Implementation of multi-nucleon model in NEUT

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

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on behalf of

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for T2K collaboration.

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AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

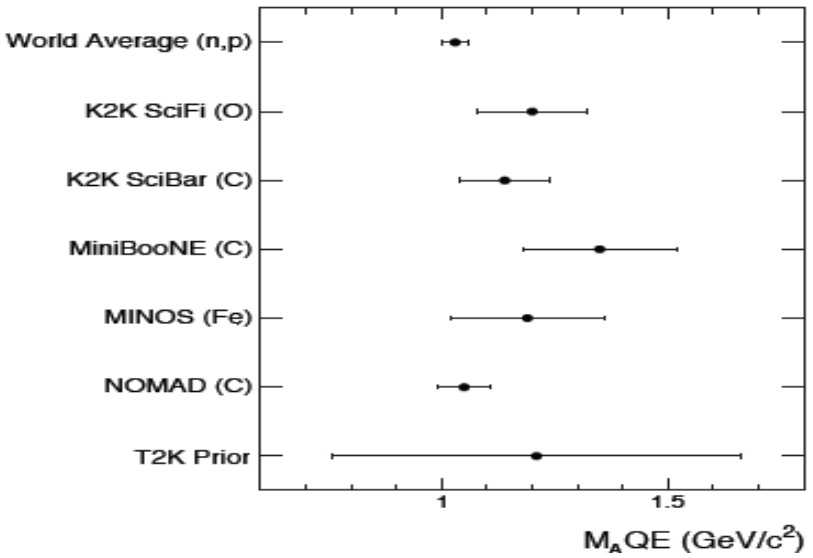
Colorado State University

5th December 2013

INT Seattle, Washington

Status of CCQE @ T2K

Concerns for higher value of axial mass Ma=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.

From ND280

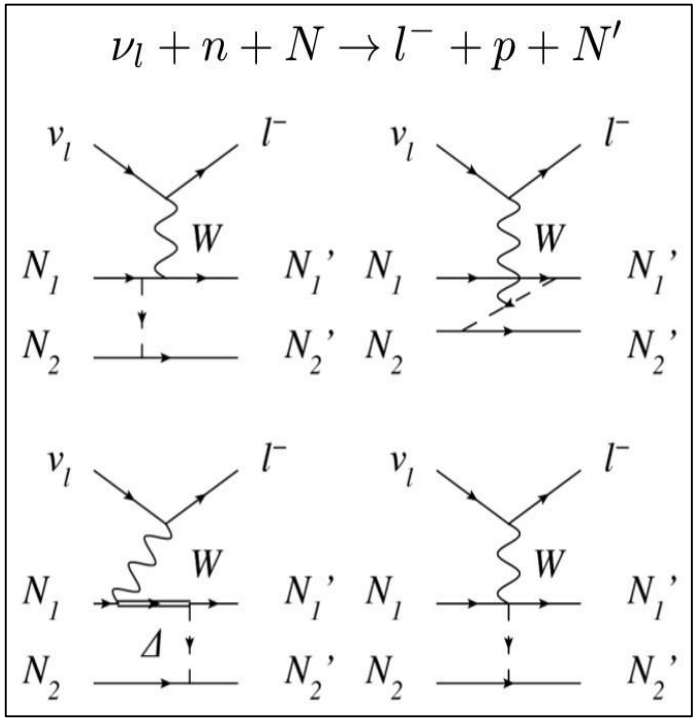
T2K Error Sources	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	w/ ND280 fit
Beam only	11.6	7.5
M_A^{QE}	21.5	3.2
M_A^{RES}	3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)	9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)	4.2	2.0
NC1π^0 norm.	0.6	0.4

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.

