident electron energy, normalized to the same area. The blue and green histograms show the number of 2.2 and 4.4 GeV events; the red and magenta show the same events, weighted by $1/\sigma_{Mott}$ 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 $^{12}\text{C}(e, e')$ 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. All charged current and neutral current processes can be simulated, with the full kinematics of all particles exiting the nucleus provided in the output. However, they 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.

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, many event generators approximate final state interactions with semi-classical cascade models. Mis-modelling, in the theory or the approximations in event generators, can lead to bias in extracted neutrino cross sections or oscillation parameters.

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. We need to quantitatively understand as many of these as possible. These are very difficult to disentangle in neutrino experiments where the incident neutrino energy is unknown.

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.

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.

Many modern neutrino detectors such as MicroBooNE, NO ν A, MINER ν A, and the proposed DUNE detectors can detect all final-state charged particles above a certain threshold and not just the scattered lepton. These detectors can therefore provide far more information about certain reaction channels. It is therefore important to provide electron scattering data to test the different reaction channels in the event generators.

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 $p, d, ^{12}\text{C}$, 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 $^{48}\text{Ti}(e, e'p)$ in Hall A in order to measure their spectral functions [17]. 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.

Target	2.2 GeV (e, e')	2.2 GeV ($e, e'p$)	4.4 GeV (e, e')	4.4 GeV ($e, e'p$)
^3He	24.5	9.3	4.1	1.5
^4He	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.

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 ^3He , ^4He , ^{12}C and Fe targets from the e2a data set (see Table II). There is a little data at 1.1 GeV on ^3He and ^{12}C from the e2a data set. There is also 4.4 GeV data on ^3He 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 4.4 GeV e2a data from ^3He , ^4He , and ^{12}C 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

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

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 detect both the electron and a proton, then we can write that

$$E_{tot} = E_e + T_p + \epsilon \quad (2)$$

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 NO ν A, MINER ν A, and MicroBooNE.

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,

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

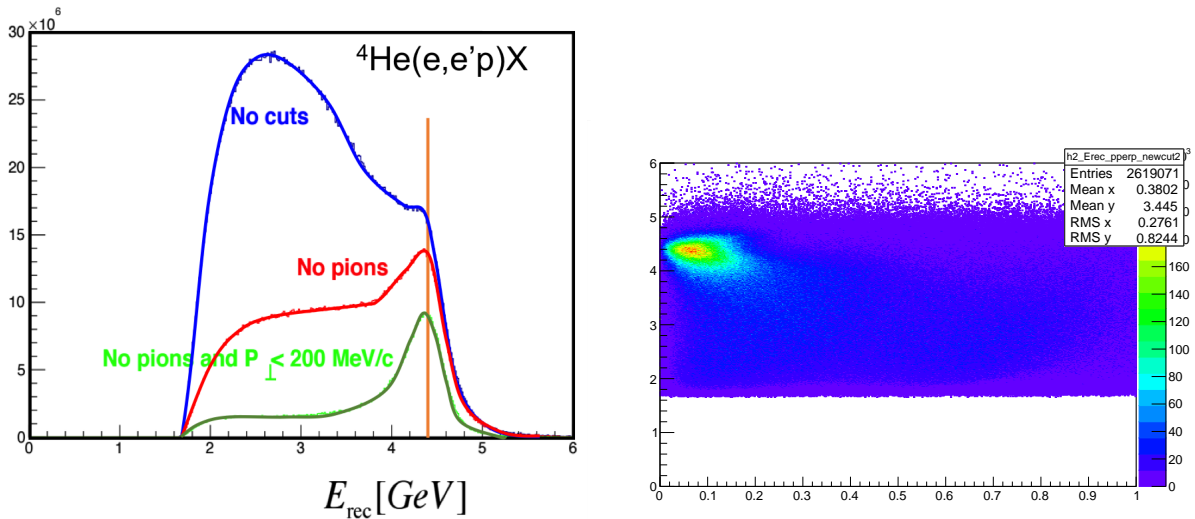


FIG. 6: (left) PRELIMINARY. The reconstructed incident electron energy using just the scattered electron kinematics for 4.4 GeV ${}^4\text{He}(e, e'p)$ events with (blue) no cuts, (red) no detected charged pions and (green) no detected charged pions and $p_\perp^{tot} = |\vec{p}_\perp^e + \vec{p}_\perp^p| < 200$ MeV/c. 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. The QE region can be quite clearly seen in the upper left corner.

