NEUT
Status, plan and new demands

Yoshinari Hayato

for the NEUT contributors

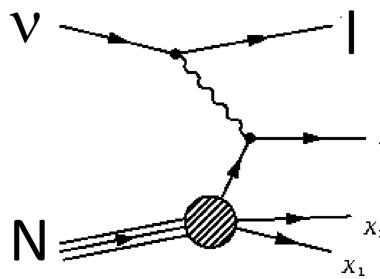
Importance of SIS/DIS in the atmospheric neutrino studies

Compare appearance probabilities of ν_e and $\overline{\nu_e}$

Statistically separate ν_e and $\overline{\nu_e}$

Dominant interaction (a few ~ 10 GeV)

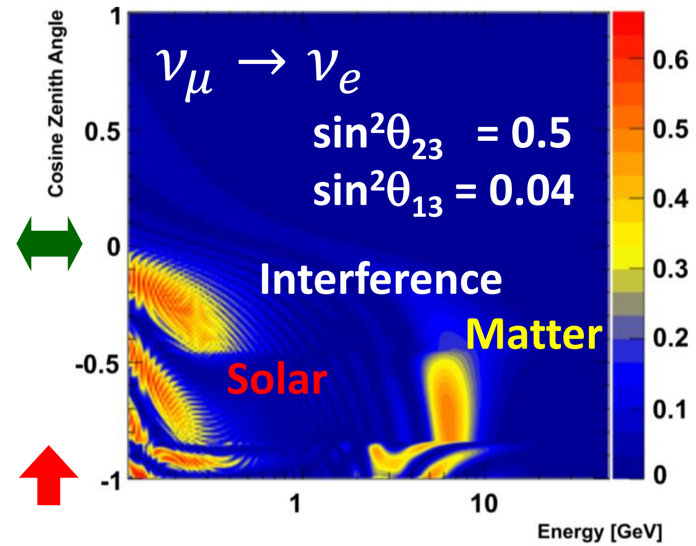
→ Deep inelastic scattering

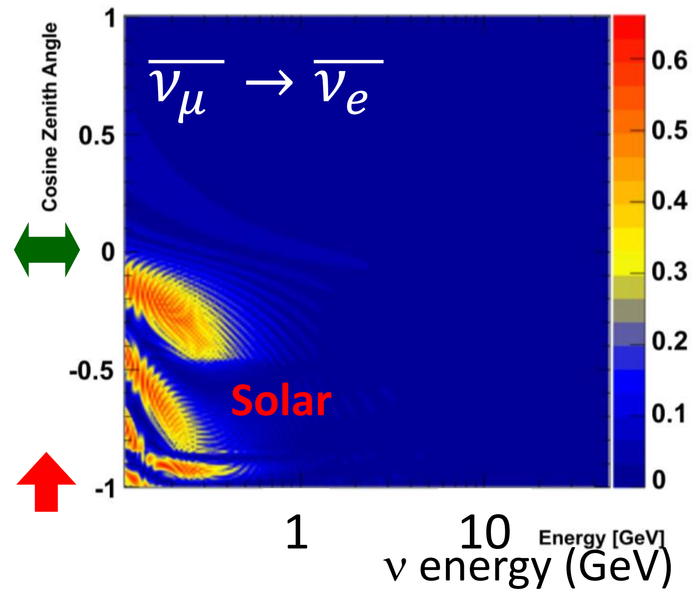


Differential cross-sections are different

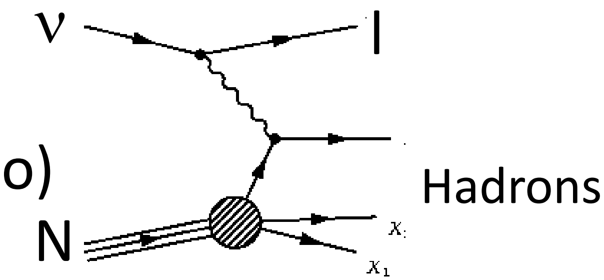
Observables	ν_e *CC*	$\overline{\nu_e}$ *CC*
Number of rings	More	Fewer
Transverse momentum	Larger	Smaller
# of decay electrons	More	Fewer
Signal efficiency	52.9%	71%
Purity	58.4%	27.5%

Normal hierarchy





of neutrons ~ Why this information is important?



Multiplicity of neutrons have relation with

a) neutrino flavor (neutrino or anti-neutrino)

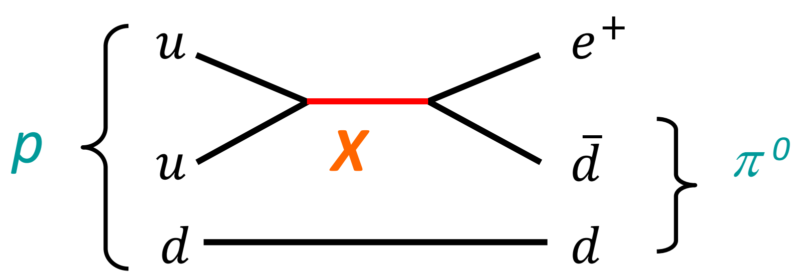
b) energy transfer to the hadronic system

# of neutrons provides additional information to the "visible rings" in the water Cherenkov detector.

Existence of neutrons is useful to identify proton decay backgrounds.

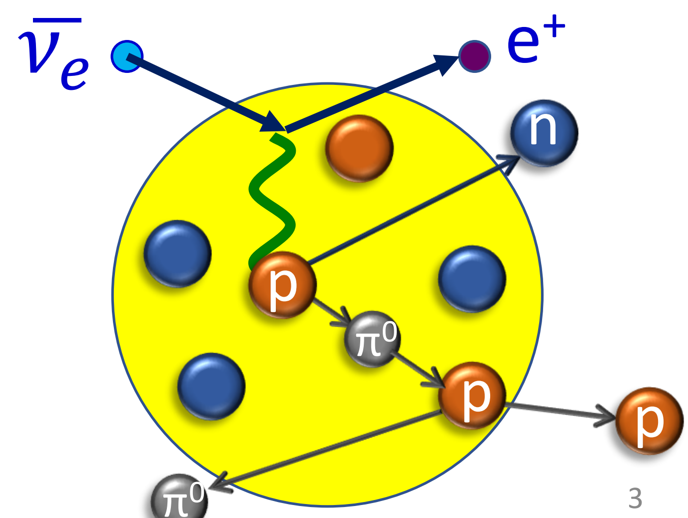
Proton decay signal

$$p \rightarrow e^+ + \pi^0$$



Background (example)

$$\bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n$$

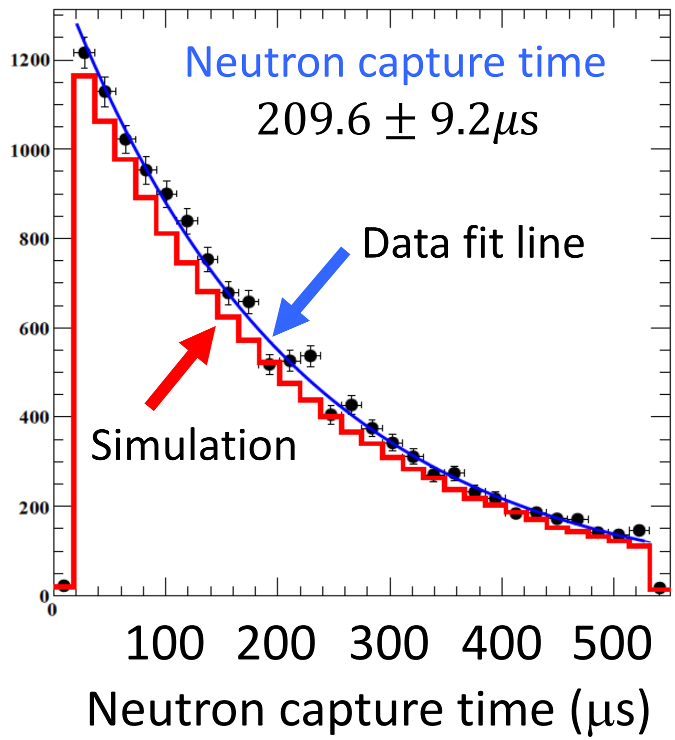


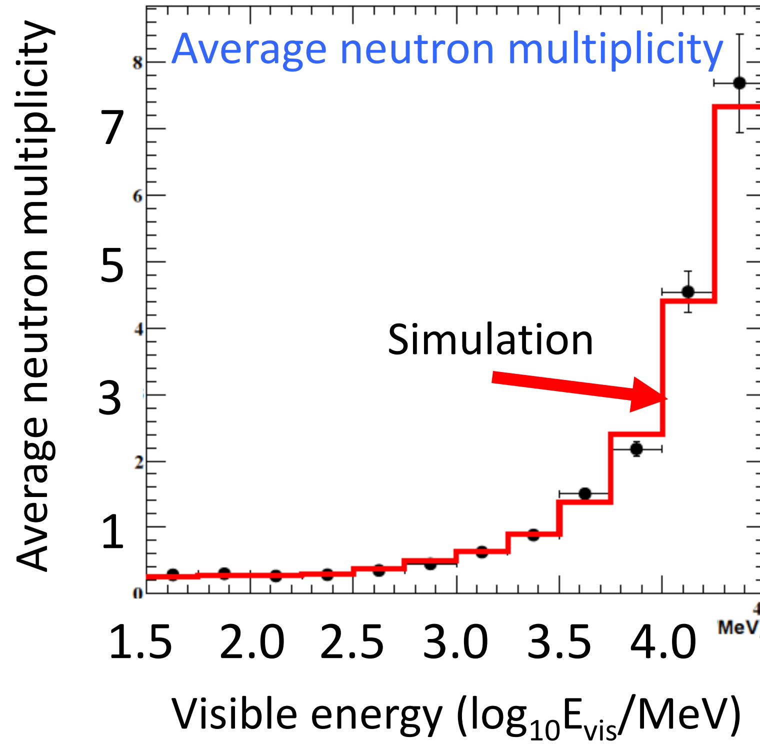
of neutrons ~ Why this information is important?

Neutron tagging method has been established for SK-IV. ($\epsilon \sim 20\%$)

(Paper is in preparation)

Detect 2.2 MeV γ from neutron capture by proton.





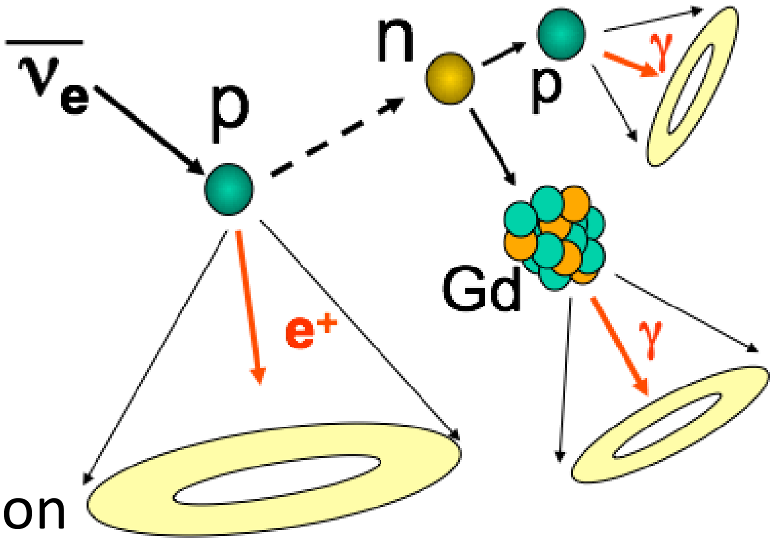
Because the energy of γ is so low, the efficiency is not so excellent.

of neutrons ~ Why this information is important?

- SK-Gd is in preparation.
  Add 0.2% $Gd_2(SO_4)_3$ to improve neutron detection.

➡ Once, Gd is fully loaded,
neutron tagging efficiency
becomes 90%.

➡ ν_e / $\overline{\nu_e}$ separation
energy determination
and
proton decay background rejection
performances are expected to be improved.



Since May 31st, 2018, we opened the SK tank and
now working on the detector upgrade
to introduce $Gd_2(SO_4)_3$ in 2019.

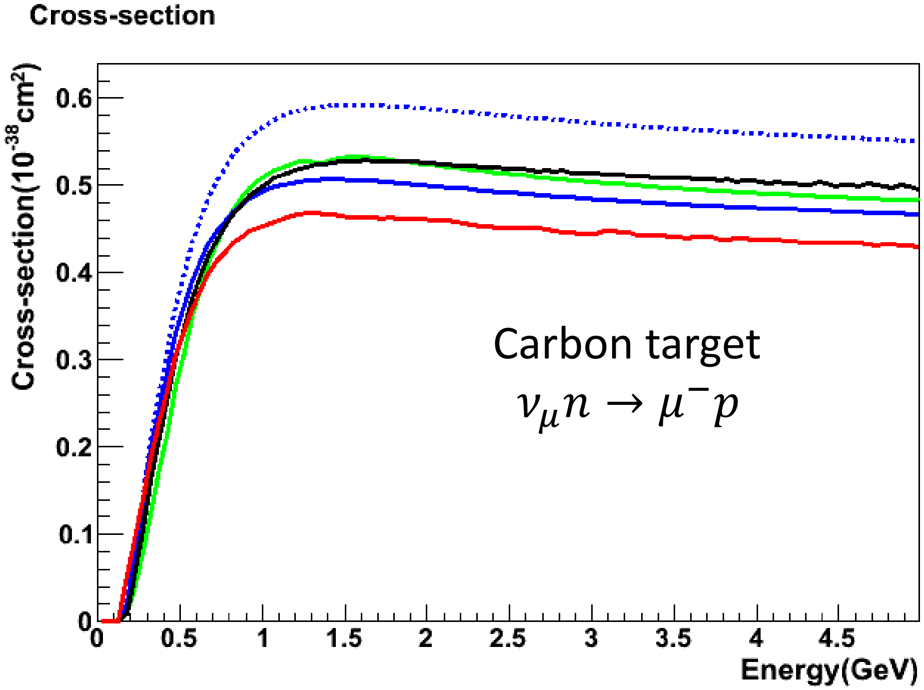
Current release ~ NEUT 5.4.0.x

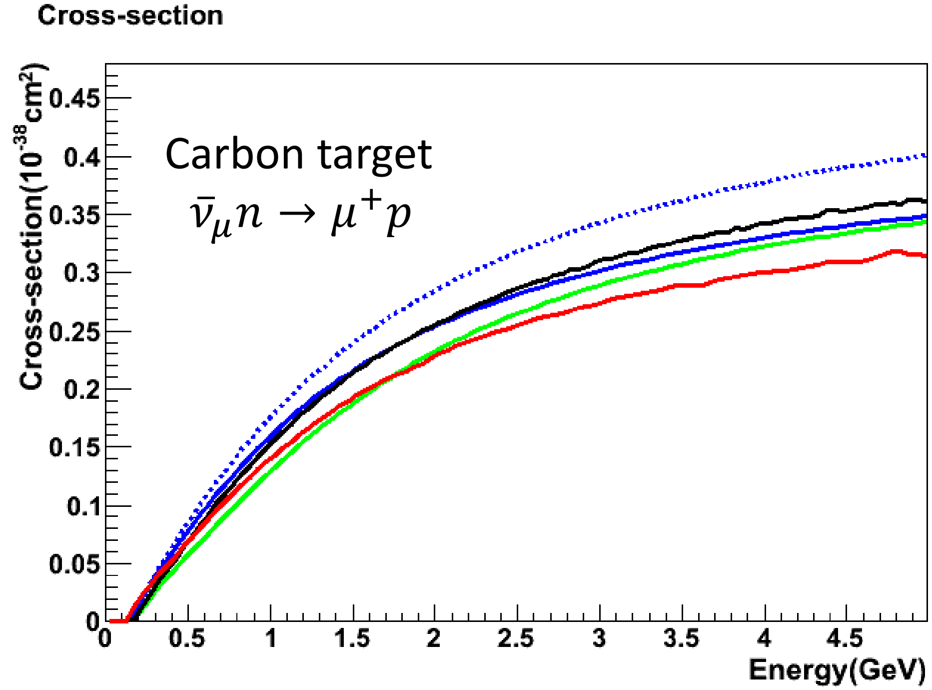
Default models in this release
- Charged current quasi-elastic
  - Local Fermi-gas model (J. Nieves/F. Sanchez/B. Bourguille)
- Neutral current elastic
  - Simple global Fermi-gas model
- Single π production
  - Rein-Sehgal model with Garczyk-Sobczyk form factors
- Multi pion production (W<2GeV)
  - Custom code using GRV98 PDF with Bodek-Yang correction
- Deep inelastic scattering (W>2GeV)
  - PYTHIA 5.72 (GRV98 PDF with Bodek-Yang correction)

- Nuclear effect
  - Cascade model
  - Pion interaction mean free paths have been re-tuned using various data including recent DUET results.

