Recent updates of Neut

Yoshinari Hayato (Kamioka, ICRR, Univ. of Tokyo)
for the Neut developers

Status of the improvements ~ Neut

Neut 5.3.7 : Latest release
Neut 5.4.0 : Final checks are ongoing
Neut 5.4.1 : Almost ready (expected to be released in late July)

• Radiative corrections	5.3.7
• Local Fermi Gas model for CCQE	5.4.0
• 2p2h hadron tensor	5.4.0
• CC Multi-pion D_2 tune	5.4.0
• Alternative CCQE Axial Form factors	5.4.0
• Berger-Sehgal CC1pi coherent	5.4.0
• Improved FSI pass through	5.4.0
• Diffractive pion production	5.4.0
• Updated single pion model	5.4.1
• Alternative single pion model	5.4.1

What's new in Neut 5.4.0

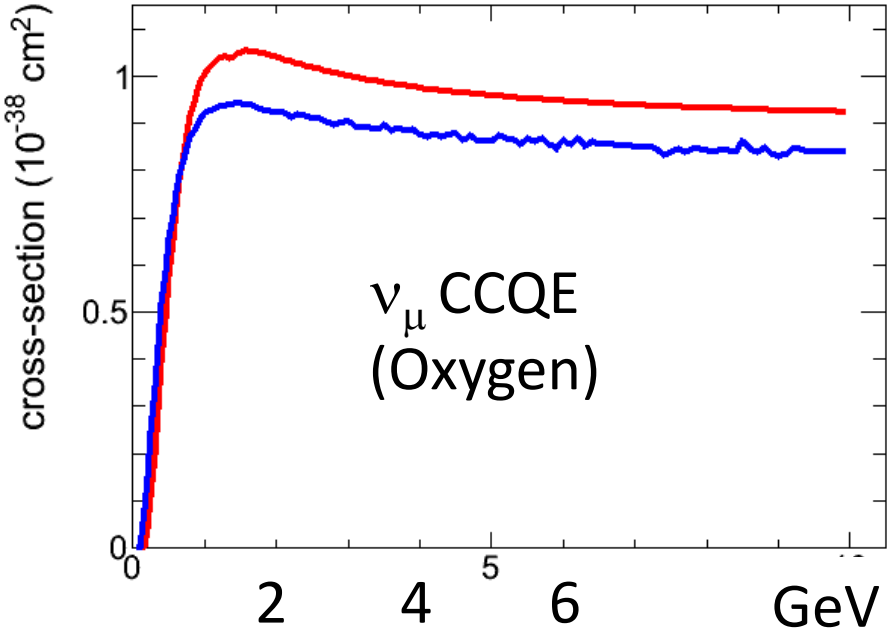
- CCQE
  - Local Fermi gas model
  - Alternative axial vector form factors
  - Radiative correction

- Multi-nucleon CCQE-like scattering
  - Implementation which uses Hadronic tensor
    - (Easy to import new model calculations.)

Local Fermi-gas CCQE in Neut

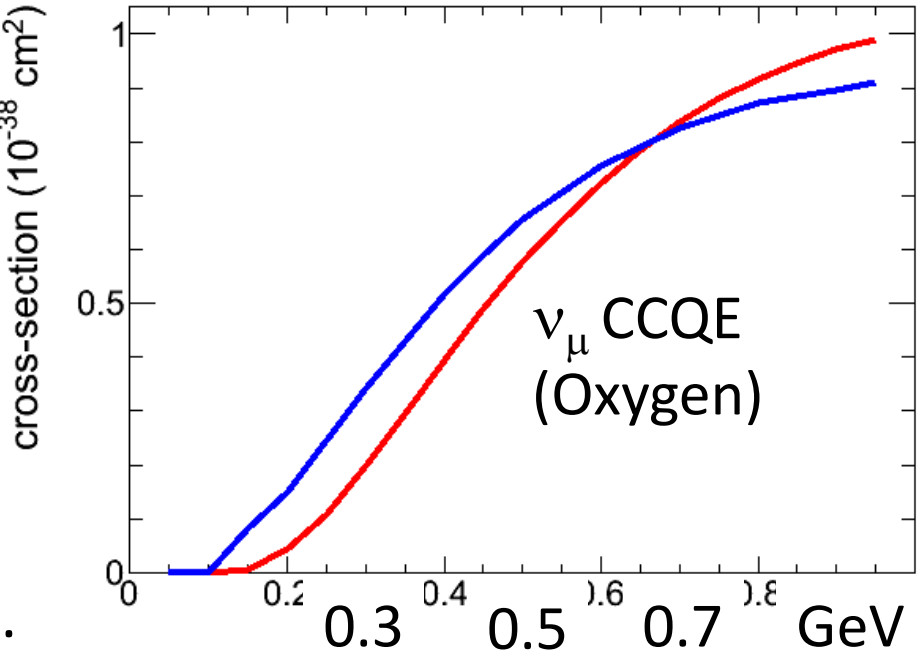
Based on the model and code by J. Nieves et al.

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)

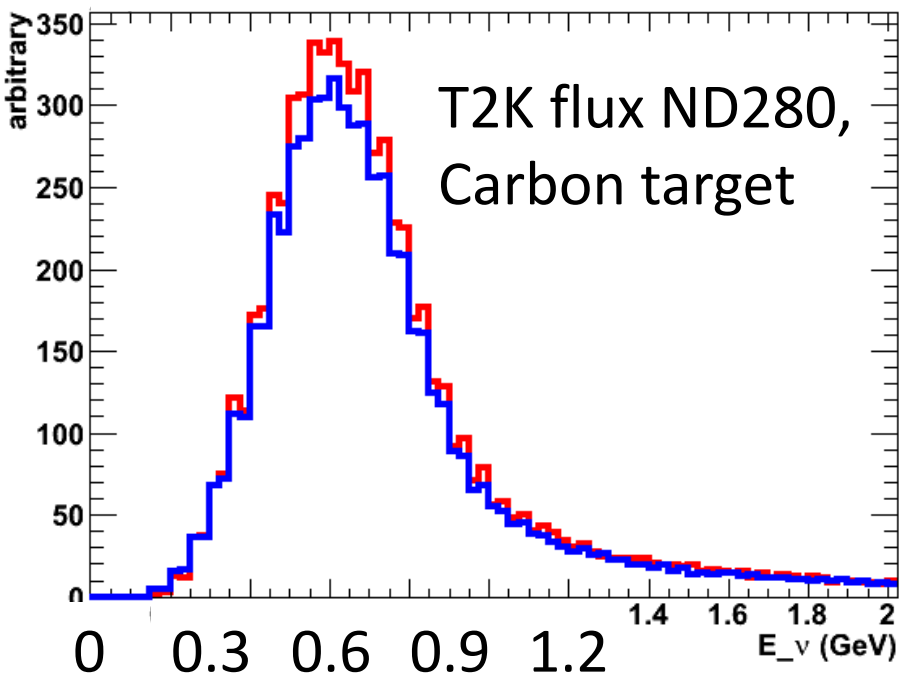
New model gives smaller cross-section in high energy region.

Local Fermi-gas CCQE in Neut

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

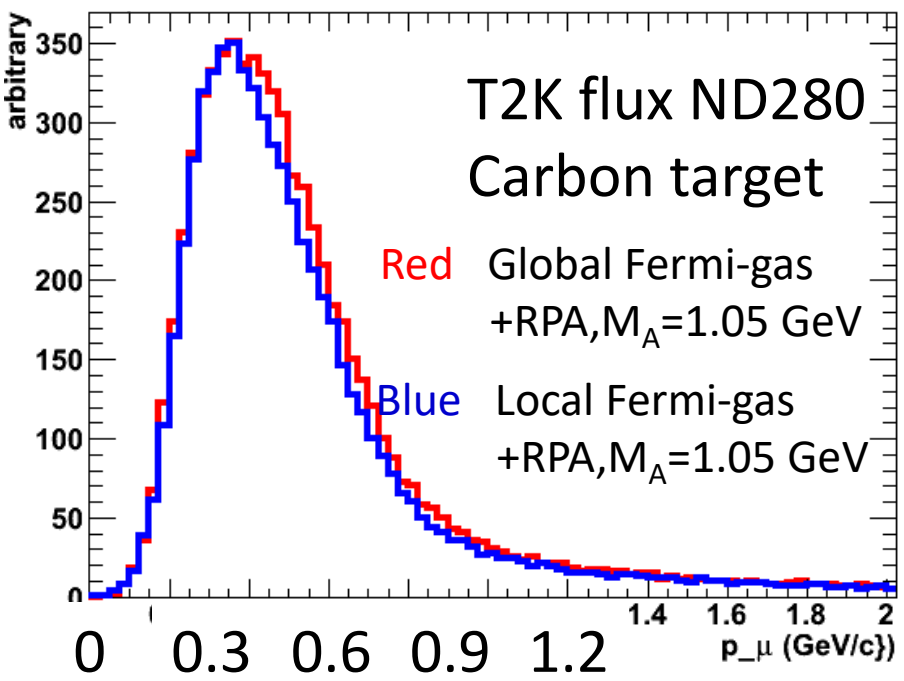
NEUT implementation: B. Bourguille and F. Sanchez

E_ν distribution



E_ν (GeV)

Outgoing μ^- momentum



P_μ (GeV)

The momentum is slightly softer with the new LFG model.

