NEUT Strategy (Current status and plan)

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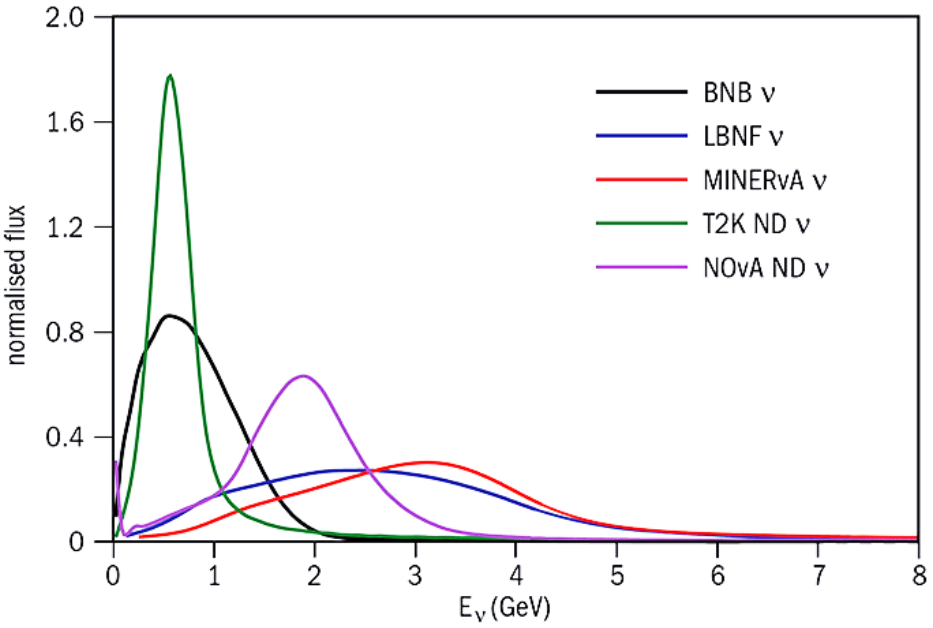
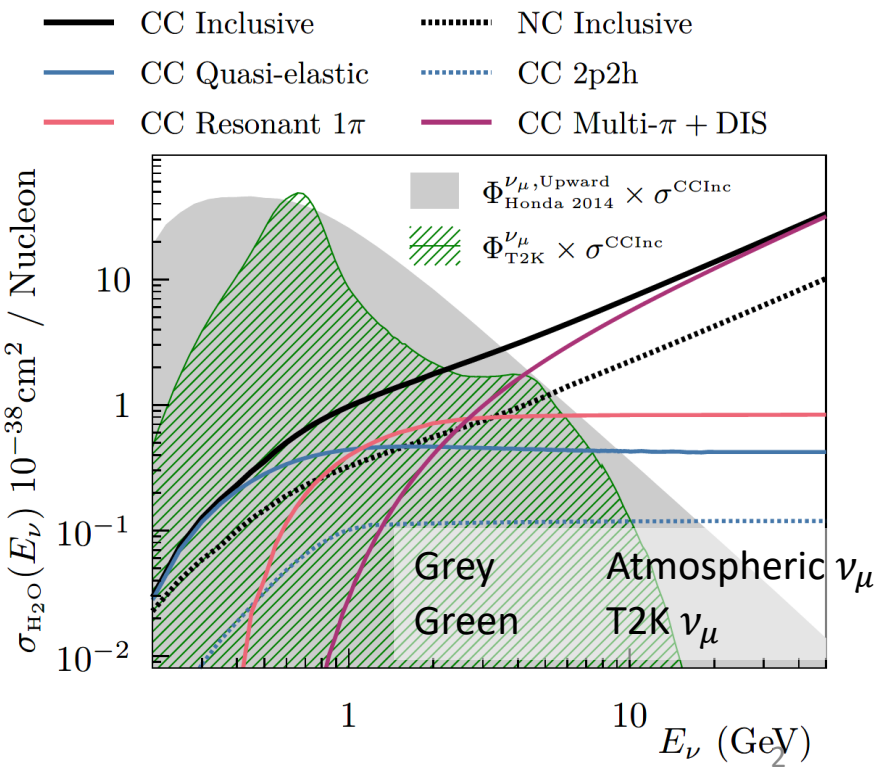
for the NEUT contributors

