Neutrino Energy Reconstruction Methods Using Electron Scattering Data

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Abstract

The precise measurement of neutrino properties is among the highest priorities in fundamental particle physics, involving many experiments worldwide. Since the experiments rely on the interactions of neutrinos with bound nucleons inside atomic nuclei, the planned advances in the scope and precision of these experiments requires a commensurate effort in the understanding and modeling of the hadronic and nuclear physics of these interactions, which is incorporated as a nuclear model in neutrino event generators. This model is essential to every phase of experimental analyses and its theoretical uncertainties play an important role in interpreting every result.

Any nuclear model used to describe neutrino-nucleus scattering should first be validated against these data. Since the vector part of the weak response is related to the electro-magnetic response through CVC, such a test is necessary, but not sufficient, to ensure the validity of a model for given kinematics, namely given values of the transferred energy $\omega (=\nu$ for neutrinos) and momentum $q$.

The main challenges in connecting electron and neutrino reactions:
• matching models used to predict neutrino-nucleus observables to electron scattering data.
• expanding theory to include more semi-inclusive predictions.
• provide semi-inclusive neutron, proton and pion data sets with broad angular range.

The cross section for neutrino scattering from nuclei is sensitive to the same underlying structure determined by QCD, and as probed with pure electromagnetic processes, such as charged lepton scattering from nucleons and nuclei. As such, there are a number of ways that electron scattering data inform $\nu - \Lambda$ cross section modeling, as well as providing a test-bed for model validation. In contrast to past and current neutrino beams, charged lepton scattering has the distinct advantage of nearly monochromatic beams with well determined energies, allowing for a significantly cleaner kinematic separation of the various production mechanisms in inclusive scattering, such as resonance production and nucleon elastic scattering. In addition to providing important experimental input such as nucleon isovector elastic form factors and resonance transition form factors, electron scattering data provide critical information on the distributions of initial state momentum and energy for nucleons in nuclei, the importance of 2-body currents and final state interaction effects. In this analysis, we will give a brief overview of the experimental input provided by electron scattering data.
1. Introduction

According to the Standard Model (SM) ([1],[2]), the elementary particles can be divided into two main groups: fermions, which are the constituents of matter, and bosons, which are the carriers of interactions. The neutrinos are the lightest fermions and, to the best of our knowledge, exist in three types. They interact only via the weak interaction making the observation of neutrinos an experimental challenge. While many properties of the neutrino are still unknown, the known ones (e.g. limits on their mass, mass difference and mixing angles) are very hard to explain within the SM. This makes measuring various neutrino properties fruitful ground when searching for new physics beyond the SM. Specifically, measurements of the neutrino charge-parity (CP) symmetry-violation phase may help explain the matter anti-matter asymmetry of our universe.

Each successive generation of neutrino oscillation measurements has improved in sensitivity in order to look for more and more subtle effects. It is becoming clear that in order to realize the next generation of experiments, improvements must be made in understanding and modeling of neutrino-nucleus interactions, both in order to correctly quantify the systematic uncertainties they induce and to avoid possible biases.

Various neutrino experiments are currently taking places around the world, using different neutrino sources and detector materials. While accelerator-based experiments traditionally use water/liquid scintillator-based detectors, a new generation of state-of-the-art Liquid Argon Time Projection Chamber (LArTPC) detectors is coming online at FNAL, with the recent commencement of data-taking of the MicroBooNE experiment [5], the forthcoming SBN program, and the future DUNE experiment [6]. LArTPC detectors are showing great promise by producing bubble-chamber-like images of neutrino-scattering events that allow accurate measurements of neutrino-interactions, even in cases of very complex final states. Such measurements give more information on the underlying nuclear interactions, which could allow a reduction of both the systematical effects and the possible bias that neutrino-nucleus interaction models might induce.

2. Benchmarking Neutrino Event Generators Using Electron Scattering Data

In accelerator-based experiments, neutrinos are traditionally detected via their nuclear interaction with the detector material. These interactions are simulated using so-called "event generators" that provide a framework that aims to model 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 on an event-by-event basis. However, the generators typically employ models that are 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 are known to interfere strongly. Furthermore, they typically treat the primary interaction and final state interactions separately and incoherently.

