Neut
Questions and answers

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for the Neut developers

What is NEUT

Neutrino-Nucleus interaction simulation program library

developed by SK and T2K collaborators

(mainly) for Super-Kamiokande and T2K experiments

Energy range

~100MeV ~ 10 TeV

Various nuclear targets

Mainly targets are light nuclei (C, O, and H) but can handle Ar, Fe or heavier target.

Channels

Primary neutrino interactions

Quasi Elastic,

Single meson productions,

Multi-pion productions

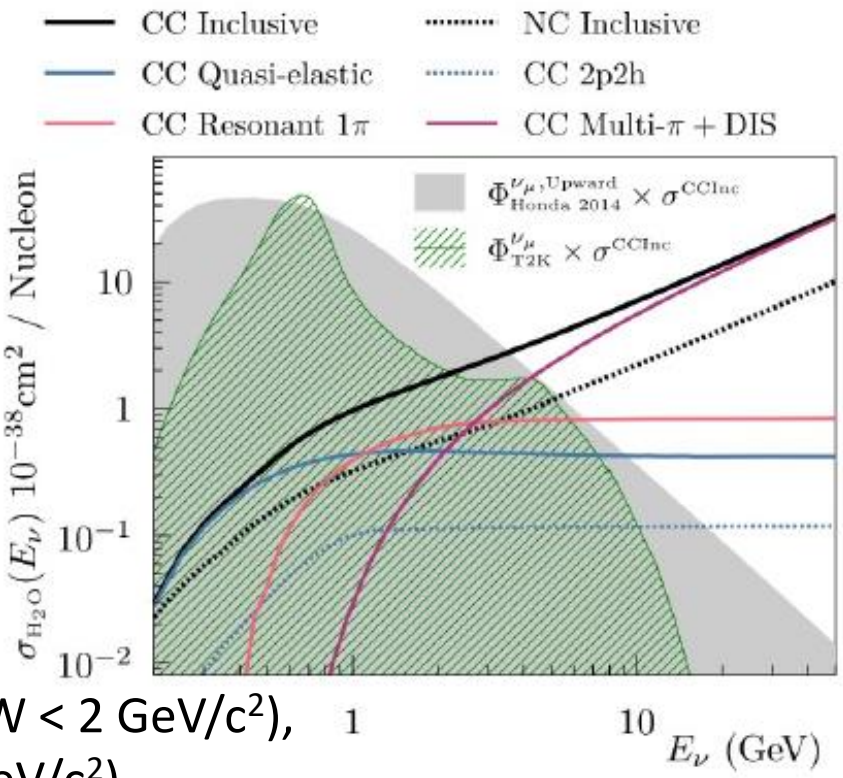
(shallow inelastic scattering, $W < 2$ GeV/c^2),

Deep inelastic scattering ($W > 2$ GeV/c^2),

CCQE-like 2p2h (meson exchange current model).

Secondary hadron interactions in nucleus

pion, kaon, eta, omega and nucleon.



Y.H. and L. Pickering
EPJS,230, 4469–448

Question #1

1. What are some recent and exciting developments in your generator?

Implemented in the latest release (Neut 5.6.2)

- Single pion production
  DCC (Dynamical Coupled Channel) model
- Multi-pion production (SIS) and DIS updates
  Recent Bodek-Yang correction
  Correct NC DIS cross-section
  Multiple pion multiplicity models (for Multi-pion mode)
- CCQE-like 2p2h
  Treat additional nuclei using extra/interpolation
- New radiative correction
  γ emission together with charged lepton.
  Two kinds of distributions, isotropic or forward-biased.
- Improved nuclear effect of K and eta