https://arxiv.org/abs/2106.15809

Introduction

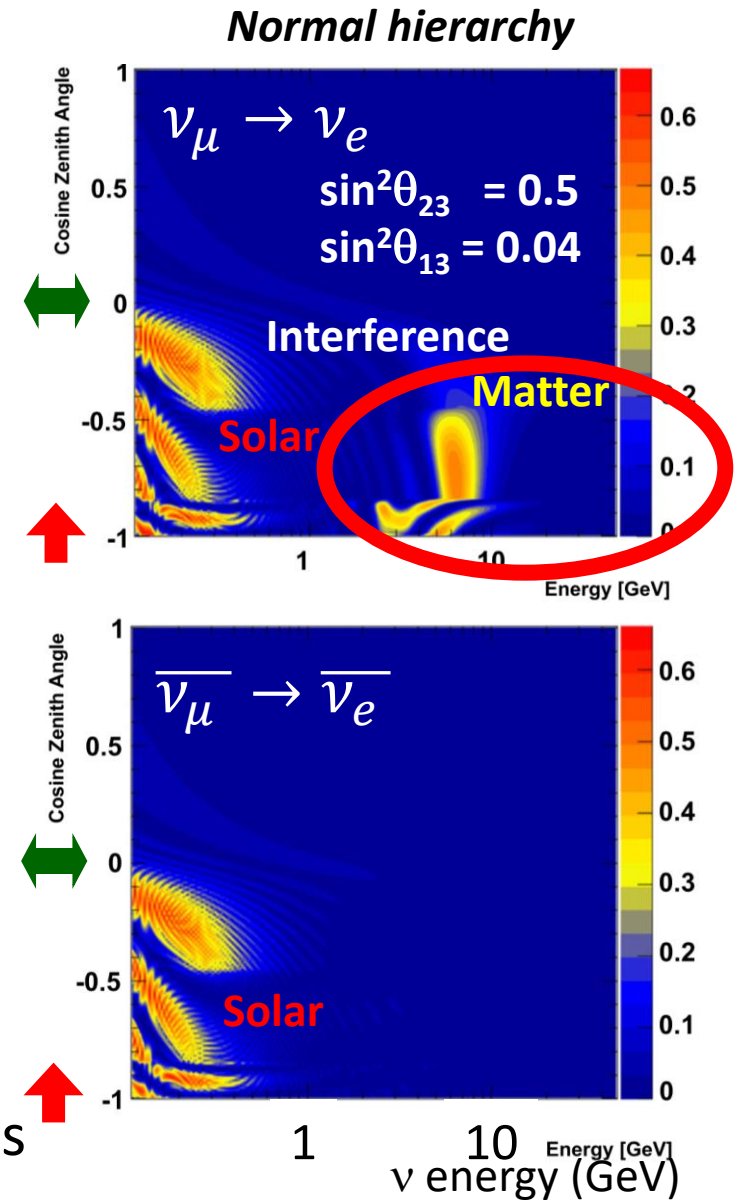
- NEUT is designed to simulate neutrino-nucleus interactions from ~100 MeV to TeV.
- Supports interactions with major nuclei, from Boron to Lead and free proton (Hydrogen).





Introduction

- Atmospheric neutrino
  - Neutrino mass hierarchy
  - → Matter effect in GeV region
  - → Single π and multi π (SIS) dominant
- Proton decay searches
  - Precise background estimation
- T2K
  - Improve sensitivity of CP
  - → Higher statistics with minimum systematic error
  - → Use events with π (mainly single π production) together with CCQE-like (0π) events



Not only QE and 2p2h (multi-nucleon) but 1 π production and SIS models and FSI must be improved.

Recent status of NEUT

- Next release (5.5.0) is in preparation.
  - Two different treatments of the separation/binding energy in Local Fermi-gas CCQE and 2p2h models (F. Sanchez et al.)
  - Alternative Axial form factors for CCQE (P. Stowell)
  - Improvements in multi-pi (SIS) channel (C. Bronner, J. Xia)
  - Kaon FSI bug fix and improvement (R. Matsumoto)

  - Improvements/Enhancements in reweighting (S. Dolan, L. Pickering, C. Wret, and many T2K members)

  - Change of the library structure and building method (L. Pickering)
  - New experimental features
    New style card file and I/O data format (L. Pickering)

https://arxiv.org/abs/2106.15809

Local Fermi-gas CCQE and 2p2h model

Kinematics determination

B. Bourguille, and J. Nieves, and F. Sanchez, JHEP04, 004 (2021)

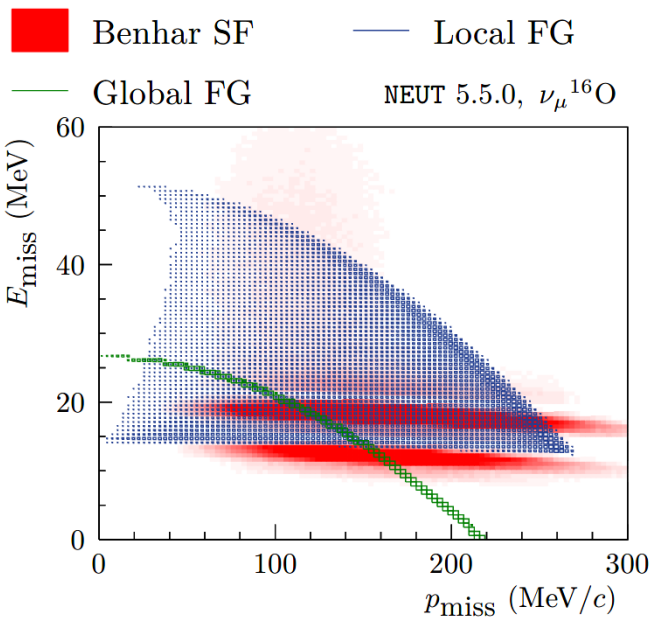
$$\overrightarrow{p_\nu} + \overrightarrow{p_N} = \overrightarrow{p_\mu} + \overrightarrow{p_{N'}}$$