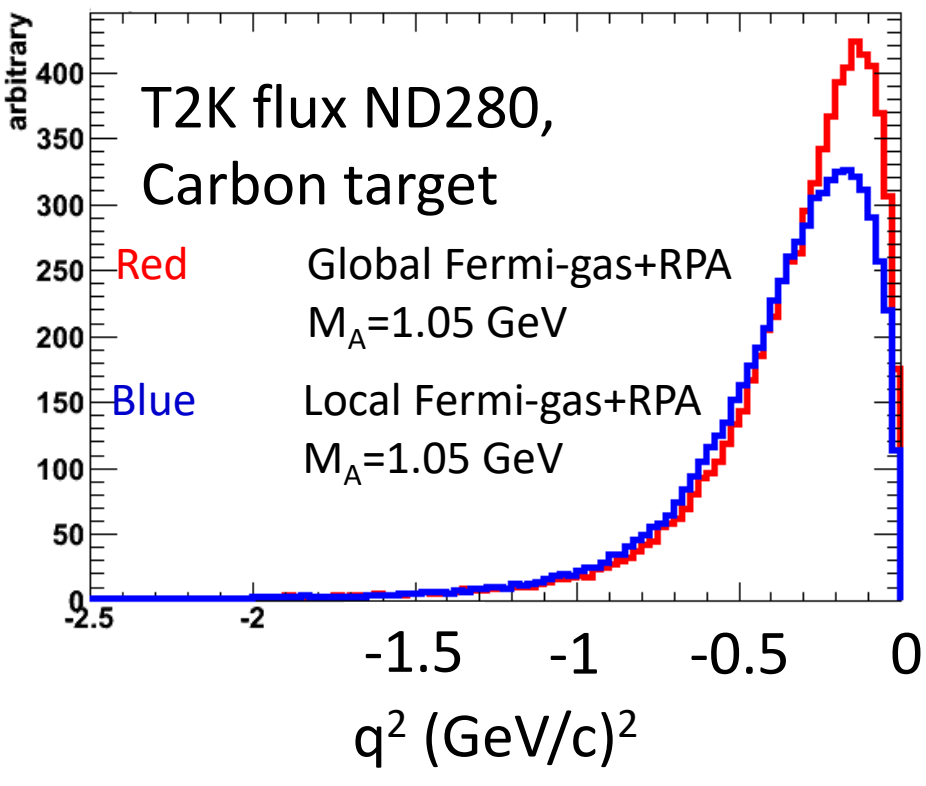
(Low energy cross-section is comparable but smaller in high energy.)

Local Fermi-gas CCQE in Neut

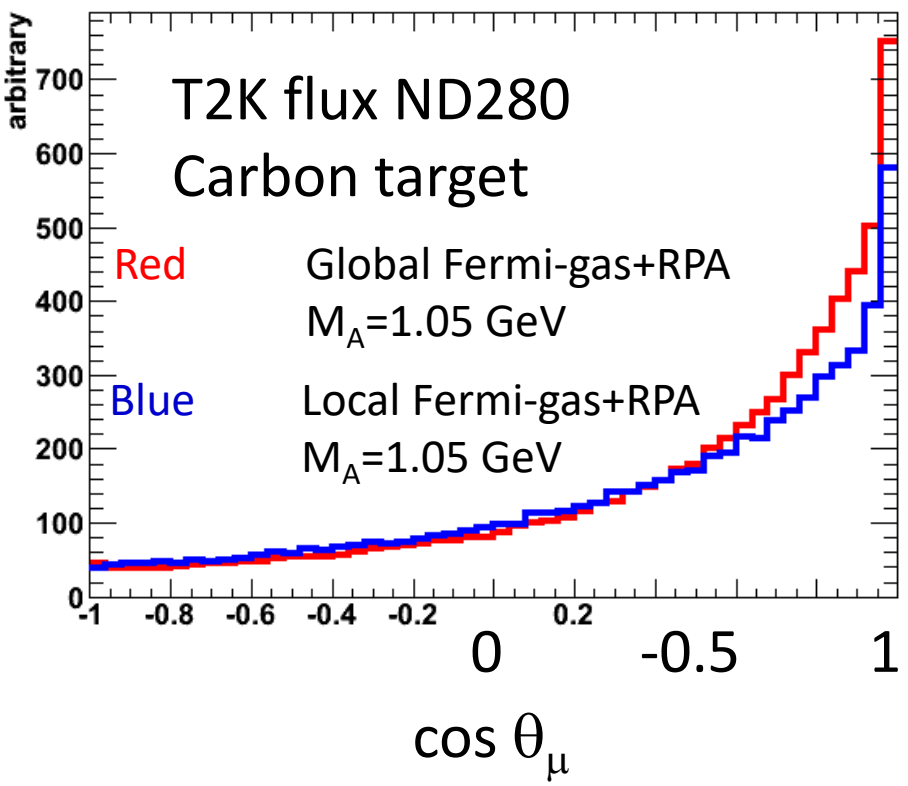
Based on the model and code by J. Nieves et al.

NEUT implementation: B. Bourguille and F. Sanchez

q^2 distribution



Outgoing μ^- direction



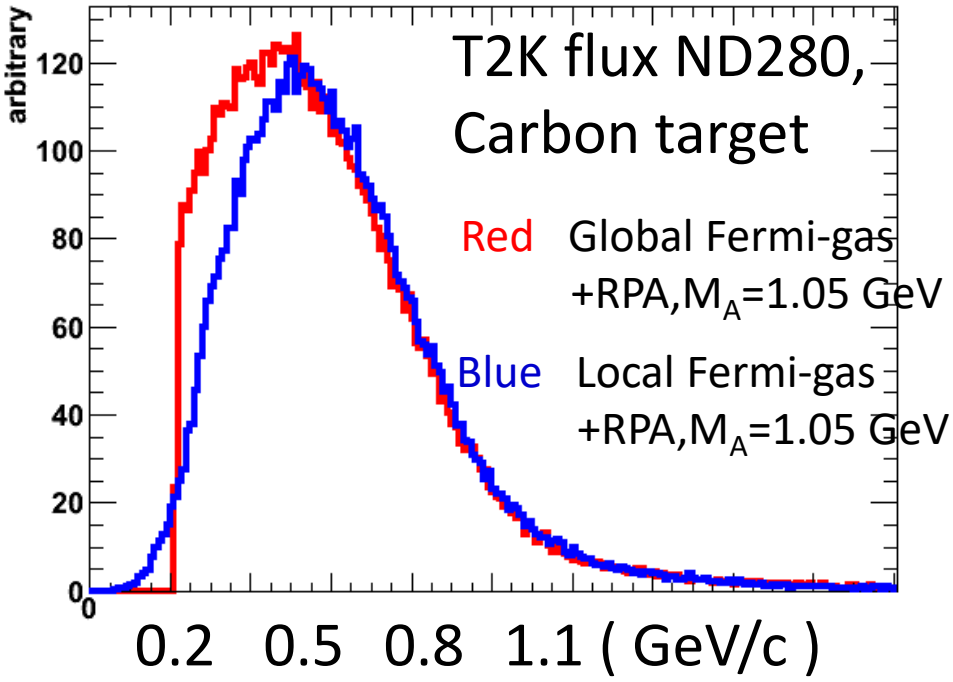
Forward going leptons and small q^2 regions are suppressed with the new LFG model

