Status of neutrino-nucleus interaction simulation program libraries ~ Monte Carlo Generators ~

Yoshinari Hayato

(Kamioka obs., ICRR, The Univ. of Tokyo)

Thanks to the authors of GENIE, GIBUU, Neut and NuWro.

Introduction

Uncertainties from neutrino – nucleus interactions
became one of the largest source in the neutrino oscillation analyses.

T2K systematic errors for # of events ~ Phys. Rev. D 96, 011102(R)

Source of uncertainty	**ν 1 ring μ**	**$\bar{\nu}$ 1 ring μ**
SK detector	3.9%	3.3%
SK final state & secondary interactions	1.5%	2.1%
Flux & ν interactions constrained by ND280	2.8%	3.3%
Neutral current interactions	0.8%	0.8%
Total	5.0%	5.2%

Total systematic error have to be smaller than a few % in few years.
Urgent task to reduce the systematic uncertainties

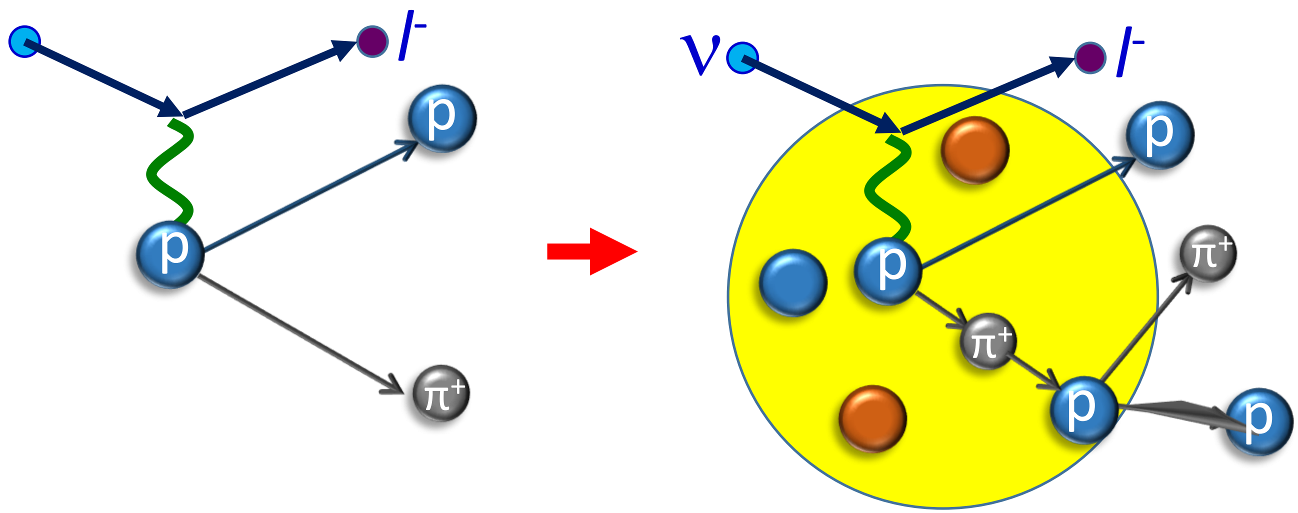
Need to improve the understandings of neutrino-nucleus interactions

Introduction

Most of the neutrino – nucleus interaction simulation programs
(generators)
have been using rather simple and (semi-) classical approach.

1) Impulse approximation for most of the interactions
   (based on neutrino – nucleon interaction)
2) Rather simple nuclear structure
3) Semi-classical transportation of particles in nucleus
   or particle-nucleus scattering

*) GIBUU is different from the other generators.



Introduction

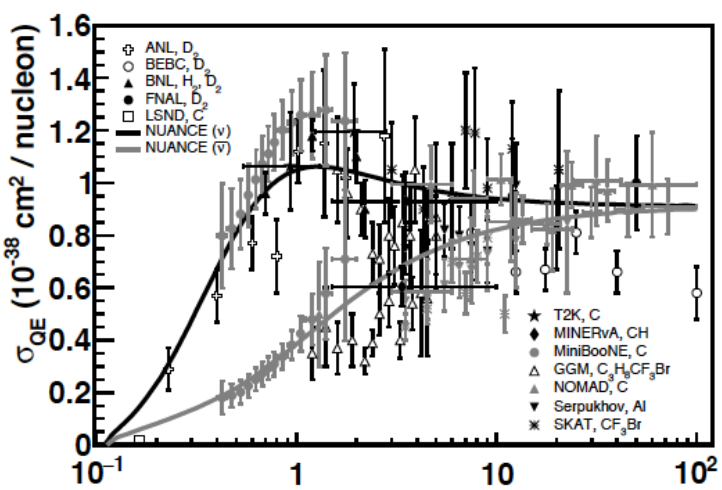
Recent experimental results of neutrino-nucleus scattering have shown that the simple and semi-classical pictures are not sufficient.

1) Forward going lepton is highly suppressed.

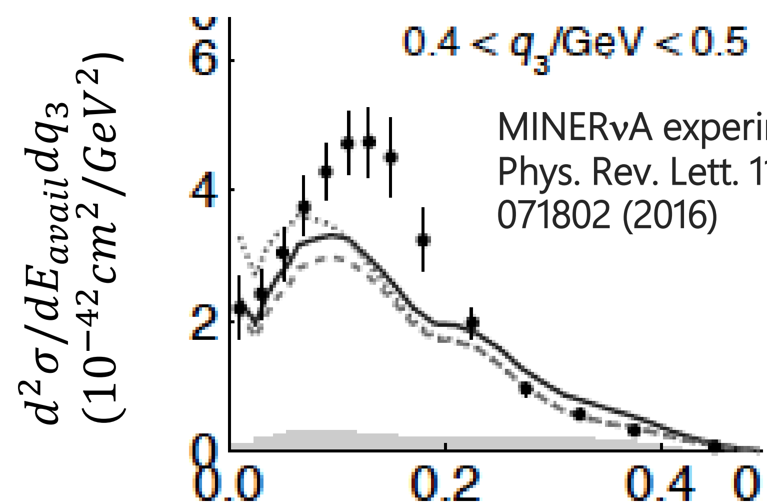
2) Numbers of "1 lepton observed" events are much larger than simple model.

3) Numbers of large angle scattering events are larger.

4) Observed hadron energies do not agree.



Particle data book (2016)



MINERνA experiment
Phys. Rev. Lett. 116, 071802 (2016)

Available Energy(GeV)

Introduction

There are many theoretical attempts to explain the data:

Spectral function, Local Fermi-gas model, Super Scaling, Random phase approximation, Multi-nucleon interactions, ab-initio calculations etc...

New models are introduced in the course of the developments of the neutrino – nucleus interaction simulation programs (generators).

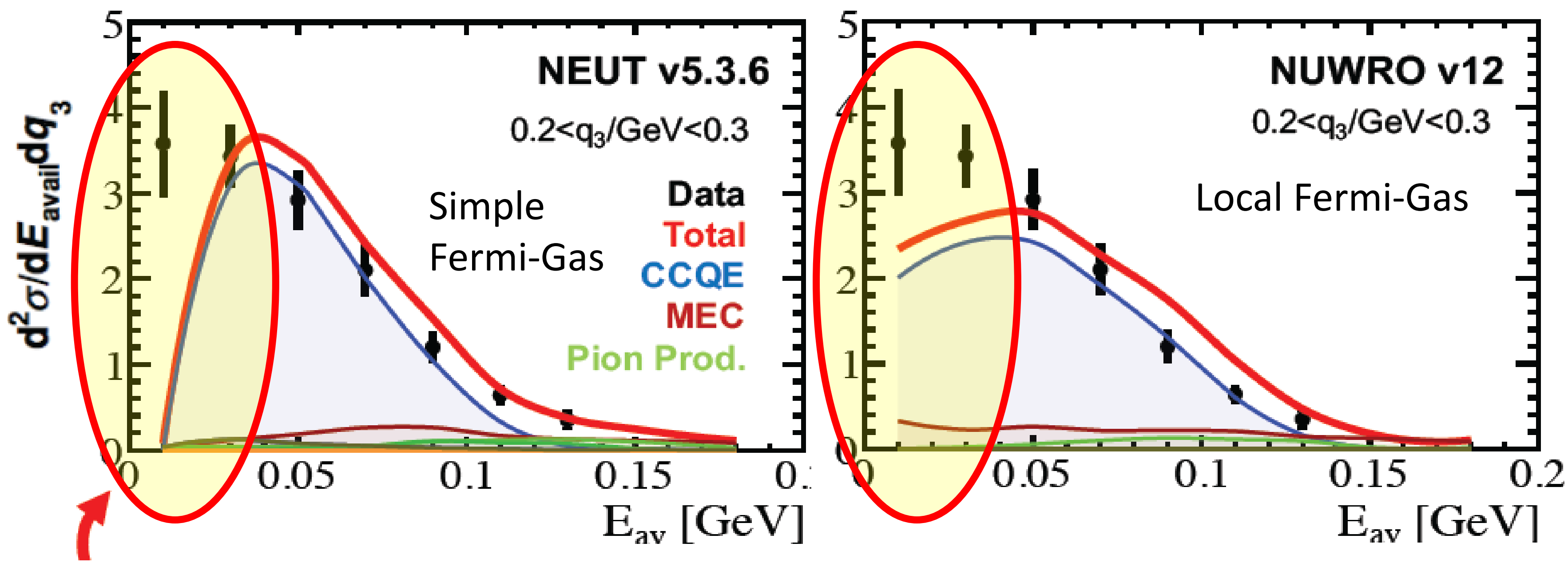
GENIE	Be universal and comprehensive
GIBUU	Framework to encode “best possible” theory
Neut	Mainly for specific experiments (SK, T2K etc.)
NuWro	Provide the latest model useful for the community

Recent measurements

MINERνA Low q_3 sample indicates that
the existence of low momentum protons.