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- Single pion production

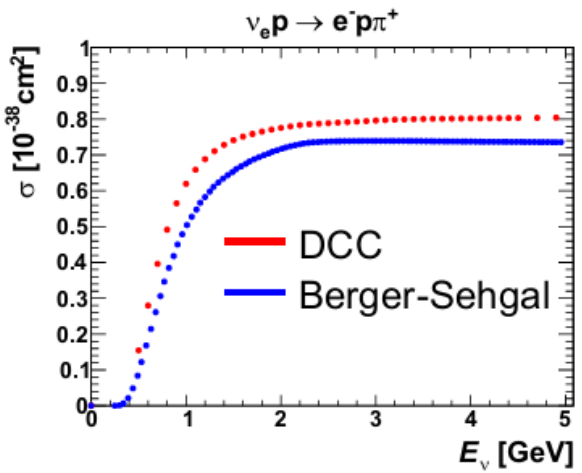
  DCC (Dynamical Coupled-Channel) model

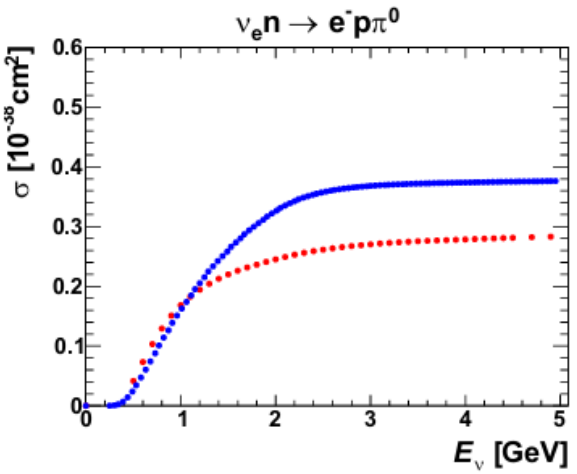
  S. X. Nakamura, H. Kamano, and T. Sato, Phys. Rev. D **92,** 074024 (2015).

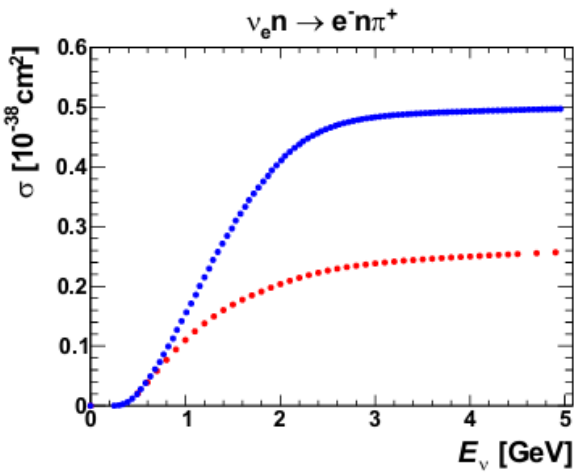
  Authors provided their code to calculate cross-sections.

$$(\sigma(E_\nu), \frac{d^2\sigma}{dq^2 dw})$$

  Cross-sections are quite different from the ones from Rein, Berger and Sehgal model in Neut.







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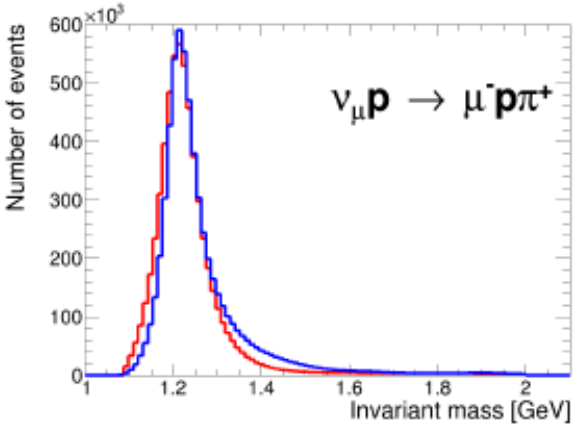
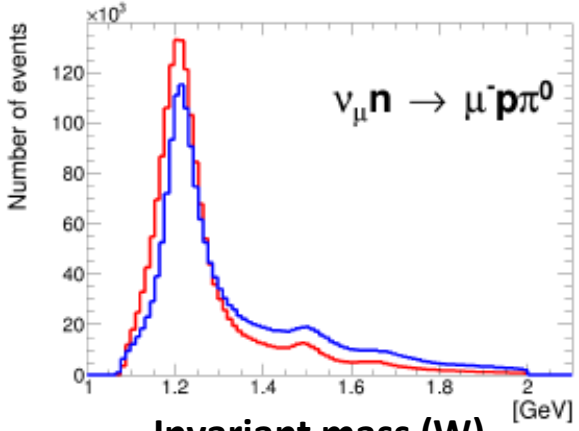
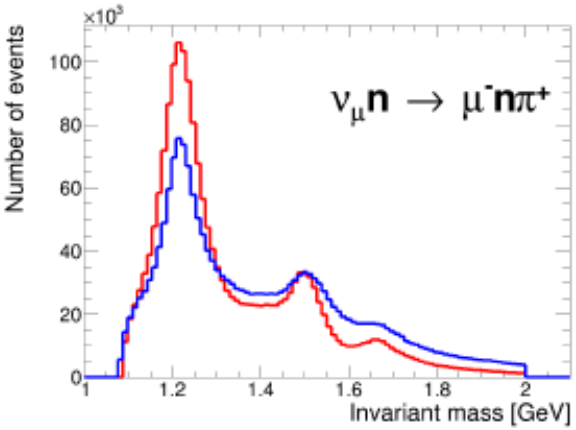