CCQE in NEUT

Vector form factor	BBBA05
Axial vector form factor	Dipole



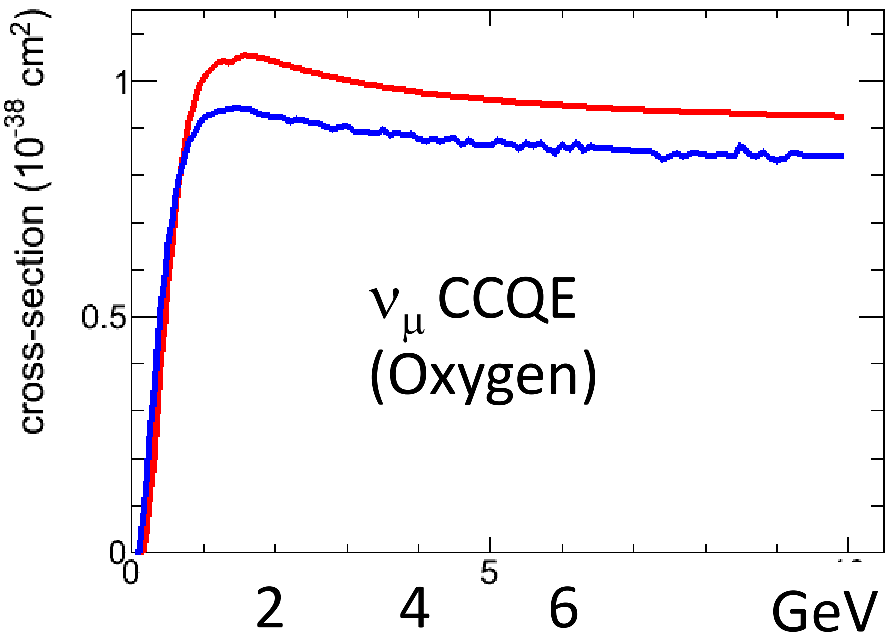


solid blue	Global Fermi-gas	(Smith-Moniz)	M_A=1.05GeV/c^2
dotted blue	Global Fermi-gas	(Smith-Moniz)	M_A=1.21GeV/c^2
green	Global Fermi-gas + RPA	(Smith-Moniz)	M_A=1.05GeV/c^2
red	Local Fermi-gas + RPA	(J. Nieves et al.)	M_A=1.05GeV/c^2
black	Spectral function	(Ankowski, Benhar)	M_A=1.21GeV/c^2

Local Fermi-gas CCQE in NEUT

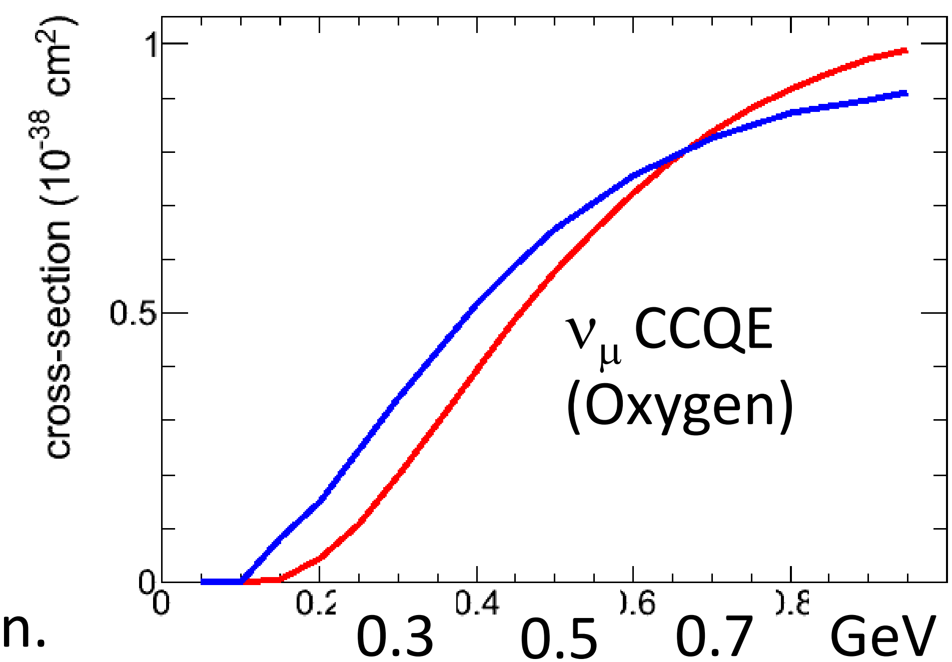
Based on the model and code by J. Nieves et al.

NEUT implementation: B. Bourguille and F. Sanchez



Red : Global Fermi-gas, with RPA, M_A=1.05 GeV

Blue : Local Fermi-gas, with RPA, M_A=1.05 GeV



LFG gives larger cross-section in lowest energy region (small q^2 is still allowed)

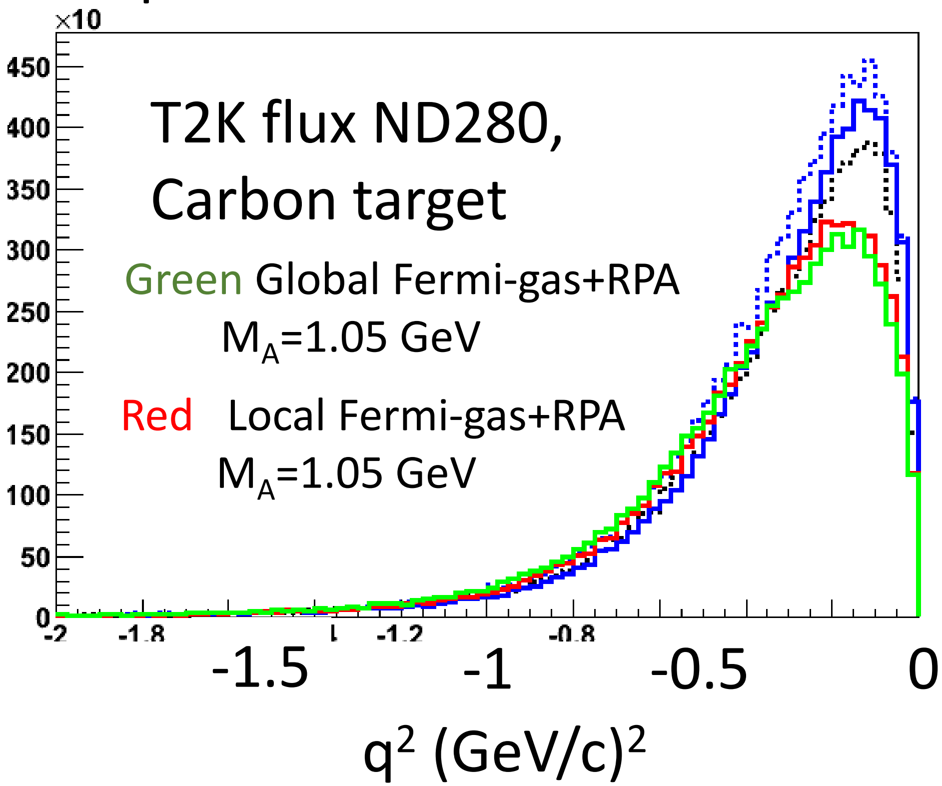
New model gives smaller cross-section in high energy region.

CCQE cross-sections ~ NEUT

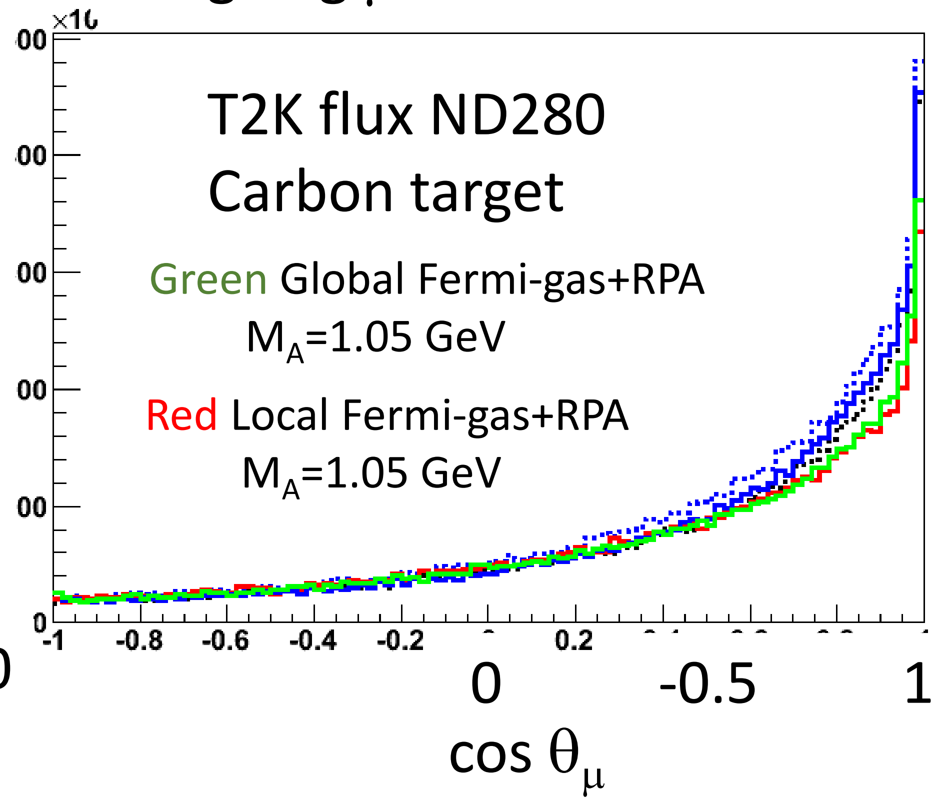
Based on the model and code by J. Nieves et al.

NEUT implementation: B. Bourguille and F. Sanchez

q^2 distribution



Outgoing μ^- direction



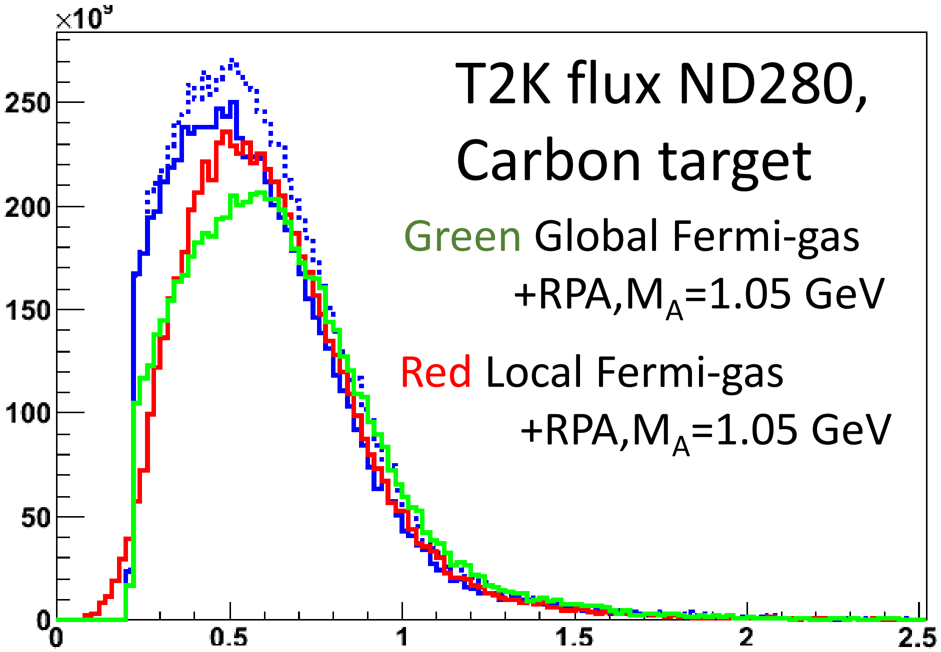
solid blue line	Global Fermi-gas	(Smith-Moniz)	M_A=1.05GeV/c^2
dotted blue line	Global Fermi-gas	(Smith-Moniz)	M_A=1.21GeV/c^2
dotted black line	Spectral function	(Ankowski, Benhar)	M_A=1.21GeV/c^2

Local Fermi-gas CCQE in Neut

Based on the model and code by J. Nieves et al.

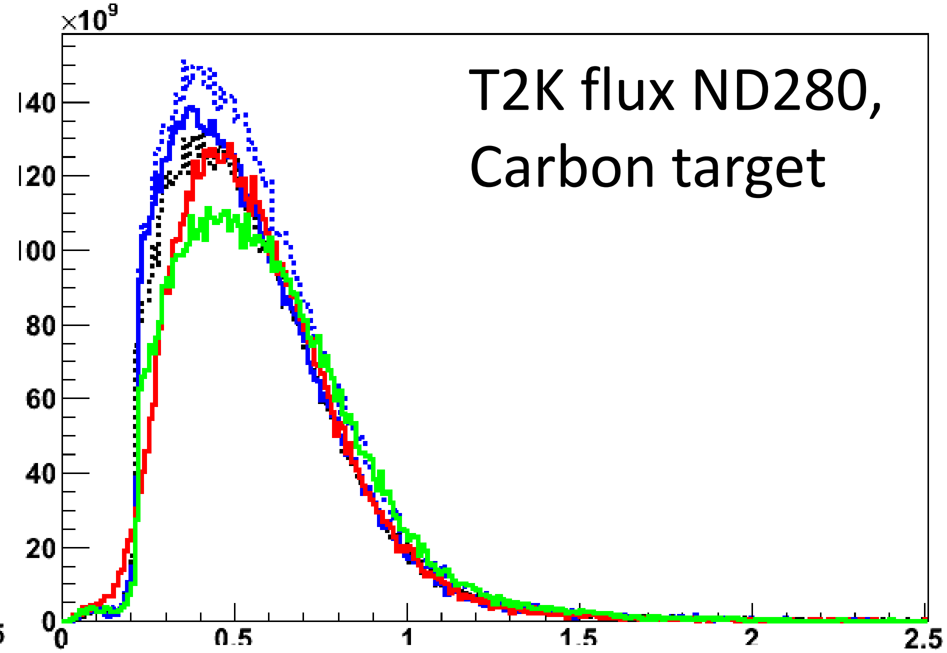
NEUT implementation: B. Bourguille and F. Sanchez

Proton momentum (*before FSI*)



0.2 0.5 0.8 1.1 (GeV/c)

Proton momentum (*after FSI*)



0.2 0.5 0.8 1.1 (GeV/c)

Global Fermi-gas	(Smith-Moniz)	M_A=1.05GeV/c^2
Global Fermi-gas	(Smith-Moniz)	M_A=1.21GeV/c^2
Spectral function	(Ankowski, Benhar)	M_A=1.21GeV/c^2

Alternative Axial vector form factors

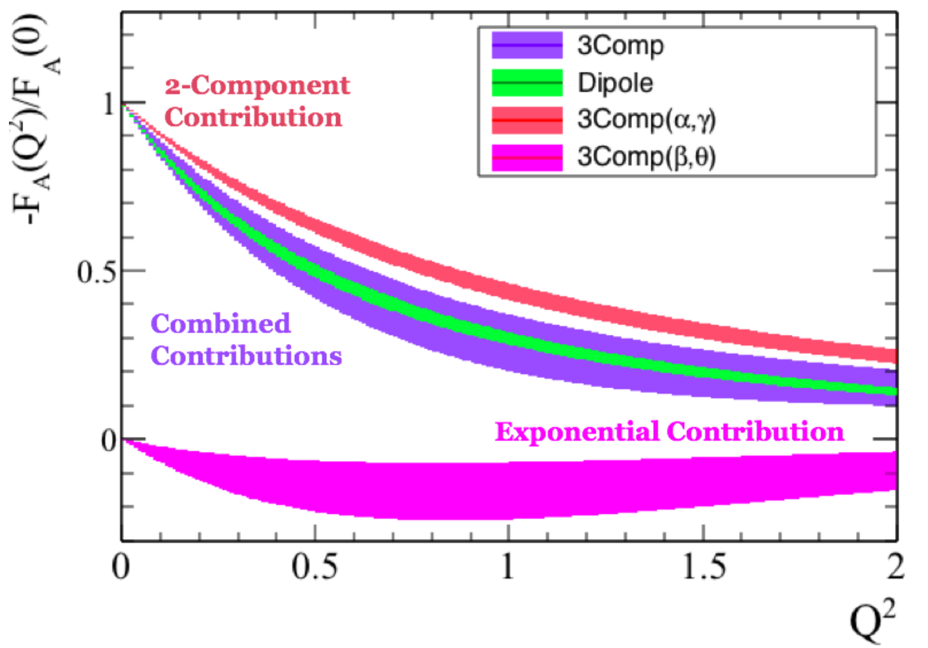
Recently, several non-dipole Axial vector form factors are proposed.
Some of them are implemented for the reweighting studies
by P. Stowell.