Available energy = (Visible) hadron energy distribution

Patrick Stowell @ NuFact16 Data from PRL 116, 071802 (2016)



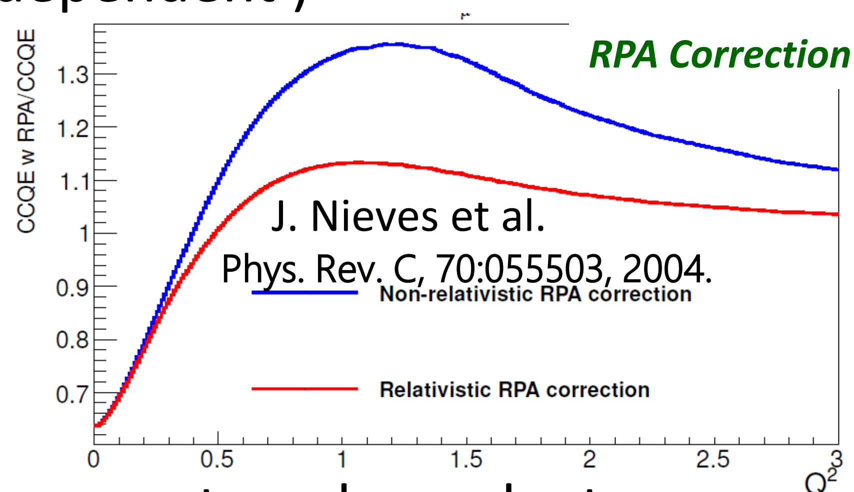
Limitation of uniform nucleus model (“Global Fermi gas model”) is clearly seen.

Necessary to use “Local Fermi Gas” or further sophisticated models.

Charged current quasi-elastic scattering

Recent models and implementations

- Local Fermi gas model
  Use density dependent Fermi surface momentum (P_F)
  Dense region has large P_F peripheral region has small P_F
- RPA correction
  To take into account the correlations of nucleons
  in the medium. (This correction depends on the treatment
  of the initial state ~ model dependent)



J. Nieves et al.
Phys. Rev. C, 70:055503, 2004.

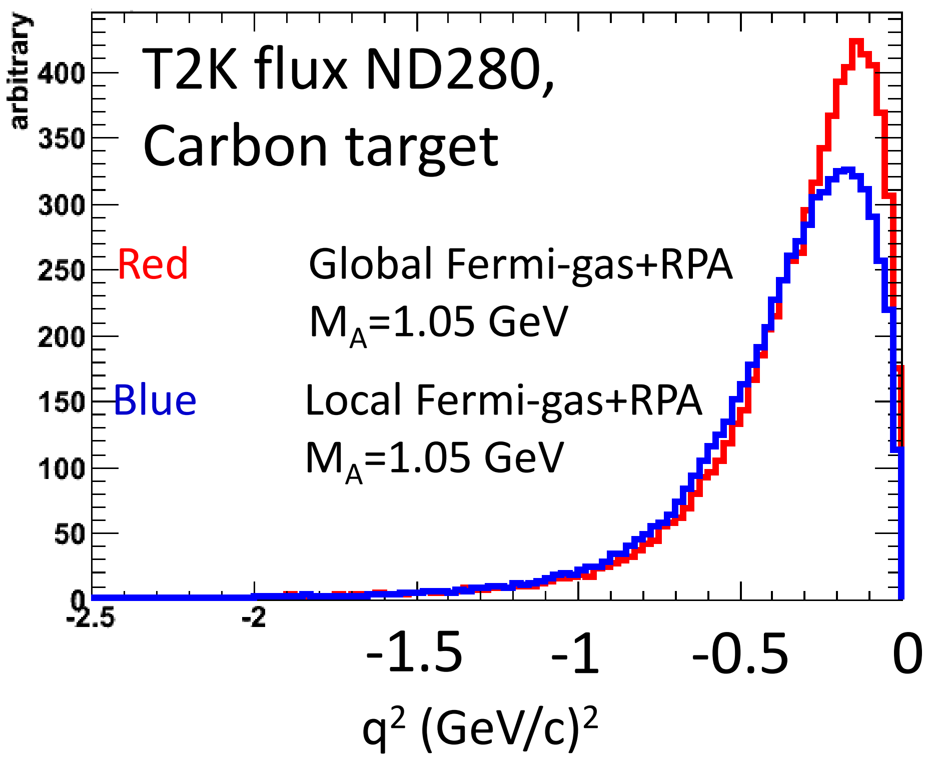
GENIE, Neut and NuWro
based on J. Nieves at al.

GIBUU
local Fermi-gas model
with density and momentum dependent
nuclear mean field correction.

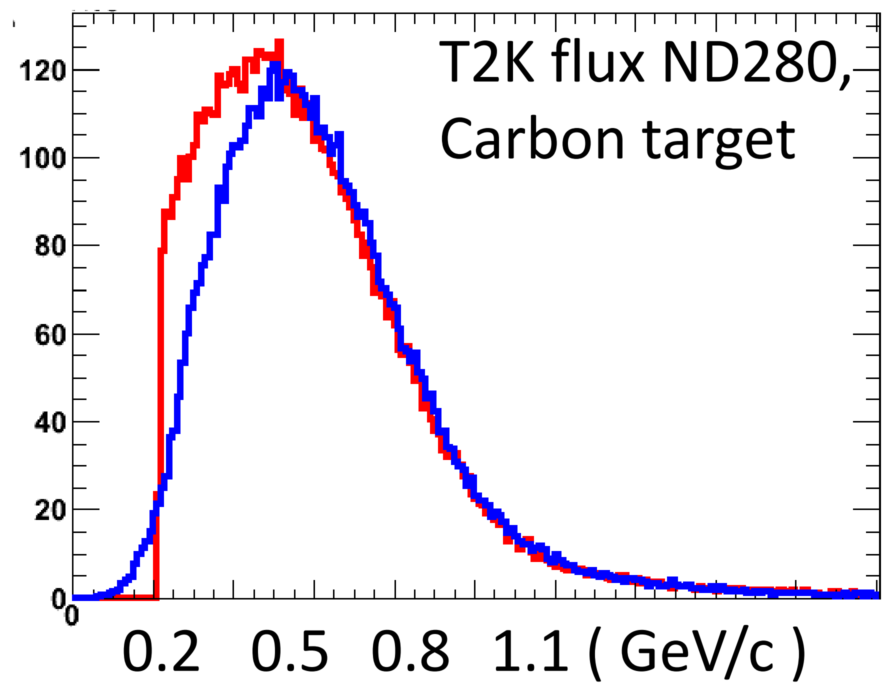
Charged current quasi-elastic scattering

Comparison between simple Fermi-gas and
Local Fermi gas with RPA correction (Neut)
(model by J. Nieves et al., Implemented by B. Bourguille and F. Sanchez)

q^2 distribution



Proton momentum (*before FSI*)



Small q^2 region is highly suppressed and
nucleon momentum distribution below 500MeV/c is different.

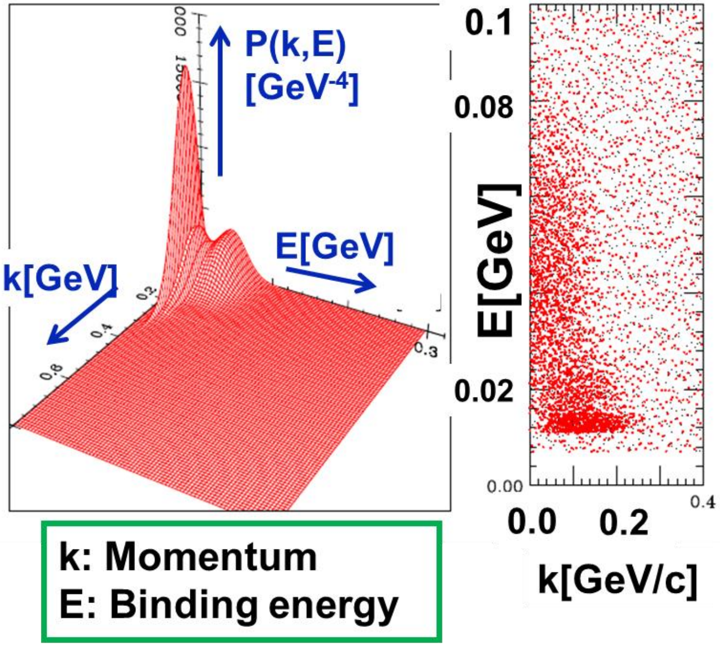
Charged current quasi-elastic scattering

Recent models and implementations

Spectral function

GENIE, Neut and NuWro uses the one by Benhar et al.