Invariant mass (W)



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- Multi-pion (SIS) and DIS updates

  Newer Bodek-Yang correction is implemented. (arXiv: hep-ph:2108.09240v2)

  value of K^{axial}_{val}, introduction of K_{LW}^{ax},

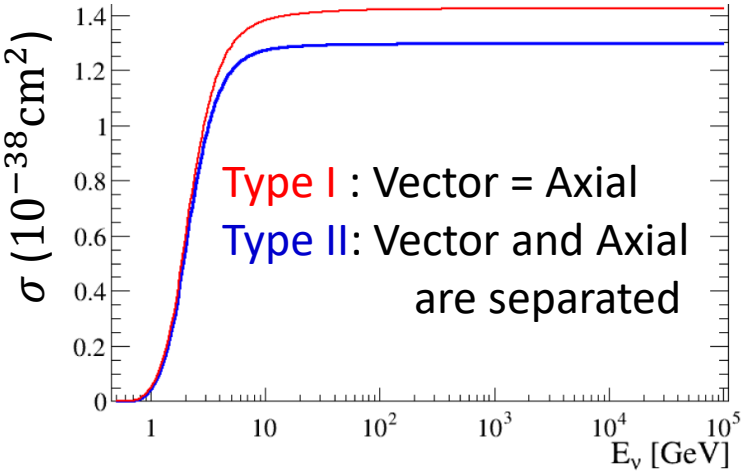
  increase sea quark and antiquark contributions

  Corrected NC DIS cross-section

  (Previous versions used simple scaling to CC.)

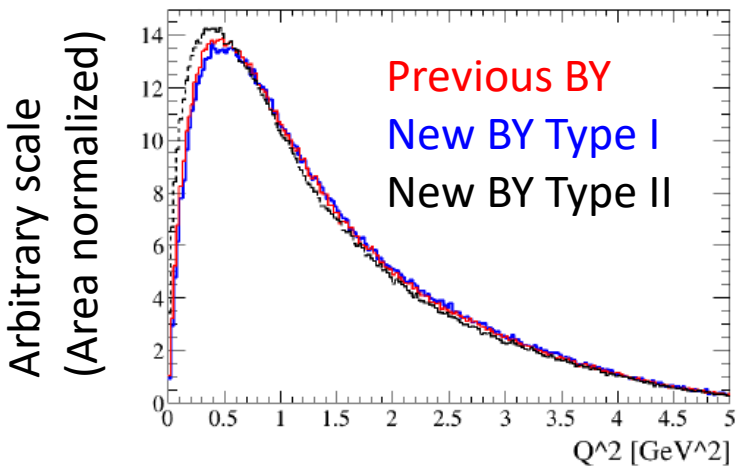
Cross-section for $\nu_\mu + n \rightarrow \mu^- + N + n\pi$

(N: nucleon, n > 1, W < 2GeV/c^2)



Q^2 for 4 GeV ν_μ on water,

(n_{had} > 1, W < 2GeV/c2)