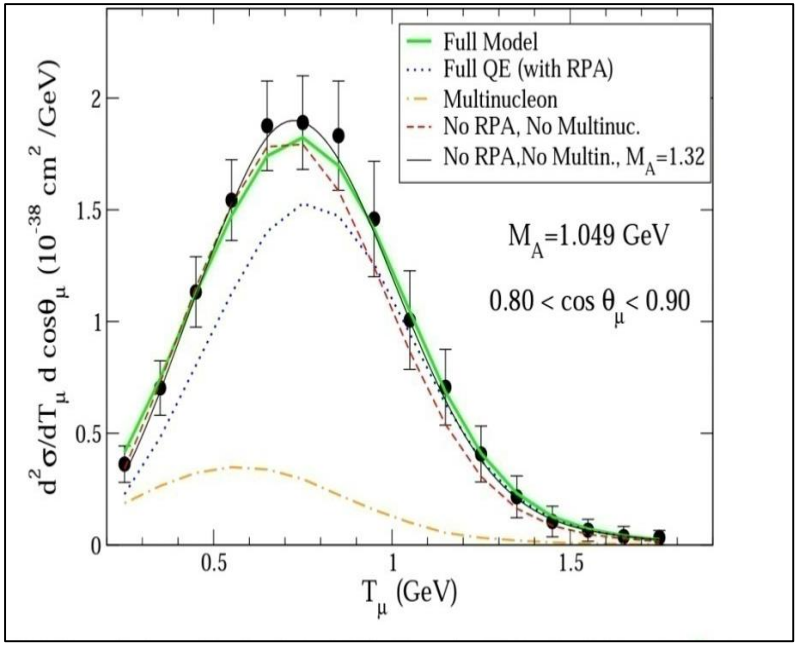


This interaction likely to contribute as CCQE, if any nucleon is left undetected

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

Nieves et.al. 2p2h model

- Provides lepton kinematics. Double differential cross-section in lab frame.
- Uses local fermi gas model
- Valid for isoscalar targets only
- No hadron information (integrated out)
- Isospin breakdown now available (not implemented).

Ref: Phys.Rev.C70:055503,2004

Jan Sobczyk's Multinucleon-ejection model

Uses minimal assumptions to obtain sensible hadron kinematics:

1. Initial state nucleon uncorrelated
2. Nucleon initial momenta same as 1p1h
3. Energy shared equally between final state nucleons
4. Energy conserved

Probably does not contain all relevant physics.

Ref: Phys Rev C 86, 015504 (2012)

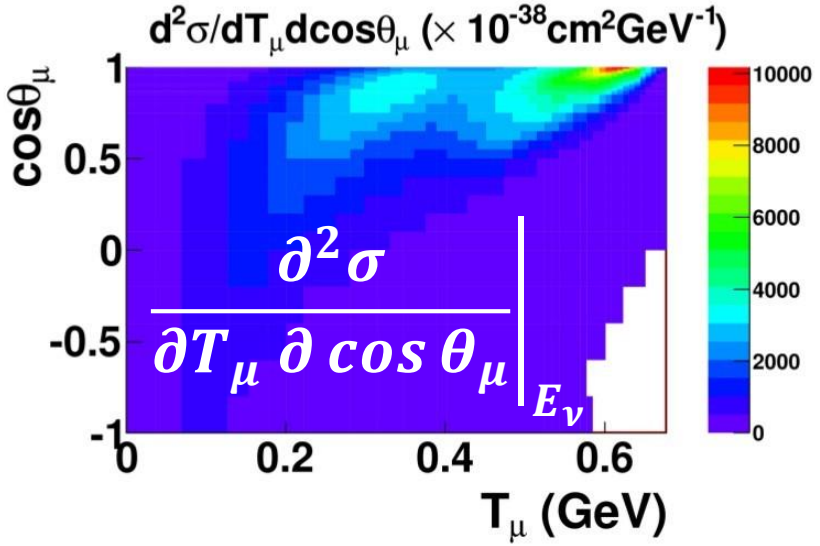
...Selection of interaction-> Lepton F.S.->Hadron F.S

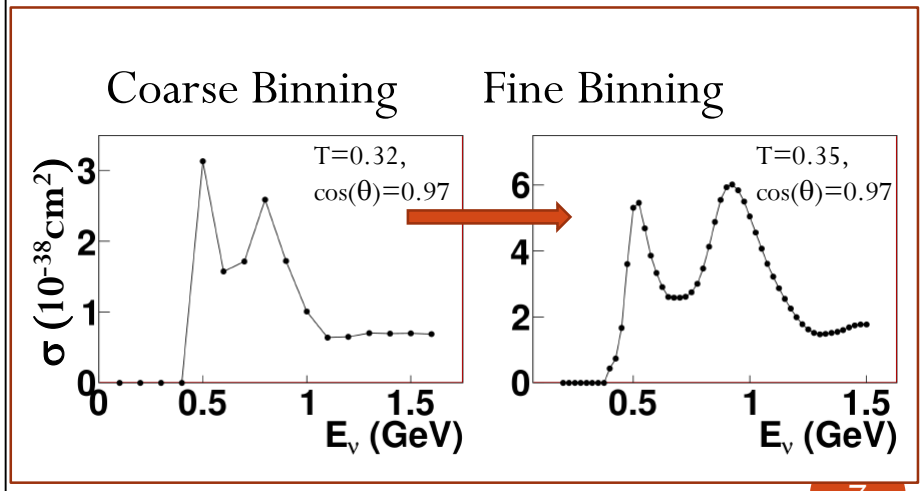
Implementation: Look Up Tables

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: ν_μ, ν_e, $\overline{\nu}_\mu$, $\overline{\nu}_e$
  - Neutrino Energy: E_ν
- Binning was optimally chosen
  - to cover all the features of the model.
  - optimize computation time.
  - Result: ~95,000 bins.





