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Electrons for Neutrinos

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The ability of current and next generation accelerator based neutrino oscillation measurements to reach their desired sensitivity requires a high level of understanding of the neutrino-nucleus interactions. This includes precise estimation of the relevant cross sections for the incident neutrino energy from the measured final state particles. Incomplete understanding of these interactions can skew the reconstructed neutrino spectrum and thereby bias the extraction of fundamental oscillation parameters and searches for new physics. In this talk, I will present new results of wide phase-space electron scattering data, collected with the CLAS spectrometer at the Thomas Jefferson National Accelerator Facility (JLab), where the reconstruction of the incoming lepton energy from the measured final state is being tested. Disagreements with current event generators, used in the analysis of neutrino oscillation measurements, are observed which indicate underestimation of nuclear effects.

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[*] Speaker

1. Introduction

An international effort is underway to perform precision measurements of neutrino oscillation parameters and to search for CP violation in the lepton sector [1]. A positive observation of CP violation in neutrino oscillations, in conjunction with the resolution of the mass hierarchy and precise determinations of mixing angles, might shed light on the predominance of matter over antimatter in our present-day universe. This effort requires large detectors and intense beams; ultimately, we are looking for what is likely to be a small difference between neutrino and antineutrino oscillation in matter, or an excess in appearance of one type of neutrino over the other. To isolate this small difference, we need an unprecedented understanding of how neutrinos and antineutrinos interact with atomic nuclei.

Neutrino-oscillation parameters are extracted from the energy distribution of the oscillated neutrinos, which has to be reconstructed from the hadronic final states observed in the detector and, in the case of charged-current transitions, from the kinematics of the outgoing lepton and hadrons. Current neutrino oscillation experiments rely heavily on interaction models. Recent experiments, like T2K and NOvA, have significant uncertainties in the selected ν_e signal due to the uncertainties in the ν-nucleus cross-sections and the final-state interactions (7.7% for the NOvA experiment [2] and 6% for the T2K experiment[3]). Improving the systematic uncertainty from the current 5–15% to 1–3% is critical.

The oscillation experiments use near-detector data or external data sets to constrain the models; however, the uncertainties are still significant after applying the constraints. A new effort has been formed to use electron data to constrain interaction models for neutrino processes. These proceedings summarize the progress with the analysis of the electron scattering data constraints for neutrino oscillation studies.

1.1 Neutrinos and Electrons

Neutrino experiments are challenged by wide band neutrino beam energy and the modeling of nuclear effects. Modeling neutrino interactions includes initial nuclear state (nucleon motion, long range corrections, short range correlactions, nucleon removal energies and form factors) and final state interactions (reinteactions of outgoing particles and knockout of new particles). Since the energy of the incident neutrino must be reconstructed on an event-by-event basis from the outgoing particles produced after the neutrino interaction occurs, accurate nuclear models are absolutely necessary.

Electron experiments have the critical advantage of a monoenergetic beam. Electron and neutrino interactions with nuclei share the same vector part of the nuclear current and identical nuclear effects, such as final-state interactions. Electron data provide a pure measurement of the vector component, so that neutrino near-detector data can be used to properly constrain the axial-vector piece. Thus, by comparing electron-nucleus scattering to simulated electron data, it is possible to constrain the current neutrino event generator nuclear models.

Neutrino event generators are critical in connecting theoretical calculations to neutrino data for the determination of oscillation parameters. They are used to estimate the signal and the backgrounds, efficiency corrections, systematic errors, train algorithms, and compare with final results. An event generator called GENIE [4] is used in all neutrino experiments at Fermilab, including the Short Baseline Program, the oscillation experiment, NOvA, and in the future, DUNE. This is the event generator we focus on in our studies.

