

**Electrons for Neutrinos**  
**Addressing Critical Neutrino-Nucleus Issues**  
**Proposal to Jefferson Lab PAC 45**

**DRAFT**

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## Abstract

In order to measure neutrino mixing parameters, neutrino oscillation experiments need to reconstruct the incident neutrino energy. This 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 selections by rejecting pions and then estimate the neutrino energy based on lepton kinematic information alone. 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 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 approximately 1, 2.2, 4.4, 6.6 and 8.8 GeV from  $^4\text{He}$ , C, O,  $^{40}\text{Ar}$ , and Pb targets. We will also need 2.5 days of overhead for target and energy changes. The energies and targets span those used in major neutrino experiments, including MicroBooNE, MINER $\nu$ A, NO $\nu$ 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 NO $\nu$ 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. 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 discovery 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  $\nu_\mu$  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 phenomenologists [3–10] indicate that if neutrino interactions are not modeled correctly, then the

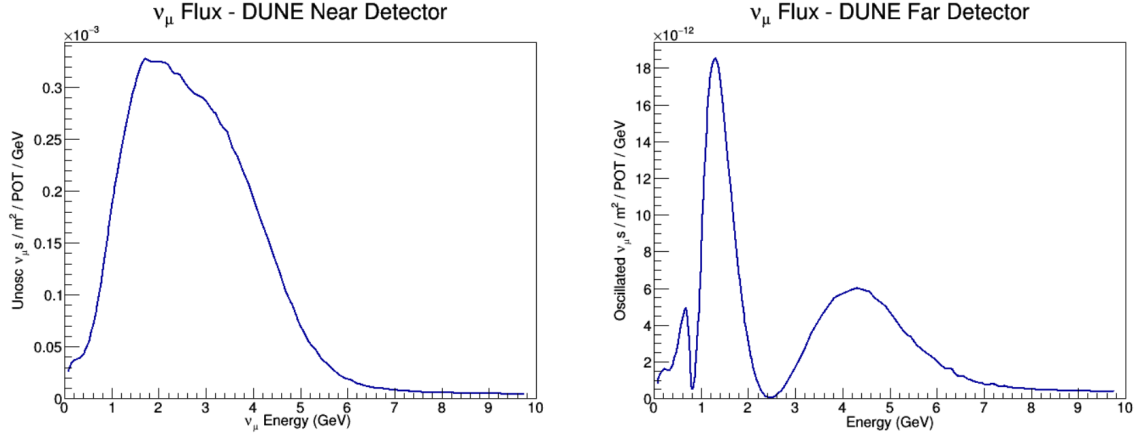


FIG. 1: The expected incident energy distribution of the DUNE  $\nu_\mu$  beam at the near detector (left) and the far detector (right).

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  $L/E_\nu$  where  $E_\nu$  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 MINERνA 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 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 gadolinium-doped water Cherenkov detector will do the first mea-

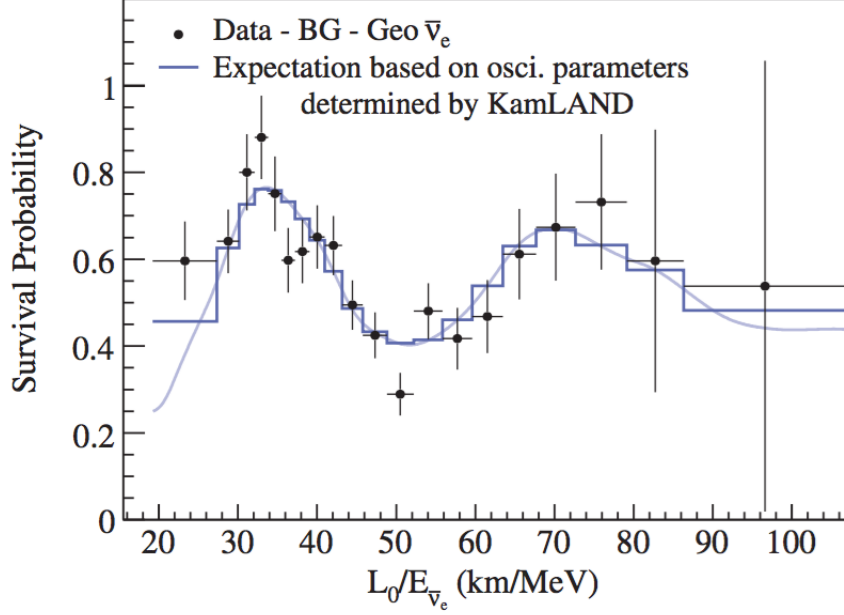


FIG. 2: Neutrino oscillation plot from KamLAND [11]. Note that the horizontal axis is distance divided by reconstructed neutrino energy.