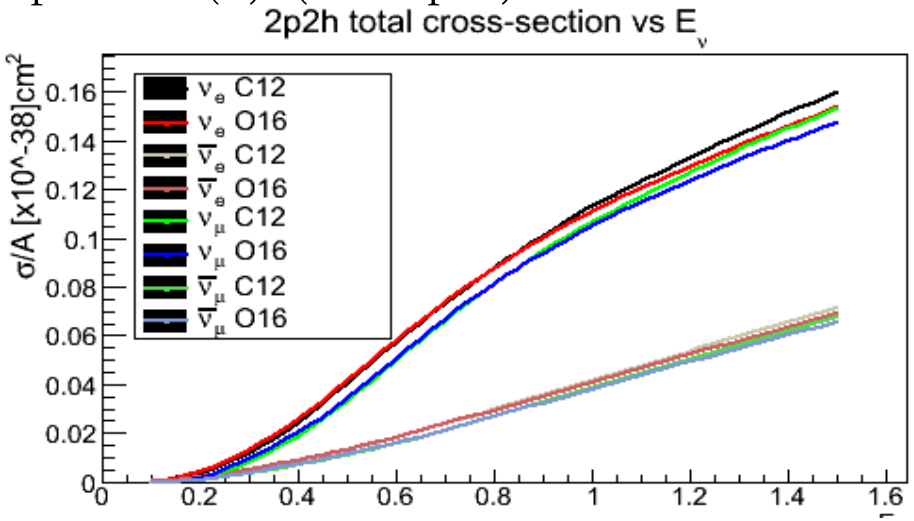
Implementation: Total cross-section

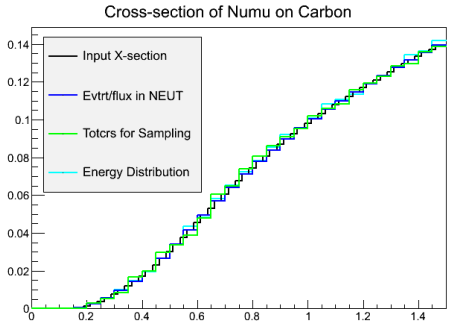
What it is use for:

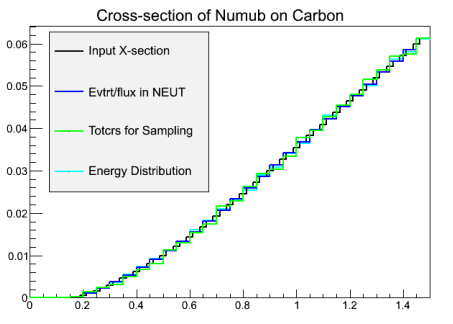
- Event rate (E) = Flux(E) x Sum of σ(E) over all interaction.
- To sample an interaction following the pdf of σ(E) (here 2p2h)

- Total cross-section calculated by integrating over T_μ-cosθ, for each energy..
- For given neutrino energy, total cross-section is interpolated using linear interpolation.
- Note: for any target that is not ^{12}C or ^{16}O, set σ to zero.

...