$$E_\nu + (m_N + T_N - T_F) = E_\mu + S_N + E^{\infty}_{N'}$$

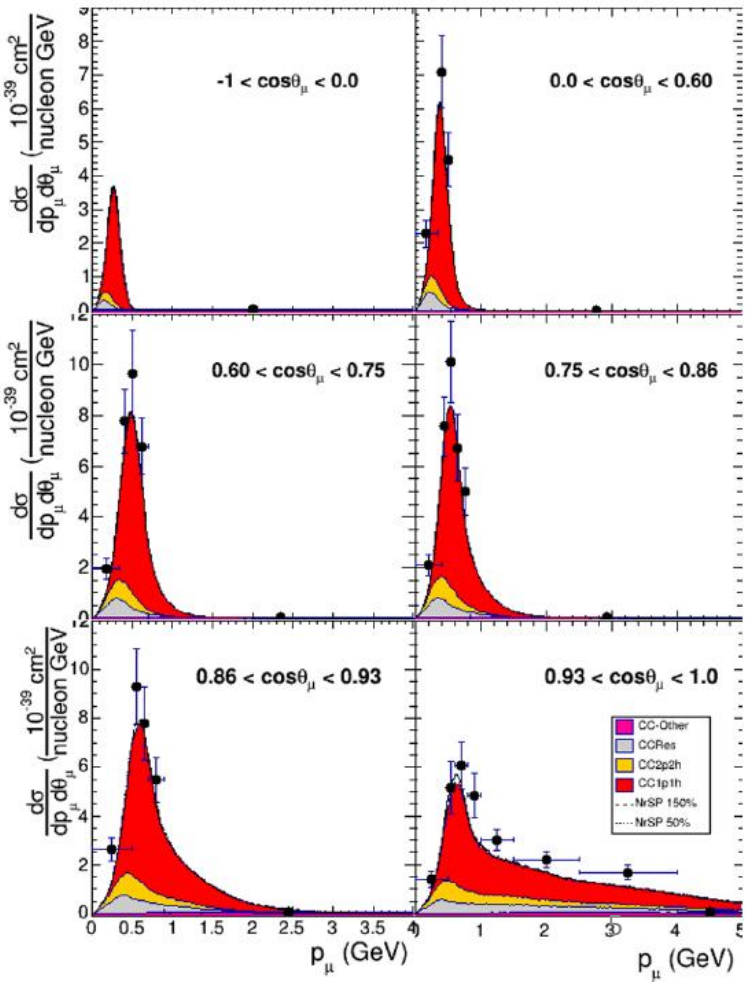
T_N Kinetic energy of the knocked-out nucleon in the target nucleus

T_F kinetic energy of the nucleon at the Fermi level for the given position

$S_N = M'_{A-1} - M_A + m_N$



Comparison with T2K 0π data (From JHEP 04,004)



Alternative Axial vector form factors

(P. Stowell)

For quasi-elastic scatterings, three axial vector form factors are implemented.

By default, dipole form is used but the others are available for various studies.

- 3 component model

$$F_{\mathrm{A}}^{3-Comp}(Q^2) = \left[g_A(1+\gamma Q^2)^{-2} \times \left(1-\alpha+\alpha\frac{m_a^2}{m_a^2+Q^2}\right)\right] + \left[\lambda g_A Q^2 e^{\lambda-\beta Q^2}\right]$$