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

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

surements 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].

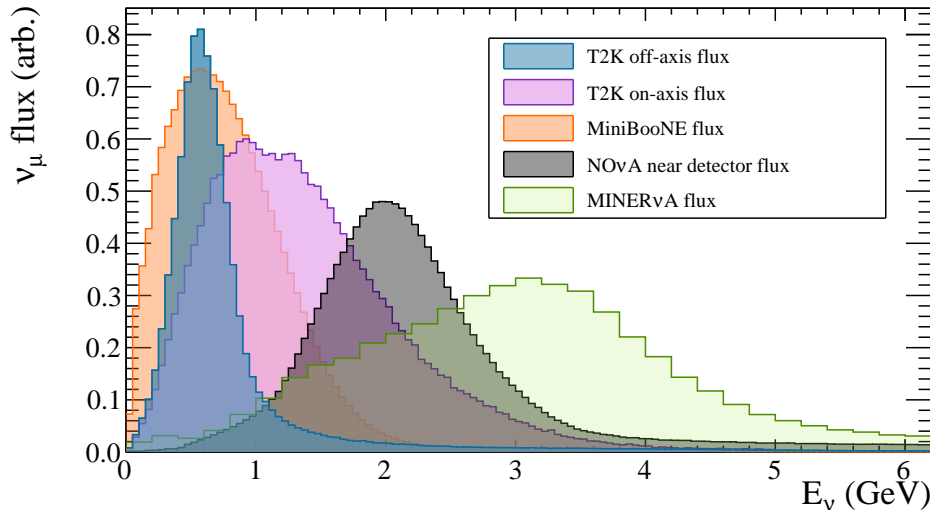


FIG. 3: Current neutrino sources, in arbitrary units, shown as a function of neutrino energy. The T2K off-axis flux is similar to what will be used for the future Hyper-Kamiokande experiment flux, and the MINER $\nu$ A flux is similar to the future DUNE experiment flux.

## 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)  $\nu$  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 low  $Q^2$ ) quasielastic and  $\Delta$  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  $\Delta$  and the  $\Delta$  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

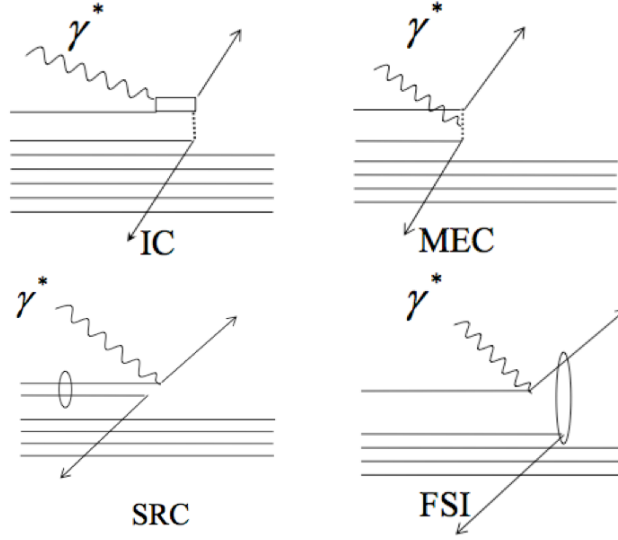


FIG. 4: Two body diagrams. (upper left) IC: the virtual photon is absorbed on a nucleon, exciting it to a  $\Delta$ , which de-excites via  $\Delta N \rightarrow NN$ ; (upper right) MEC: the virtual photon is absorbed on a meson being exchanged between two nucleons, resulting in the the knockout of both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

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  $\theta^{-4}$  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.

### 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  $4\pi$  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.

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 spec-



trometers 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 $\nu$ A, MINER $\nu$ A, and the proposed DUNE detectors can detect all 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  $p, d, C, Al$  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 [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.