We started with e2a $(e, e'p)$ events. We applied the standard CLAS e2a momentum corrections, vertex corrections, particle ID cuts, and fiducial cuts. In analogy with neutrino

experiment analyses, we then selected events with zero 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. We reweighted each of the events by $1/\sigma_{Mott}$ to remove the effects of the virtual-photon propagator and to better compare to neutrino data.

Fig. 6 shows the reconstructed energy using Eq. 1 for 4.4 GeV electrons on ^4He for all events, for events with no detected pions, and for events with no detected pions and with $p_{\perp}^{tot} < 200$ MeV/c. It also shows the reconstructed energy plotted versus the $(e, e'p)$ perpendicular momentum. The QE events are almost all located at $p_{\perp} < 200$ MeV/c.

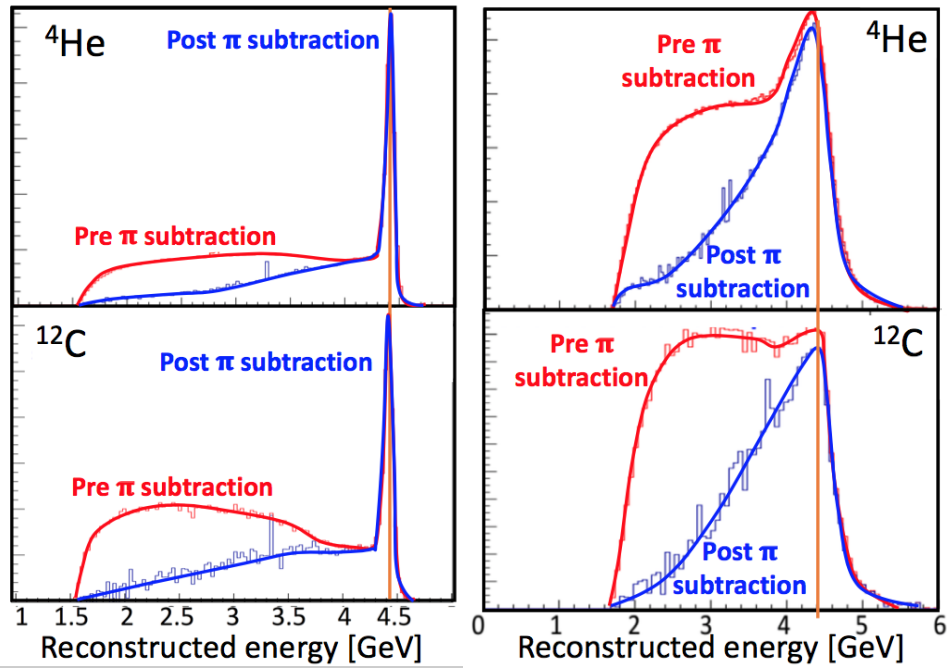


FIG. 7: PRELIMINARY. (left) The reconstructed incident electron energy $E_{tot} = E_e + T_p + \epsilon$ (Eq. 2) for 4.4 GeV ^4He $(e, e'p)$ (top) and $\text{C}(e, e'p)$ (bottom) events before and after subtracting the undetected pions; (right) the same for the using just the scattered electron kinematics (Eq. 1). The ^4He before plot should be the same as the red histogram in Fig. 6. The events are weighted by $1/\sigma_{Mott}$ to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

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 and subtracted this estimated contribution from the data (see Fig 7 right). The background is now dramatically decreased but there are still a very significant number of events that do