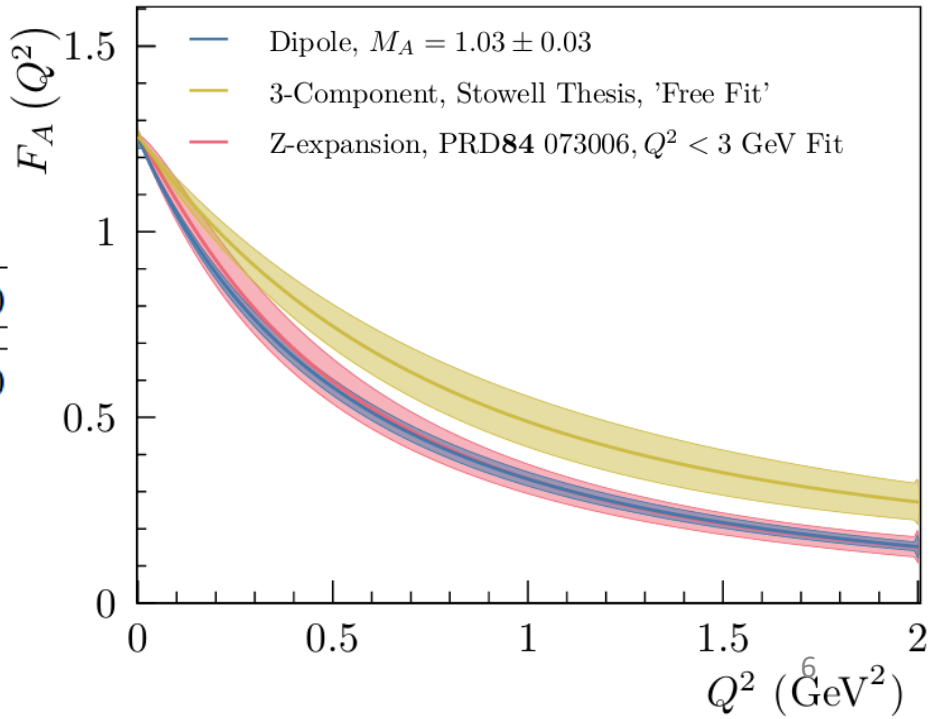
- Z-expansion model

$$F_{\mathrm{A}}(Q^2) = \sum_{k=0}^{N} a_k z(Q^2)^k,$$

$$z(Q^2) = \frac{\sqrt{t_c+Q^2}-\sqrt{t_c-t_0}}{\sqrt{t_c+Q^2}+\sqrt{t_c-t_0}}$$

- Dipole model

$$F_A(Q^2) = \frac{F_A(0)}{\left(1+\frac{Q^2}{M_{\mathrm{A}}^2}\right)^2}$$



Improvements in multi-π (SIS) channel

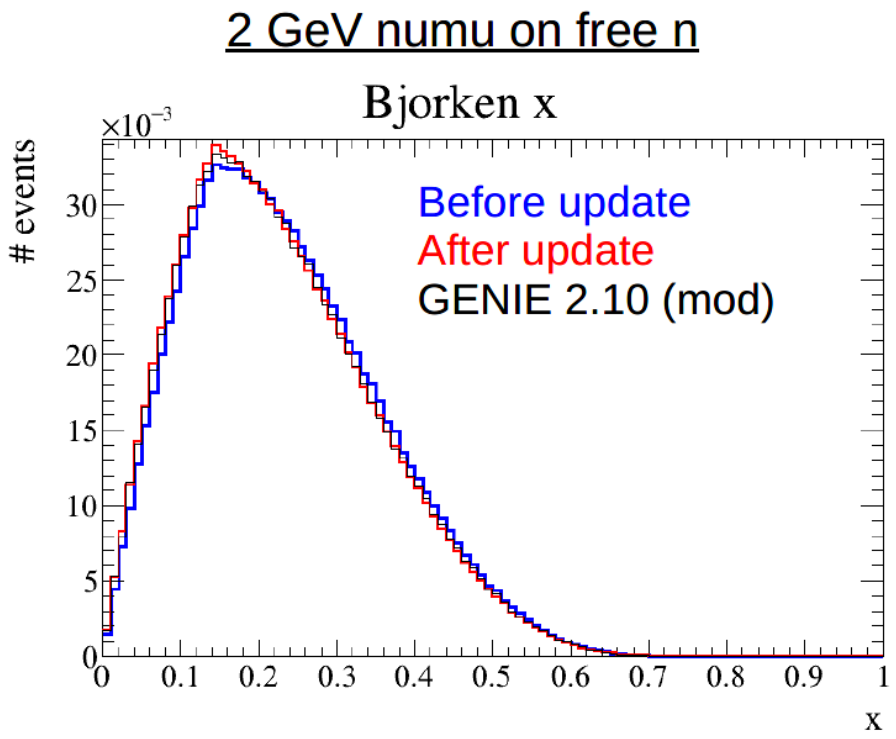
(C. Bronner)

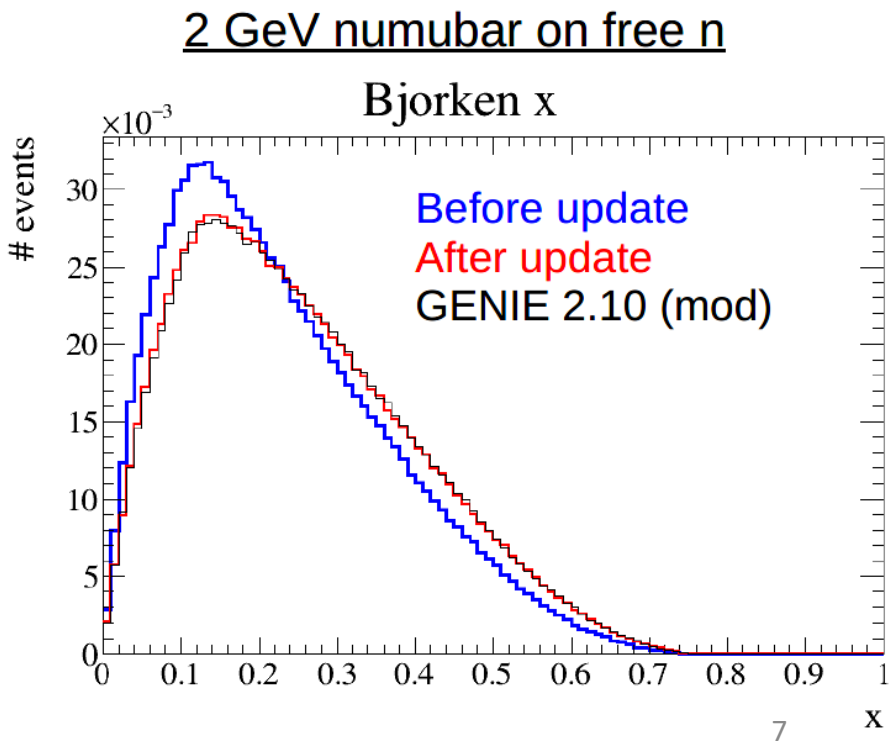
Neutral current interactions

In the past releases, NEUT uses the formulas for CC were used for NC as approximation.

Now, correct formulas are used.

Multi-pion mode (W<2GeV/c^2, # of pions > 1)





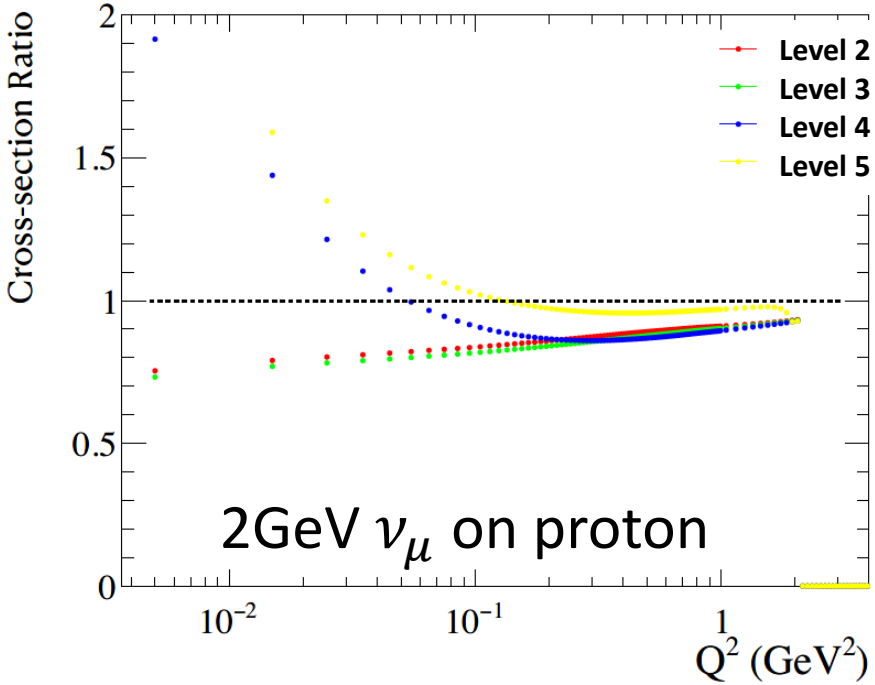
Improvements in multi-p (SIS) and DIS channels