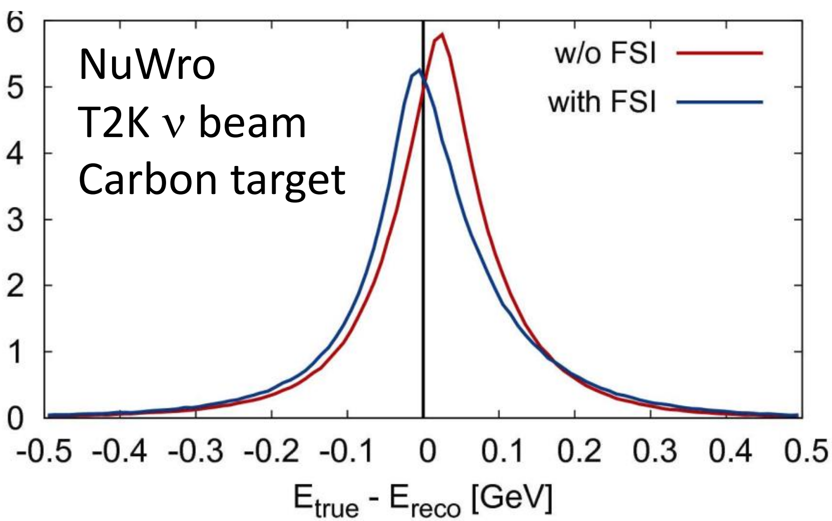
GIBUU uses momentum-dependent potential together the with local Fermi gas model. (PRC94 (2016), 035502)



O. Benhar et al. PRD72 (2005) 053005

Final state interaction for spectral function (NuWro)

Comparisons of true-reconstructed energy



Effects on the kinematics of the final state lepton from the interaction between the knocked out nucleon and the spectator system.

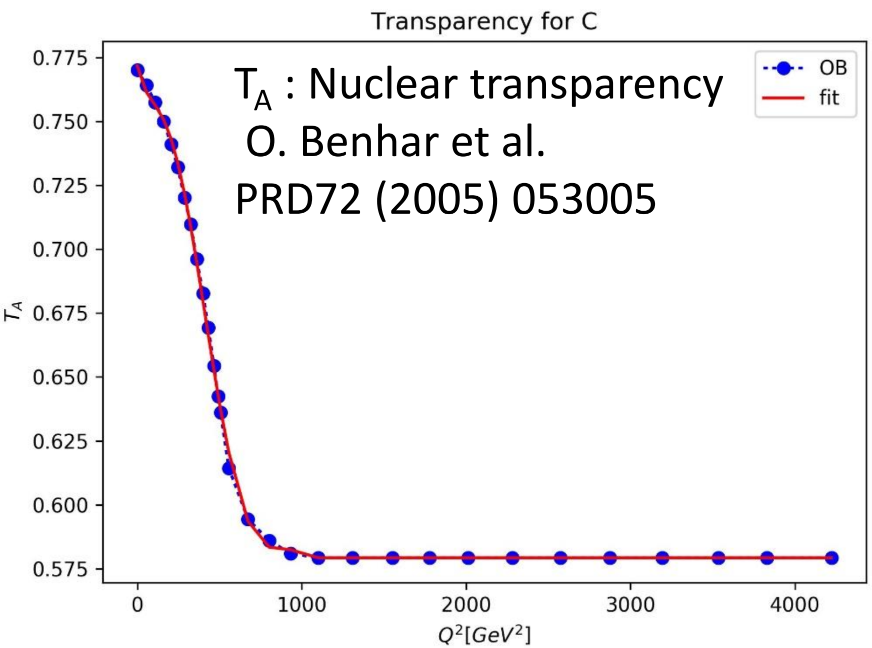
Charged current quasi-elastic scattering

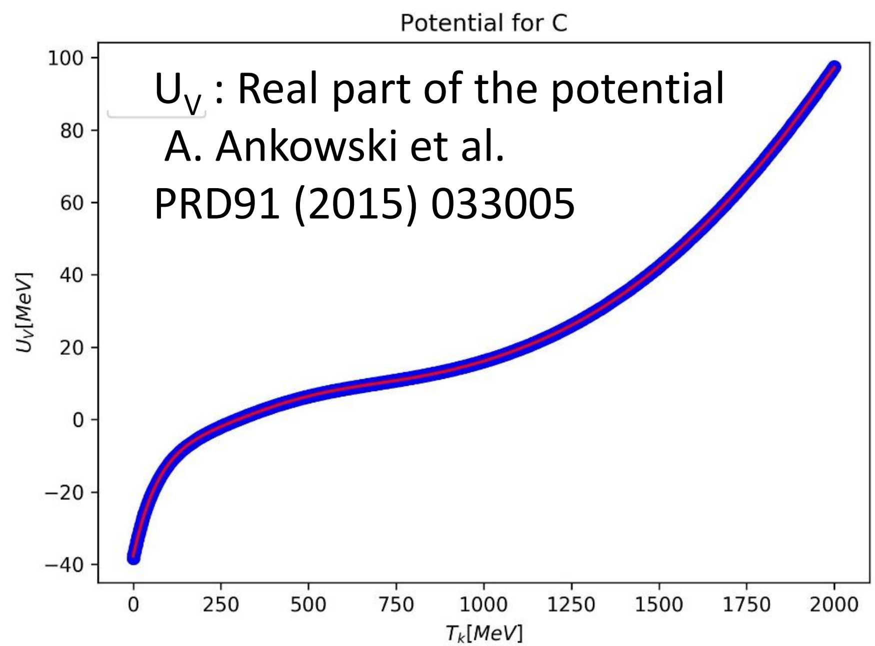
Recent models and implementations

Spectral function with FSI correction (in NuWro)

$$f_q(\omega) = \delta(\omega)\sqrt{T_a} + \left(1 - \sqrt{T_A}\right)\frac{1}{\pi}\frac{U_W}{U_W^2 + \omega^2}$$

$U = U_V + iU_W$ (potential)





Charged current quasi-elastic scattering

Alternative axial vector form factors

Historically, dipole form ($F_A(q^2) = -\frac{1.276}{\left(1-(q^2 / M_A^2\right)^2}$) was used.

However, vector form factors are known to be deviated from dipole form.

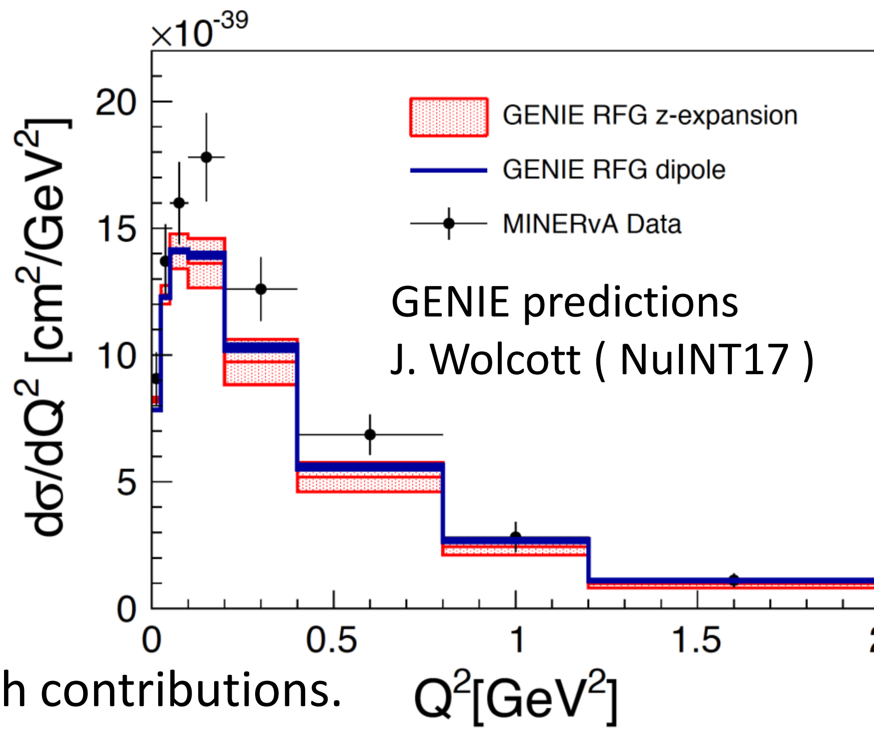
Z-expansion form factor

$$F_A(q^2) = \Sigma a_k z(q^2)^k$$

a_k : Fit the D_2 data

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

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



Parameters are extracted from deuterium experiments to minimize 2p2h contributions.