2. Electron Scattering with CLAS For Neutrinos

The first electrons-for-neutrinos $e4\nu$ analysis using 1999 CLAS-detector [5] data on He, C and Fe targets with monochromatic electron beams of 1.2, 2.3 and 4.5 GeV at the Thomas Jefferson National Accelerator Facility (JLab) is presented. CLAS was a large acceptance spectrometer with about a 2π solid angle for charged particles. The analysis focused on Quasi Elastic (QE) like events, by selecting events with one electron, one proton of momentum larger than 300 MeV/c, and no charged pions of momenta larger than 150 MeV/c. In addition, the minimum CLAS electron scattering angle corresponded to minimum momentum transfers of $Q^2 > 0.1, 0.4$, and 0.8 (GeV^2) for beam energies of 1.2, 2.3, and 4.5 GeV, respectively. The minimum hadron momenta correspond to the CLAS detection thresholds. To achieve the QE event sample, the undetected pions and photons are subtracted; more details about the background subtraction can be found at[6].

2.1 First Test of Energy Reconstruction

Oscillation experiments with Cherenkov detectors[3] use the lepton energy and momentum to reconstruct the neutrino energy, and tracking detectors[2] use all charged particles to reconstruct the neutrino energy. Using the lepton momentum and angle the energy is reconstructed using:

$$E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l\cos\theta_l)}. \tag{1}$$

Where E_l is the energy of lepton, θ_l is the angle of lepton, m_l is the mass of lepton, k_l is the momentum of outgoing lepton, M_N is the mass of the nucleon and ϵ is the constant effective binding energy. Left plot on figure 1 shows the reconstructed energy in data and simulations. Two version of GENIE are shown: the solid black curve is the GENIE SuSAv2 and the dotted is the GENIE G2018[4]. The disagreement in the quasi-elastic is due to inexact modeling of the nuclear ground state momentum, and the disagreement in the resonance tail is due to the use of resonance form factors that are not up-to-date (RES) and the way the nonresonant contribution was modeled.

Using the outgoing proton and electron, a calorimetric energy can be reconstructed

$$E_{cal} = E'_e + T_p + E_{binding}, \tag{2}$$

where the $E_{binding}$ is the removal energy and is assumed to be a constant based on the A and (A-1) system masses. Right plot on figure 1 shows the cross section as a function of E_{cal} for 1.159, 2.257 and 4.453 GeV events on Carbon (C) and for 2.257 and 4.453 GeV for events on Iron (Fe). Error bars show the statistical and systematic uncertainties [6]. Disagreement between the data and the simulations is shown. The agreement is poor as the energy and the A dependence increase. These differences could lead to significant misreconstruction of the incident neutrino flux at the far detector.

2.2 Transverse Missing Momentum

Another useful observable is the transverse missing momentum, $P_T = P_T^e + P_T^p$ where P_T^e and P_T^p are the three-momenta of the detected lepton and proton perpendicular to the direction

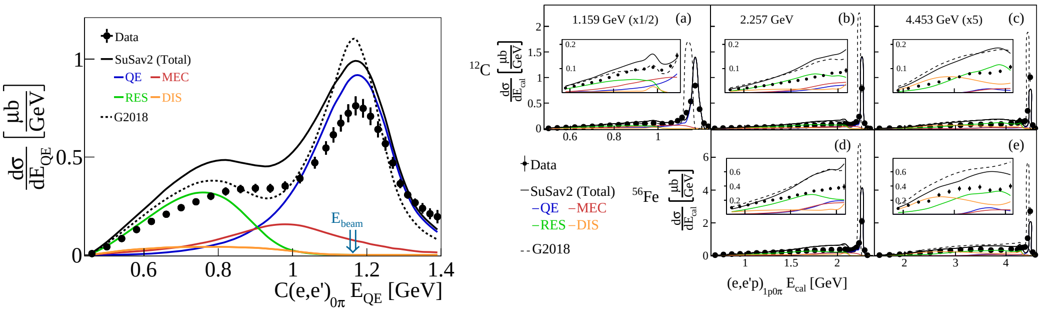

Figure 1: Left: Cross section as a function of Quasi-Elastic Reconstructed Energy for 1.159 GeV $C(e,e')_{0\pi}$. Right: Cross section as a function of Calorimetric Energy for Carbon at 1.159 GeV, 2.257 GeV, 4,453 GeV and Fe at 2.257 GeV and 4.453 GeV. Data is shown versus two versions of GENIE predictions, black solid line for SuSav2 and black dashed line for G2018. Error bars show the statistical and systematic uncertainties.[6]. Each channel quasi-elastic (QE), resonance (RES), Meson exchange current (MEC) and deep inelastic (DIS) are shown to highlight the regions with disagreement.