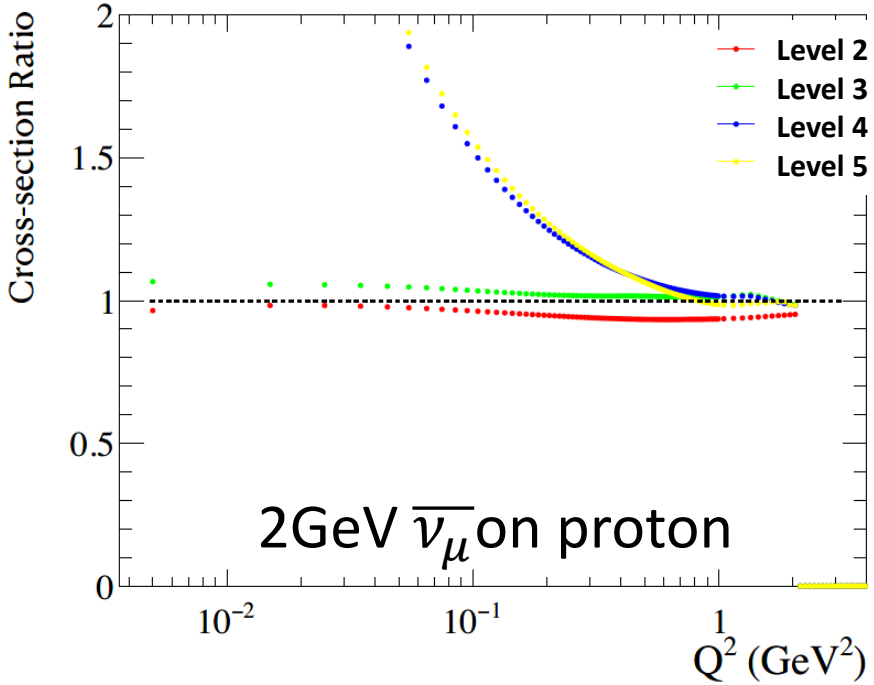
(C. Bronner, J. Xia)

Introducing (slightly) newer prescriptions by Bodek and Yang.

(arXiv:1011.6592v2)

- New values for the parameters of vector PDFs (Level 2)
- Double ratio *H(x, Q2)* multiplied by xF_3 (Level 3)
- New parameters that separate the axial PDFs in F_2 (Level 4)
- New factor *KLW,* multiplied by valence u and d quark probability distributions (Level 5)





Will be revised with the latest publication by authors. *(arXiv.org:2108.09240)*

Kaon FSI bug fixes and improvements

(R. Matsumoto)

Actual interaction probability in the code was too small.

(Due to the bug in the code.)

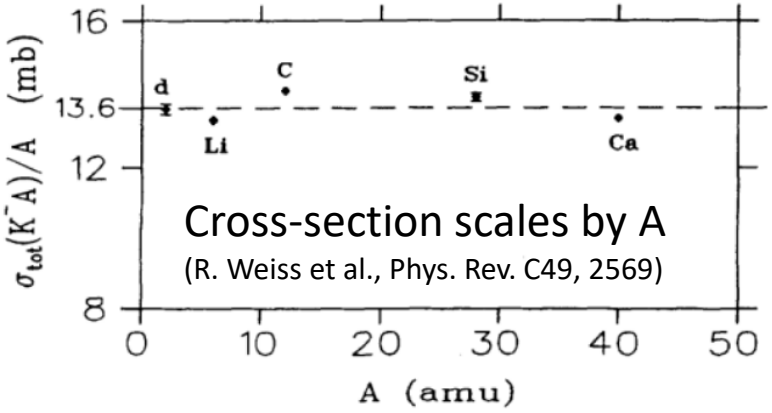
- Cross-section formula was corrected.
- Total cross-section was replaced and introduced “ad-hoc” scaling parameter to reproduce the external K^+ scattering data.

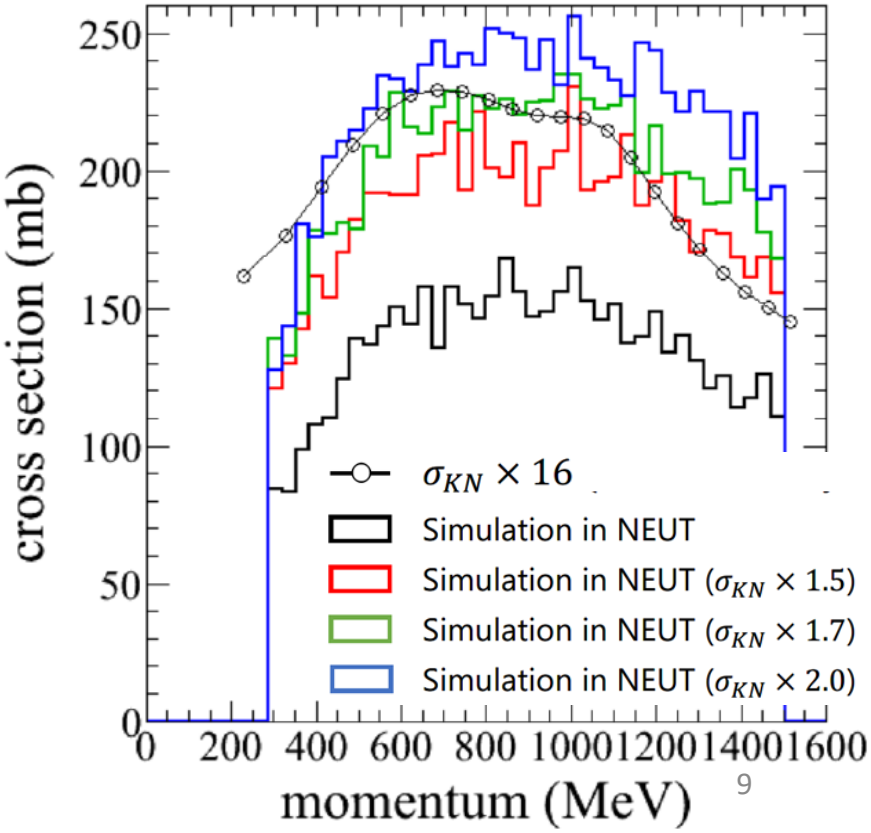
(spin1/2-spin0 elastic scattering formula)