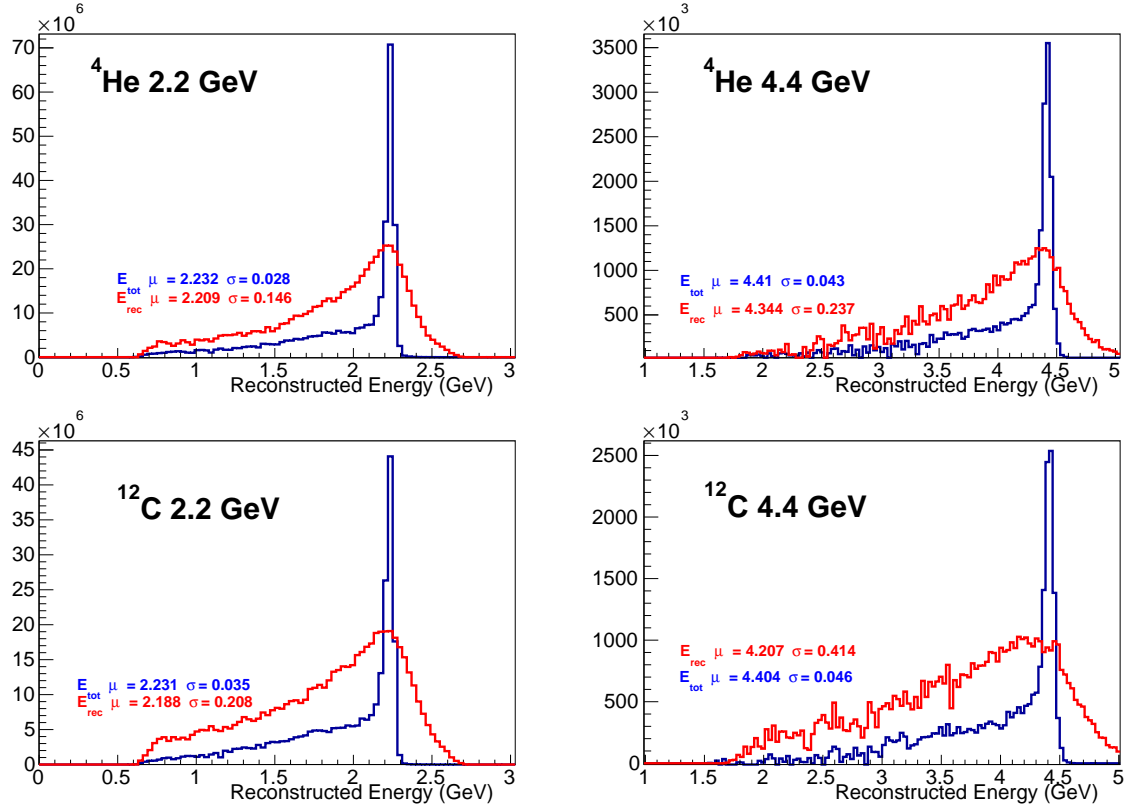


FIG. 8: PRELIMINARY. The reconstructed incident energy (blue) for $(e, e'p)$ events using $E_{\text{tot}} = E_e + T_p + \epsilon$ (Eq. 2) and (red) for (e, e') events using Eq. 1. (upper left) 2.2 GeV ${}^4\text{He}$ events; (upper right) 4.4 GeV ${}^4\text{He}$ events; (lower left) 2.2 GeV ${}^{12}\text{C}$ events, and (lower right) 4.4 GeV ${}^{12}\text{C}$ events. The horizontal axis is the reconstructed energy in GeV. The numbers are the mean and standard deviation of a gaussian fit to the peak region. The events are weighted by $1/\sigma_{\text{Mott}}$ to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

not reconstruct to the beam energy, even in this zero-pion data set.

The resolution of the reconstructed energy spectrum improves dramatically when we include information about the detected proton. See Figs. 7 left and 8. However, only a minority of even these zero-pion events are truly quasielastic (i.e., reconstruct to the beam energy).

The amount of non-QE background increases dramatically from ${}^4\text{He}$ to ${}^{12}\text{C}$ (see Figs. 7 and 8). It is difficult to determine the dividing line between the QE and the non-QE 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 QE and non-QE 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