Some data already exists on nuclear targets with the CLAS6 detector. There is significant data on 2.2, and 4.4 GeV electron beams incident on  $^3He, ^4He$  and  $C$  targets from the e2a and e2b data sets (see Table II). There is also 5 GeV data on  $C, Fe$  and  $Pb$  targets from the eg2 data set. The primary e2a data set contains about 1–2 mC of beam charge each at 2.2 and 4.4 GeV on  $^3He, ^4He$  and  $C$  targets. Typical beam currents were 5–10 nA and typical target thicknesses were about 200 mg/cm<sup>2</sup>. There is also about 0.2 mC of beam charge each

Target	2.2 GeV ( $e, e'$ )	2.2 GeV ( $e, e'p$ )	4.4 GeV ( $e, e'$ )	4.4 GeV ( $e, e'p$ )
$^3\text{He}$	32.6	13.2	6.2	2.2
$^4\text{He}$	52.1	19.4	13.0	4.2
C	31.5	12.2	9.3	2.6
Fe	2.2	0.9	0.8	0.2

TABLE II: Available number of e2a good events in millions. "Good" events are those passing electron and proton particle ID and fiducial cuts. **note that these events are mostly DIS events that will be useless for our purposes. A new list of events with  $W < 2$  is being prepared.**

at 1.1 GeV on  $^3\text{He}$  and C targets, and about 0.2 mC of beam charge each at 2.2 and 4.4 GeV on an Fe target. Results from the preliminary analysis of this data is presented below.

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

### A. Analysis of CLAS6 data

We have started analyzing 4.4 GeV e2a data from  $^3\text{He}$ ,  $^4\text{He}$ , and 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 $\nu$ A.

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,

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

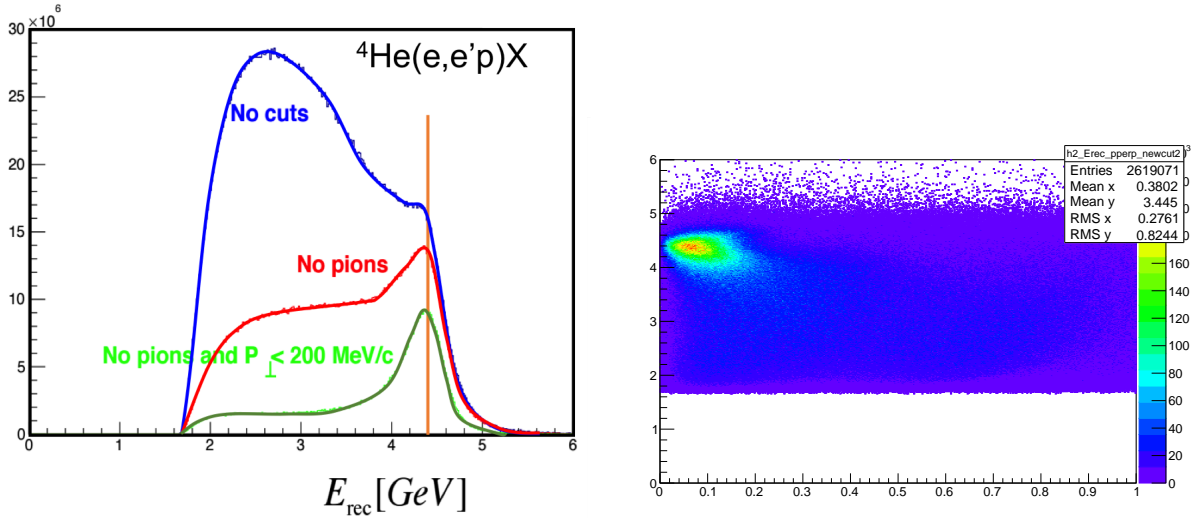


FIG. 5: (left) PRELIMINARY. The reconstructed incident electron energy using just the scattered electron kinematics for 4.4 GeV  $^4\text{He}$  ( $e, e'p$ ) events with (blue) no cuts, (red) no detected charged pions and (green) no detected charged pions and  $p_{\perp}^{tot} = |\vec{p}_{\perp}^e + \vec{p}_{\perp}^p| < 200$  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 a skim of e2a ( $e, e'p$ ) events (because we were already analyzing that data for other purposes). 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  $\pi^0$  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 compare to neutrino data.