If target nucleon spin ½ is considered, orbital quantum number l is split into $l \pm 1/2$:

$$\sigma = \frac{4\pi}{k^2}\sum_{l=0}^{\infty}\{(l+1)\left|f_{l+1/2}\right|^2 + l\left|f_{l-1/2}\right|^2\}$$

Detailed derivation is in Williams W. S. C 1971 “An Introduction to Elementary Particles” (New York: Academic).



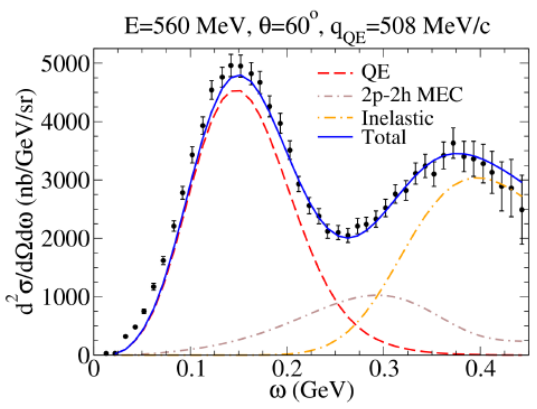


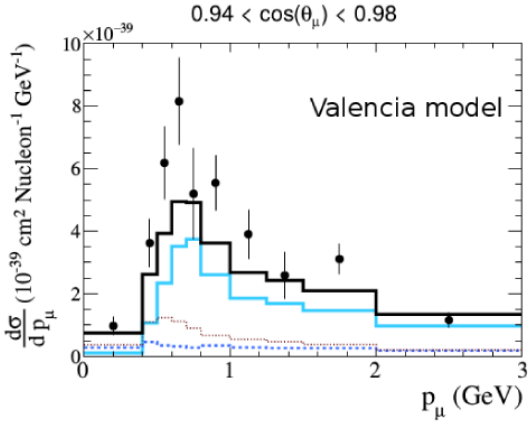
Current projects for the future releases

(G. Megias)

Implementation of SuSAv2 and RMF models in NEUT ⇒ *reweighting parameters for OA, study of nuclear-medium effects (FSI, E_b, shell model vs. SF), comparison between nuclear optical potentials and cascade models, C/O differences on ν_μ vs. ν_e and ν_l vs. $\bar{\nu}_l$, etc.*

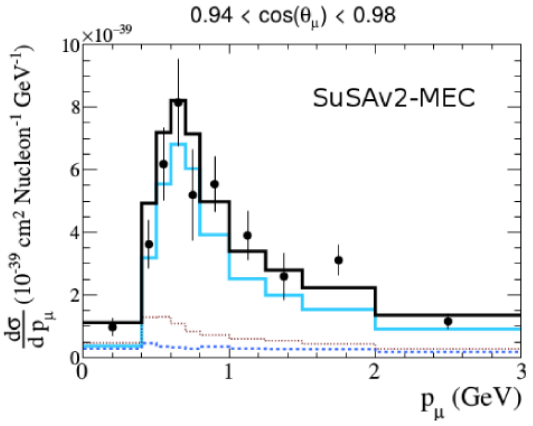
SuSAv2-MEC model vs. $(e, e')^{12}C$





Valencia model vs. T2K CC0π (^{12}C)

SuSAv2-MEC vs. T2K CC0π (^{12}C)



✪ **SuSAv2**: inclusive model based on supercaling analysis and RMF. Good agreement with (e, e') and $CC0\pi$ data. ✪ Strong q-dependence of RMF potentials at high kinematics is addressed in SuSAv2 with a blending function to introduce RPWIA (no FSI).

✪ The **ED-RMF** model introduces an Energy-Dependent potential (based on SuSAv2) to keep the strength for low p_N nucleons and make it softer for high p_N. SuSAv2≈ED-RMF inclusive predictions but ✪ ED-RMF is also a semi-inclusive model for ^{12}C, ^{16}O, ^{40}Ar, etc.

➲ Implementation carried out via pre-computed hadron tensor and CS tables, also possible integrating the full code.

➲ SuSAv2-2p2h, SuSAv2-inelastic and RMF-1π models can be implemented in the same way.

Current projects for the future releases

Single π production

- Recent T2K and SK analyses extensively use single π samples.
- Dominant background in proton decay searches.

Need to have "improved" single π production models.