We are working on to introduce them in the event generator.

3-component model

(Expansion of 2-component model by C. Adamuscin et al., Phys. Rev. C78, 035201 (2008)

$$F_A(Q^2) = F_A(0)\left(\left[\frac{1}{1+\gamma Q^2}\left(1-\alpha+\alpha\frac{m_A^2}{(m_A^2+Q^2)}\right)\right]+\left[\theta Q^2 e^{\theta-\beta Q^2}\right]\right)$$



Alternative Axial vector form factors

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Z-Expansion form factor

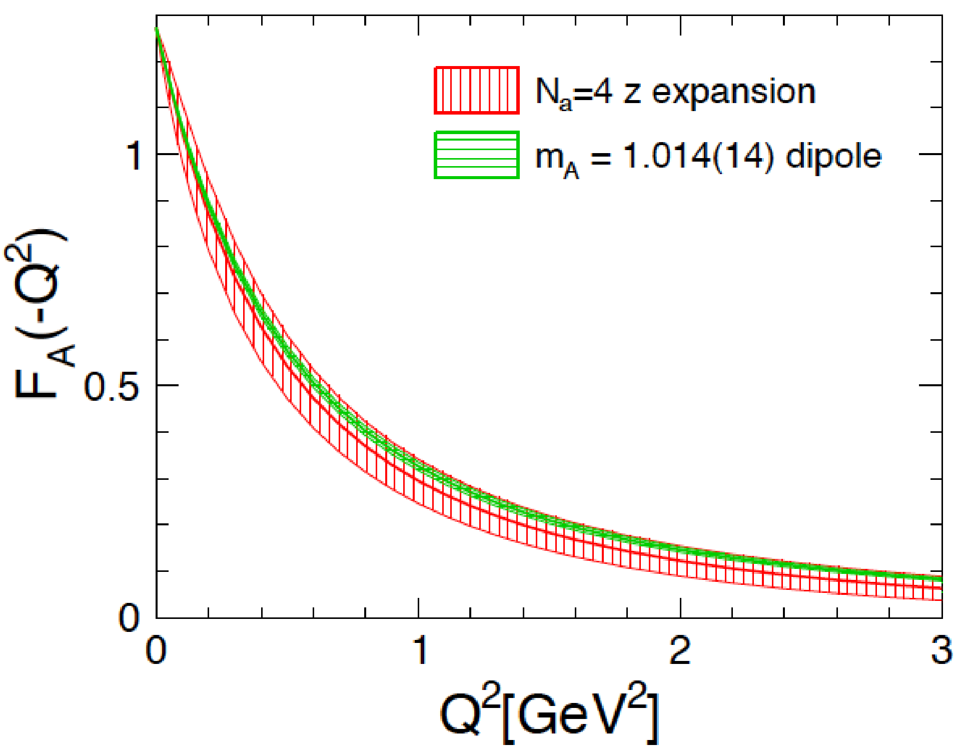
Aaron S. Meyer et al., Phys Rev. D93, 113015 (2016)

$$F_A(q^2) = \sum_{k=0}^{k_{max}} a_k z(q^2)^k,$$

$$z(q^2, t_{cut}, t_0) = \frac{\sqrt{t_{cut} - q^2} - \sqrt{t_{cut} - t_0}}{\sqrt{t_{cut} - q^2} + \sqrt{t_{cut} - t_0}},$$

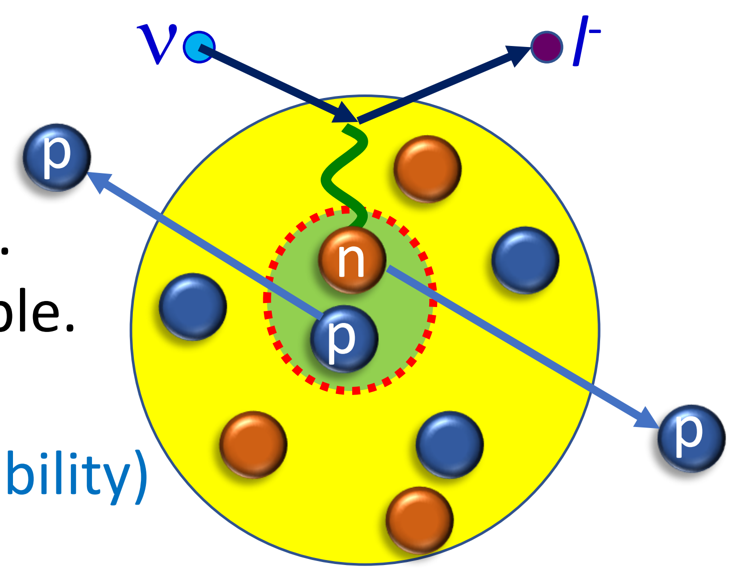
$$t_{cut} = 9m_\pi^2$$

Q^2_{max} GeV^2	t_0	$\lvert z \rvert_{max}$
1.0	0	0.44
3.0	0	0.62
1.0	$t_0^{optimal}(1.0\ \mathrm{GeV}^2) = -0.28\ \mathrm{GeV}^2$	0.23
3.0	$t_0^{optimal}(1.0\ \mathrm{GeV}^2) = -0.28\ \mathrm{GeV}^2$	0.45
3.0	$t_0^{optimal}(3.0\ \mathrm{GeV}^2) = -0.57\ \mathrm{GeV}^2$	0.35



2p2h model in NEUT

J. Nieves, F. Sanchez et al.



Lepton kinematics (T_μ, $\cos\theta_\mu$)

Two implementations

1) Pre-calculated 2D lookup table.

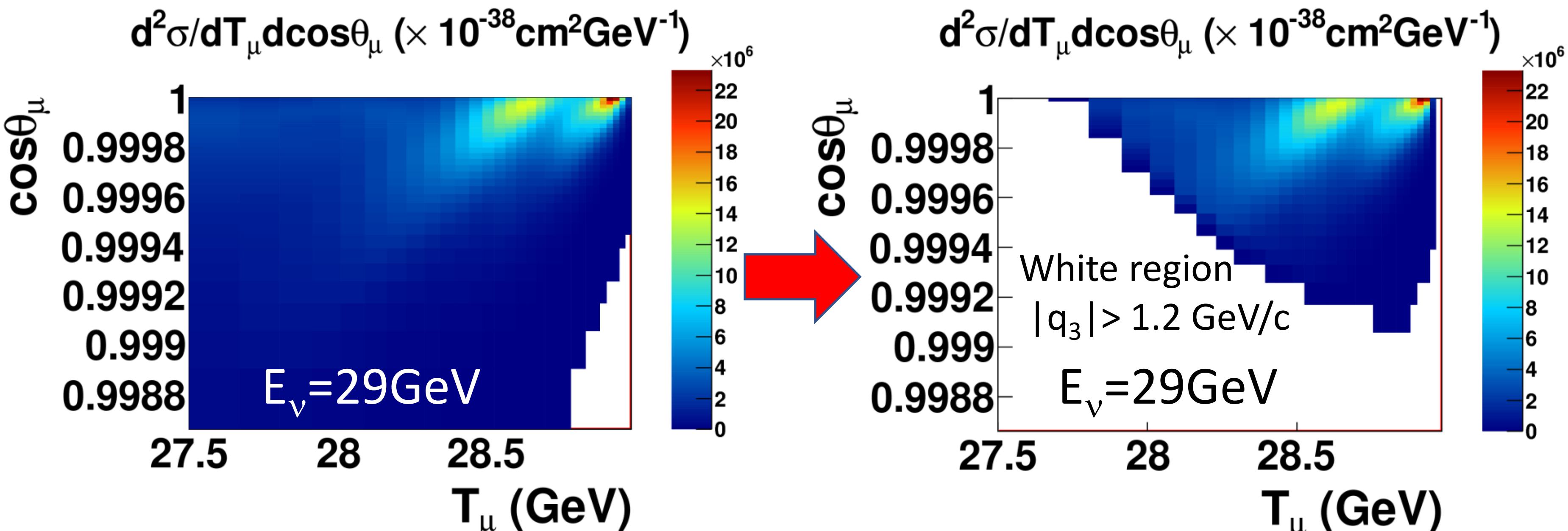
^{12}C, ^{16}O and ^{40}Ca are supported.

2) Pre-calculated hadron-tensor table.

Allowed $|q_3|$ range

(restriction from the model applicability)

$|q_3| < 1.2\text{GeV/c}$

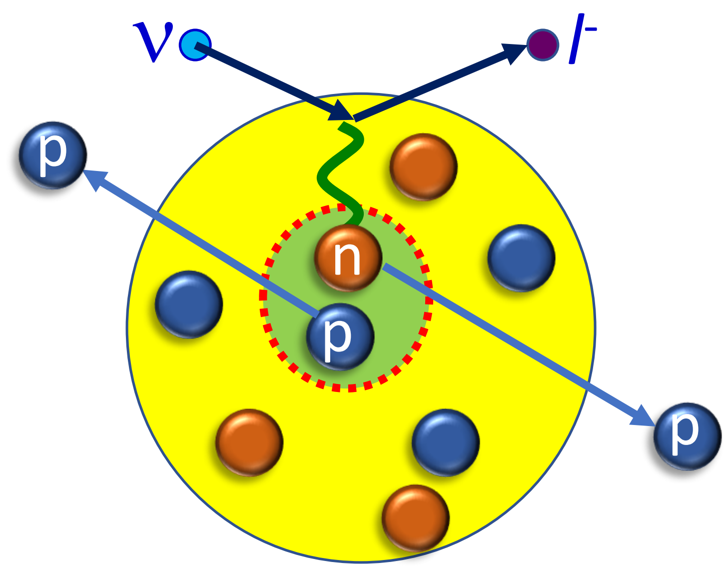


2p2h model in NEUT

J. Nieves, F. Sanchez et al.

Hadron (nucleon) kinematics

Similar to the prescription by J. Sobczyk et al.



Initial state nucleons

- Uncorrelated two nucleons
- Momentum distribution is same as 1p1h. (Local Fermi-gas)

Final state nucleons

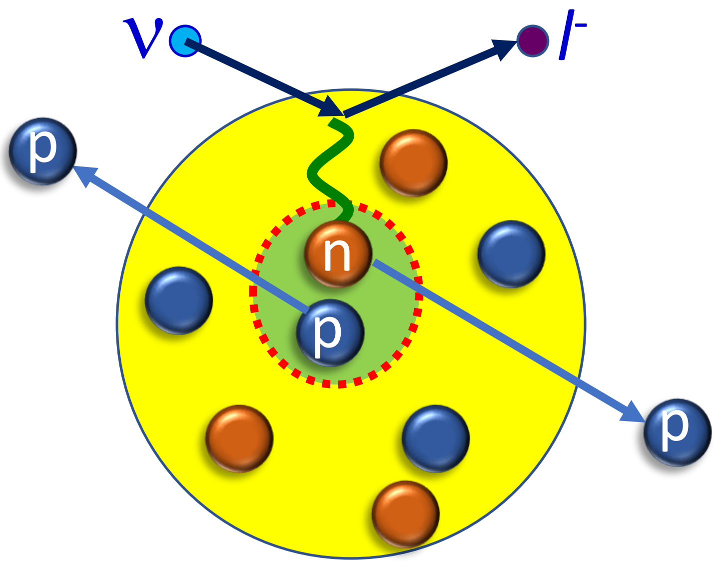
- Transferred energy is shared equally between two outgoing nucleons.
- Energy is conserved
- Additional re-scattering is handled just as same as the other interactions

2p2h model in NEUT

J. Nieves, F. Sanchez et al.

Hadron (nucleon) kinematics

Similar to the prescription by J. Sobczyk et al.

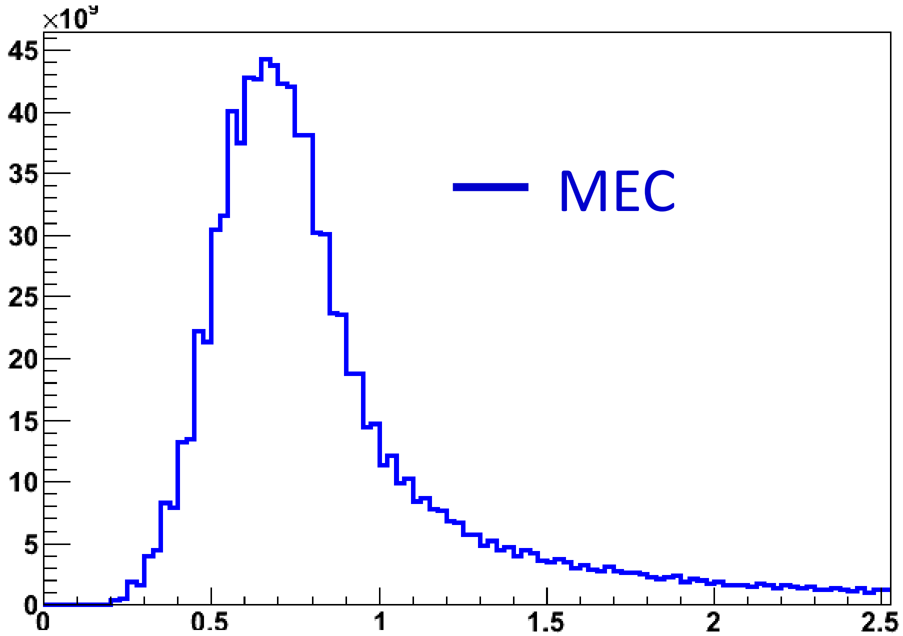


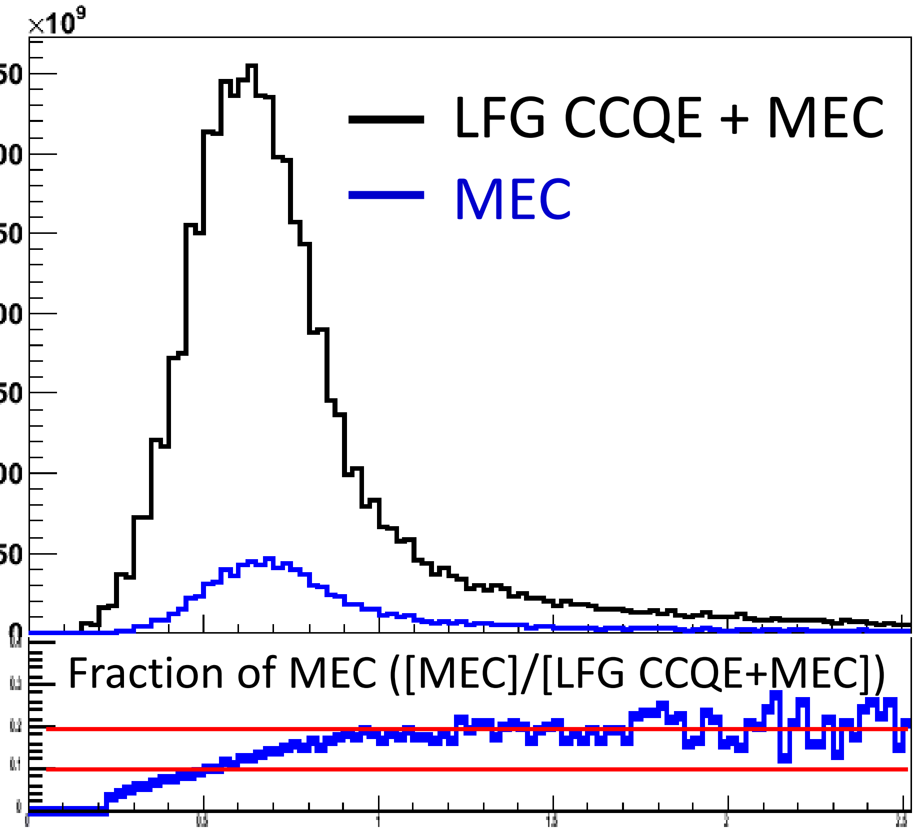
0) Calculate energy transfer to the hadron system.
1) Fix two uncorrelated nucleon momenta.
2) Boost CMS frame of nucleon system.
3) Give half of the transfer energy to each nucleon.
4) Eject direction of two nucleon isotropically.
5) Boost back to the LAB frame.
6) Check the Pauli-blocking condition. (If not satisfied, go to 1.)