Fig. 5 shows the reconstructed energy using Eq. 1 for 4.4 GeV electrons on  $^4\text{He}$  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.

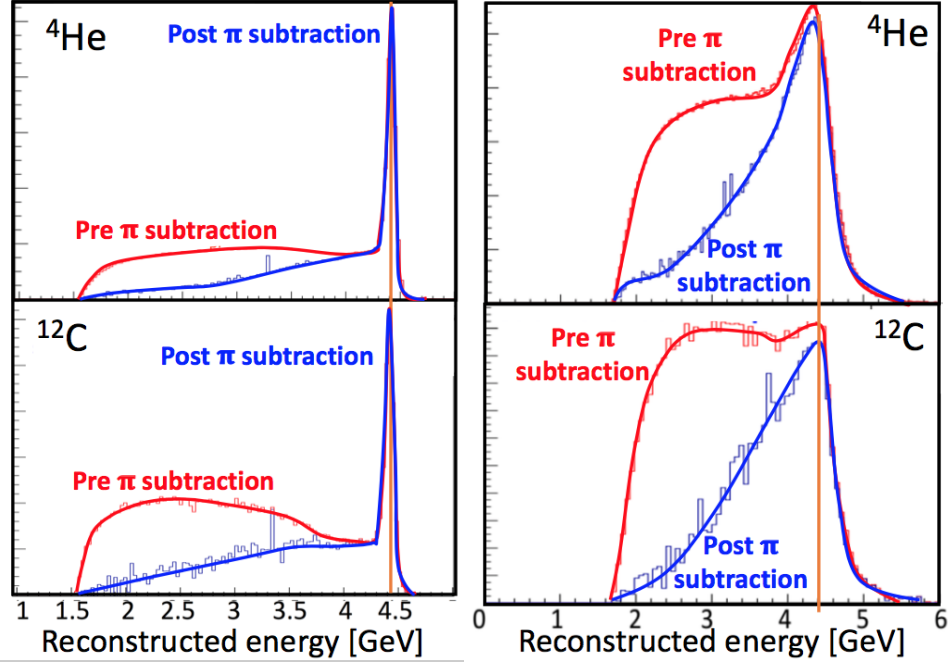


FIG. 6: PRELIMINARY. (left) The reconstructed incident electron energy  $E_{tot} = E_e + T_p + \epsilon$  (Eq. 2) for 4.4 GeV  $^4\text{He}$  ( $e, e'p$ ) (top) and  $\text{C}(e, e'p)$  (bottom) events before and after subtracting the undetected pions; (right) the same for the using just the scattered electron kinematics (Eq. 1). The  $^4\text{He}$  before plot should be the same as the red histogram in Fig. 5. 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 6 right). The background is now dramatically 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.

The resolution of the reconstructed energy spectrum improves dramatically when we include information about the detected proton. See Figs. 6 left and 7. However, only a minority of even these zero-pion events are truly quasielastic (i.e., reconstruct to the beam