Models to be implemented (in preparation)

- Dynamical coupled-channel mode model
  (S. Nakamura, H. Kamano, T. Sato, Phys. Rev. D 92, 074024)
- MK model (M. Kabirnezhad, Phys. Rev. D 97, 013002)

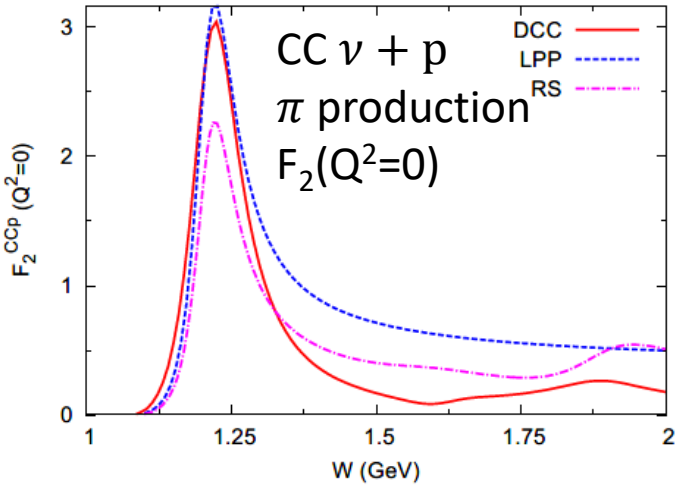
These models have electron scattering mode.

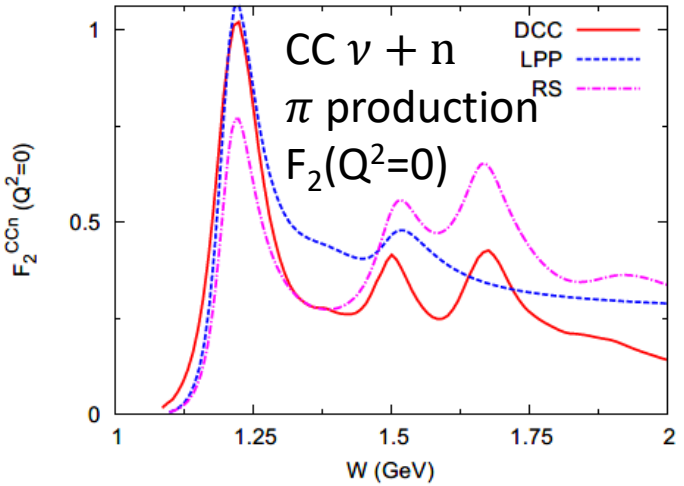
Allows us to study various nuclear effects, like
initial state nucleon motion, binding, Pauli-blocking,
final state π interactions,
could be studies by comparing the electro π production data.

Current projects for the future releases

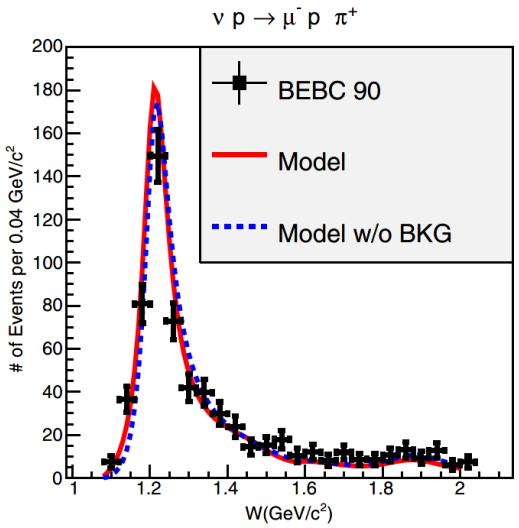
Single π production

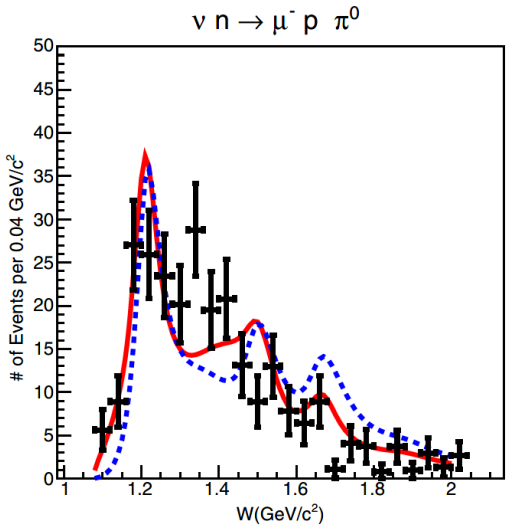
Dynamical coupled-channel mode model (Phys. Rev. D 92, 074024)

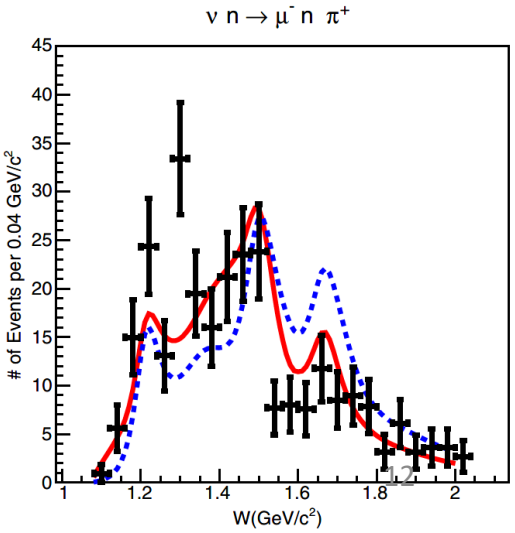




MK model (Phys. Rev. D 97, 013002)