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of the incident lepton. The cross section as a function of the transverse missing momentum is shown in Fig. 2 for 2.257 GeV $C(e,e'p)_{1p0\pi}$. The low P_T region below 200 MeV/c is dominated by quasi-elastic interactions, and the tail above 200 MeV/c is dominated by resonance events. The right plot shows E_{cal} for different regions of P_T: poor agreement between the data and MC predictions in the different regions is shown. The comparisons show that most of the quasi-elastic events do not reconstruct to the correct beam energy, and the model does not describe the exact shape of the low-energy tail for quasi-elastic energy reconstruction.

Although QE processes dominate the cross section for neutrino fluxes in the sub-GeV region, an accurate understanding of pion-production mechanisms and deep inelastic is required for experiments characterized by higher neutrino energies, such as DUNE. The MINERvA experiment collected and published a rich data set of events dominated by pion production and deep inelastic mechanisms, demonstrating that this high-energy region is poorly modeled[7]. New analyses are underway to measure pions with the available CLAS data sets.

2.3 New Data with CLAS12

JLab recently approved a dedicated $e4\nu$ run with an A scientific rating, for 90 run days. 60 days are scheduled for fall 2021. Data will be taken using targets from D to Sn, including neutrino-detector materials (C, O, and Ar), at a range of beam energies (1, 2, 4, and 6 GeV), in order to test neutrino energy reconstruction techniques and to benchmark neutrino event generators.

The experiment will use the new high-luminosity CLAS12 spectrometer that can measure very low momentum-transfer reactions (down to 5° from the beamline)[8] and has extensive neutron and photon (π^0) detection capabilities. This experiment will provide a much larger data set, with more event channels ($1p0\pi$, $1p1\pi$, etc), greater angular and kinematic coverage, and more targets than the existing CLAS data.

3. Summary

Neutrino nucleus scattering uncertainties will limit next generation oscillation experiments. It is crucial that we have accurate modeling in our event generators for precise measurements in

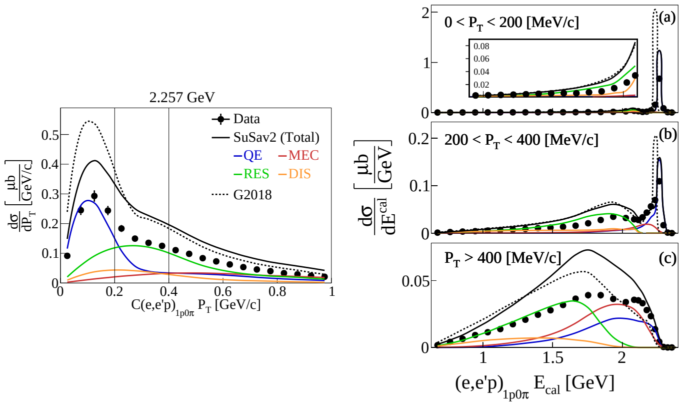

Figure 2: Cross section as a function of P_T (Left) and E_{cal} energies for different P_T regions (Right) for 2.257 GeV $C)e,e'p)_{1p0\pi}$ [6]. Data versus two version of GENIE, black solid line for SuSav2 and black dashed line for G2018. Each channel quasi-elastic (QE), resonance (RES), Meson exchange current (MEC) and deep inelastic (DIS) are shown to highlight the regions with disagreement.

DUNE and the search for CP violation.

The $e4\nu$ collaboration produced the first measurements of electron scattering with CLAS to improve the neutrino-nucleus scattering model. Comparisons with the GENIE event generator show most events do not reconstruct the correct beam energy. The data versus model disagreements will guide model improvements for quasi-elastic interactions and further analysis is underway to look at the $1p1\pi$ channel.

New data sets will be collected with CLAS12, including pion production which is the dominant channel in DUNE, a next generation accelerator neutrino oscillation experiment.

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