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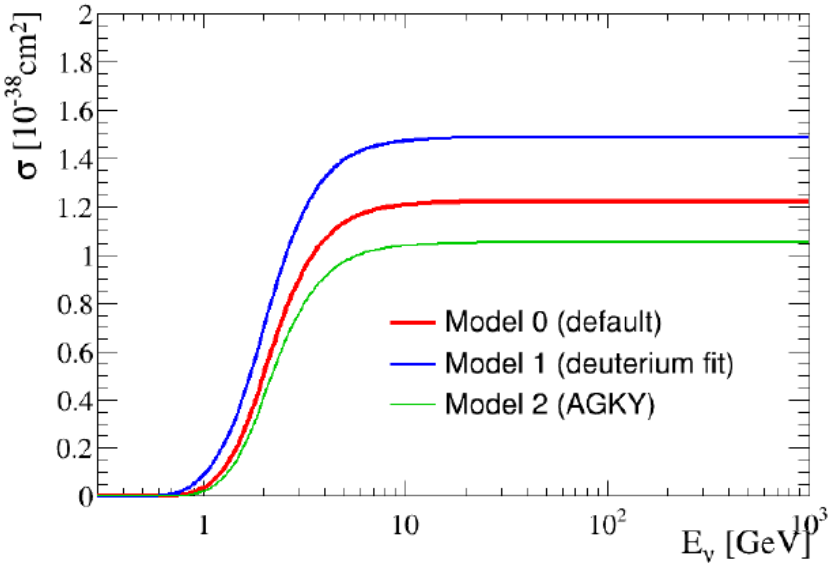
- Multi-pion (SIS) and DIS updates

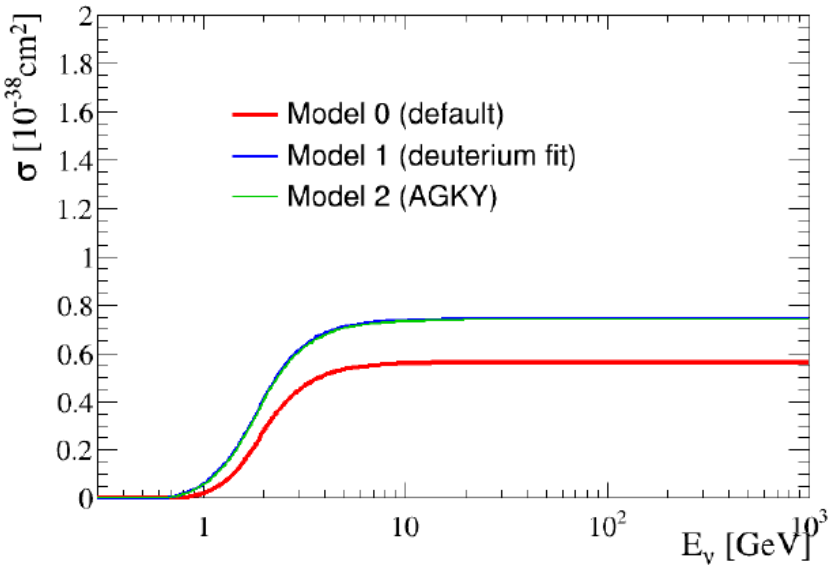
  Alternative pion multiplicity parametrization (for SIS)

  To generate "multi-pion" (# of π > 1) events with W < 2 GeV/c^2,
  We use the custom code based on the experimental data.
  Three multiplicity functions are provided.

Cross-section for $\nu_\mu + n \rightarrow \mu^- + N + \mathrm{n}\pi$
(N: nucleon, n > 1, W < 2GeV)



Cross-section for $\nu_\mu + p \rightarrow \mu^- + N + n\pi$
(N: nucleon, n > 1, W < 2GeV)



Question #1

2. What are the near-term development priorities?

- Release the “refactorized” Neut (Neut 6)
  - Minimize dependency to CERNLIB
  - New input card file format
  - New data format (HepMC-based)
  - Improve interoperability with C/C++
    - (use some features in recent standards of Fortran)
  - Provide simple API for geometry/flux drivers
- New models
  - SuSA v2 CCQE model
  - Improved nucleon re-scattering
  - Replace old PYTHIA (5) with newer version
  - Electron interactions
    - Electron elastic scattering (almost ready)
    - DCC electro-pion production

Question #2

1. What is the process of including new theory calculations into your generator? Please include new BSM interactions if these are supported.
2. If the original theory code is written in a different programming language, how is this handled? Are there plans to change the strategy?

