Implementation of multi-nucleon model in NEUT

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments


5th December 2013
INT Seattle, Washington
Status of CCQE @ T2K

Concerns for higher value of axial mass $M_a = 1.35$ from fit to recent CCQE data.

Using semi-emperical interaction model introducing ad hoc parameters such as normalisations and high MaQE to get prediction to agree with external data, like MiniBoone, **leads to higher uncertainty.**

With reduction of statistical uncertainties (at higher statistics), these systematic will limit the precision measurement of oscillation parameters.

Many theory model to describe this excess.
Multi-nucleon interaction

From past experience (e-e’), the second order expansion of many body formalism accounts for nuclear effects and predicts multi-nucleon interactions (2p2h). Now extended for ν’s!

• A gauge boson is absorbed by two nucleons or Δ resonances in hadronic current.
• Giving out multiple nucleons in final state.
• Nieves et.al model, for multinucleon interaction, with RPA corrected CCQE describes MiniBooNe data with nominal M_{a} value.

This interaction likely to contribute as CCQE, if any nucleon is left undetected
Multi-nucleon interaction

From past experience (e-e'), the second order expansion of many body formalism accounts for nuclear effects and predicts multi-nucleon interactions (2p2h). Now extended for ν's!

- Predicts lepton kinematic different from CCQE.
- So, CCQE assumption will lead to mis-reconstruction of neutrino energy (as obtained from lepton kinematics).
- Potential bias in determination of oscillation parameters.
  (Effects on T2K analysis, talk by M.Hartz)

Need to transport these models in neutrino generator
**NEUT: ν Generator**

Official MC generator for T2K, originally created for Kamiokande

**MC prediction for OA = Flux * Cross-section * Detector resolution**
For robust prediction used in the oscillation analysis, all known interaction cross-section models should be incorporated in the MC simulation with known uncertainties.

Present CCQE models in NEUT
- CCQE $d\sigma/dQ^2$: Llewellyn-Smith
- Lab frame $\sigma(E)$: Smith&Moniz Fermi-gas

New additions in CCQE regime on their way:
- Multinucleon model (Nieves. et.al )
- Spectral function
- Random Phase Approximation

*In this talk, Implementation of multi-nucleon models in NEUT.....*
Models used

<table>
<thead>
<tr>
<th>Nieves et.al. 2p2h model</th>
<th>Jan Sobczyk's Multinucleon-ejection model</th>
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<tbody>
<tr>
<td>• Provides lepton kinematics. Double differential cross-section in lab frame.</td>
<td></td>
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<tr>
<td>• Uses local fermi gas model</td>
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<tr>
<td>• Valid for isoscalar targets only</td>
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<tr>
<td>• No hadron information (integrated out)</td>
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<tr>
<td>• Isospin breakdown now available (not implemented).</td>
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<tr>
<td>Uses minimal assumptions to obtain sensible hadron kinematics:</td>
<td></td>
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<tr>
<td>1. Initial state nucleon uncorrelated</td>
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<td>2. Nucleon initial momenta same as 1p1h</td>
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<tr>
<td>3. Energy shared equally between final state nucleons</td>
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<tr>
<td>4. Energy conserved</td>
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...Selection of interaction-> Lepton F.S.->Hadron F.S...
Implementation: Look Up Tables

Nieves provides code to calculate the double differential cross section

- Too slow for runtime calculation.
- Look up tables are easy to make, implement.

- Tables made for:
  - Target: Carbon, Oxygen
  - Neutrino Flavor: $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$
  - Neutrino Energy: $E_\nu$

- Binning was optimally chosen
  - to cover all the features of the model.
  - optimize computation time.
  - Result: $\sim$95,000 bins.
Implementation: Total cross-section

What it is use for:
- Event rate \( E = \text{Flux}(E) \times \text{Sum of } \sigma(E) \text{ over all interaction} \).
- To sample an interaction following the pdf of \( \sigma(E) \) (here 2p2h).

- Total cross-section calculated by integrating over \( T_{\mu} \cdot \cos \theta \), for each energy.
- For given neutrino energy, total cross-section is interpolated using linear interpolation.
- Note: for any target that is not \( ^{12}\text{C} \) or \( ^{16}\text{O} \), set \( \sigma \) to zero.
Implementation: Total cross-section

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...2p2h MEC added
Implementation: Lepton kinematics

When the 2p2h interaction is selected, sample the lepton kinematics from the PDF of double differential cross-sections.

- For given $E_\nu$, interpolate cross-section for grid of $T_\mu - \cos\theta$ values, from adjacent energy bins.
- Sample $T_\mu - \cos\theta$ using selection-rejection method.
- Differential cross-section for sampled point is obtained by bi-linearly interpolation from the grid of $T_\mu - \cos\theta$ bins.

Determines $Q^2$ of an event...
Implementation: High energy extension

The Problem: the initial model was valid only below 1.5 GeV.

Why? Not all channels contributing to 2p2h are accounted for, which could contribute constructively or destructively at higher energies.

The Solution: a cut on three momentum transfer

The model is valid for $|q_3| \leq 1.2$ GeV. (arXiv 1307.8105.v1)

\[ |q_3| = \sqrt{|p_\mu|^2 + |p_\nu|^2 - 2|p_\mu||p_\nu| \cos \theta_{\mu\nu}} \]

- Confirmed to work up to and beyond 10 GeV
- This limit contains the interesting features of the model.

As T2K has significant flux above 1.5 GeV, this extension was implemented.
Implementation: High energy extension

- With the $|q_3| \leq 1.2$ GeV cut implemented:
  - There is little impact at low neutrino energy
  - There is a large effect at high neutrino energy

But the features of the model are still present, even at high energies

Lepton scattering angle restricted by $q_3$ cut.
Implementation: High energy extension

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**Lepton scattering angle restricted by $q_3$ cut.**
Implementation: hadron kinematics

- Nieves’ model does not provide information for the outgoing hadrons.
- Implemented Jan Sobczyk's Multinucleon-ejection model, based on the implementation in NuWro, but with some modifications.

1) Given $Q^2$, choose interaction position in nucleus (this decides max nucleon momenta)
2) Choose two uncorrelated nucleon momenta. (Check energy conservation to allow 2 real nucleons)
3) Boost to CoM frame of nucleon system (momentum + $Q$)
4) Divide energy evenly between two nucleons and eject in random directions
5) Boost back into lab frame
6) Impose Pauli-blocking

Energy/ Momentum Conservation
(Initial – Final)

All within floating point precision, including a known energy bias.
Future work - for this model

• In Progress:
  • Isospin breakdown
    • Currently using a fixed ratio.
    • Recent Nieves publication gives a procedure to model the isospin breakdown.

• Things we’d like to implement:
  • Non-isoscalar targets
  • More realistic hadron kinematics
Alternate models

A number of other models have been, and are being, studied with NEUT

- Martini et.al model
  - Based on many body formalism provides an alternate prediction to 2p2h cross-section.
  - Being used to evaluate the systematics attributed to model differences.

- Transverse Enhancement Model
  In the kinematic region where 2p2h model fails, alternate model like TEM model could be substituted.

- RPA
  A rather complimentary model which, along with npnh model, explains MiniBooNe results.

- And after this meeting, possibly more!
Summary

• A number of models that describe the CCQE cross-section discrepancies through nuclear effects are now available and in development.

• Of these, Nieves model is now in NEUT, both to gauge the influence of this new interactions on oscillation analysis and for testing the against T2K data.

• Studies are being carried out to test this model by fitting experimental data, to see how models or combination of models perform.

• This implementation is ready to be used for next T2K analysis.