2p2h model in NEUT

J. Nieves, F. Sanchez et al.

E_ν distribution





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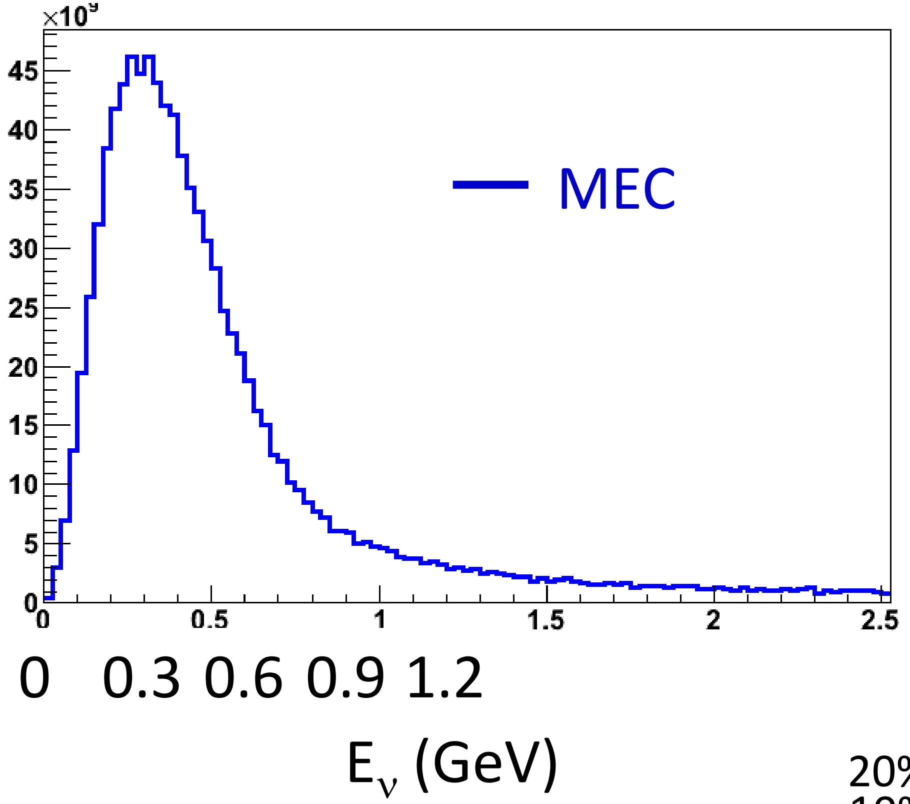
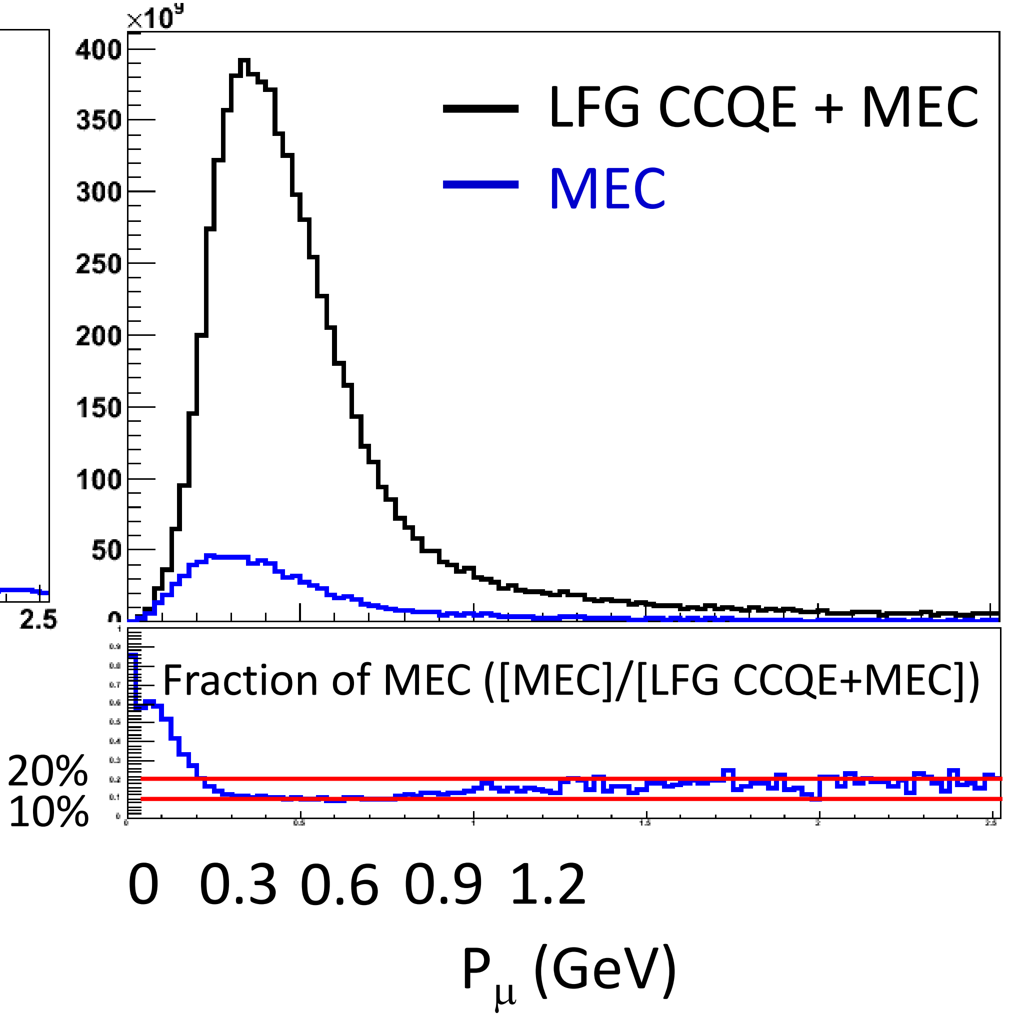
Outgoing μ^- momentum

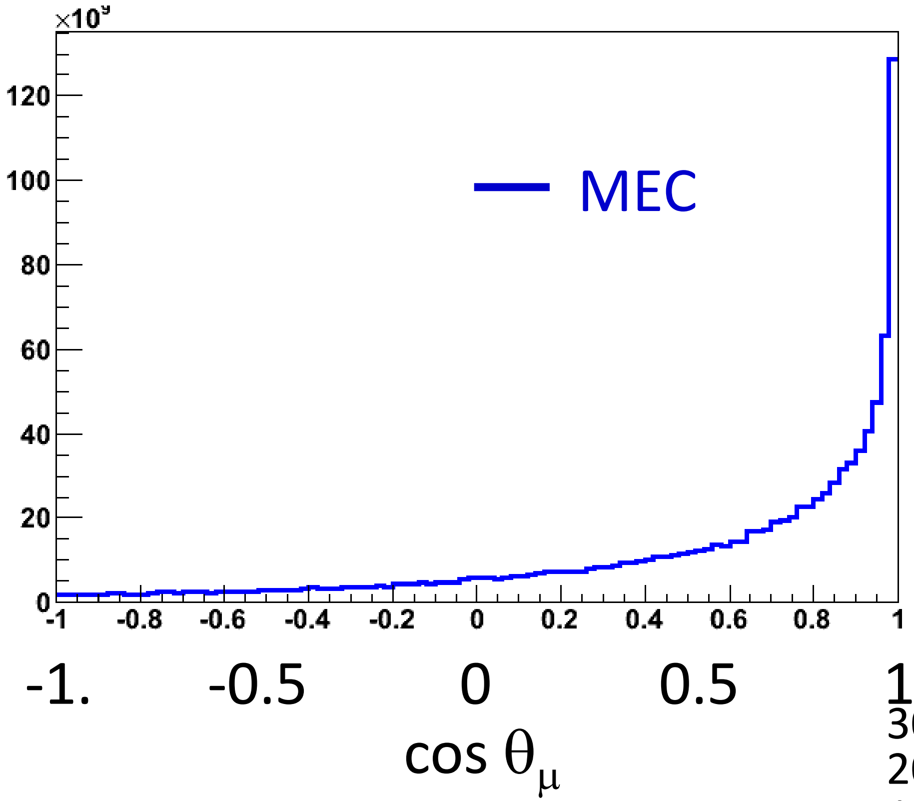


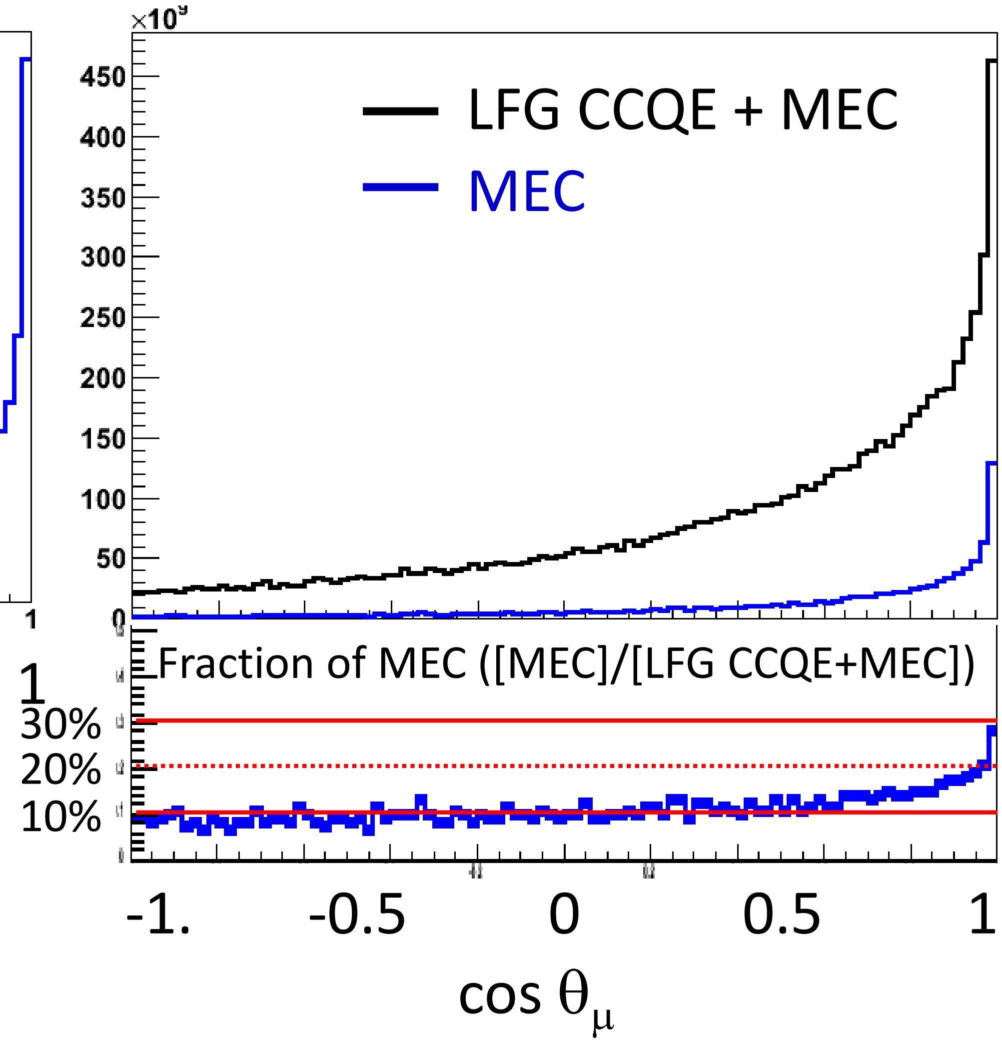


2p2h model in NEUT

J. Nieves, F. Sanchez et al.

Outgoing μ^- direction





2p2h model in NEUT

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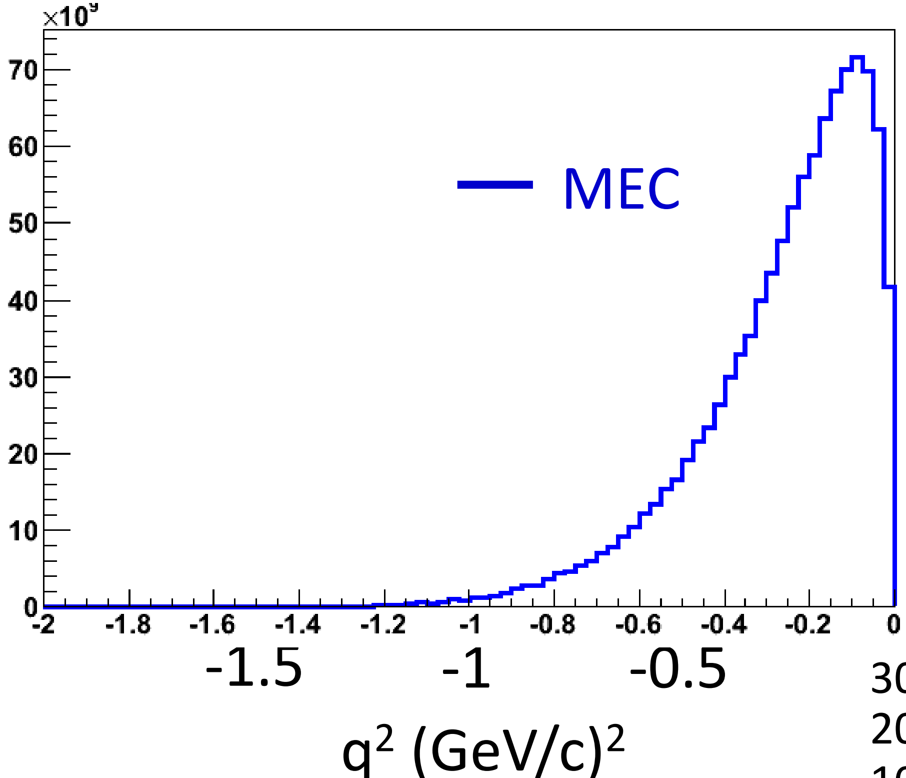
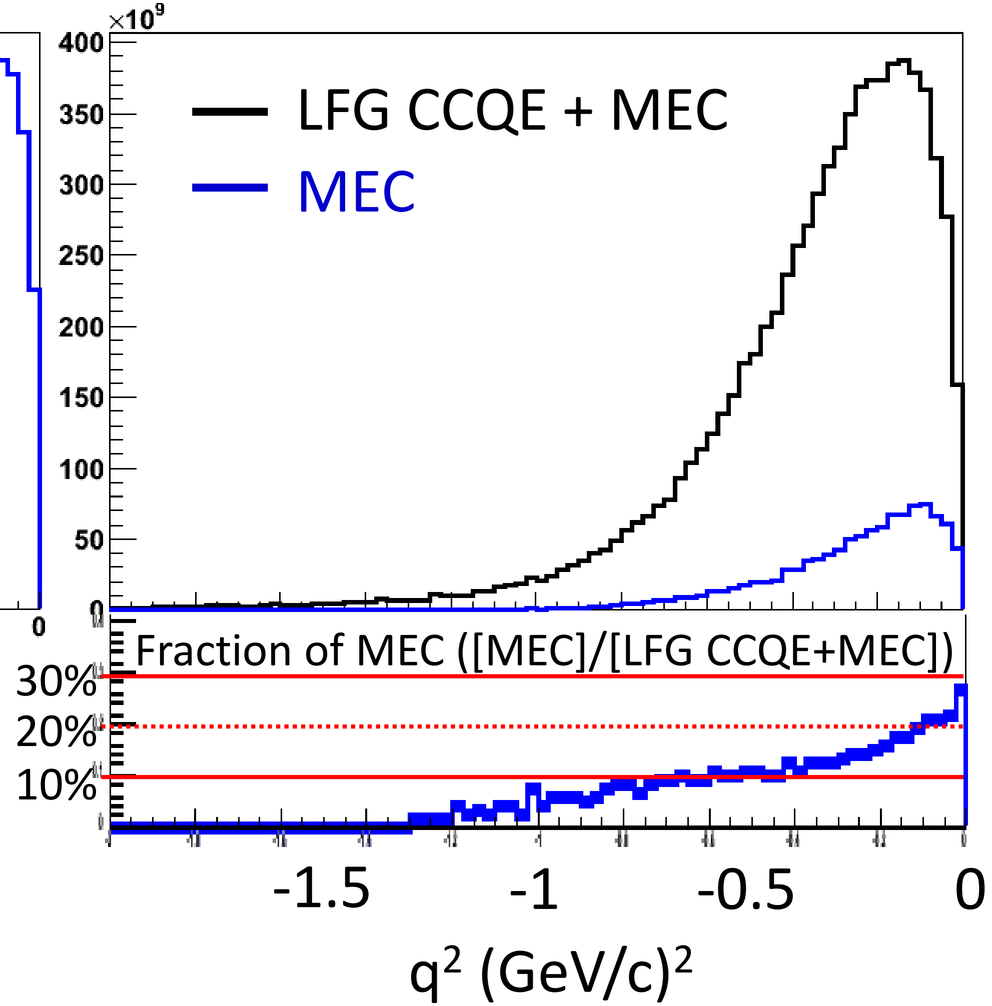
q^2 distribution