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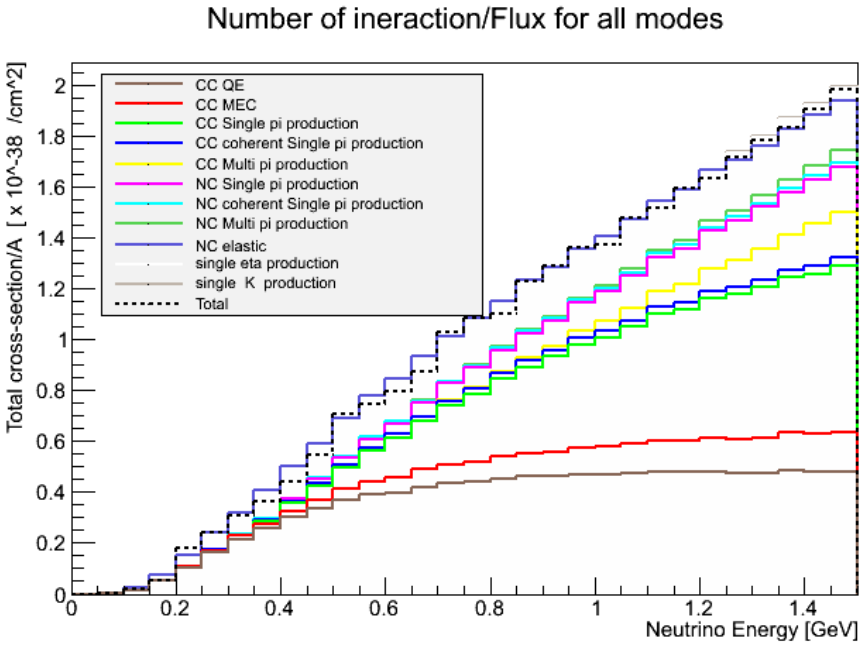
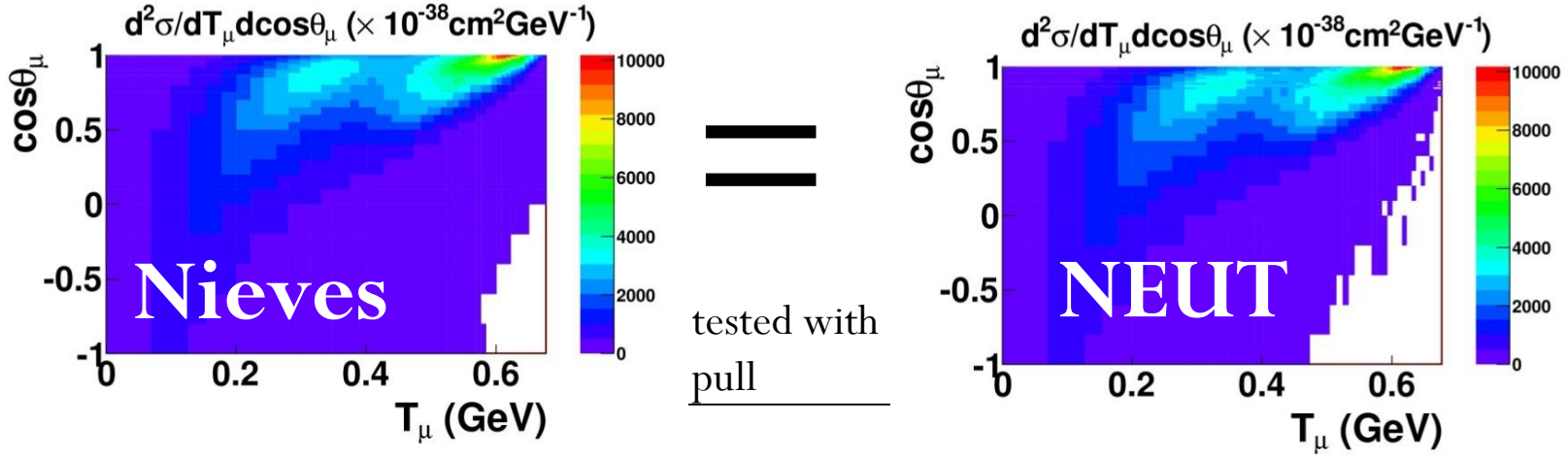


…2p2h MEC added

Implementation: Lepton kinematics

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

- For given Eν, interpolate cross-section for grid of T_μ- cosθ values, from adjacent energy bins.
- Sample T_μ- cosθ using selection-rejection method.
- Differential cross-section for sampled point is obtained by bi-linearly interpolation from the grid of T_μ- cosθ bins.



Determines Q^2 of an event…

Implementation: High energy extension

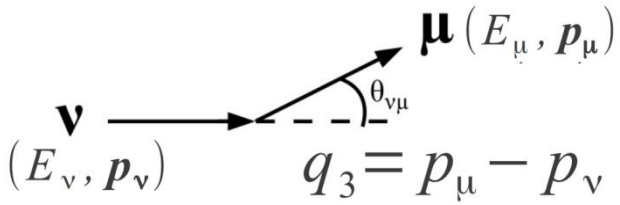
The Problem: the initial model was valid only below 1.5 GeV.