(Z-expansion form factor is available in GENIE and Neut)

Charged current quasi-elastic scattering

Alternative axial vector form factors

2-component and 3-component models (P. Stowell for Neut)

2-component model : C. Adamuscin et al., PRC 78 035201(2008)

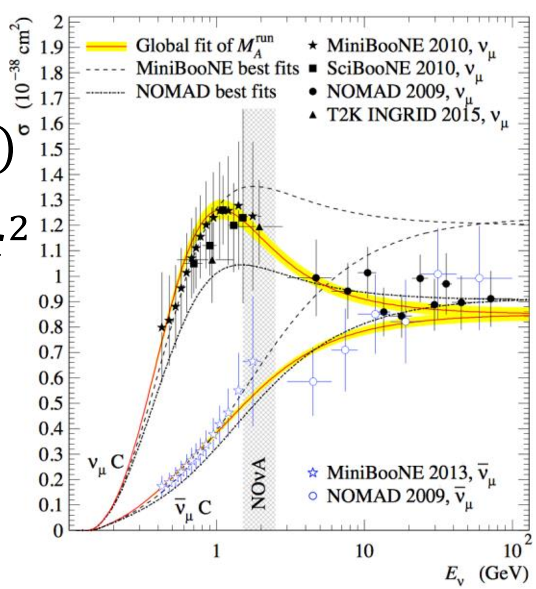
$$F_A(Q^2) = F_A(0)\left(\left[\frac{1}{1+\gamma Q^2}\left(1-\alpha+\alpha\frac{m_A^2}{(m_A^2+Q^2)}\right)\right]+\left[\theta Q^2 e^{\theta-\beta Q^2}\right]\right)$$

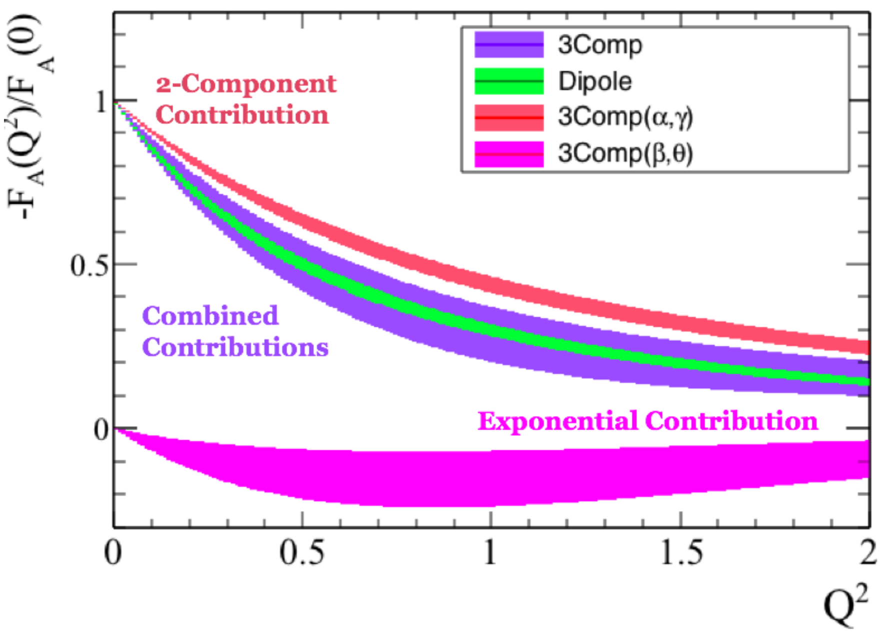
($\theta = 0$ for 2 component model)

Nuclear form factor (running M_A) in GENIE

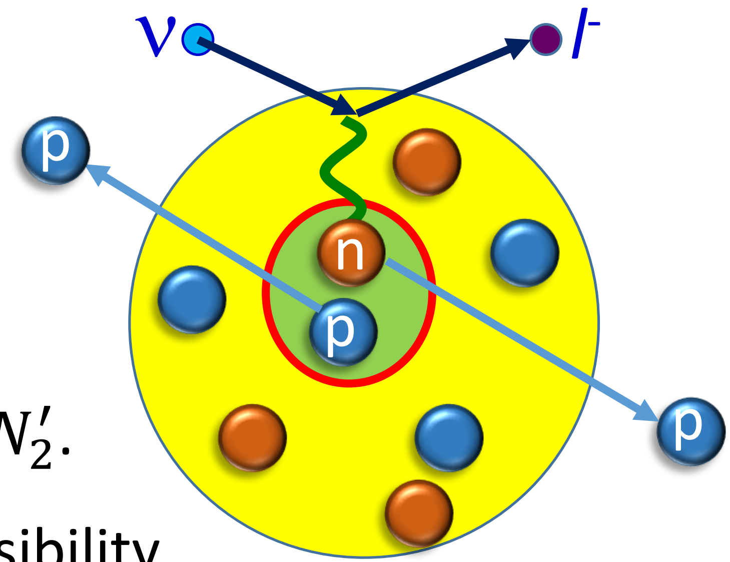
Kolupaeva et al.,
Mod.Phys.Lett. A31 165077 (2016) 1650077

$$M_A = M_{A0}\left(1+\frac{E_0}{E_\nu}\right)$$
$$M_0 = 1.006\ GeV/c^2$$
$$E_0 = 0.334\ GeV$$





Multi-nucleon scattering



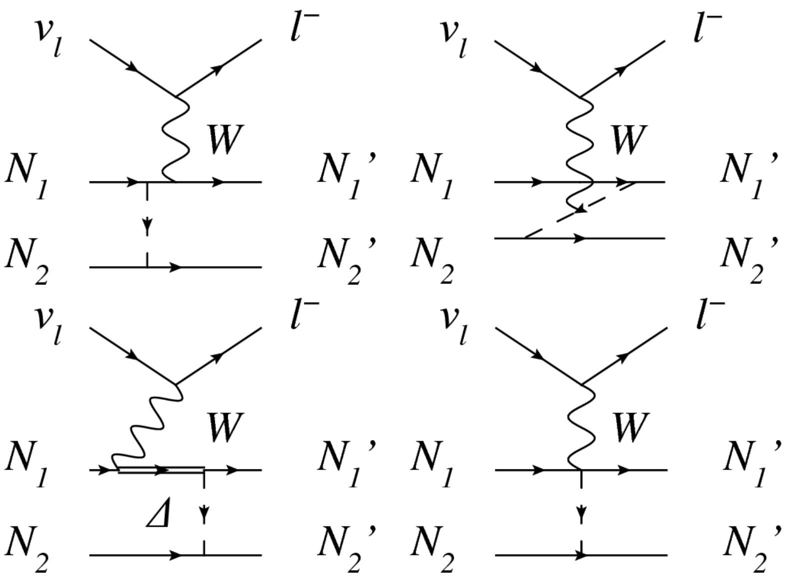
Recent nuclear target experiments
have difficulties in distinguishing