Local Fermi-gas CCQE in Neut

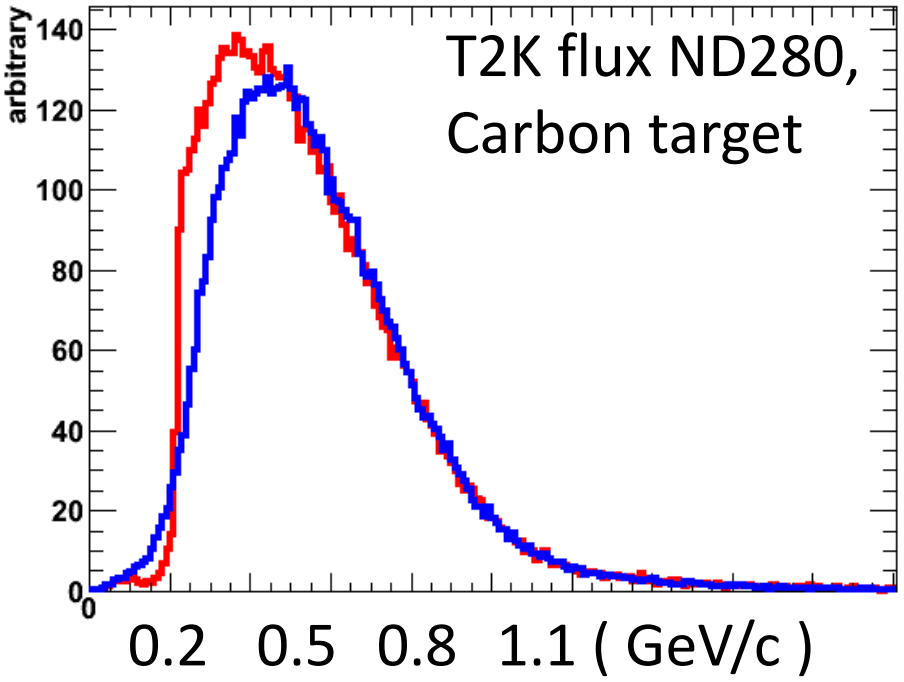
Based on the model and code by J. Nieves et al.

NEUT implementation: B. Bourguille and F. Sanchez

Proton momentum (*before FSI*)



Proton momentum (*after FSI*)



Nucleon momentum has tail below 0.2 GeV/c as expected.

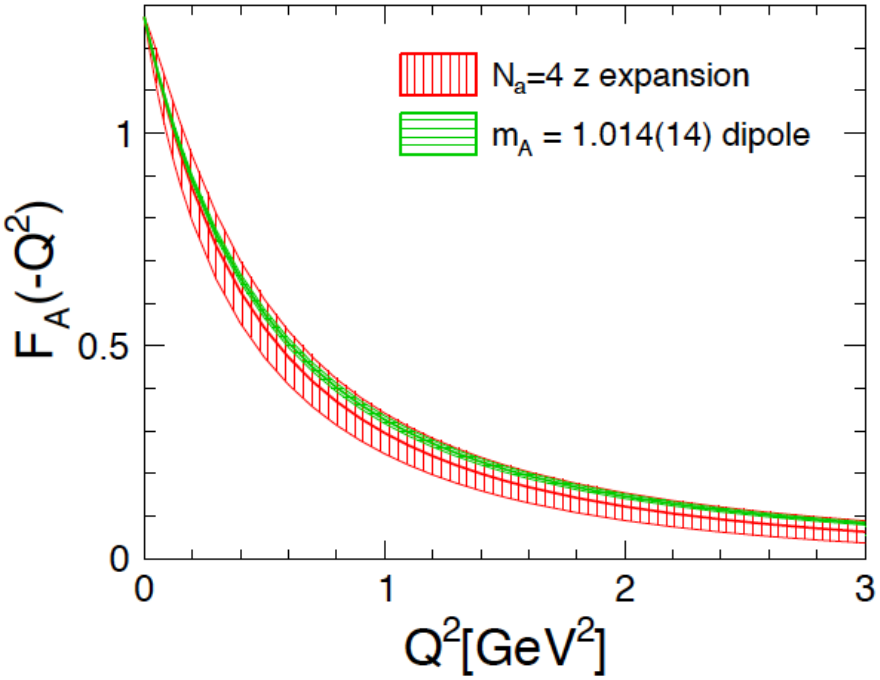
Shape in p_p<500 MeV/c is different with the new LFG model.

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.