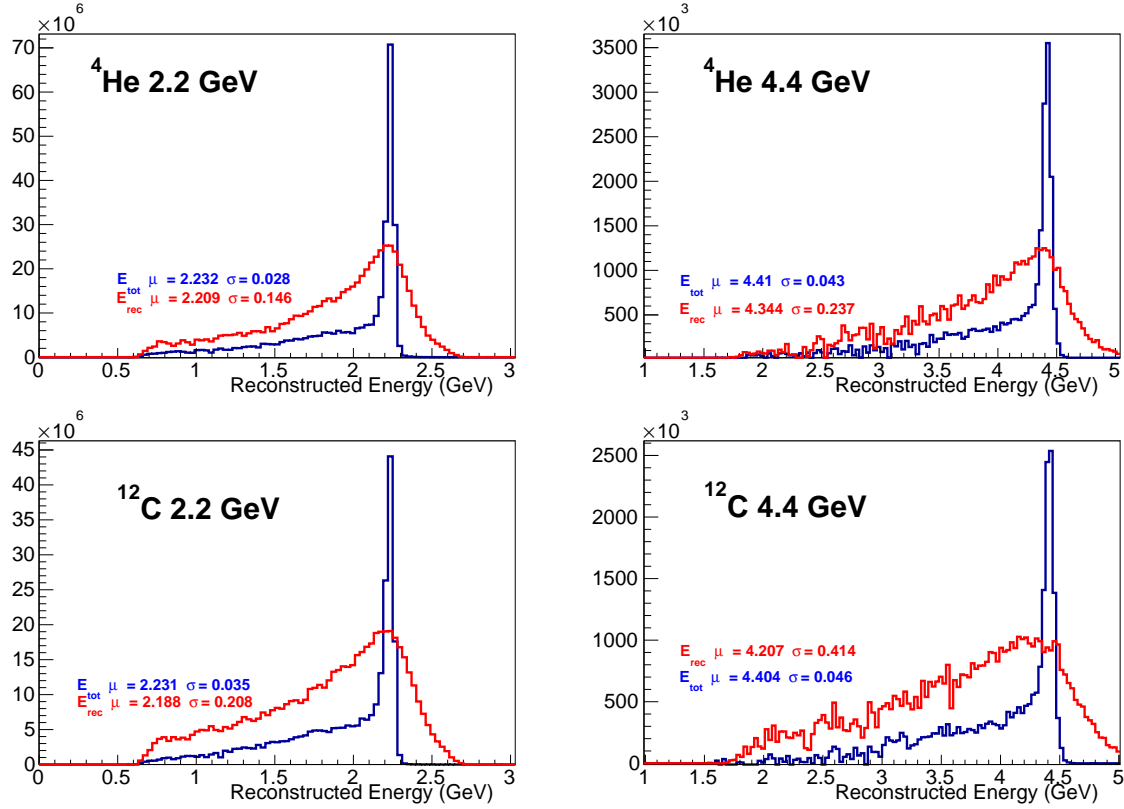


FIG. 7: PRELIMINARY. The reconstructed incident energy (blue) for  $(e, e'p)$  events using  $E_{\text{tot}} = E_e + T_p + \epsilon$  (Eq. 2) and (red) for  $(e, e')$  events using Eq. 1. (upper left) 2.2 GeV  $^4\text{He}$  events; (upper right) 4.4 GeV  $^4\text{He}$  events; (lower left) 2.2 GeV C events, and (lower right) 4.4 GeV 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.

energy).

The amount of non-QE background increases dramatically from  $^4\text{He}$  to C (see Figs. 6 and 7). It is difficult to determine the dividing line between the QE and the non-QE events 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; there is a narrow peak at the beam energy and a broad slowly decreasing background that extends to lower energies. This background is also significantly larger in C than  $^4\text{He}$ .

Fig. 8 shows the reconstructed energy of Eqs. 1 and 2 for  $^4\text{He}$  and 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