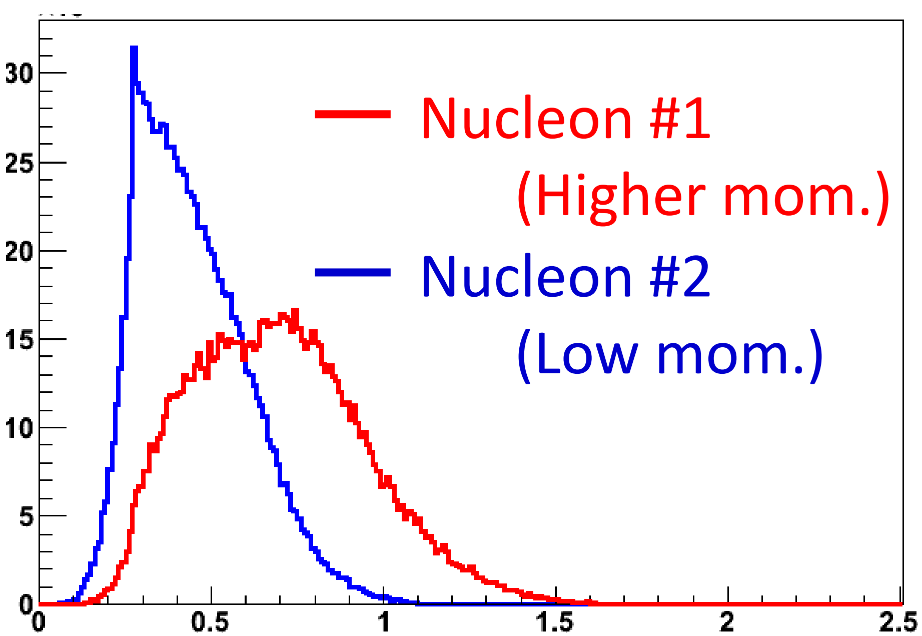




2p2h model in NEUT

J. Nieves, F. Sanchez et al.

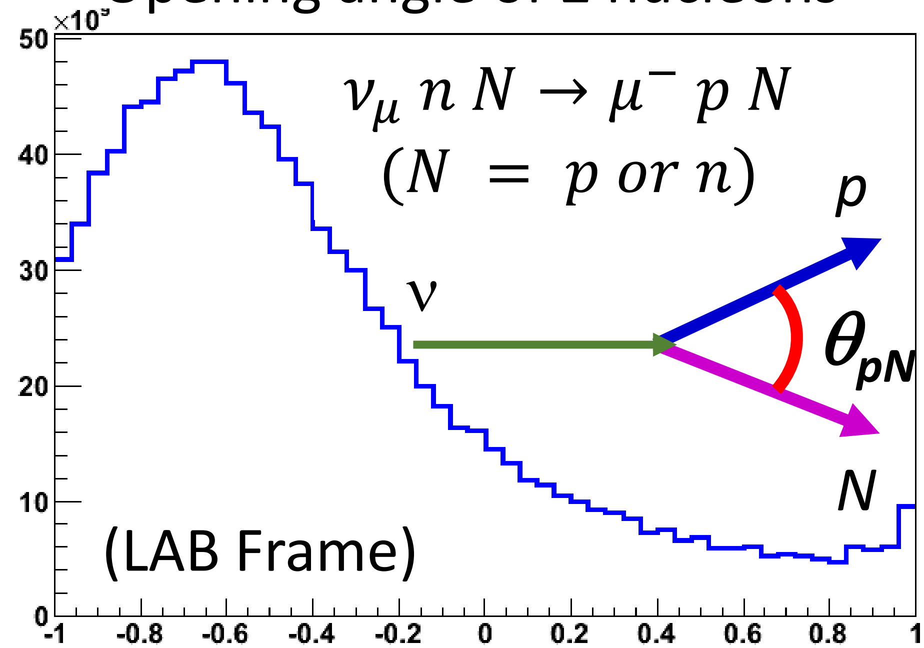
Outgoing momenta of nucleons



0 0.3 0.6 0.9 1.2

E_ν (GeV)

Opening angle of 2 nucleons



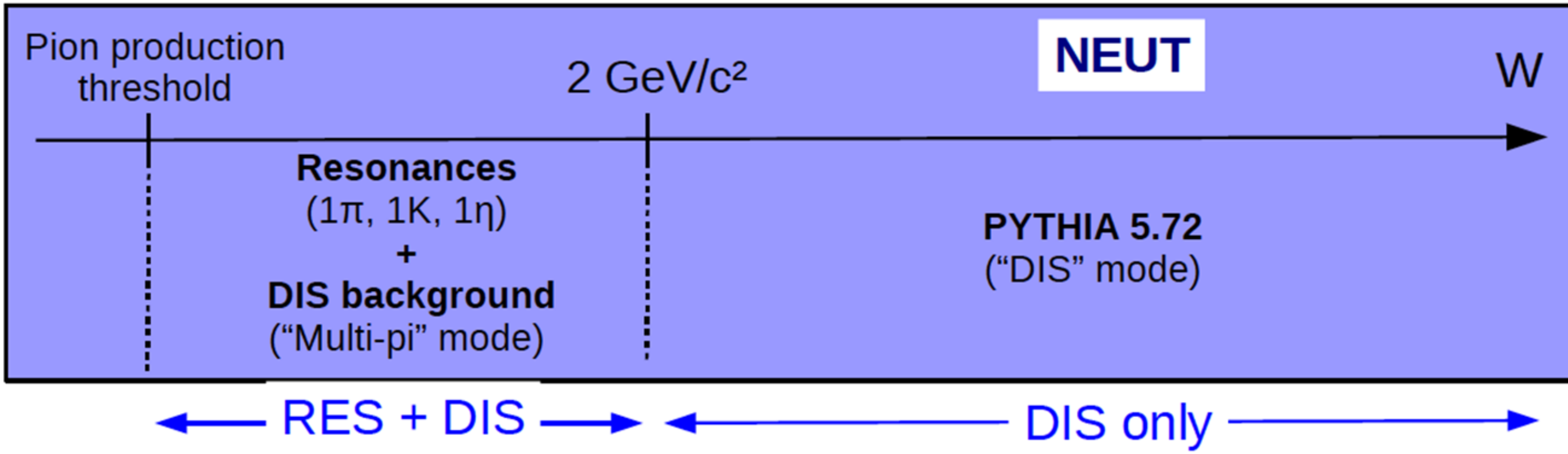
-1 0.5 0 -0.5 1

cos θ_{pN}

Implemented interactions and models

Multi-pion production (W<2GeV) & DIS (W>2GeV)

(Recent improvements and bug fixes by C. Bronner)
[C. Bronner, arXiv:1607.06558]



Cross-section of multi-pion mode (W<2GeV)

$$\sigma_{multi-\pi}(E_\nu) = \int_{M_N+2\times M_\pi}^{2} \sigma(E_\nu, W) \times Prob.(W) dW$$

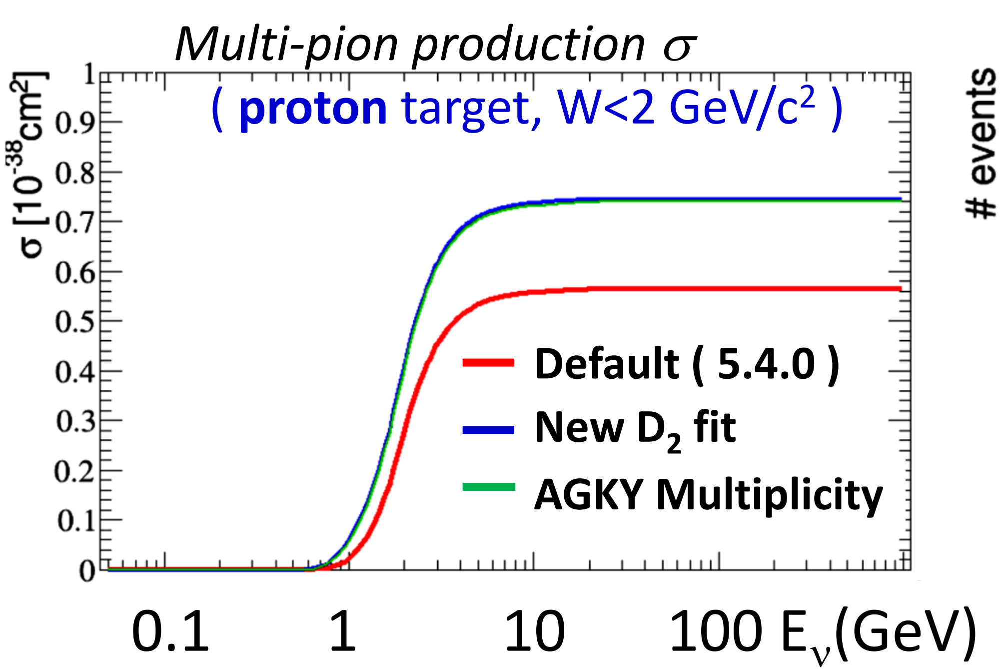
Prob.(W) : Probability to produce more than 1 pion as a function of W, which is extracted from experimental data.

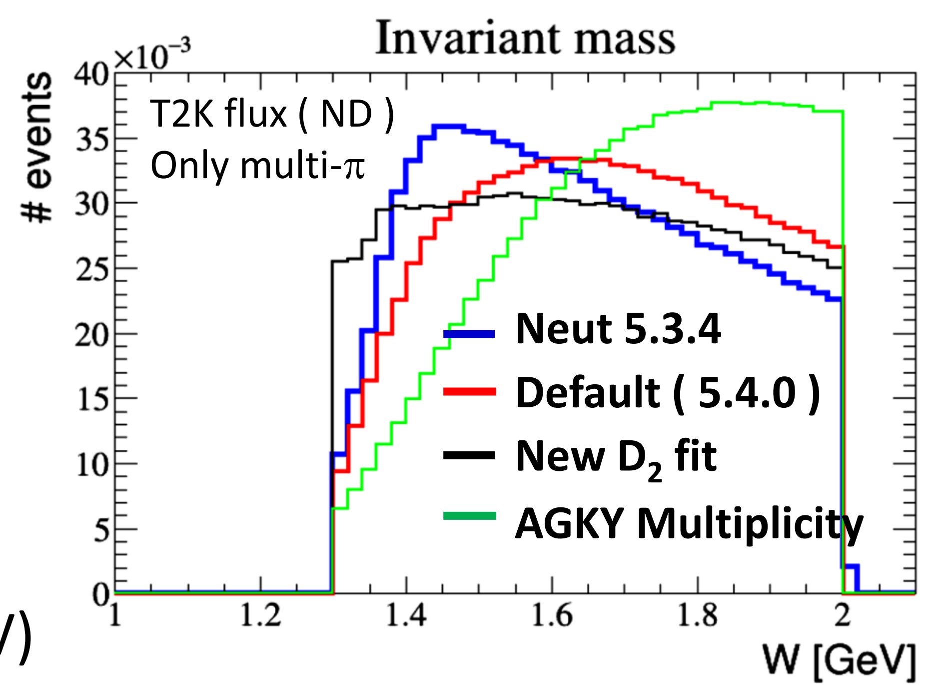
Implemented interactions and models

Multi-pion production (W<2GeV) & DIS (W>2GeV)

(Recent improvements and bug fixes by C. Bronner)
[C. Bronner, arXiv:1607.06558]

- Update more recent version of Bodek-Yang corrections
- Use of CKM matrix elements for structure functions
- Bug fixes mainly in multi-pion production mode ($W<2GeV/c^2$)
- Tune parameters of multiplicity ($W<2GeV/c^2$ only)





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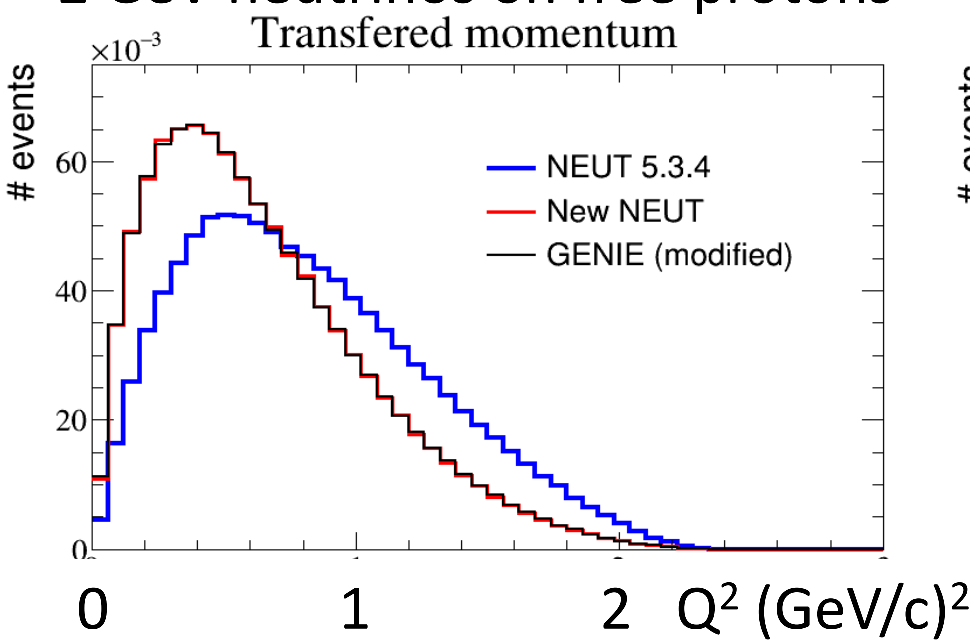
2 GeV neutrinos on free protons



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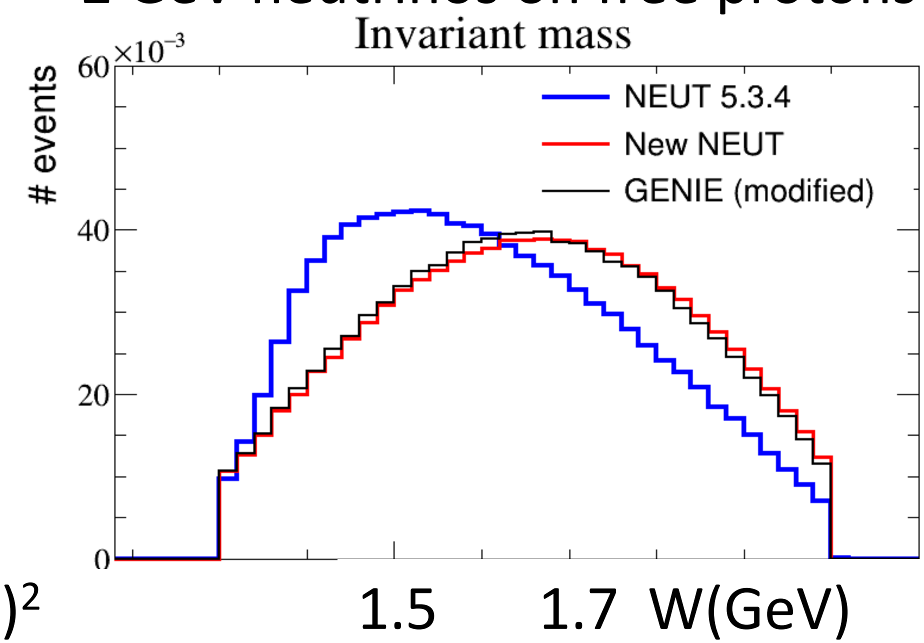