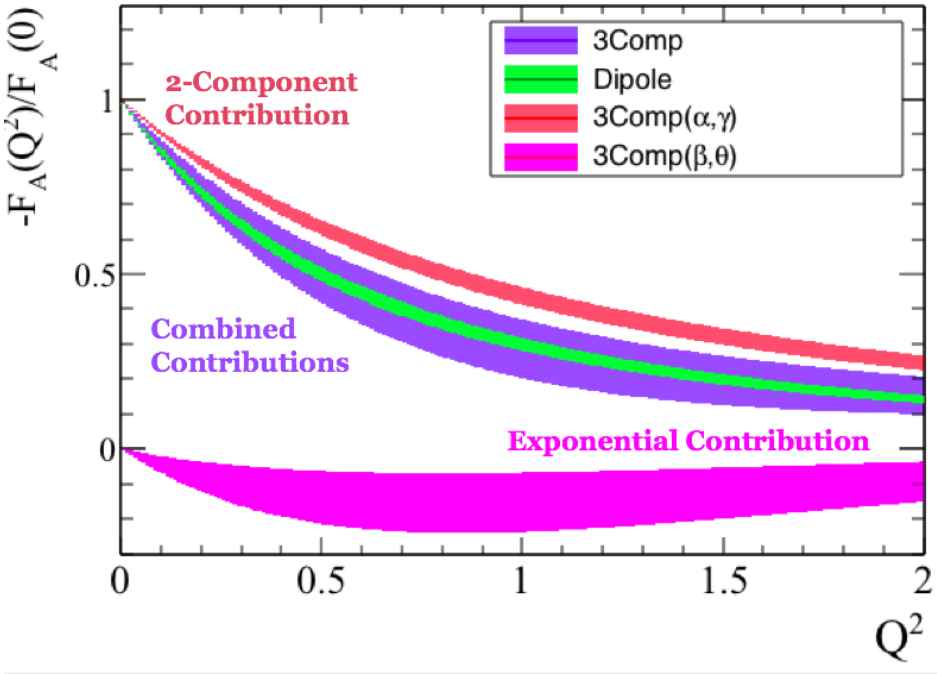
Z-Expansion form factor

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



3-component model

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

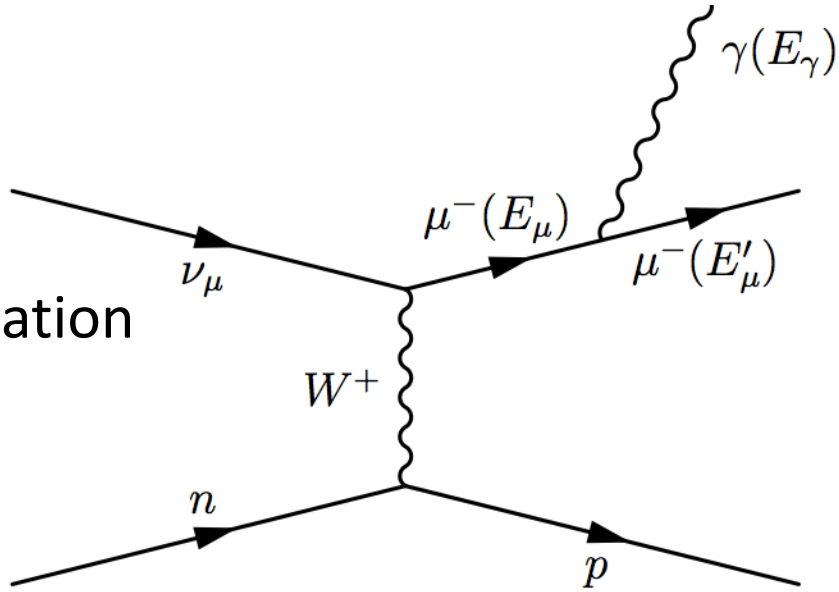


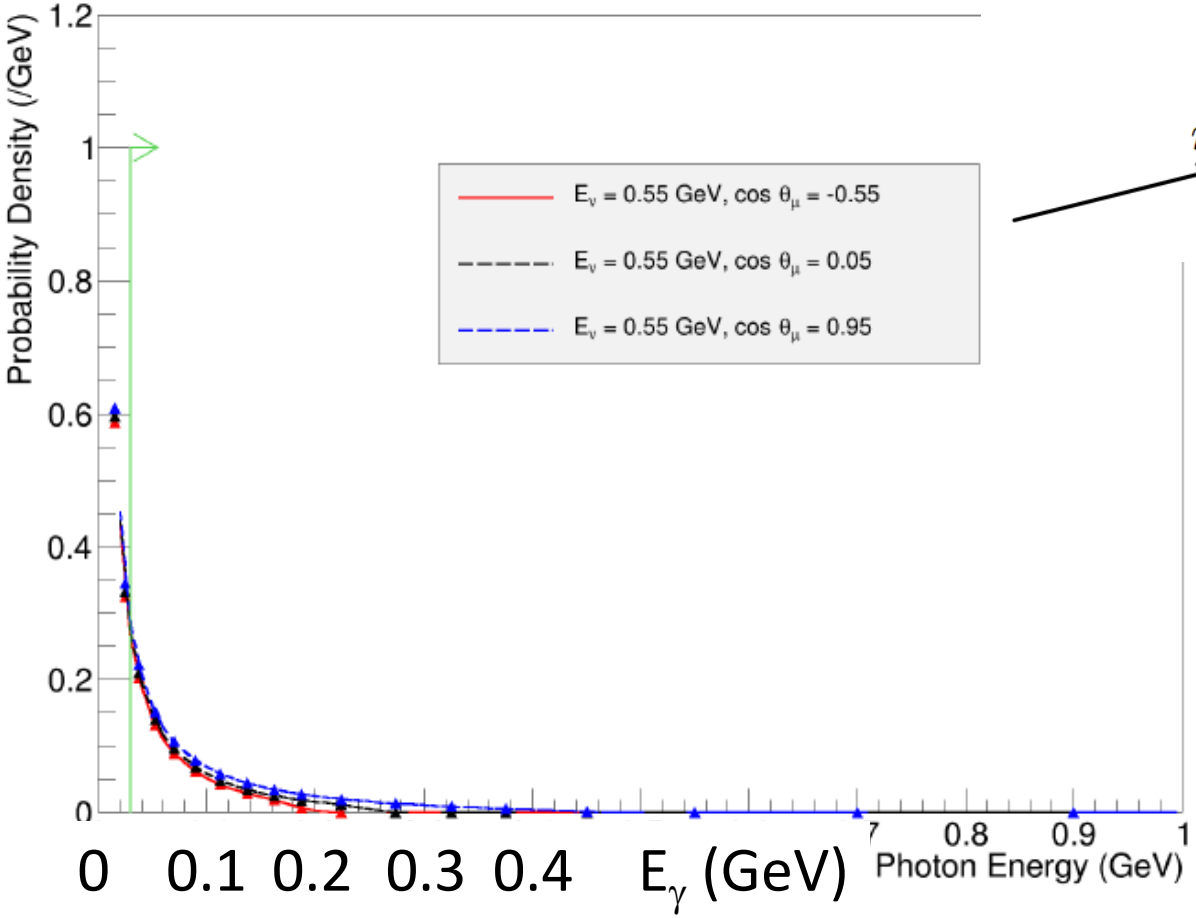
Radiative CCQE

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

Additional photon emission

may affect the flavor identification





(By K. Iwamoto and K. McFarland)

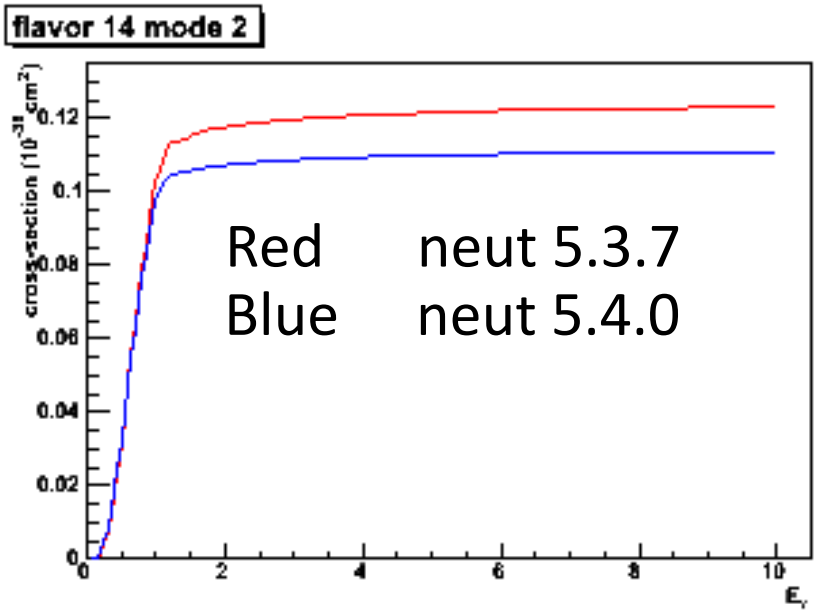
Multi-nucleon (2p2h) scattering in Neut

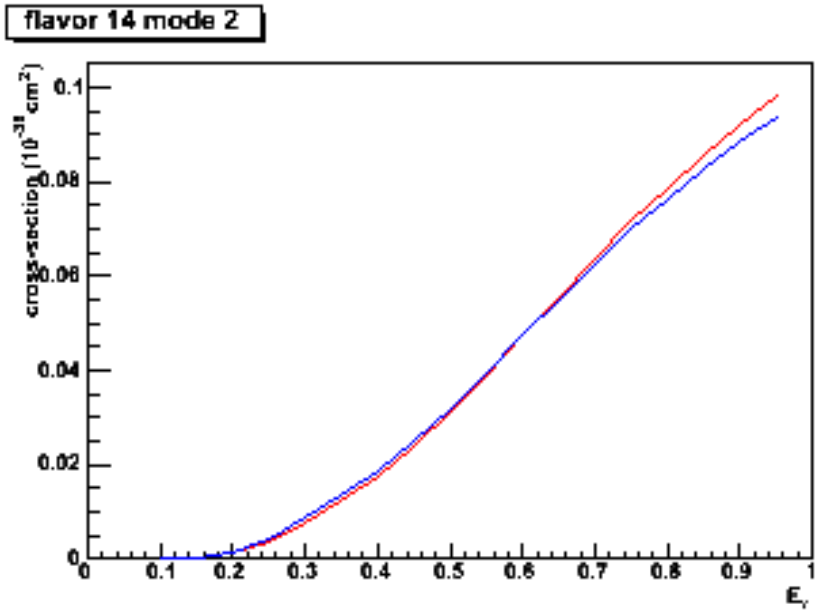
Neut 5.4.0 includes 2p2h implementation
which uses hadron tensors
instead of pre-calculated cross-section tables.

→ Easy to incorporate the other models

Based on the model by Nieves et al.
Adapt the model for Neut by F. Sanchez et al.

Cross-section became smaller because there were some changes in the treatments of Pauli-blocking and binding energy.