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1. 2 major cases. T2K or SK collaborators implement new models by themselves, or consult theorists, obtain their codes or collaborate with them, and add to Neut.

2. We try to use the code by authors as much as possible. We use Fortran, C and C++ and all the provided codes in the past use one of them. Therefore, we did not care until now. We don’t change this philosophy unless we can not use the provided code (not callable) from C or C++.

Question #3

1. How do you handle flux and geometry within your generator?
2. Are there important requirements in these interfaces?

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1. Geometry driver is independently developed by each experiment group. SK has dedicated atmospheric neutrino driver in their own library. T2K is using “neutgeom”, which is distributed with Neut but not supported by us at this moment.
2. Necessary to define standard API to use
   1. total cross-section functions,
      ($\sigma(E_\nu, \mathrm{flavor}, \mathrm{target\ nucleus})$)
   2. individual cross-section functions,
      ($\sigma(E_\nu, \mathrm{flavor}, \mathrm{interaction\ mode}, \mathrm{targt\ nucleus})$)
   3. single event generator for given E_ν, flavor, interaction mode, target nucleus.

   (Need to define API to configure various parameters, also.)

Question 4

1. What information do you store in the output files?

1. What we store are
   - Used models and model parameters
   - Target nucleus
   - Interaction mode
   - Differential cross-section
   - Random seeds
   - Origin of neutrino (parent pi/k/mu vectors for accelerator neutrino)
   - Information of initial, intermediate and final particles

     Initial particles (neutrinos, nucleons or nucleus)

     Particles generated by the initial neutrino interactions

     Particles interacted in the nucleus (before leaving the nucleus)

     4 momentum
     Interaction position
     Time
     Parent particle
     Kind of the interaction in nucleus (for FSI)
     Status after the interaction

Question 5

1. How are systematic uncertainties handled on your generator's predictions?
2. Are there plans for new development in this area?

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1. NEUT has reweighting functions
   - Returns “weight” to an event for different model or model parameters in Neut.
     - For the primary neutrino interactions, returns the ratio of the differential cross-sections.
     - For the secondary interaction, returns the ratio of the probability to occur the secondary interaction.

   Also, there are reweighting library called “T2K-reweight” is extensively used in the T2K analysis.
   NUISANCE also works with Neut.

2. T2K continuously improving the tools to perform systematic error evaluation and various fake data studies.

Question 6

1. What is your generator group's level of interest in helping to define and maintain public, standardized tools for flux, geometry, output storage, etc.?

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1. Highly interested in. If this is realize, various issues we have in the joint analysis like T2K/NOνA are expected to be easier to solve (or simplified).

    - Standard output data format will make it easy to exchange the generated vectors.
    - Standard flux data format (and driver) will help to develop neutrino flux simulation programs, also.
    - Standard geometry driver will help to adopt one generator to the other experiments.

Summary

- New version of Neut (5.6.2) was released recently.
  - DCC single pion production is implemented.
    - We use ($\sigma(E_\nu), \frac{d^2\sigma}{dq^2 dw}$) of the model, but not the pion angular distribution model of theirs, so far.
  - Various updates for multi-pi (SIS) and DIS
    - Recent Bodek-Yang correction
    - Multiple pion multiplicity models (for SIS)
    - Correct NC DIS cross-section
  - Supports additional nuclei in simulating CCQE-like 2p2h
  - New radiative correction (CCQE)
  - Improved nuclear effect of K and eta
- Preparing the “refactorized” Neut as Neut 6
  - Improved interoperability with C++ (and C)
  - Less dependence on CERNLIB
  - Support new configuration and output data format files