Current projects for the future releases

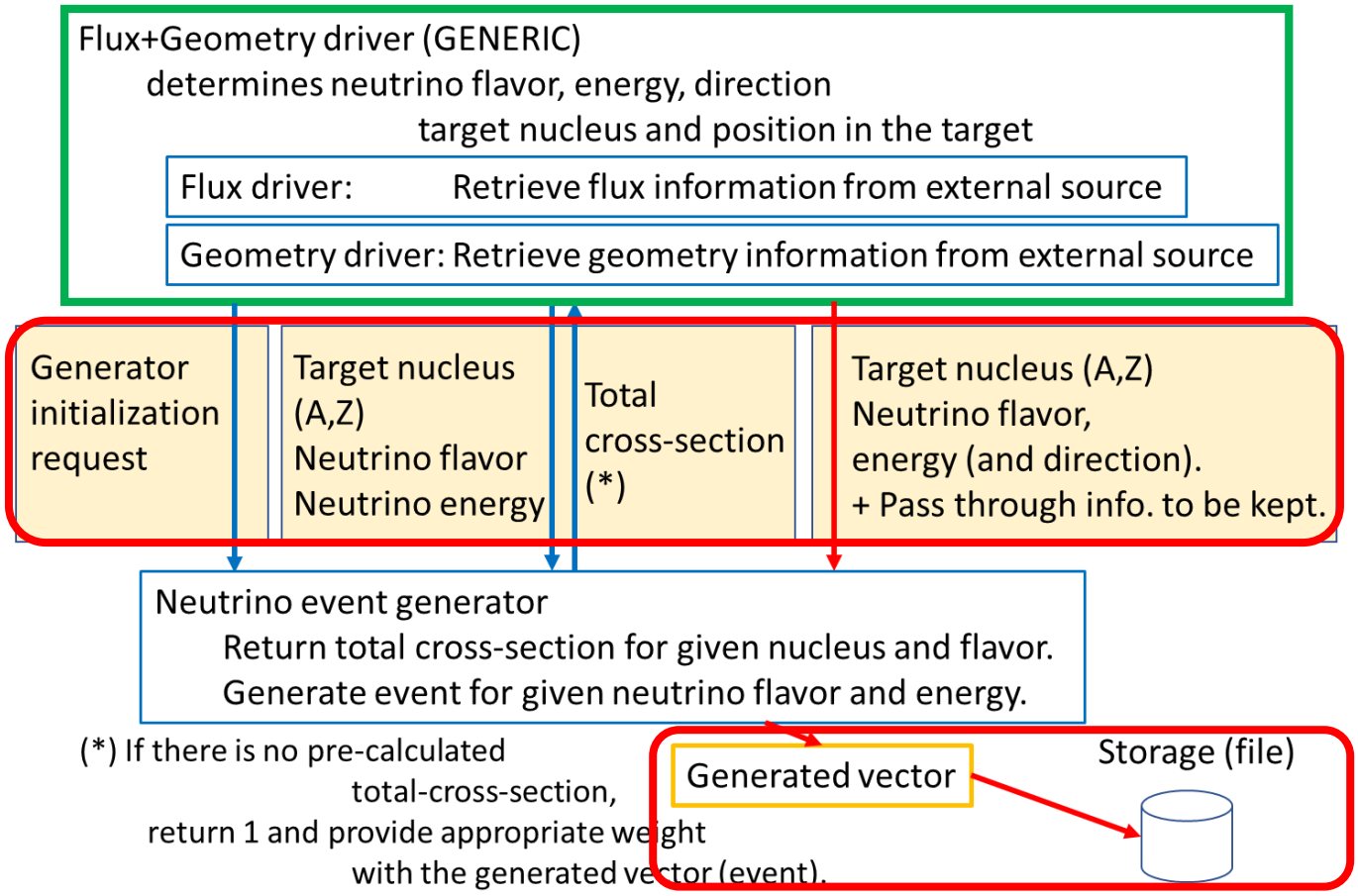
- It is time to seriously think about “inter-operability”.
  - Users want to use different generators for systematic error evaluations or design/optimize the detector design.
  - However, it is not straightforward to use different generators.
  - Detector geometry definitions and flux drivers are different from experiment to experiment.
  - Output data formats of each generator are different.

Discussed at the workshop @ FNAL in January 2020.

Try to define standard API and common data formats.

- NEUT does not have a “generic” flux driver nor detector geometry driver. (Dedicated for SK and T2K.)
- Try to provide simple API and new common data format.

Current projects for the future releases



Define API

Define "common" data format

- HepMC based (standard in HEP)
- Flux info.
- Generator specific info. (model, parameters etc.)
- Flux specific info. (decay points. etc.)

Current projects for the future releases (longer term)

- Get rid of the dependency on CERNLIB
  - Current usage of CERNLIB in NEUT
    - Configuration (card) file handling
    - Random number generator
    - Numerical functions (integration, particle decay kinematics)
    - PYTHIA/JetSet for DIS event generator
      - PYTHIA/JetSet in CERNLIB support neutrino DIS event generation and current NEUT relies on this.
  - Current work
    - Support alternative configuration (card) file format (independent from CERNLIB)
    - Study possible use of new versions of PYTHIA/JetSet. (Still under study)

Summary

Next release of NEUT includes various improvements and bug fixes.

- Two different treatments of the separation/binding energy in Local Fermi-gas CCQE and 2p2h models (F. Sanchez et al.)
- Alternative Axial form factors for CCQE (P. Stowell)
- Improvements in multi-pi (SIS) channel (C. Bronner, J. Xia)
- Kaon FSI bug fix and improvement (R. Matsumoto)

New model implementation is going on.

- SuSA v2 and RMF CCQE and 2p2h models (G. Megias et al.)
- New single pion models (DCC model by Sato et al., MK model by M. Kabirnezhad)

Solve several difficulties in using NEUT

- Simple API to be used from external programs.
- Provide generic flux and geometry drivers, compatible with the accelerator experiments.
- Support the “standard” data format driven by community.
- Eliminate dependence on CERNLIB (This requires some more time..)

(At the WG1+WG2 session, Clarence-san, Jaafar-san and Jordan-san give series of talks.)