At the same time, there are crucial assumptions inherent in generators and theoretical models which have implications for neutrino experiments. For instance, many of the models implemented in event generators do not include the most up-to-date theory understanding. Furthermore, event generators are a combination of many different (possibly inconsistent) models. Such "Franken-models" may not produce correct total or differential cross sections. In addition, many event generators approximate final state interactions using semi-classical cascade models. As mis-modelling of nuclear interactions can bias the extracted neutrino cross sections and oscillation parameters, this issue must be studied in detail.

Experiments like MINERvA and other short-baseline detectors all have extensive cross-section measurement programs which are used to constrain event generators and, at the same time, study their biases. However, obtaining high-precision constraints using measurements alone is non-
trivial since the measurements contain an unavoidable convolution of the (usually wide) energy spread of the incoming neutrino beam, the different vector and axial response functions of the nucleus, multinucleon effects, nuclear-final state interactions in addition to any measurement resolution or other detector-specific effects. De-convoluting all of these effects that contribute to the measured cross-section is a hard task that limits the ability of data to constrain the individual components of event generators.

\[ \text{Data} - \text{GENIE comparison for the } Q^2 \text{ distribution.} \]
Testing neutrino event generators against mono-energetic, wide phase-space, electron scattering data can complement these activity. While electrons and neutrinos do not have identical nuclear interactions, there are many similarities that allow electron data to constrain parts of the generator model space. These constraints can effectively complement those coming from short base-line neutrino cross-section measurements, such as the axial nuclear response.

A concrete example can be seen in the benchmarking of models of nuclear final state interactions. The propagation of a nucleon through the nuclear medium is strongly dependent on the momentum transfer of the reaction and is relatively independent of whether the interaction was initiated by an electron or by a neutrino. As the majority of generators used for neutrino scattering can also be run under an electron scattering configuration, we can mitigate the residual difference between electron and neutrino interactions by comparing electron to neutrino mode. This connection can thus be exploited to test and tune the models in event generators. Furthermore, the same parameters used to quantify the agreement with electron scattering data can be provided to neutrino oscillation experiments, so that the impact of mis-modelling (see e.g. Fig. 1) can be quantified and reduced. This makes electron scattering data a critical input to those physics programs.

Currently, the Jefferson-Lab data mining collaboration is working on comparisons of their electron scattering data measured using the CLAS detector with the predictions of the GENIE event generator running in electron scattering mode. To properly compare the generator output to data, I passed the generated events through acceptance and efficiency maps before applying the same event selection cuts that were applied to the data. Figures 2 and 3 shows an example from a recent comparison of QE \((e,e'p)\) events measured in \(^{12}\)C using a 4.461 GeV electron beam. The data is compared to a simulation where we used the GENIE neutrino event generator and
a Correlated Fermi Gas (CFG) model that has been implemented for the nuclear ground state. We are planning to continue this work in the coming year to ensure detailed comparisons of electron scattering data will be done with the relevant event generators. At the moment only GENIE is being used but we are planning to expand to using GiBUU in the near future.

3. Projected Impact on Neutrino Oscillation Uncertainties
A concrete example of how this analysis impacts current and future experiments can be seen when considering semi-inclusive neutron measurements to study the difference between neutrino and antineutrino oscillations to search for CP violation. CP violation is not the only cause for asymmetry between neutrinos and anti-neutrinos and their interactions with nuclei. Protons and neutrons already have different weak couplings, different final state interactions and also occur in different numbers in the case of asymmetric nuclei (of which Ar in LArTPC detectors is an example). Achieving the systematic uncertainty requirements of the DUNE experiment will require modeling of these nuclear physics effects in great detail and doing so to very high accuracy. In addition, the development of observables like the ratios mentioned above—with reduced sensitivities to the details of the nuclear models—are also crucial.

The work that has been presented here takes a significant step in this direction, since the use of electron scattering data to benchmark event generators is an important step in our quest to perform high-precision neutrino oscillation measurements.

References
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