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)

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



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

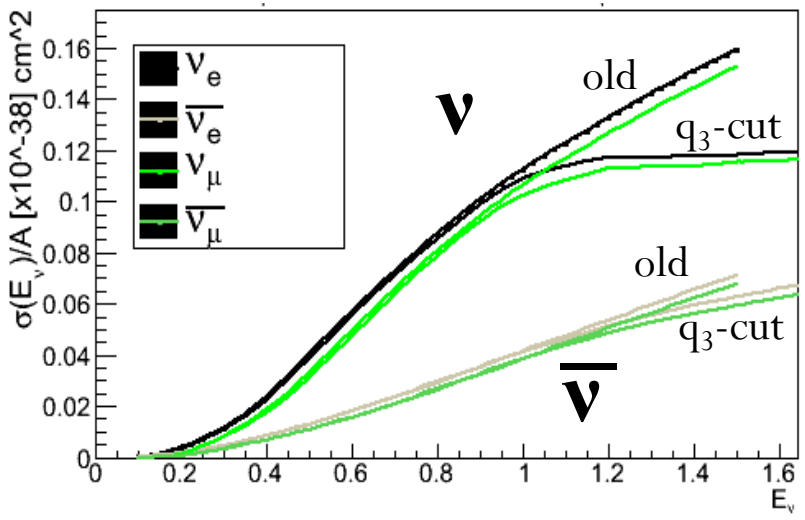
As T2K has significant flux above 1.5 GeV, this extension was implemented.

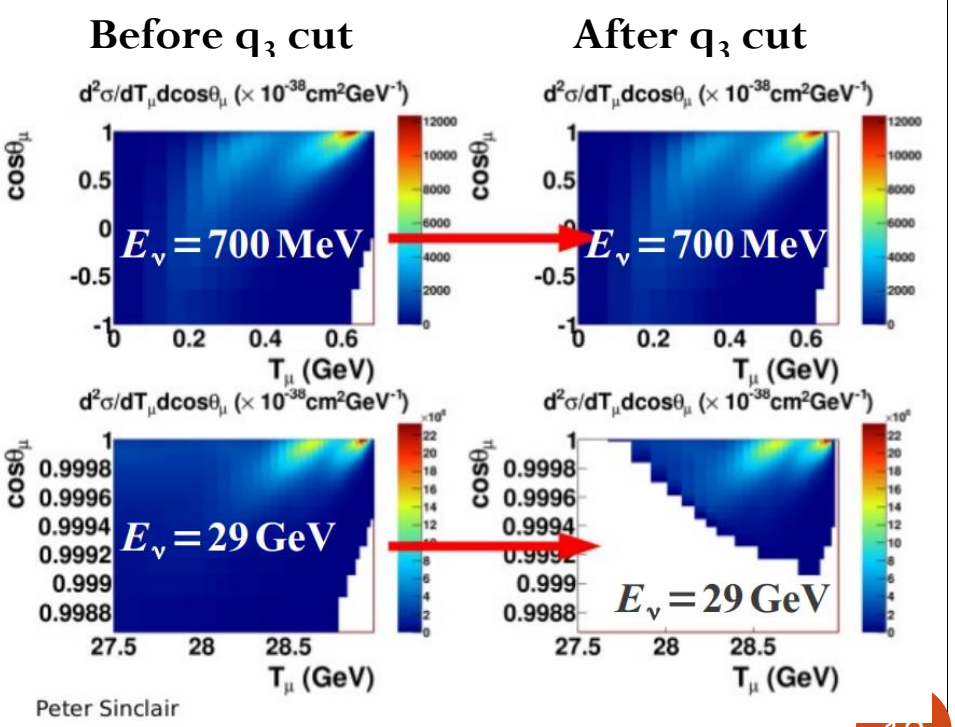
Implementation: High energy extension

- 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

2p2h Cross Section on Carbon





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Lepton scattering angle restricted by q3 cut.