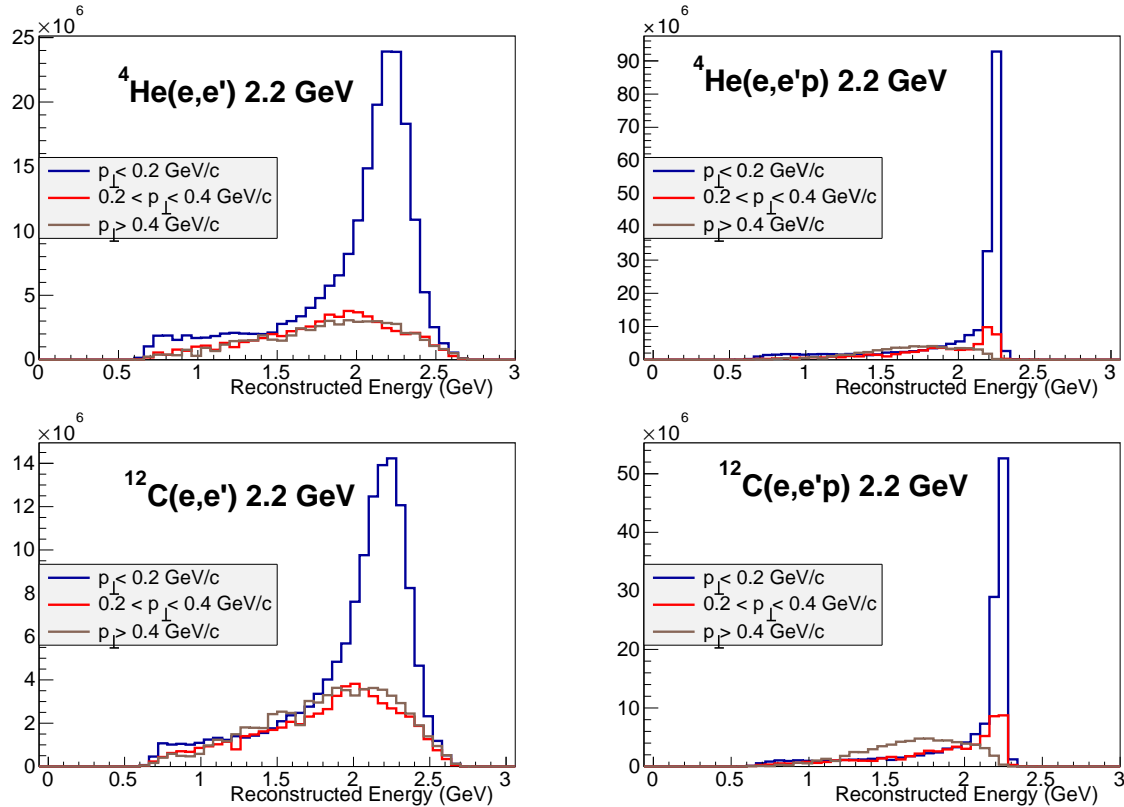


FIG. 9: PRELIMINARY. The pion-subtracted reconstructed $(e, e'p)$ incident electron energy using (left) just the lepton information of Eq. 1 and (right) the total energy of Eq. 2 for different p_{\perp} slices. (top) ${}^4\text{He}$; (bottom) ${}^{12}\text{C}$. The events are weighted by $1/\sigma_{Mott}$ to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

decreasing background that extends to lower energies. This background is also significantly larger in ${}^{12}\text{C}$ than ${}^4\text{He}$.

Fig. 9 shows the reconstructed energy of Eqs. 1 and 2 for ${}^4\text{He}$ and ${}^{12}\text{C}$ at 2.2 GeV cut on different bands of perpendicular momentum (Eq. 3). This shows the effects of Fermi motion, FSI and soft particle production. Describing data like this for a wide variety of targets and beam energies will be a stringent test of the event generators.

V. THE PROPOSED MEASUREMENT

We would like 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 ${}^{12}\text{C}$, ${}^{16}\text{O}$ and ${}^{40}\text{Ar}$. 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 ^4He , ^{12}C , ^{16}O , ^{40}Ar , and Pb.

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 $\text{NO}\nu\text{A}$ (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, 6.6 and 8.8 GeV incident energies.

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 typi-

cally not detected in neutrino experiments, even in hermetic detectors such as MicroBooNE and MINER ν A, leading to misidentification of the incident neutrino energy. This effect is especially important for CP violation studies as discussed in the next section.

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.