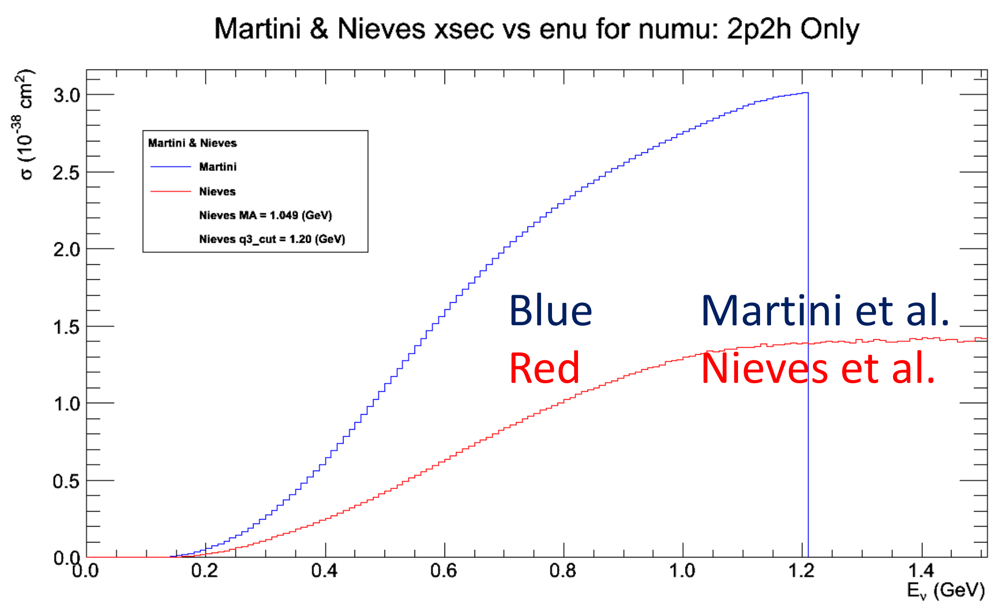
$$\nu + n \to l^- + p$$

from

$$\nu + N_1 + N_2 \to l^- + N_1' + N_2'.$$

M. Martini et al. suggested this possibility.



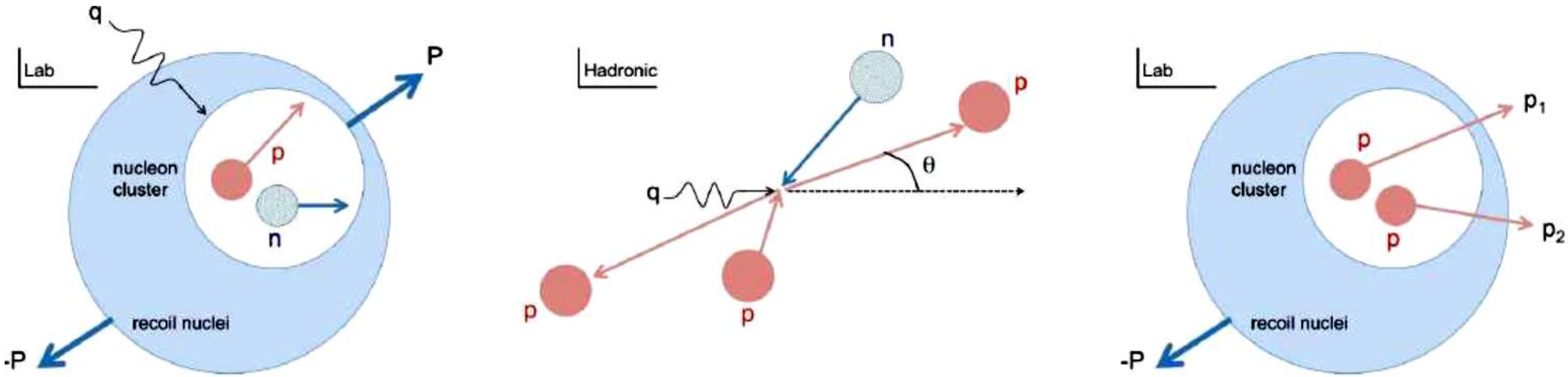


Model by Nieves at al. is implemented in GENIE, Neut and NuWro.

Multi-nucleon scattering

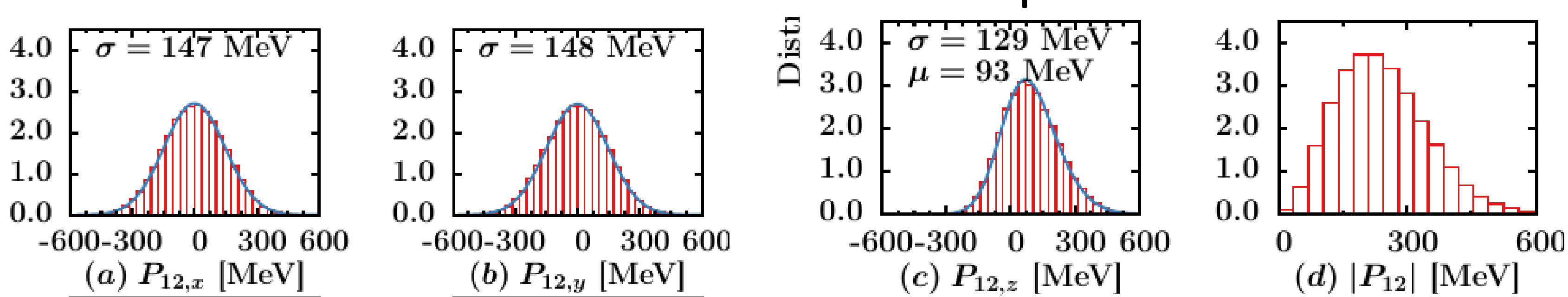
Model by Nieves at al. does not specify the nucleon kinematics.

Hadron (nucleon) kinematics prescription by J. Sobczyk (PRC86 (2012) 015504)



Detail implementations are different for each generator.

NuWro uses distribution extracted from experimental data.

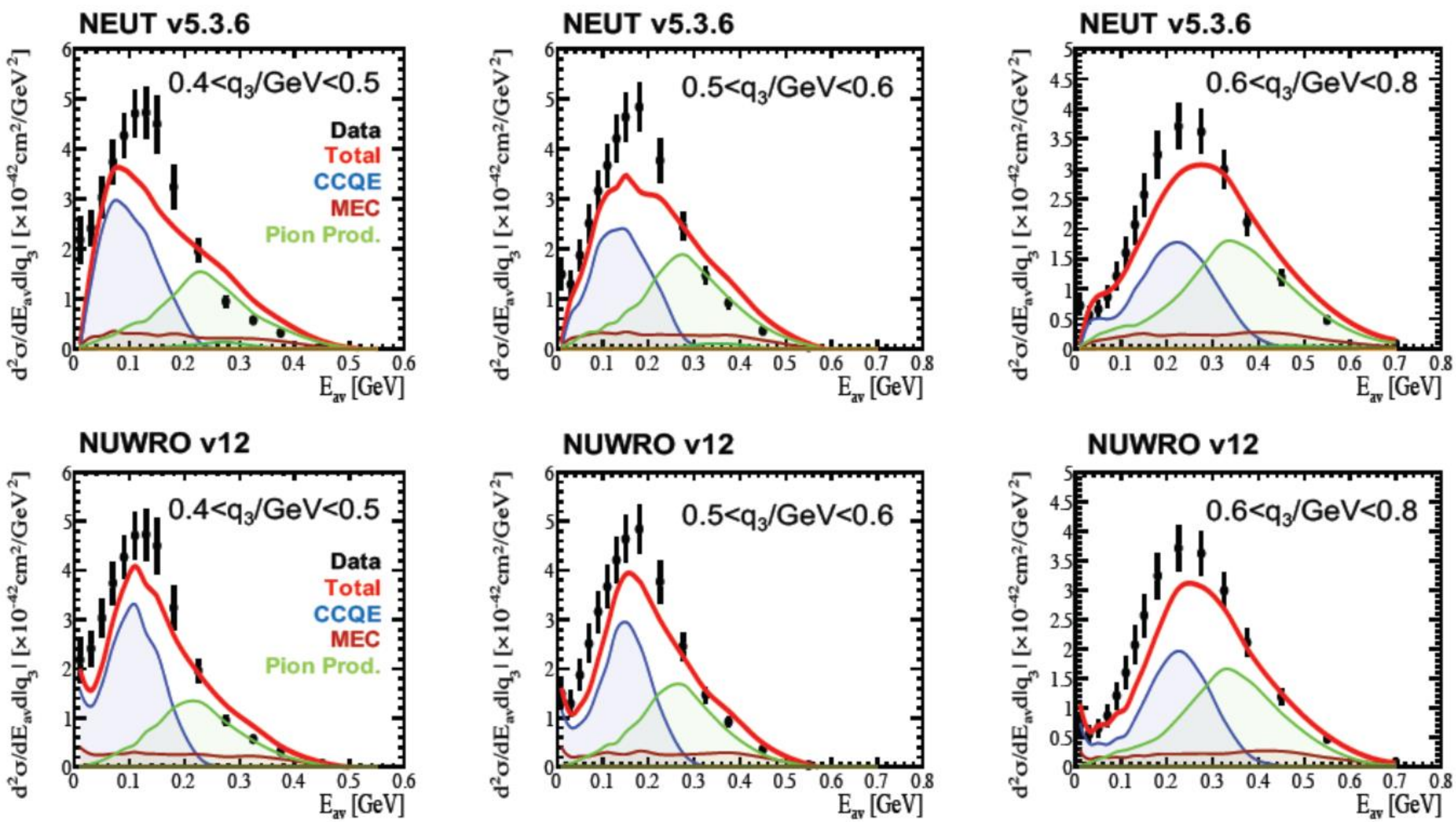


C. Colle et al., Phys.Rev. C89 (2014) 024603

Multi-nucleon scattering

Hadronic energy (available energy) is not so simple to reproduce with the given models.

(These are from MINERνA but similar discrepancies are observed in NOνA.)