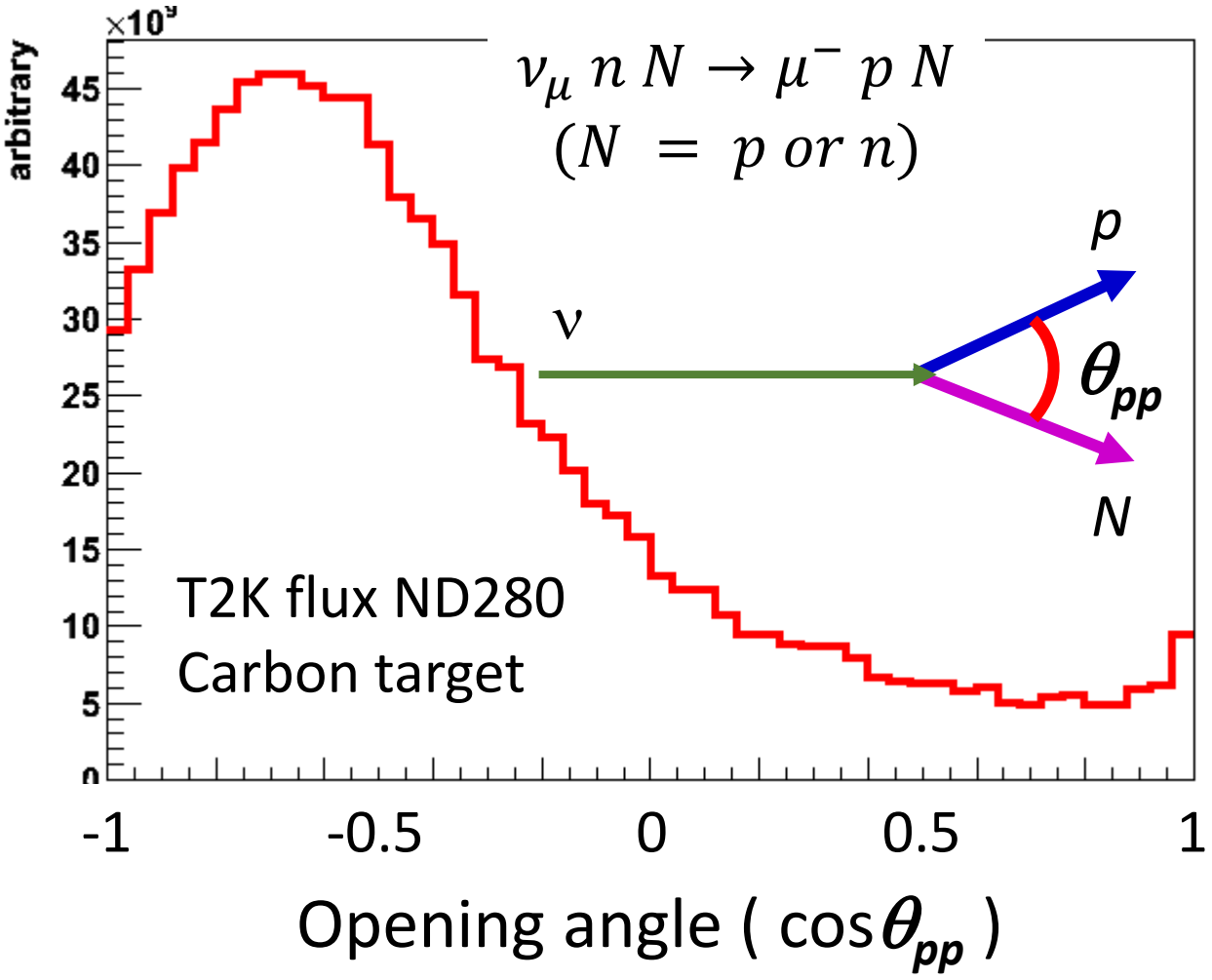


Multi-nucleon (2p2h) scattering in Neut

Outgoing hadron : Code by F. Sanchez et al.

Opening angle of 2 nucleons

(in Lab. Frame, before nuclear re-scattering)



What's new in Neut 5.4.0

- DIS
  Inclusion of CKM matrix elements
  Bodek-Yang correction updates/fixes
  Multiplicity tunings

- Diffractive π production
  Rein's model (PCAC, $E_\nu > 2GeV$)

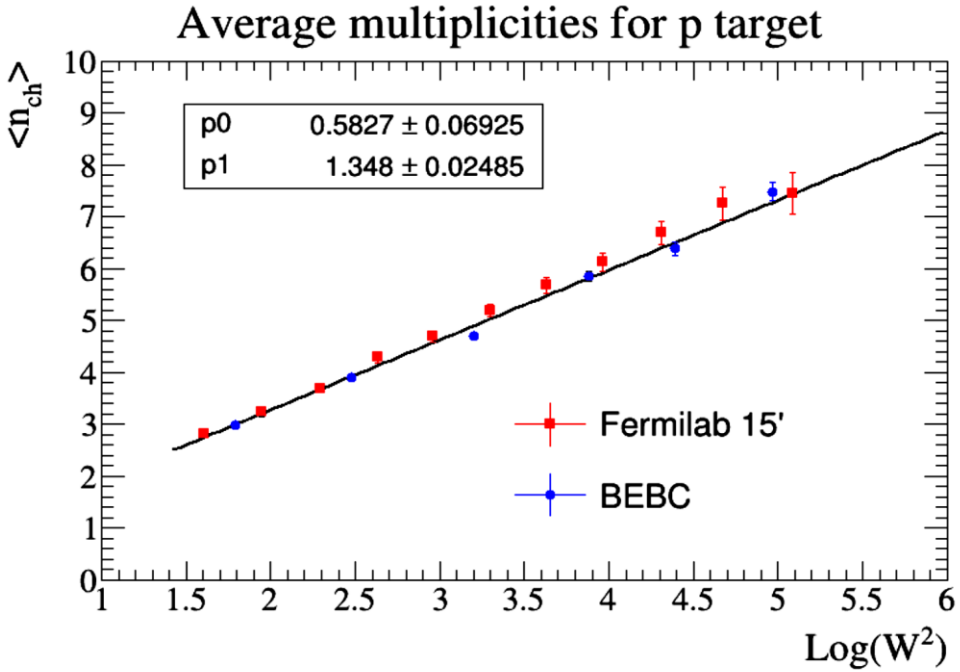
- Coherent π production
  Berger-Sehgal model

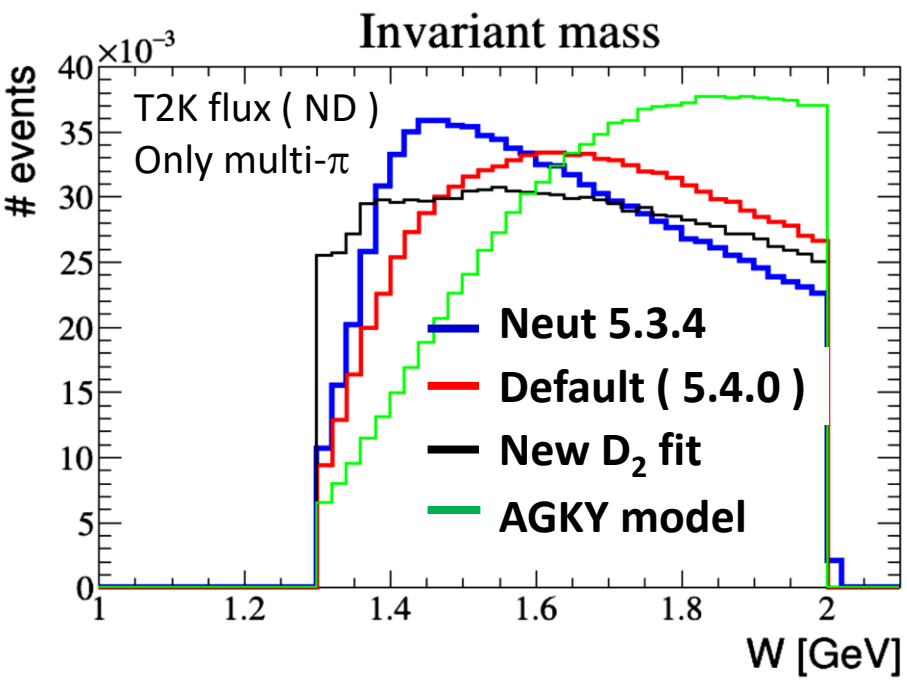
Multi-pion production & DIS improvements in Neut

Improvements and bug fixes by C. Bronner

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)

New Multiplicity parameter fit [C. Bronner, arXiv:1607.06558]