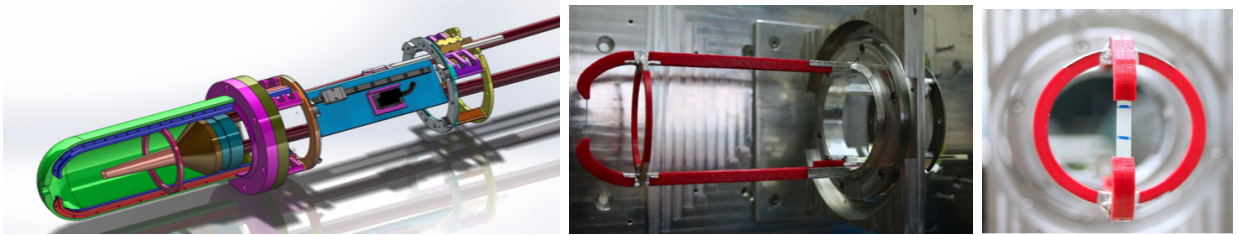


FIG. 10: The CLAS12 target system under development at UTFSM. (left) a drawing of the system showing the target vacuum enclosure (green), the tapering liquid target cell (copper), and the upper (blue) and lower (red) supports for the solid target tape; (middle) the prototype solid target system with 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. 10. The target system is already fully designed and key components have been tested. It can be ready for use in 2018.

We plan to generate yield maps and cross sections for different types of events (zero pion, zero pion one proton, 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 $\mathcal{L} = 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for nuclear targets, about 10 times greater than CLAS6. The data shown in Fig. 9 each represent about 5 days of beam time at a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ 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

in order to study the neutron channels and to subdivide the data into different bins in Q^2 and reaction channel. 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 4 days at each beam energy and target at 8.8 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 capabilities of CLAS12, we are requesting time to remeasure ^4He 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 also take 4 hours. Thus, we request another 16 hours of overhead per beam energy for beam energy and target changes for a total of 3.5 days.

Our total request is for 41 days, including 36.5 days of data taking, 1 day of calibration, and 3.5 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. 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 ^3He , ^4He and ^{12}C nuclei with additional data for 5 GeV electrons on C, Al, Fe,

Energy (GeV)	H	⁴ He	¹² C	¹⁶ O	⁴⁰ Ar	Pb	Total
1	0.2	0.5	0.5	0.5	0.5	0.5	2.5
2.2	0.2	1	1	1	1	1	5
4.4	0.2	1	1	1	1	1	5
6.6	0.2	2	2	0	2	2	8
8.8	0.2	4	4	0	4	4	16
Total (days)	1	8.5	8.5	2.5	8.5	8.5	37.5

TABLE III: Beam time requested for each beam energy and target (days). The H target is for calibration. This does not include 2/3 day of overhead per beam energy (3.5 days total) for energy and target changes.

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 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 ⁴⁰Ar 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.

B. Projected impact on neutrino uncertainties

As of now, no direct quantification of the impact of this proposal on oscillation analyses is possible, due to the limited oscillation analysis studies done by current and future experiments. 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, 18]. The flux integrated nature of near detector and neutrino nuclear scattering data alone is insufficient to probe all parameters in the model.

A concrete example of how this proposal impacts 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 $\bar{\nu} \rightarrow e^+$, antineutrino interactions have more neutrons in the final state than neutrinos. 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.

Figure 11 shows the predicted neutron multiplicity for charged current interactions where there are no pions in the final state. There is a dramatic difference between the expected number of neutrons for neutrino and antineutrino beam modes, which is far greater than the quoted uncertainties of the nominal model (GENIE with red error bars). There are also very significant differences among the predictions of the three models. There is currently no data to validate any of the models for neutrons. The semi-inclusive neutron eA data sets of this proposal will be a new window on these models and are crucial for dCP measurements.