Implemented interactions and models

Multi-pion production (W<2GeV) & DIS (W>2GeV)

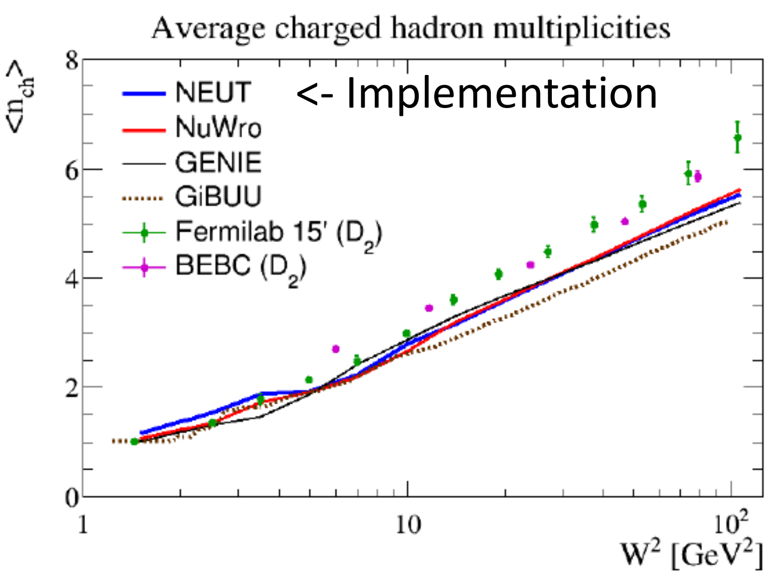
(Recent improvements and bug fixes by C. Bronner)
[C. Bronner, arXiv:1607.06558]

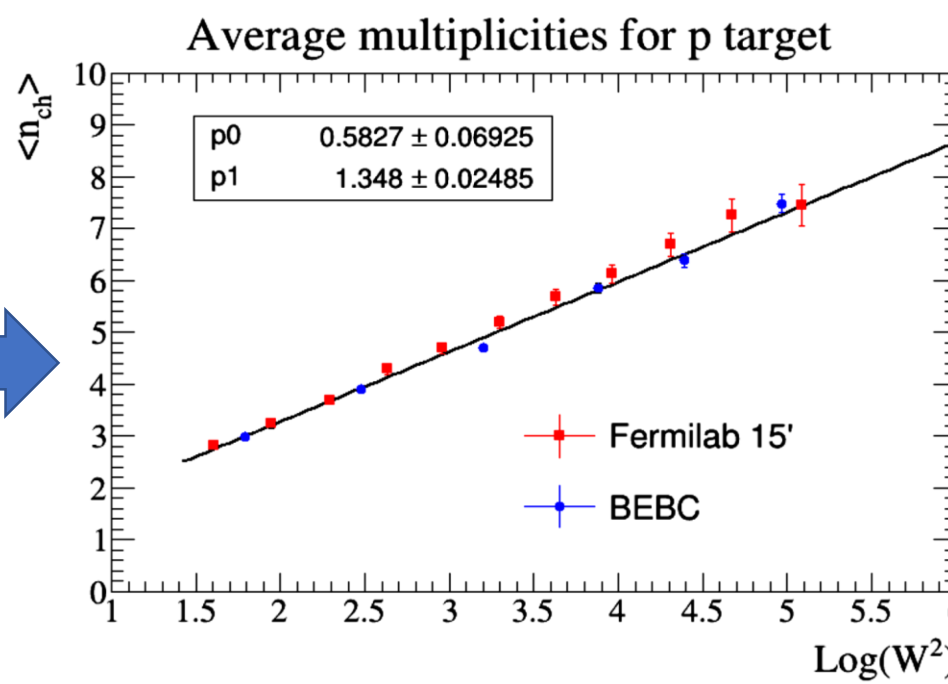
Fit the old data to reproduce average multiplicity.

It is not simple to change the multiplicity distributions in PYTHIA.

Therefore, we use this “fit results”

for the systematic uncertainty studies by reweighting.

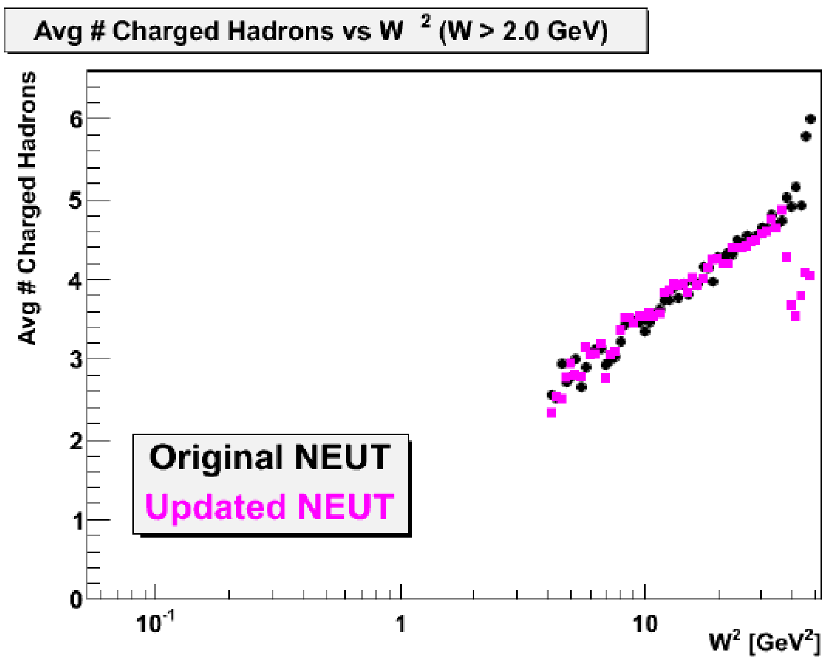


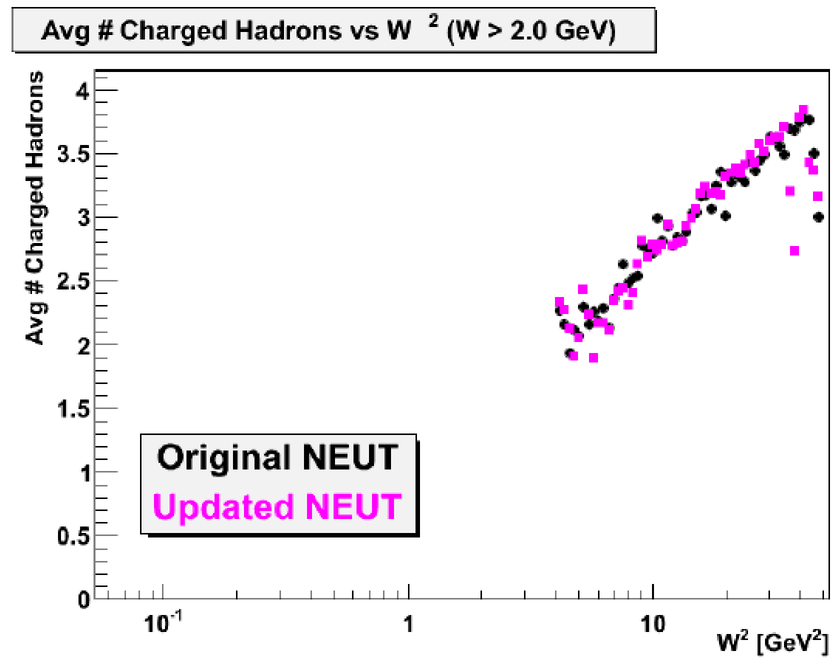


High W mode
Pythia 6 tests (J. Morrison - MSU)

- Other generators (NuWro, GENIE) use PYTHIA 6
- Does not allow E_{CM}<5.3 GeV: other generators pass hit quark, spectator diquark and W to Pythia and just use fragmentation routines

Tests in NEUT with PYTHIA 6 and 25 GeV neutrinos





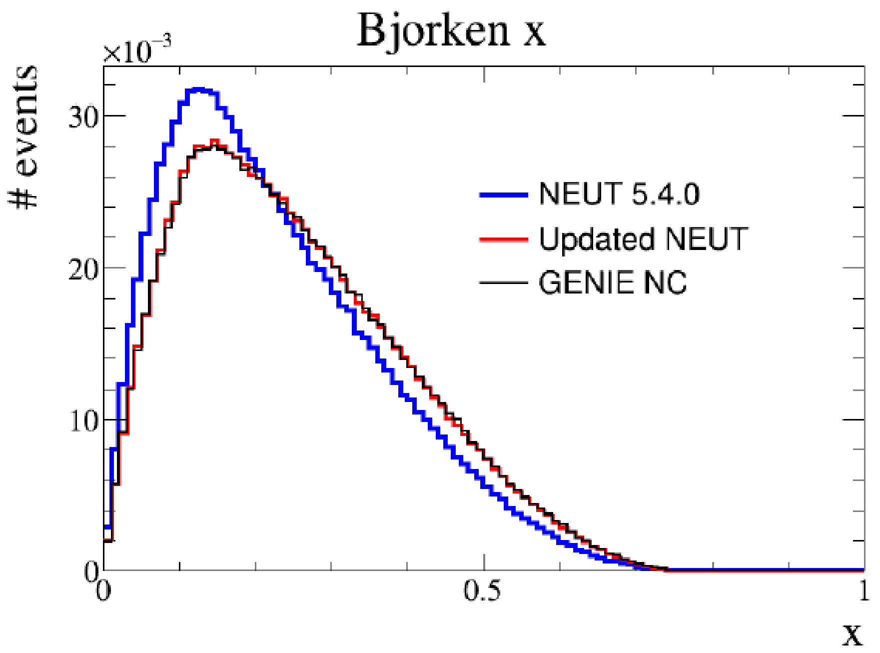
Hadronization looks similar, main difference with other generators is (W,Q^2) generated by PYTHIA 5 vs according to $d^2\sigma/dxdy$

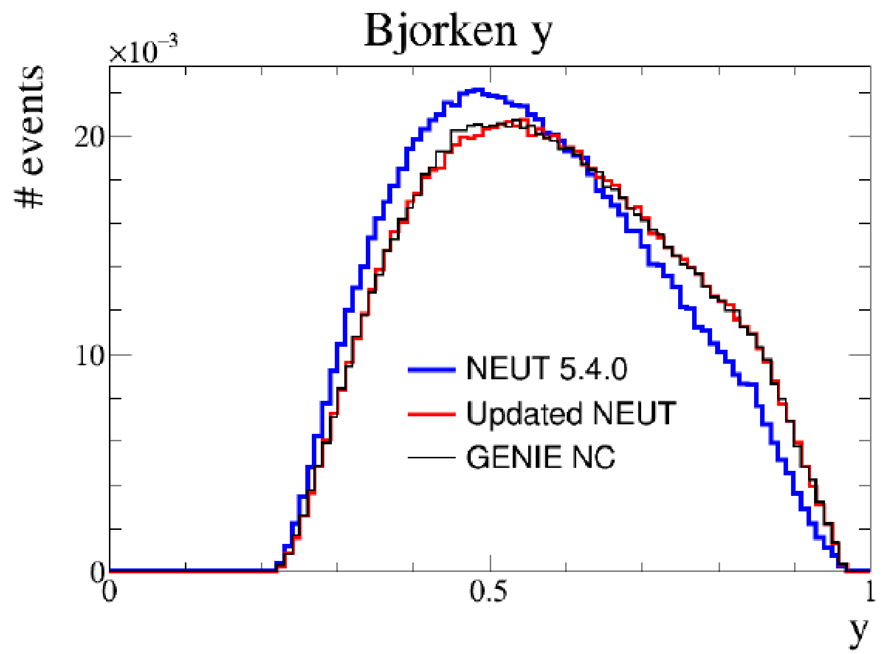
(C. Bronner)

Neutral current modes

- So far only presented CC DIS modes
  In 5.4.0, NC DIS modes uses CC structure functions (without CKM matrix element), and NC DIS cross-section obtained from CC one

- Started working on implementing correct NC structure functions.
  After this updates, low W NC mode compatible with GENIE
  (2 GeV $\bar{\nu}_{\mu}$ on free neutrons, usual settings to have agreement)





- Next step will be to compute NC cross-section by integrating $d^2\sigma/dxdy$

(C. Bronner)

Plan for the future releases of NEUT

- New single pion models
  1) Minoo's work (presented yesterday) : Coming soon!
  2) DCC model by Sato-san and Nakamura-san
- New CCQE/multi-nucleon scattering models
  1) Relativistic Green's function model
  2) Improved spectral function model
  3) **Neutral current** multi-nucleon scattering model
- Improvements in the Neutral current multi-pion production and Deep inelastic scatterings
- Improvements in the nucleon re-scattering.

- Reorganization of the code
- Standard event (data) format?

  It is a good time to think about the `common' data format to make it easy to compare events from different simulation program libraries.

Summary

Continuous efforts to improve the simulation program library
and we have almost completed major improvements.

There are some missing pieces in the current release:

1) Single pion production new model and improvements
by Minoo-san and Clarense-san

2) Neutral current multi pion / deep inelastic scattering
by Christophe-san

These updates will be included in the next release.
(Hopefully by the end of this year.)

Introduction of new sophisticated models are planned.

CCQE/multi-nucleon interactions (both CC and NC)

Single pion productions

Implemented interactions and models

1) Neutrino interactions
    1) Charged current quasi-elastic scattering
        1) $\bar{\nu} + p$ (free) Llewellyn-Smith
        2) ν or $\bar{\nu}$ + N (bound)
            Total cross-section
                Global Fermi-gas (Smith-Moniz)
                Spectral function (Omar et al.)
                Local Fermi-gas (Nieves et al.)
            Kinematics
                Custom code for Global Fermi-gas
                Follow the authors' prescription for the others
    2) 2p2h
        Model by Nieves et al.
        Kinematics of hadrons
            Similar to the prescription by Sobczyk.

Implemented interactions and models

1) Neutrino interactions

3) Neutral current quasi-elastic scattering

1) ν or $\bar{\nu} + p$ (free) and ν or $\bar{\nu}$ + N (bound)

Total cross-section

Simple scaling from charged current (Global Fermi-gas).

Spectral function (Omar et al.)

Kinematics

Custom code for Global Fermi-gas. (Similar to the charged current)

Follow the authors' prescription for the spectral function model.

Implemented interactions and models

1) Neutrino interactions (con't)
   - 4) Resonance (+ non-resonant) single π production (W<2GeV)
     1) Rein-Sehgal (original form factor)
     2) Rein-Sehgal (Garczyk-Sobczyk form factor)
     3) Minoo's (inspired by Rein's) <- in progress (debugging)
   - 5) Multi-pion production (W<2GeV, # of π > 1)
     - Structure function (PDF) GRV98 with Bodek-Yang corr.
     - Multiplicity and kinematics Custom code
   - 6) Deep inelastic scattering (W>2GeV)
     - Structure function (PDF) GRV98 with Bodek-Yang corr.
     - Multiplicity and kinematics PYTHIA (in CERNlib2005)

Implemented interactions and models

1) Neutrino interactions (con't)

7) Resonance single meson or gamma production

Rein-Sehgal inspired K, ω, η and γ productions.

(No strangeness violating K production).

8) Coherent π production

1) Rein-Sehgal (original)
2) Rein-Sehgal (with some lepton-mass corrections)
3) Berger-Sehgal

9) Diffractive π production

Rein-Sehgal (original)

10) lepton scatterings (off by default)

Implemented interactions and models

2) Final state interactions

Semi-classical cascade simulation

1) pion interactions

Delta region (p_π < 500MeV/c)

Mean free path : Salcedo, Oset et al.

Scaled to reproduce π-A exp. data.

(ρ dependences are not changed.)

Kinematics : results from phase shift analyses

Local Fermi-gas model is used.

Medium correction by Seki et al.

+ Emission of nucleons after absorption.

Higher energy region (P_π > 500MeV/c)

Mean free path : Extracted from π-A exp. data.

No ρ dependence considered.

Kinematics : Same as delta region.