Multi-pion production & DIS improvements in Neut

Improvements and bug fixes by C. Bronner

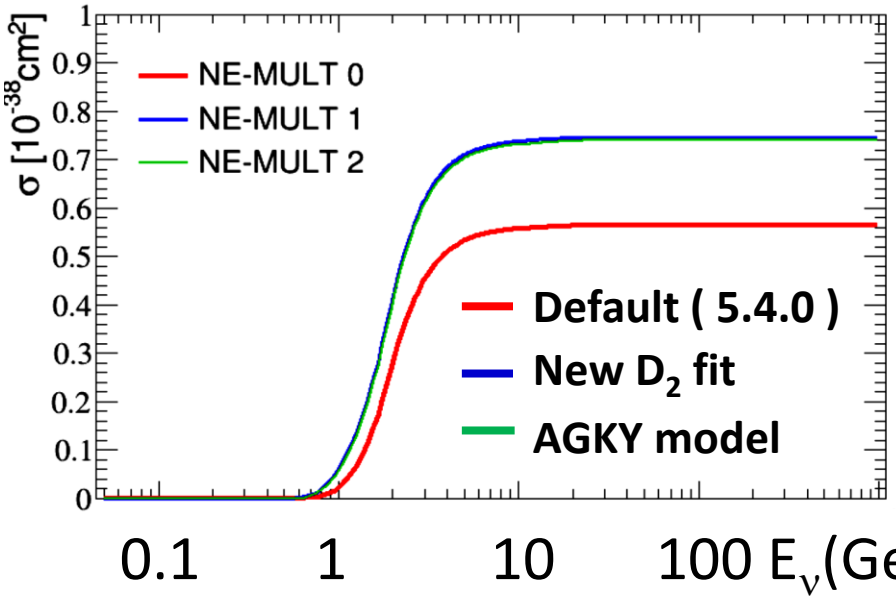
Change of the multiplicity

changes the cross-section of multi-pion mode (W<2 GeV/c^2)

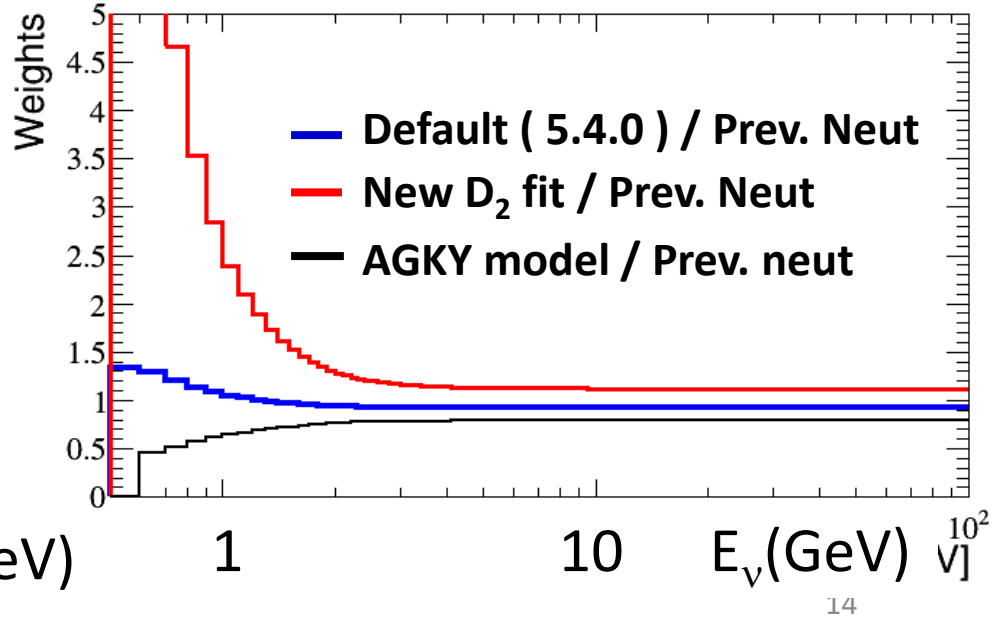
~ at least 2π have to be produced for W<2 GeV/c^2

to avoid the double-counting (overlap with 1 π production)

Multi-pion production σ
*(**proton** target, W<2 GeV/c^2)*



Multi-pion production σ ratio
*(**neutron** target, W<2 GeV/c^2)*



Multi-pion production & DIS improvements in Neut

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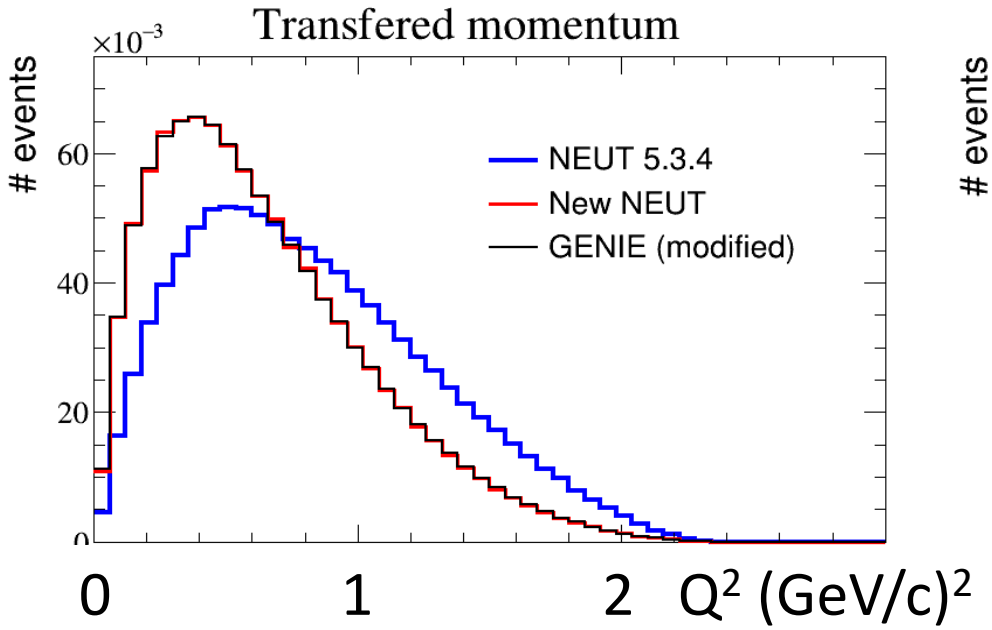
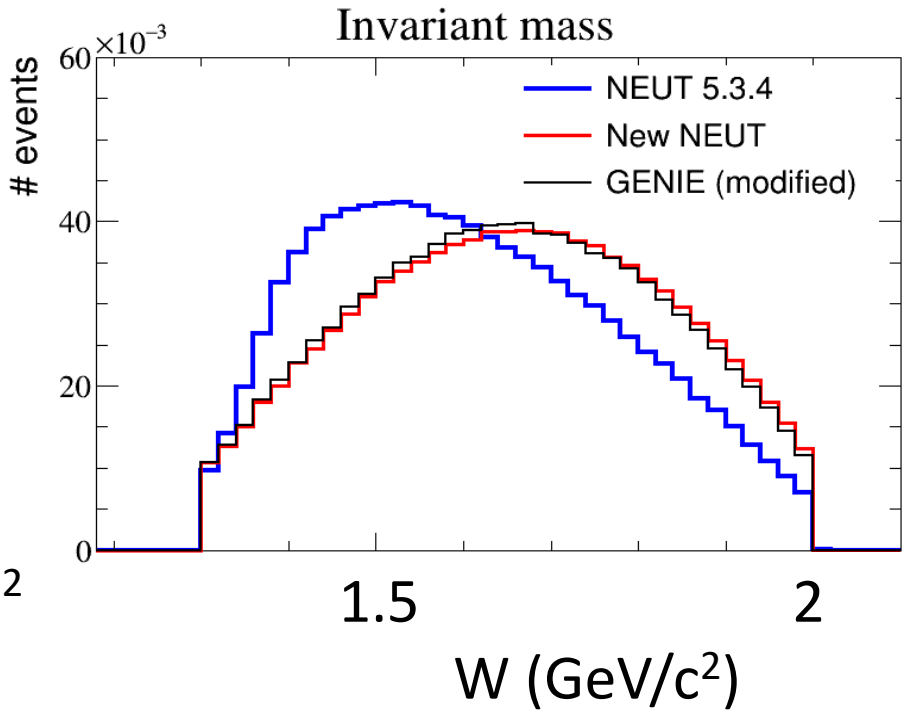
Tune parameters of multiplicity ($W<2GeV/c^2$ only)

2 GeV neutrinos on free protons



2 GeV neutrinos on free protons



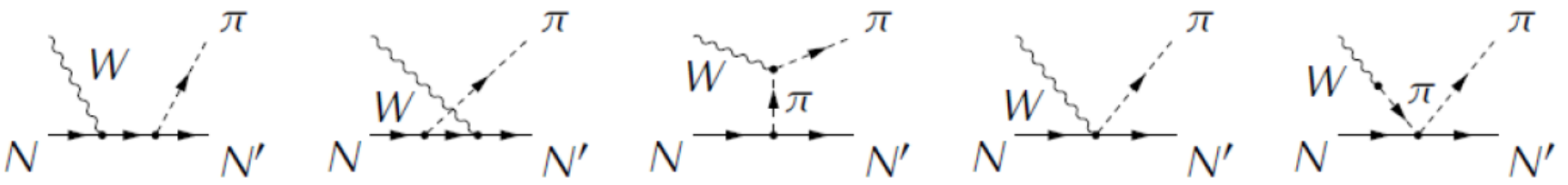
What's new in neut 5.4.1

- Single π production (* work in progress *)