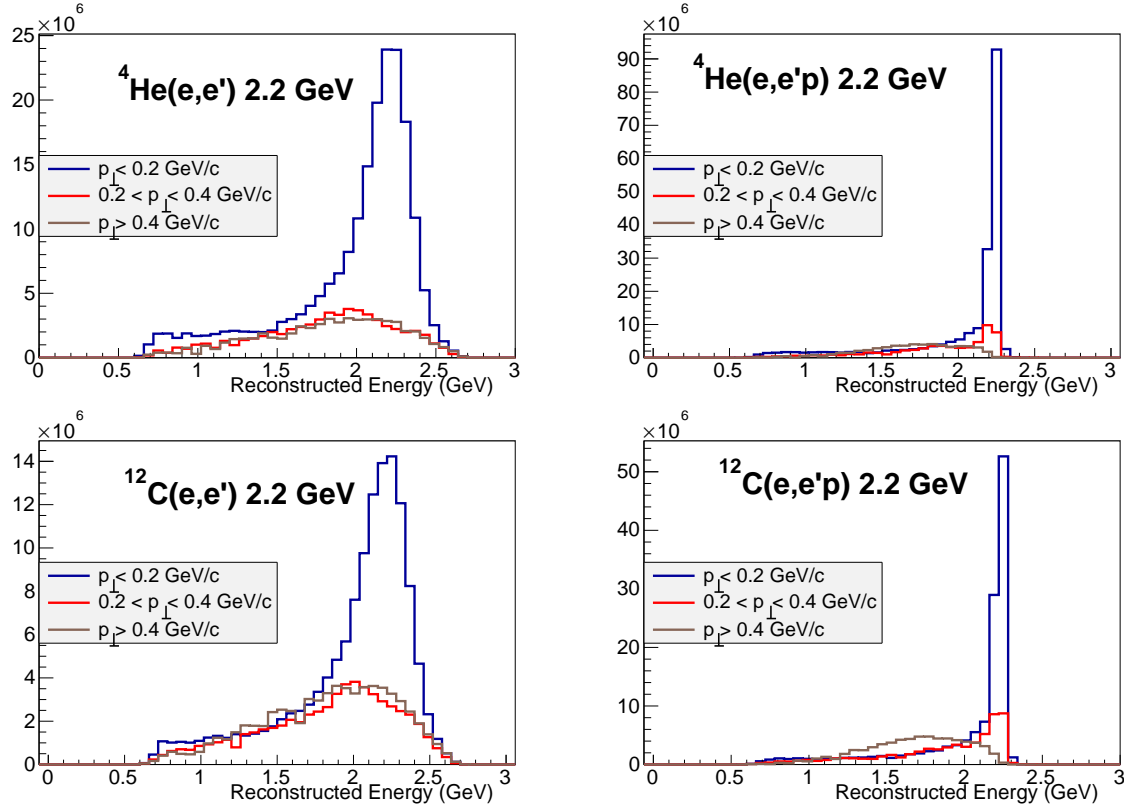


FIG. 8: PRELIMINARY. The pion-subtracted reconstructed incident electron energy using (left) just the  $(e, e')$  lepton information of Eq. 1 and (right) the  $(e, e'p)$  total energy of Eq. 2 for different  $p_{\perp}$  slices. (top)  ${}^4\text{He}$ ; (bottom) C. The events are weighted by  $1/\sigma_{Mott}$  to more closely resemble the angular distribution of a neutrino reaction. All results are preliminary.

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 test neutrino energy reconstruction techniques and to provide data to dramatically improve neutrino event generators. By spanning a range of nuclei both heavier and lighter than typical neutrino targets we can help significantly constrain the  $A$  dependence of the event generator physics models. We plan to measure scattering on  ${}^4\text{He}$ , C, Ar, and Pb. We chose Ar rather than Fe because it will be used in the proposed DUNE detectors. The heavier targets (C, Ar, Pb) and higher energies will directly benefit  $\text{NO}\nu\text{A}$  and DUNE.

In addition, we plan to measure both C and 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 C and 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 NO $\nu$ 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. We plan to measure at 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.

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 MINER $\nu$ 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 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). This system has a small liquid target cell followed by solid targets on a moveable "tape" system. See Fig. 9. The target system is already fully designed and key components have been tested. It can be ready for use in 2018.

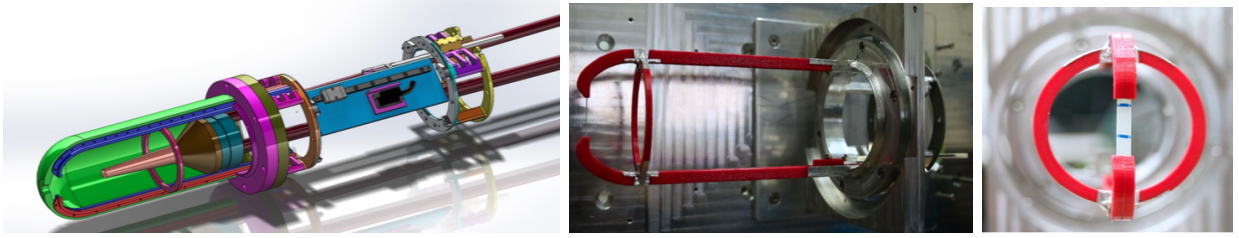


FIG. 9: The CLAS12 target system under development at UTFSM. (left) a drawing of the system showing the target vacuum enclosure (green), the tapering liquid target cell (copper), and the upper (blue) and lower (red) supports for the solid target tape; (middle) the prototype solid target system with the 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 plan to generate yield maps 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 (and dramatically reduce the analysis time needed to produce them).

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. 8 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 2 days at each beam energy and target at 8.8 GeV due to the decreased cross section at higher energies. 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 C and O with the exact same beam energies and detectors in order to provide meaningful 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



Energy (GeV)	$^4\text{He}$	C	O	Ar	Pb	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	1	1	1	5
6.6	1.5	1.5	0	1.5	1.5	6
8.8	2	2	0	2	2	8
Total (days)	6	6	2.5	6	6	26.5

TABLE III: Beam time requested for each beam energy and target (days). This does not include 1/2 day of overhead per beam energy (2.5 days total) for energy and target changes.

are requesting time to remeasure  $^4\text{He}$  at 2.2 and 4.4 GeV. This will approximately double the statistics of the CLAS6 data, with an even greater improvement in the neutron channels.