Implemented interactions and models

2) Final state interactions

Semi-classical cascade simulation

2) nucleon interactions

Lindenbaum - Sternheimer (Phys.Rev.105 1957)

with modifications in MECC7/GCLAOR.

$$\mathrm{N} + \mathrm{N} \rightarrow \mathrm{N} + \mathrm{N}$$
$$\mathrm{N} + \mathrm{N} \rightarrow \mathrm{N}^* + \mathrm{N}, \mathrm{N}^* \rightarrow \mathrm{N}' + \pi\ (+\pi)$$
$$\mathrm{N} + \mathrm{N} \rightarrow \mathrm{N}^* + \mathrm{N}^*, \mathrm{N}^* \rightarrow \mathrm{N}' + \pi\ (+\pi)$$

Interaction probabilities and kinematics

based on the experimental data.

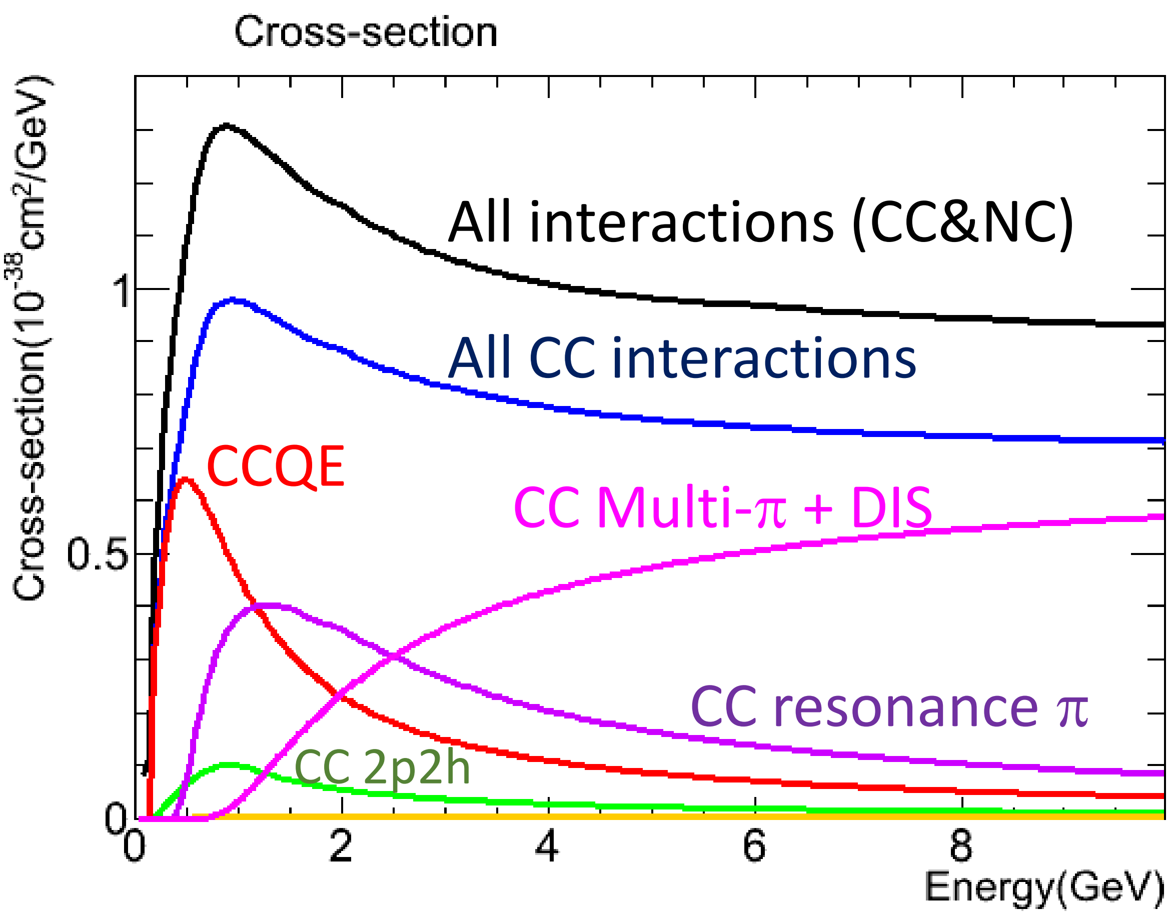
Pauli-blocking

Local Fermi-gas model

Implemented interactions and models

Cross-section for Carbon (NEUT 5.4.0)

$$\text{Averaged nucleon cross-section} = \frac{\left(Z * \sigma(\nu+p)+(A-Z)*\sigma(\nu+n)\right)}{A}$$



Used models (default)

CCQE	Local Fermi-gas
CC2p2h	J. Nieves et al.
CC1π	Rein-Sehgal with G-S form factor
multi-π	Custom code
DIS	PYTHIA
Coherent π	Berger-Sehgal

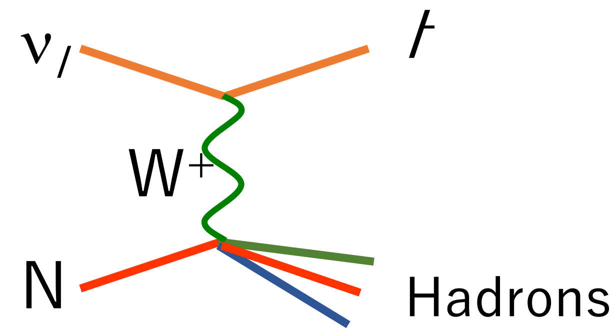
Implemented interactions and models

Multi-pion production (W<2GeV) & DIS (W>2GeV)

(Recent improvements and bug fixes by C. Bronner)

$$\frac{d^2\sigma^\nu}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi}\left[(1 - y + \frac{1}{2}y^2 + C_1)F_2(x) + y(1 - \frac{1}{2}y + C_2)[xF_3(x)]\right]$$

[C. Bronner, arXiv:1607.06558]



F_2 and xF_3 are the compositions of parton distribution functions (PDFs).

We are using rather old GRV98 PDF.

The thresholds of W and q^2 is low. ($W > 2$GeV, $q^2 > 0.8$GeV^2)

Low q^2 interpolation (correction) is available. (Bodek-Yang)

Kinematics:

W (W>2GeV), PYTHIA could be used.

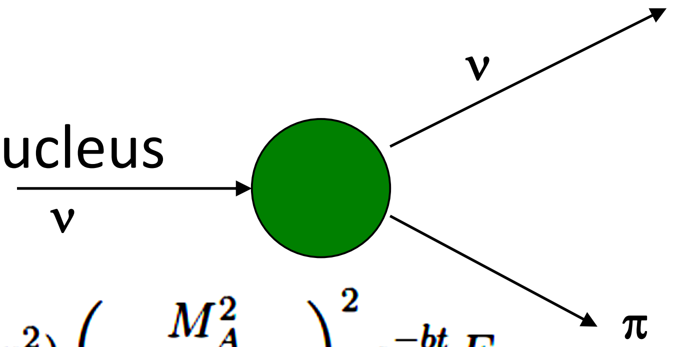
W (W<2GeV), we use customized code.

Implemented interactions and models

Coherent-pion production

π production without breaking the target nucleus

Model by Rein & Sehgal (Nucl.Phys.B223:29,1983)

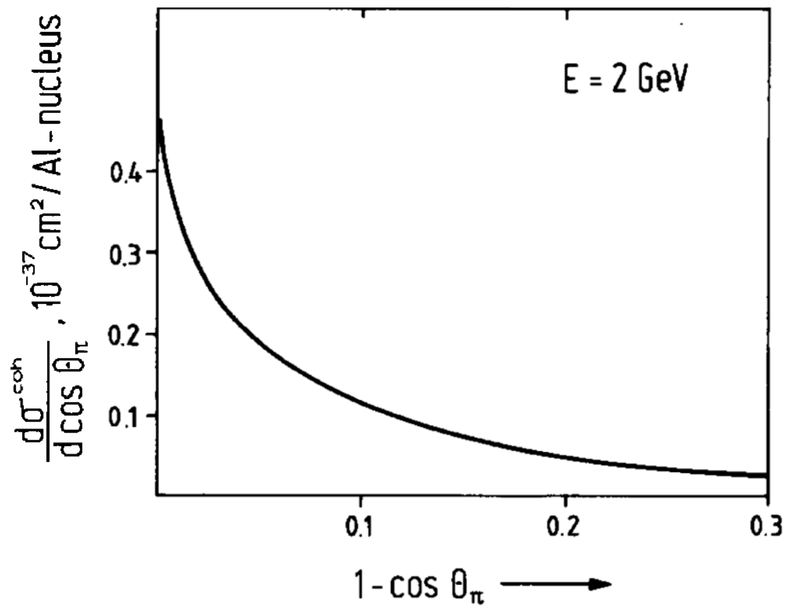


$$\frac{d^3\sigma}{dQ^2dydt} = \frac{G_F^2 m_N E_\nu}{2\pi^2} f_\pi^2 A^2 (1-y) \frac{1}{16\pi} (\sigma_{\rm tot}^{\pi N})^2 (1+r^2) \left(\frac{M_A^2}{M_A^2+Q^2}\right)^2 e^{-bt} F_{\rm abs} ,$$

$$r = \frac{\mathrm{Re}[f_{\pi N}(0)]}{\mathrm{Im}[f_{\pi N}(0)]} ,$$

- Cross-section is smaller than the resonance-mediated mode.
- Direction of π has peak in forward

(Experimentally observed
in the higher energy neutrino experiments.)



$\overset{(-)}{\nu} + {}^{12}C \rightarrow l^{\pm} + {}^{12}C + \pi^0$

In late 2000, cross-section of **charged current** coherent pion production was found to be very small in ~<GeV region.

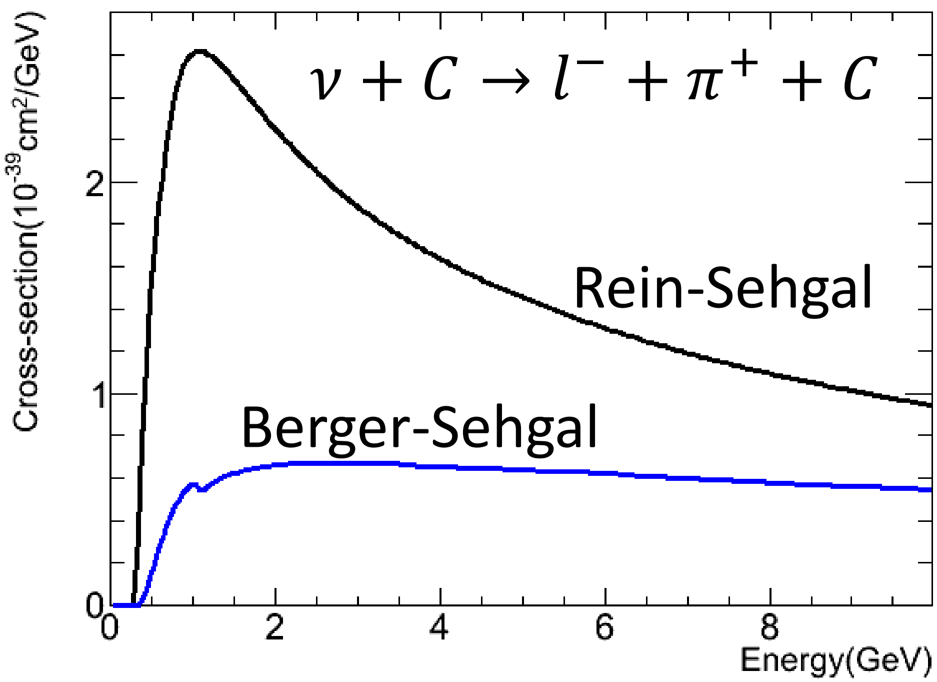
M. Hasegawa et al.(K2K collaboration) (hep-ex/0506008)

Implemented interactions and models

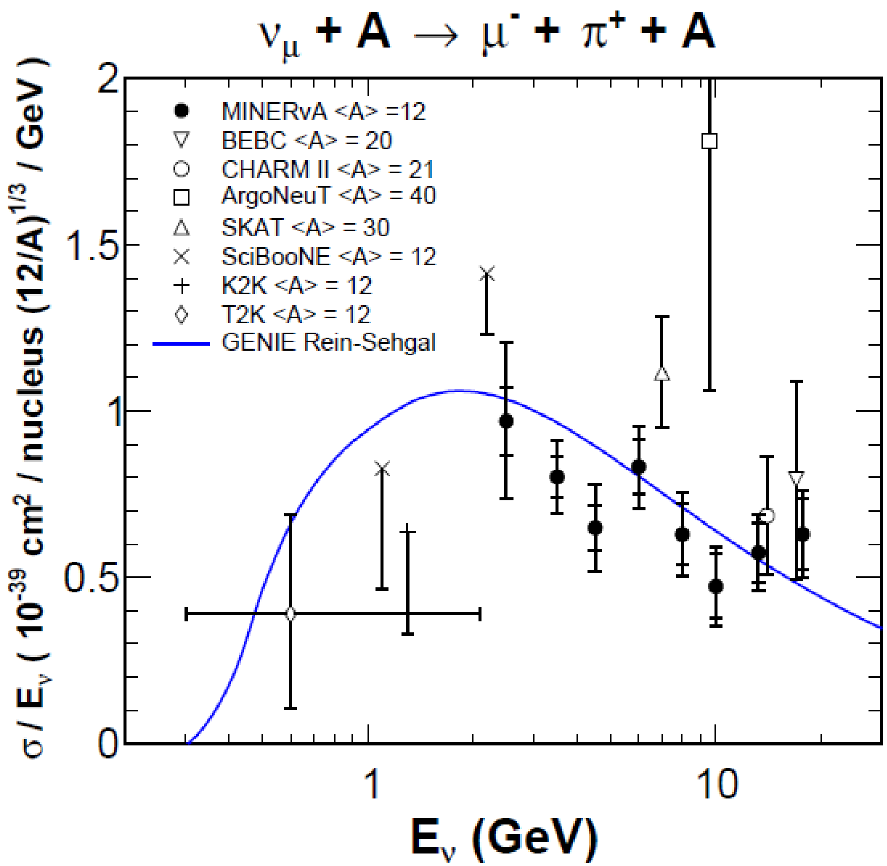
Coherent-pion production

There are several assumption, which are not appropriate for low energy region in original Rein-Sehgal.

Later Berger and Sehgal proposed improved model.



Recently, MINERνA published the charged current cross-section above 2GeV.