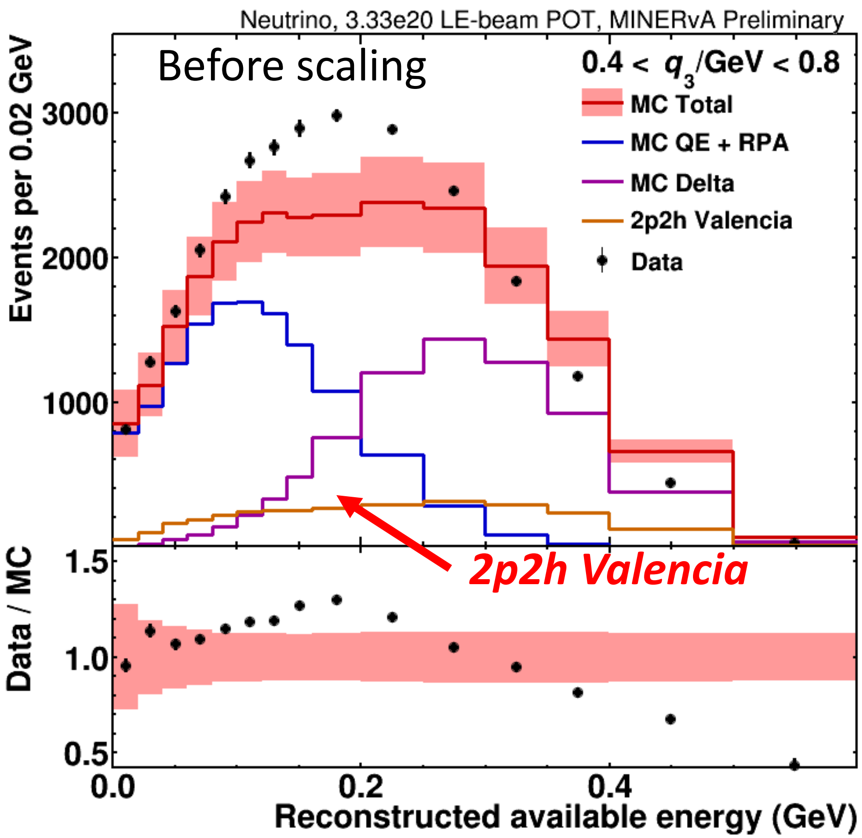


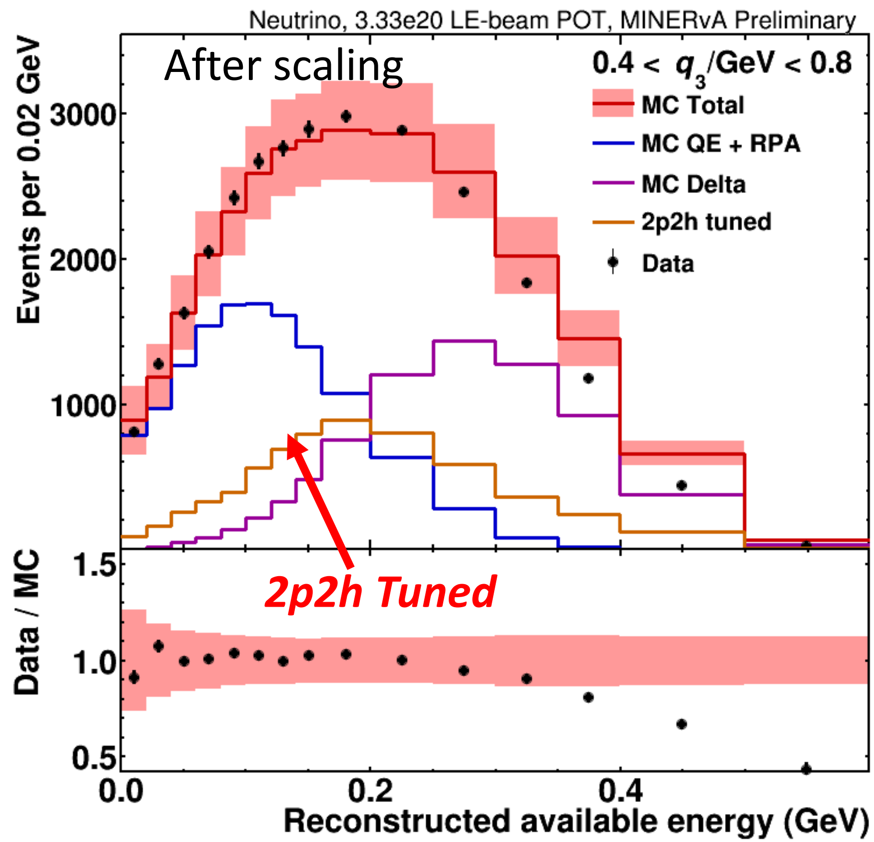
Multi-nucleon scattering

Hadronic energy (available energy) is not so simple to reproduce with the given models.

Rather large scaling (~ 50% overall, x2 in dip region) was necessary.

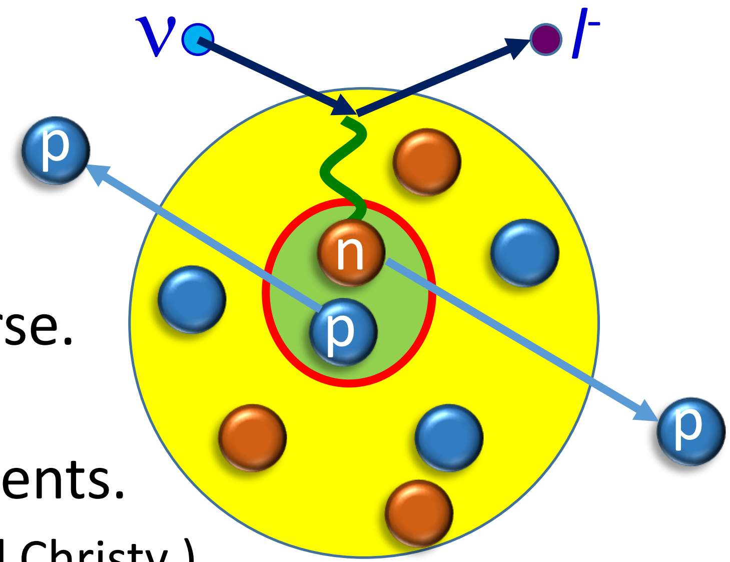
MINERνA data (R. Gran@NuINT17)





Genie 2.12.6 Schwehr, R.G., Cherdack, arXiv:1705.02932

Multi-nucleon scattering



$$\nu + N_1 + N_2 \to l^- + N_1' + N_2'.$$

In GIBUU, this interaction is assumed to be purely transverse.

Structure function (W_1^e) is extracted from electron scattering experiments.

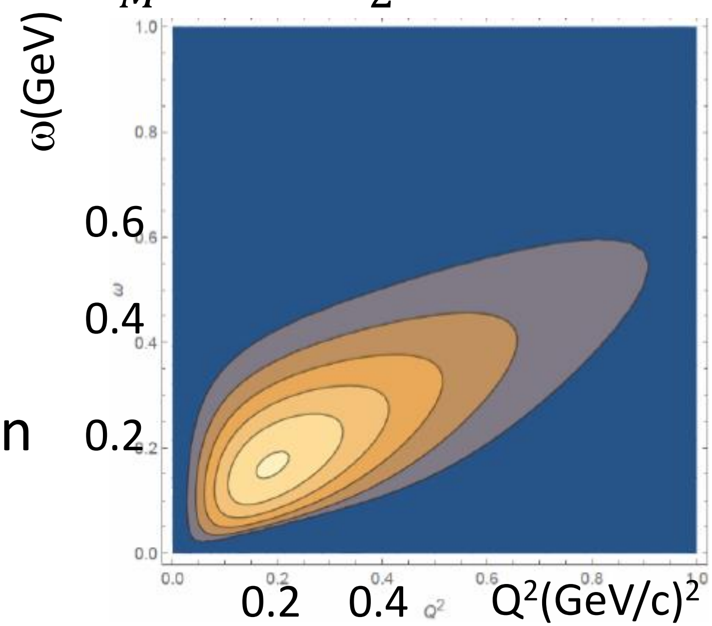
(Bosted and Christy)

$$\frac{d^2\sigma^{2p2h}}{d\Omega dE'} = \frac{G^2}{2\pi^2} E'^2 \cos^2\frac{\theta}{2}\left[2W_1^\nu\left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta}{2}\right) \mp \frac{W_3^\nu(E+E')}{M}\tan^2\frac{\theta}{2}\right]$$

$$W_1^\nu = \left[1 + \left(\frac{q}{\omega}\frac{G_A}{G_M}\right)^2\right] 2(\tau+1) W_1^e$$

τ : Isospin of the target

$$W_1^\nu = \left[G_M^2\left(\frac{\omega}{q}\right)^2 + G_A^2\right] \cdot \frac{1}{2G_A G_M} \cdot W_3^\nu$$

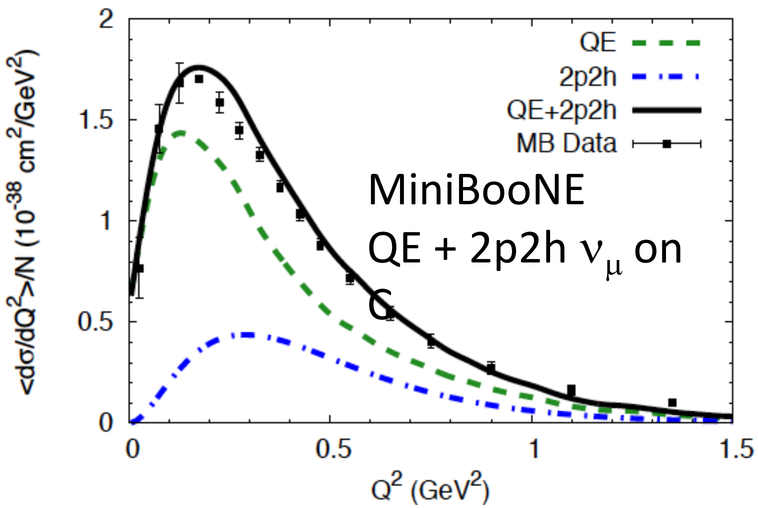


Applicable kinematic range is wide than the other models.