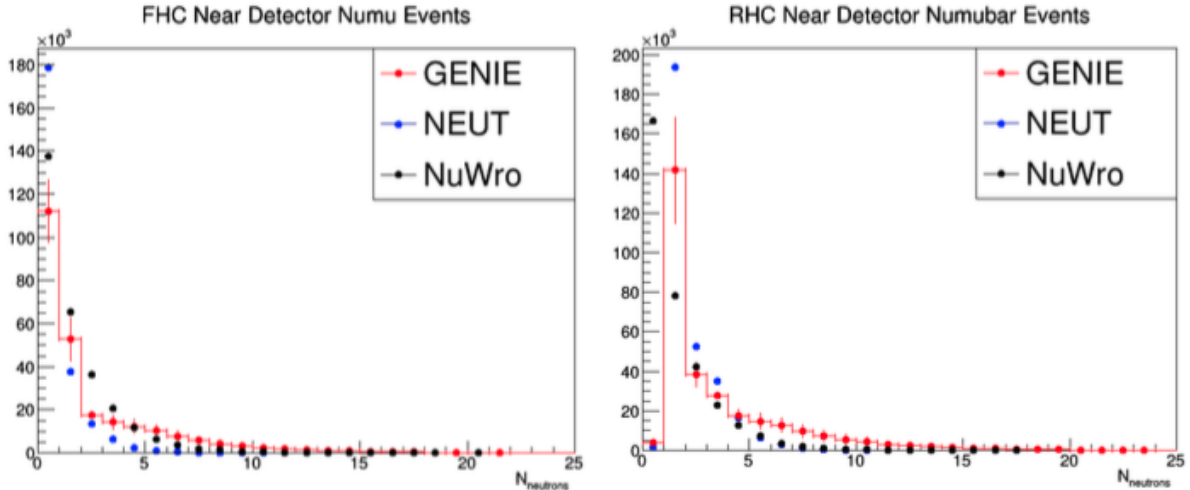


FIG. 11: (left) A histogram of the expected neutron multiplicity in DUNE for the "neutrino" beam mode. The three sets of points correspond to the three widely used neutrino event generators. (right) The same for the "anti-neutrino" beam mode.

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 26.5 days of beam time in Hall B to measure electron scattering at 1, 2.2, 4.4, 6.6 and 8.8 GeV from ^4He , ^{12}C , ^{16}O , ^{40}Ar , and Pb targets plus 1 day of calibration time on an H target and 3.5 days of overhead for energy and target changes. These energies and targets span those used in major neutrino experiments, including MicroBooNE, MINER ν A, NO ν A, 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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Fermi National Accelerator Laboratory



Joseph Lykken
Deputy Director/Chief
Research Officer

May 19, 2017

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

Office of the Director
P.O. Box 500, MS 105
Kirk Road and Pine Street
Batavia, Illinois 60510
Office: 630.840.8422
lykken@fnal.gov

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,

A handwritten signature in black ink, appearing to read "J Lykken", with a long horizontal flourish extending to the right.

Joseph Lykken

Attachment: Neutrino Proposal 2017



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



The University of Tokyo,
 Institute for Cosmic Ray Research (ICRR),
 Kamioka Observatory
 Higashi-Mozumi, Kamioka-cho, Hida-shi, Gifu,
 506-1205, JAPAN
 (email) masato@suketto.icrr.u-tokyo.ac.jp
 (TEL) +81-578-85-9611 (FAX) +81-578-85-2121

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,

A handwritten signature in black ink that reads "Masato Shiozawa". The signature is written in a cursive, flowing style.

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,

Two handwritten signatures in black ink. The first signature is 'Mark Messier' and the second is 'Peter Shanahan'.

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,

A rectangular box containing a handwritten signature in black ink that reads "Bonnie Fleming".

A handwritten signature in black ink that reads "Geralyn P. Zeller".

Bonnie Fleming
Geralyn (Sam) Zeller
MicroBooNE Spokespeople



UNIVERSITY OF
ALBERTA

Centre for Particle Physics
Department of Physics / Faculty of Science

Darren R. Grant PhD
Associate Professor of Physics
Centre for Particle Physics
University of Alberta
Edmonton, AB
Canada T6G 2E1

T (780) 492-3354
F (780) 492-3408
drg@ualberta.ca

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,

A handwritten signature in black ink, appearing to read "D. Grant".

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
Department of Physics and
Astronomy
12 Physics Hall
Ames, Iowa 50011-3160
email: wetstein@iastate.edu
phone: +1.630.885.9742

May 11, 2017

Dear Jefferson Lab Program Advisory Committee,

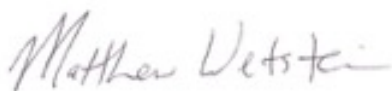
We are writing to express the support of the ANNIE collaboration for the "Electrons for Neutrinos: Addressing Critical Neutrino Nucleus Issues" experiment being proposed to the Jefferson Lab PAC.

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
(on behalf of the ANNIE collaboration)



Mayly Sanchez