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 a few hours. Thus, we request another 12 hours of overhead per beam energy for beam energy and target changes for a total of 2.5 days.

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  $^3\text{He}$ ,  $^4\text{He}$  and C nuclei with additional data for 5 GeV electrons on  $^{12}\text{C}$ ,  $^{27}\text{Al}$ ,  $^{56}\text{Fe}$ , and  $^{208}\text{Pb}$  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. It should also be noted that while current and future neutrino oscillation experiments use primarily  $^{12}\text{C}$ ,  $^{16}\text{O}$  and  $^{40}\text{Ar}$  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 on comparable momentum transfer ranges, 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, 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. Note that 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.

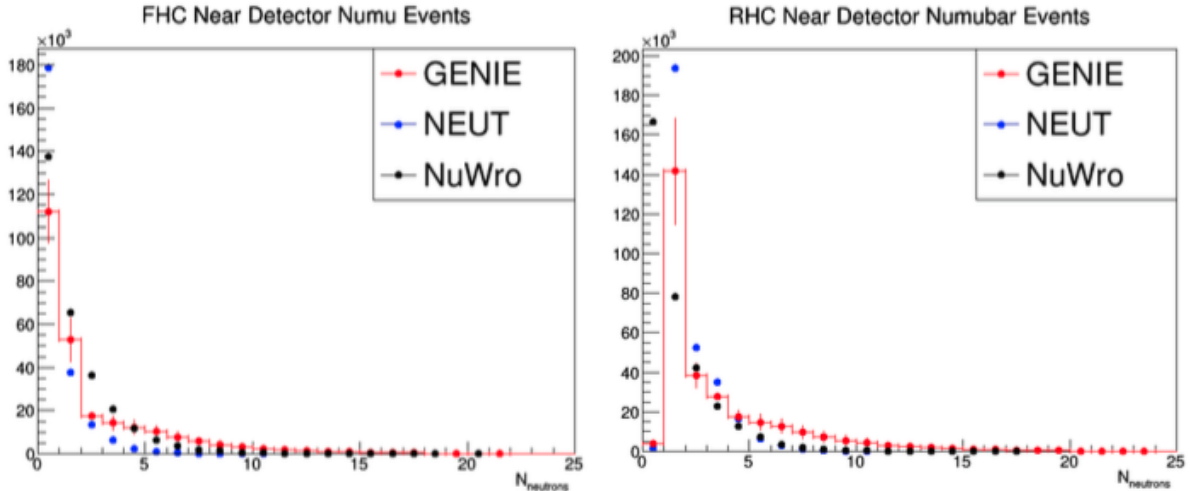


FIG. 10: (left) A histogram of the expected neutron multiplicity in DUNE for the "neutrino" beam mode. The three sets of points correspond to the three widely used neutrino event generators. (right) The same for the "anti-neutrino" beam mode.

Figure 10 shows the 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 uncertainties of the nominal model (GENIE with red error bars). There are also very significant differences among the predictions of the other 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. Semi-inclusive proton and pion information is equally important for the finite detector threshold, below which the energy is also biased.

## 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  $^4\text{He}$ , C, O,  $^{40}\text{Ar}$ , and Pb targets plus 2.5 days of overhead for energy and target changes. These energies and targets span those used in major neutrino experiments, including MicroBooNE, MINER $\nu$ A, NO $\nu$ 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.

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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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*

**IOWA STATE UNIVERSITY**  
OF SCIENCE AND TECHNOLOGY

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May 11, 2017

Dear Jefferson Lab Program Advisory Committee,

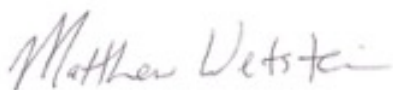
We are writing to express the support of the ANNIE collaboration for the "Electrons for Neutrinos: Addressing Critical Neutrino Nucleus Issues" experiment being proposed to the Jefferson Lab PAC.

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  
(on behalf of the ANNIE collaboration)



Mayly Sanchez