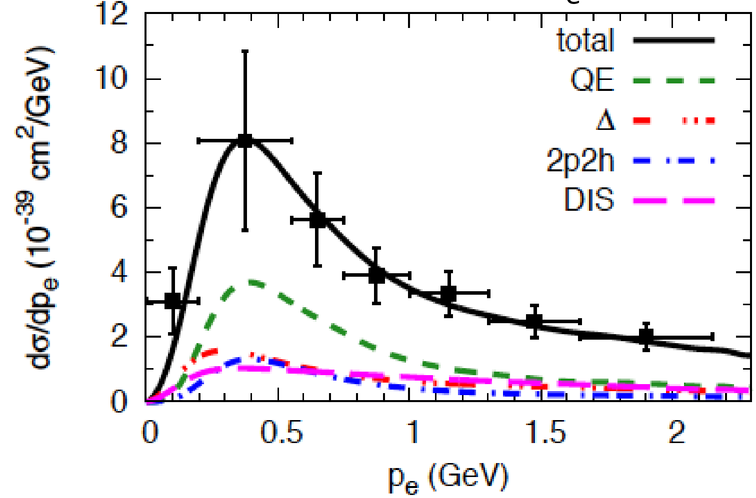
0 < W < 3.2 GeV and 0.2 < Q^2 < 5 GeV^2

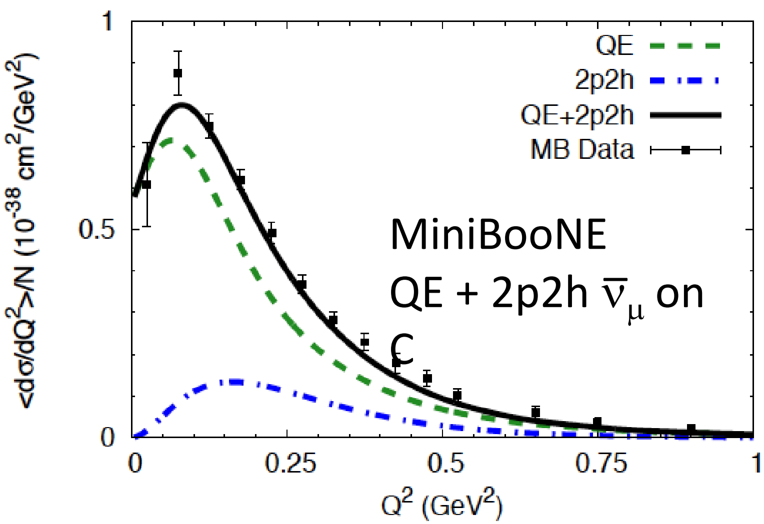
Multi-nucleon scattering

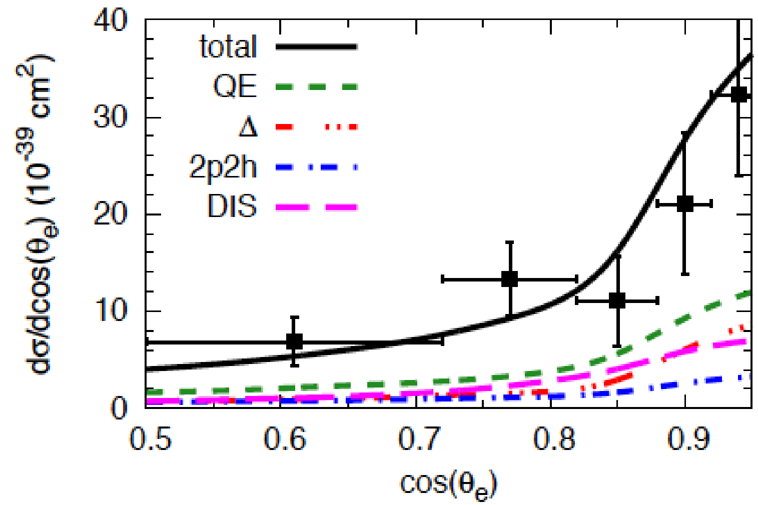
Predictions with GIBUU (Taken from PRC 94 035502)



T2K near detector ν_e on C







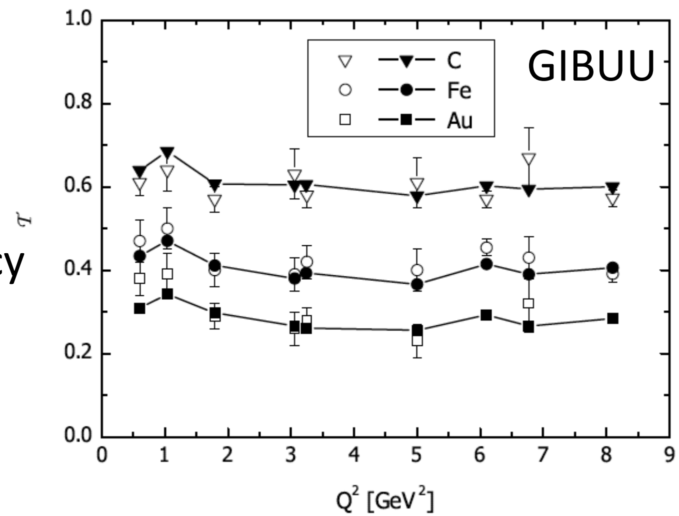
Nucleon final state interactions

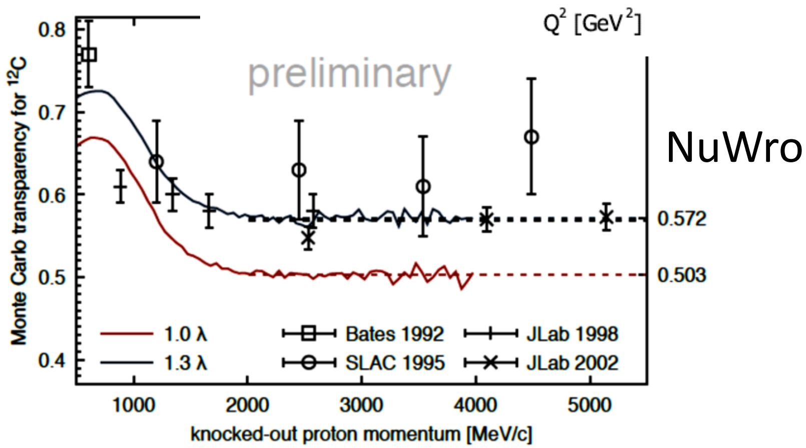
Recent and near future measurements require precise nucleon final state interactions.

Each generator started various studies on this channel.

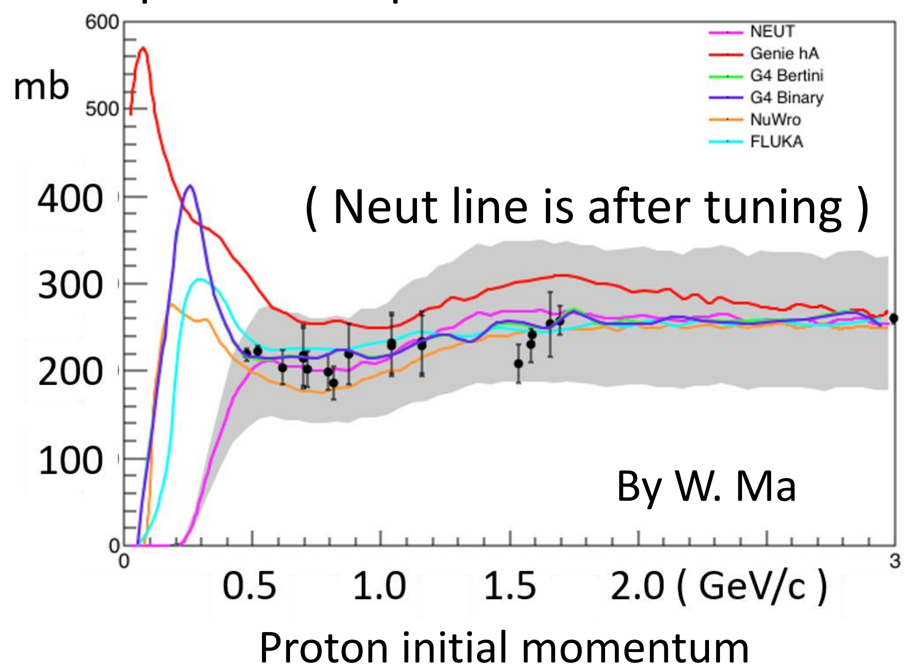
Note : GIBUU treats the nucleon interactions consistently from the beginning.