Single pion production ~ New model

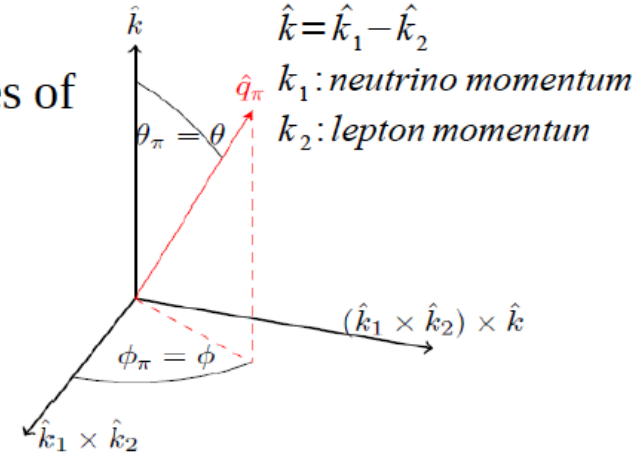
Model is implemented by M. Kabirnezhad
Adapt for Neut by C. Wret

- **The new model includes resonant (Rein-Sehgal model) and non-resonant interactions (5 diagrams from Hernandez et.al) coherently!**



E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D 76 (2007) 033005

- We need to define a common framework to calculate the helicity amplitudes, Isobaric system.
- The main challenge is to calculate helicity amplitudes of the above diagrams in this frame.
- It is suitable for neutrino generators.
- The new model output is $d\sigma / dW\, dQ^2\, d\Omega_\pi$ pion angles are part of cross-section!



The main effects of nonresonant bkg is for pion angles due to the interference terms with resonances!

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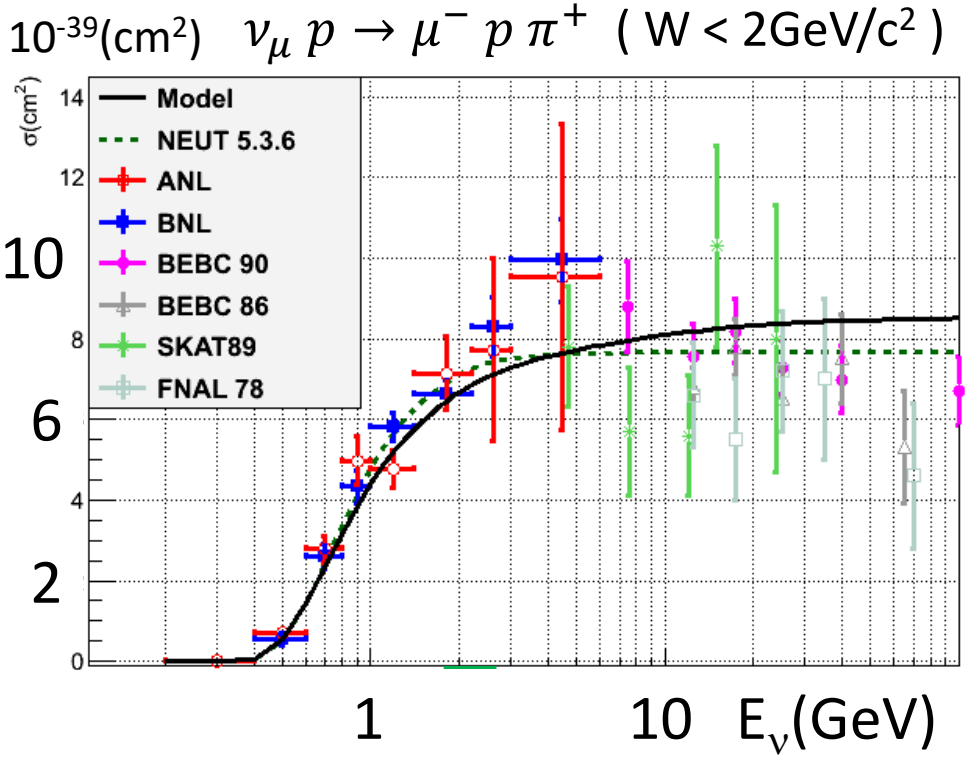
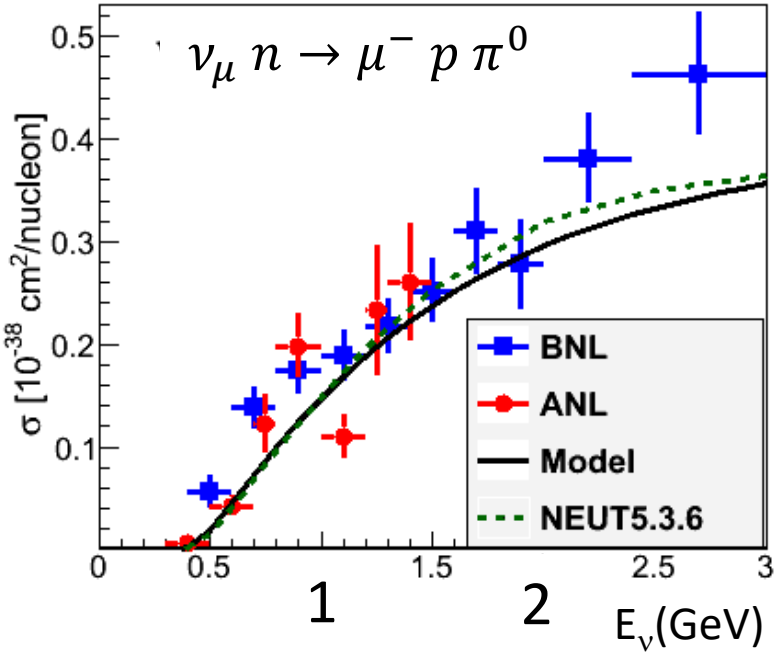
(Slide by M. Kabirnezhad)

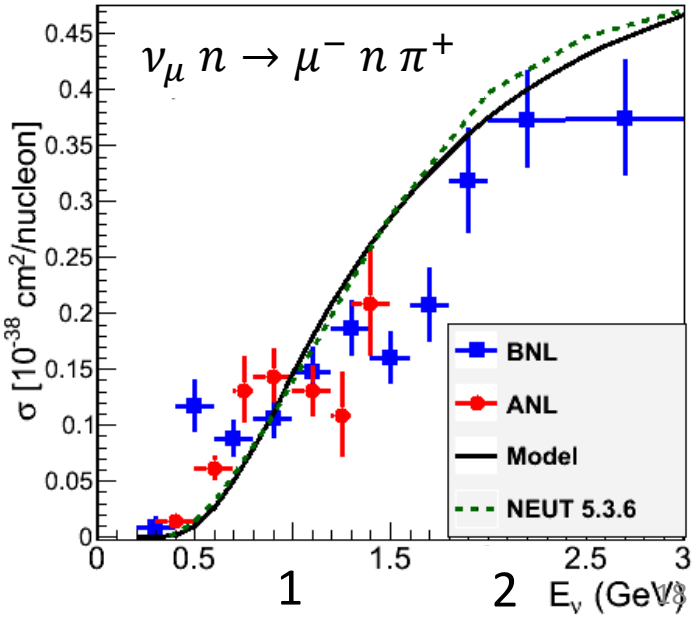
Single pion production ~ New model

New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Interaction cross-sections







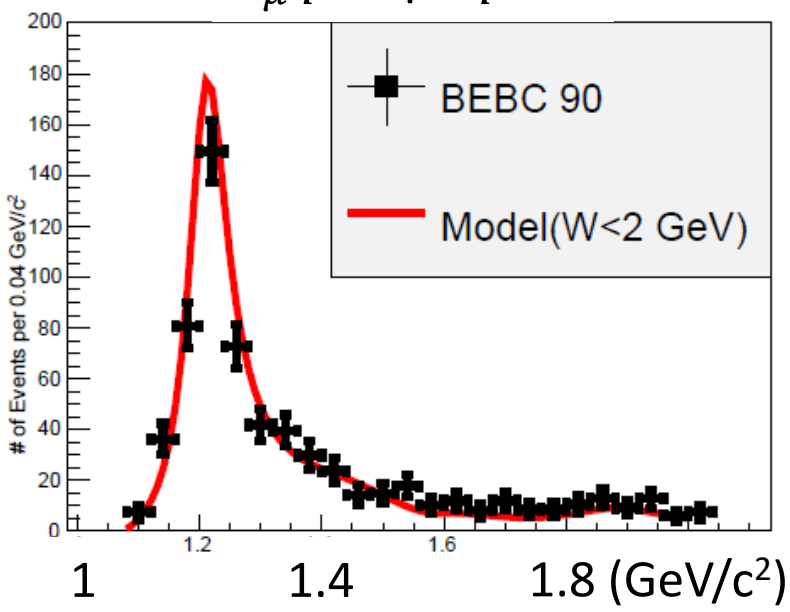
Figures by M. Kabirnezhad,
ANL & BNL data is reanalyzed by C. Wilkinson et al.