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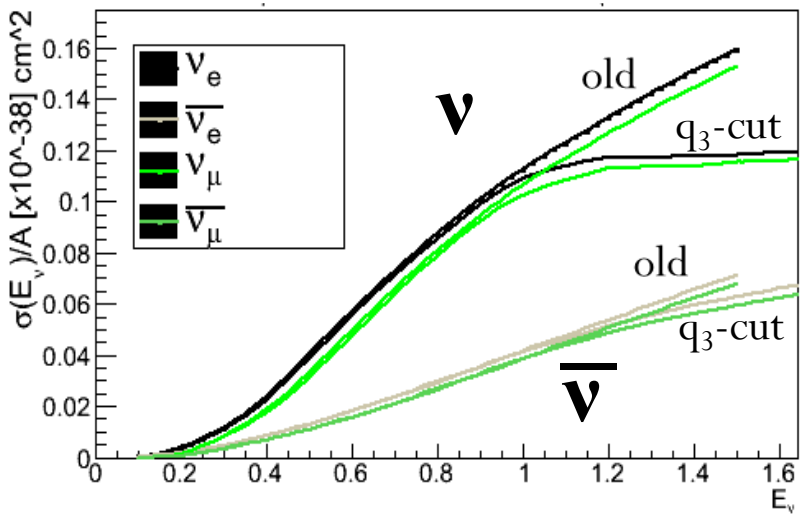
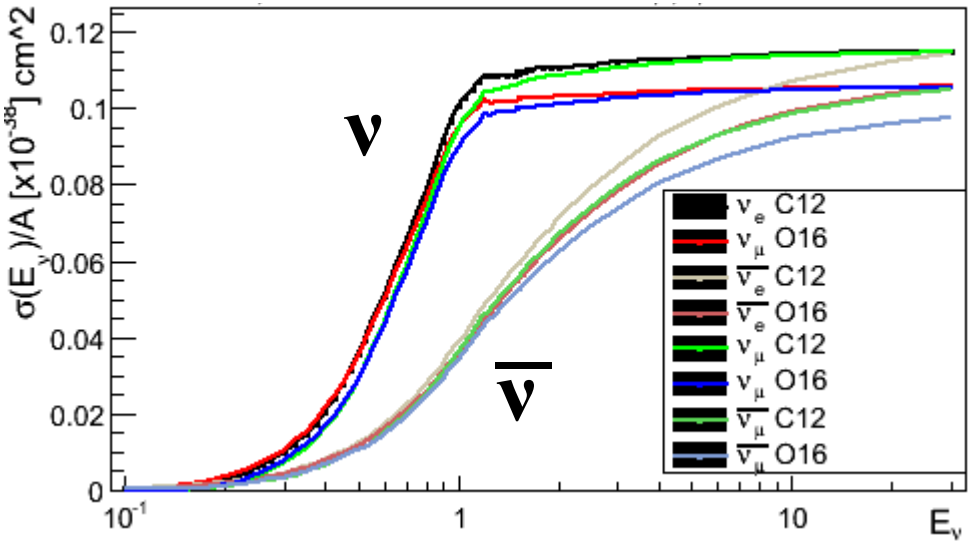


2p2h Cross Section on C & O



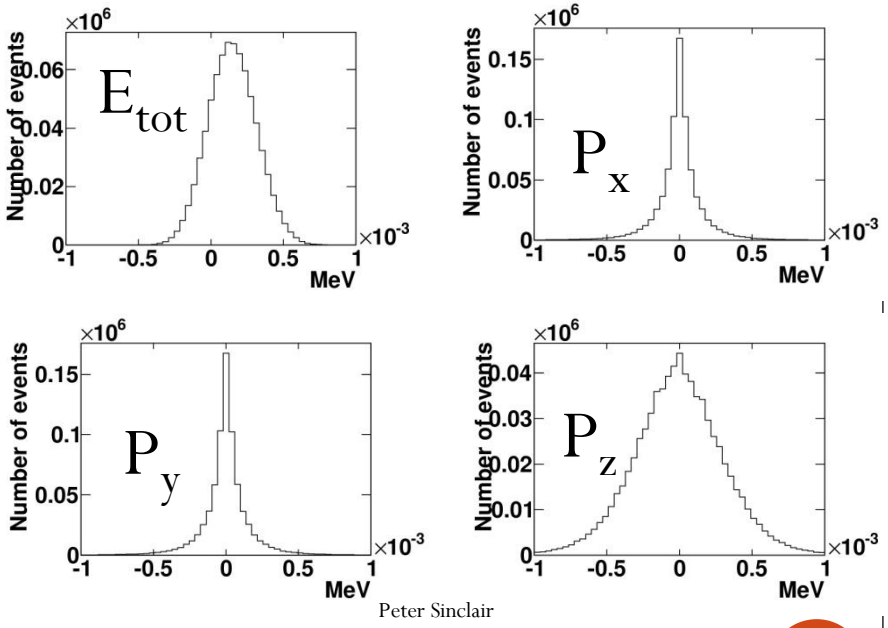
Lepton scattering angle restricted by q3 cut.

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)



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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.