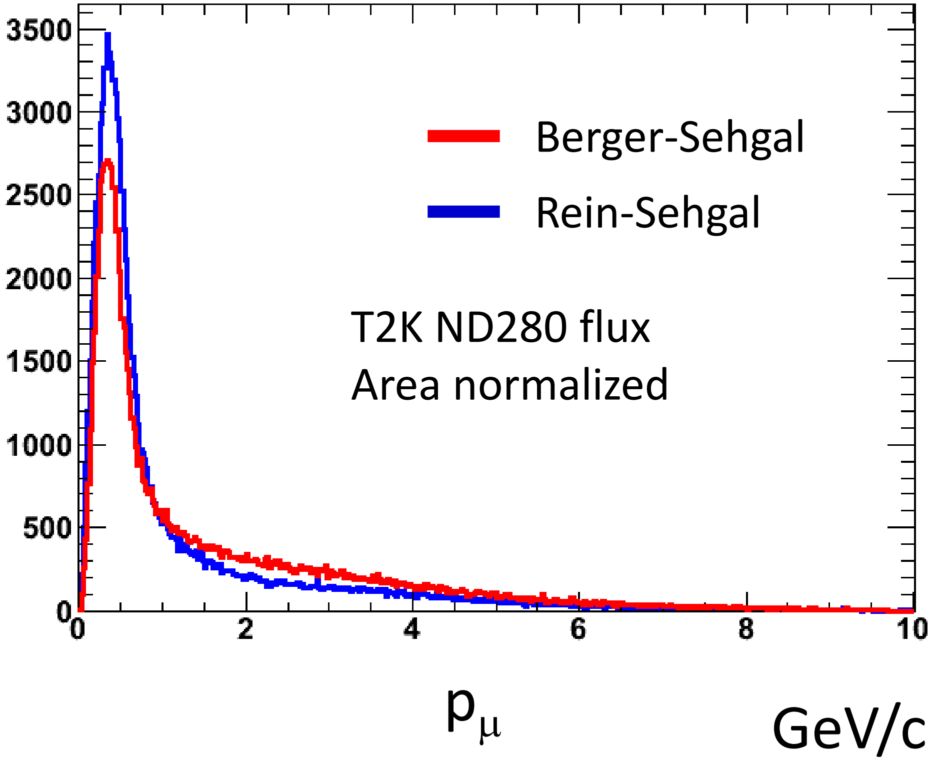


Implemented interactions and models

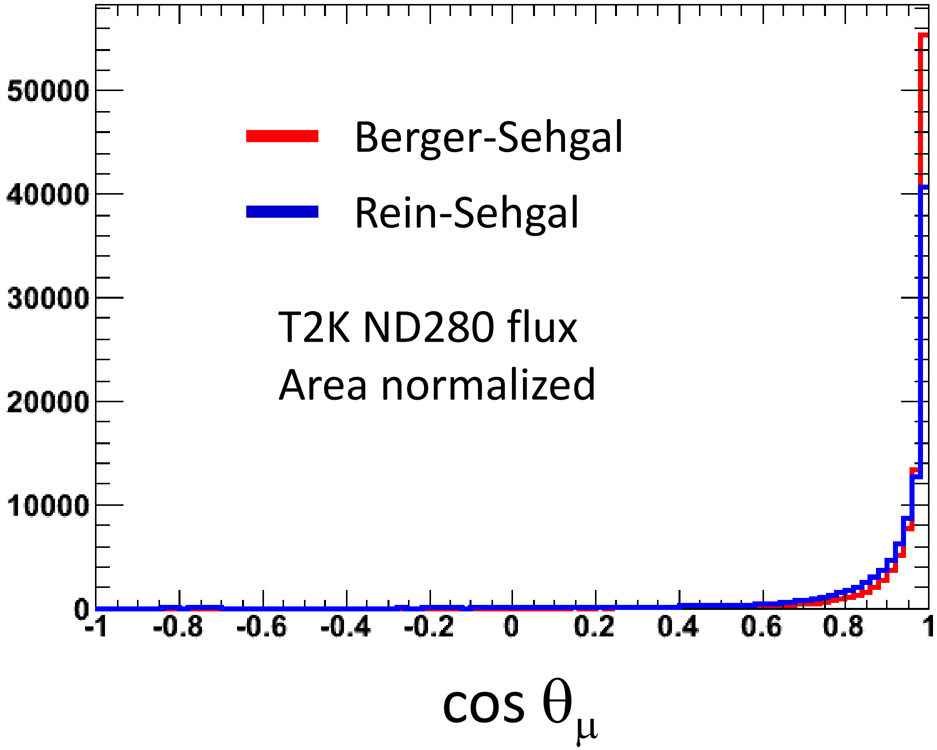
Coherent-pion production

Comparisons of Rein-Sehgal and Berger-Sehgal models

momentum of μ^-



Direction of μ^- w/respect to the beam

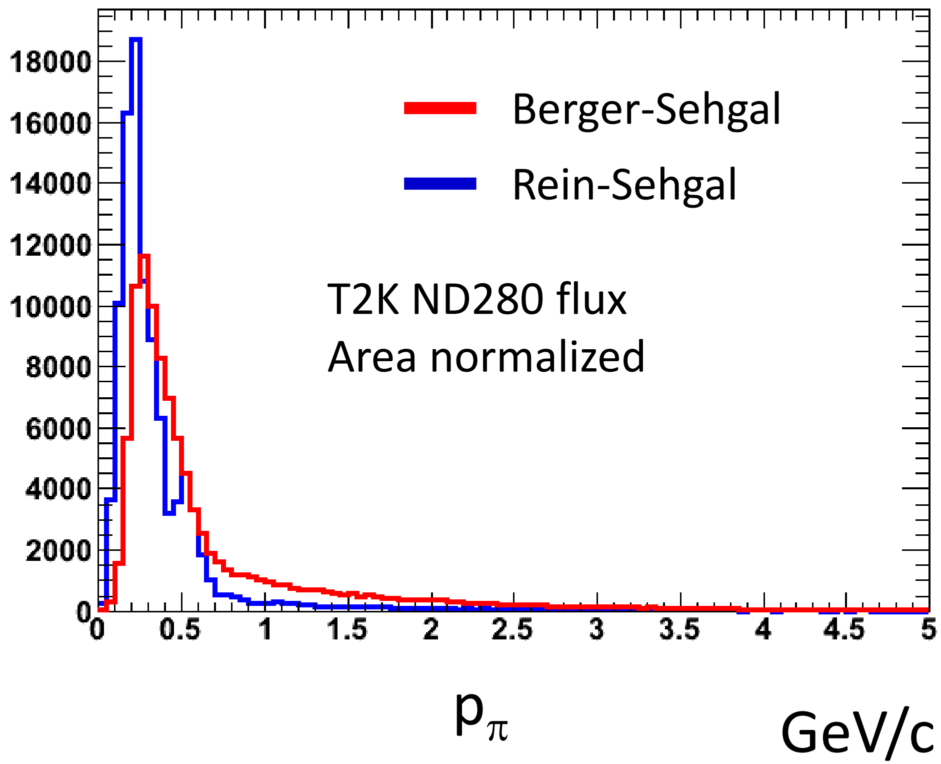


Implemented interactions and models

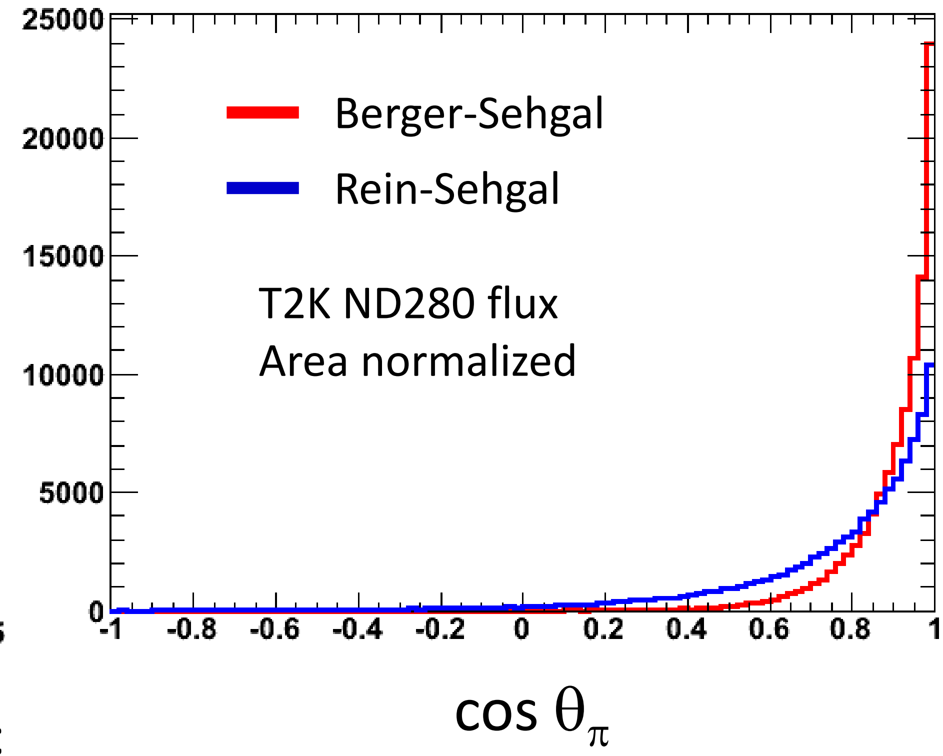
Coherent-pion production

Comparisons of Rein-Sehgal and Berger-Sehgal models

momentum of π



Direction of π
w/respect to the beam



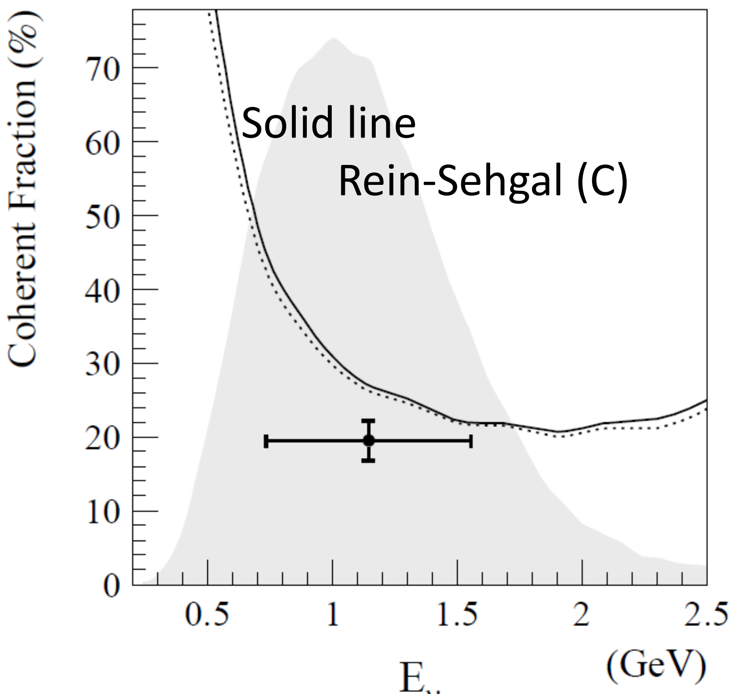
Implemented interactions and models

Coherent-pion production

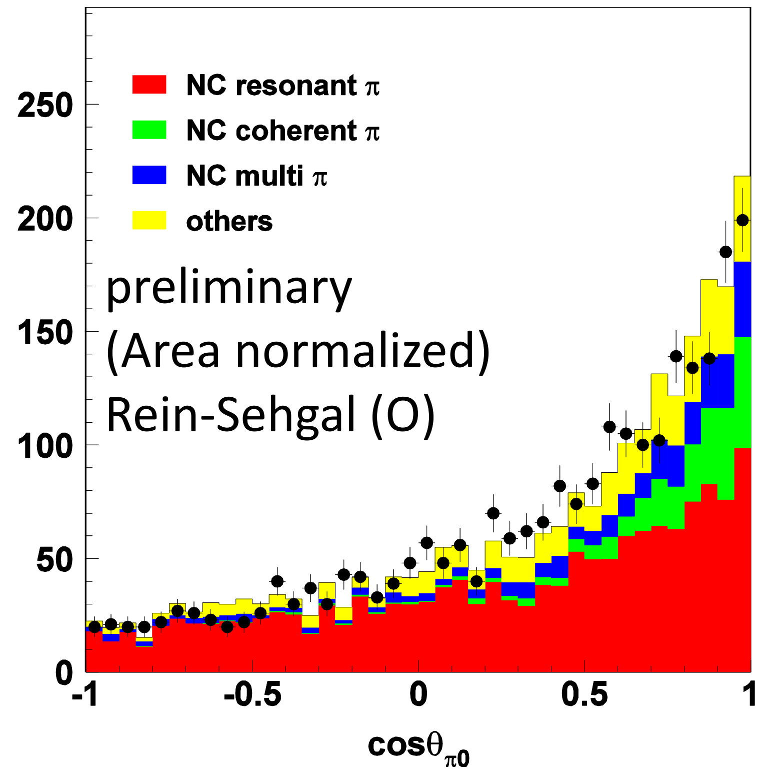
Cross-sections of neutral current coherent π production seems to be rather consistent with Rein-Sehgal model even in the low energy region..

MiniBooNE

Fraction of coherent π^0 production in all NC π^0 production



K2K angular distribution of π^0

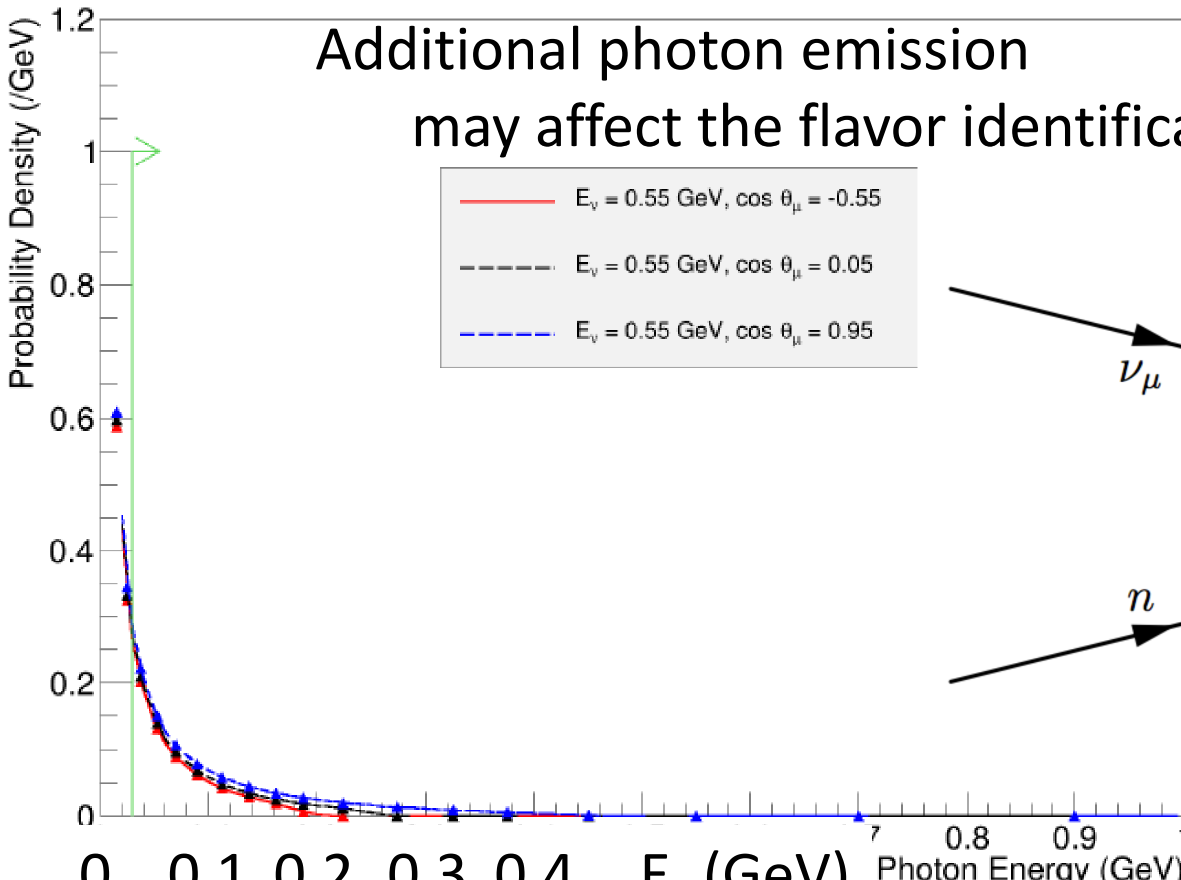


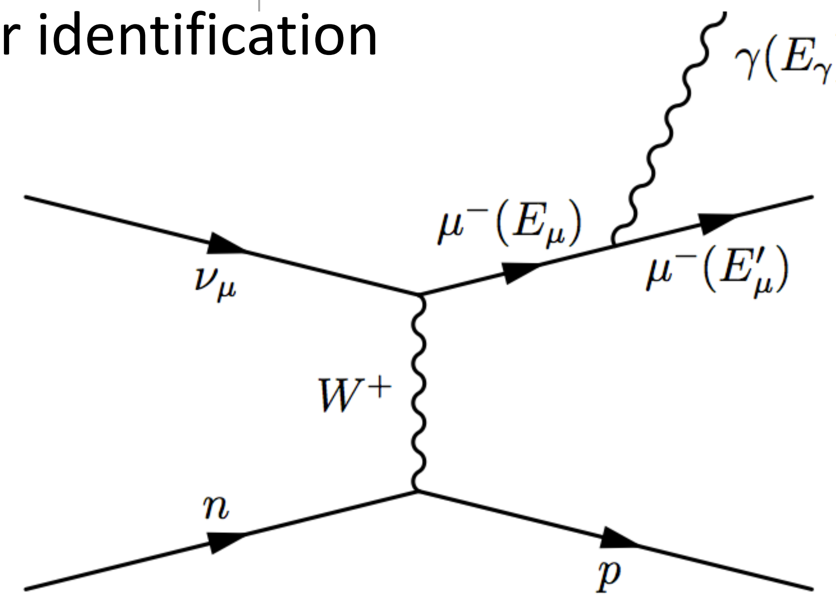
Implemented interactions and models

Radiative CCQE

$$\nu_\mu + n \rightarrow \mu^- + p + \gamma$$

Additional photon emission
may affect the flavor identification





0 0.1 0.2 0.3 0.4 E_γ (GeV)

(By K. Iwamoto and K. McFarland)