Single pion production ~ New model

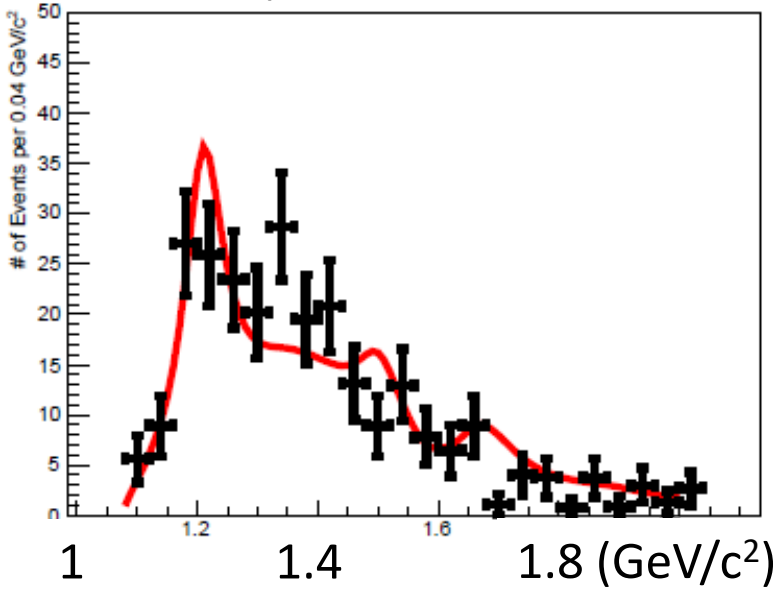
New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Intermediate resonance
Invariant mass distributions

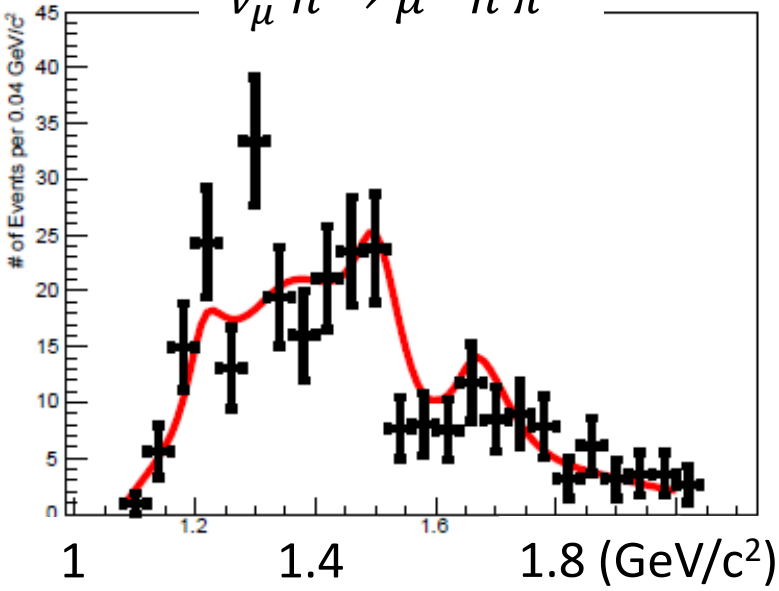
$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$



$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$



$\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$



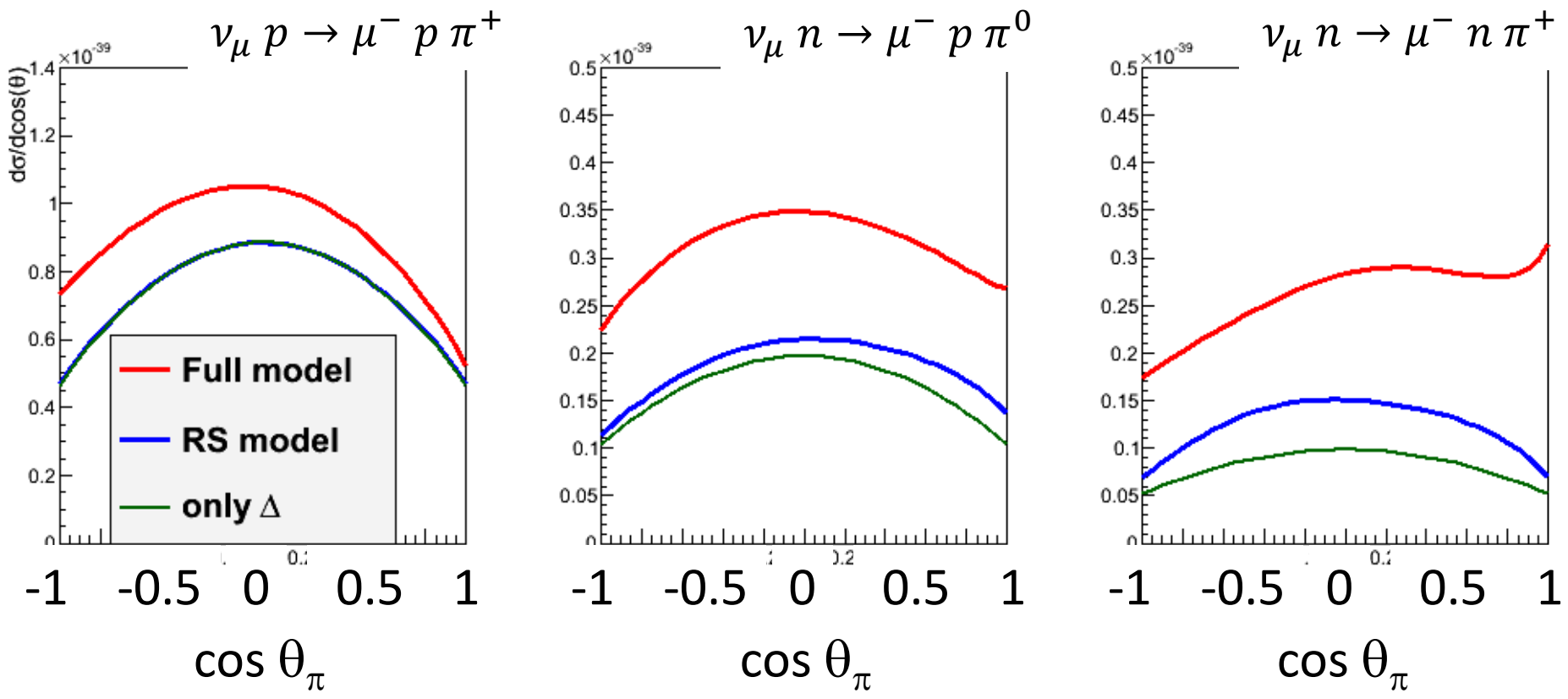
(Figures by M. Kabirnezhad)

Single pion production ~ New model

New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Angular distribution of π in the Adler frame

T2K ND280 neutrino flux



Summary (Plan of the new releases)

1) Neut 5.4.0 : Expected to be released by the middle of Jluy.
   Basically, the code is ready and final checks are ongoing.

2) Neut 5.4.1 : Expected to be released by the middle of August
   Experts are checking the code to finalize.
   Expected to be released in this summer.

After the release of Neut 5.4.1,
we are planning to update
neutral current multi-pion production
and deep inelastic scatterings and
nuclear effects of mesons and baryons.

Fin.