Nucleon transparency





Comparisons of p-C total cross-sections



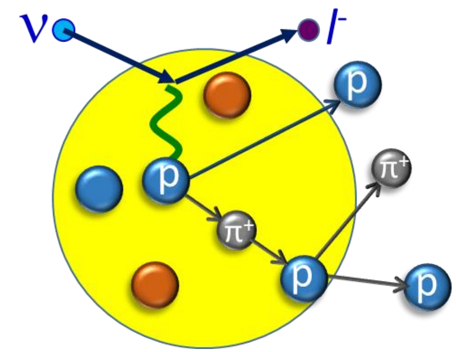
Further refinements are required.

Single pion production

Measurements of π kinematics

Various new results are coming

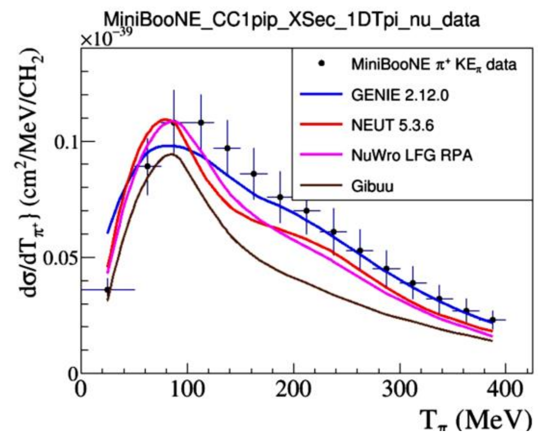
~ MINERνA, NOνA, T2K and MicroBooNE ....

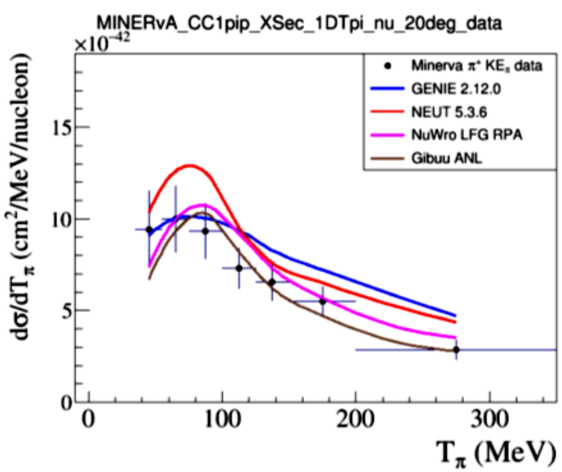


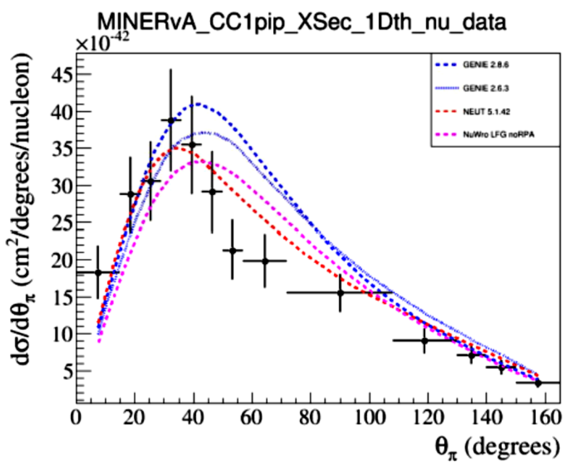
Further improvements on both ν π production

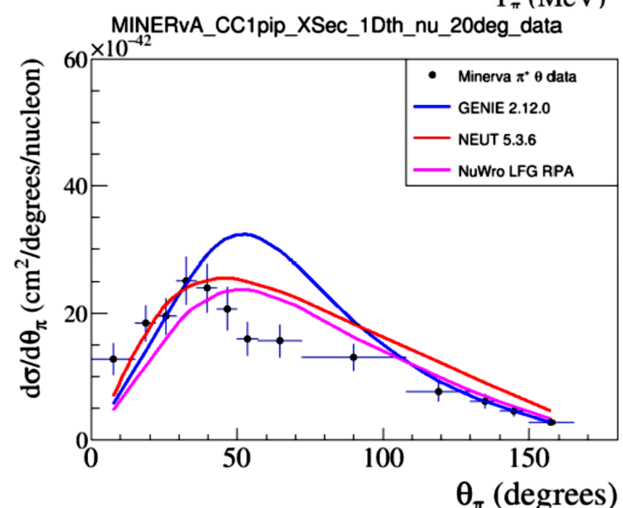
and

final state interactions of π are necessary.







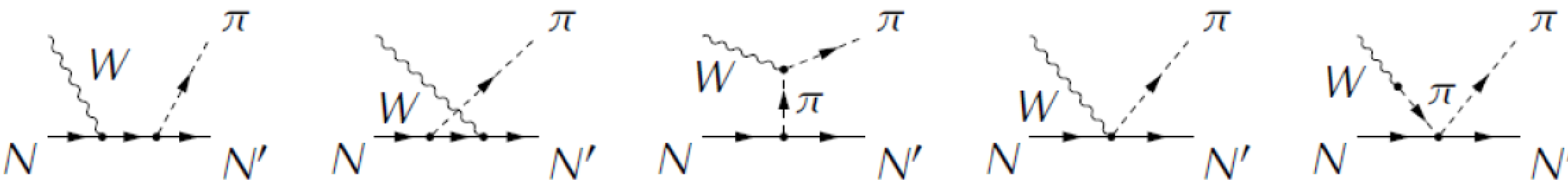


S. Dytman @ NuINT17

Single pion production ~ recent development in Neut

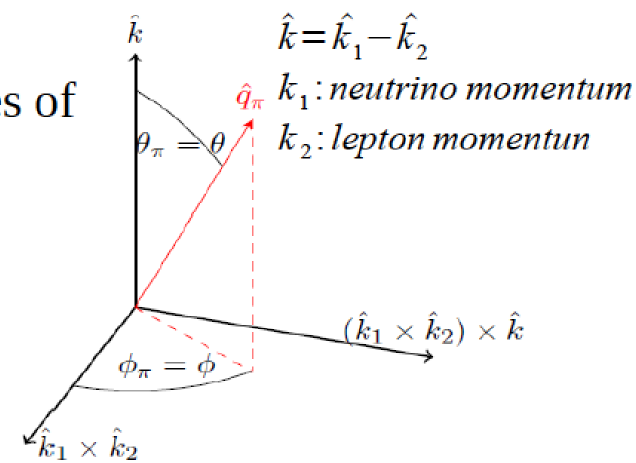
Model is implemented by M. Kabirnezhad
Adapt for Neut by C. Wret

- **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!

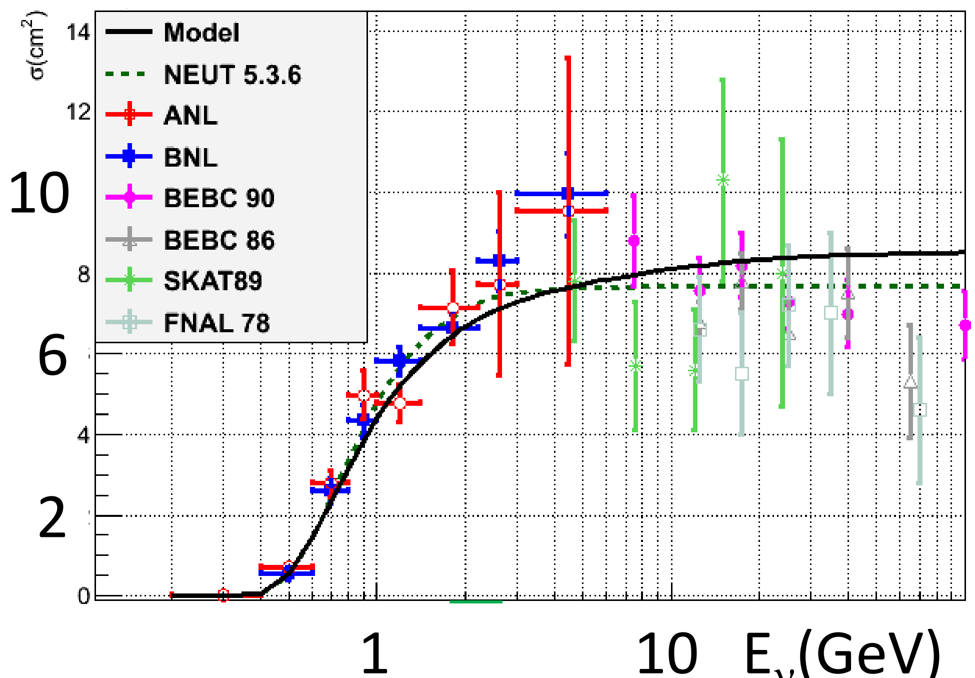
(Slide by M. Kabirnezhad)

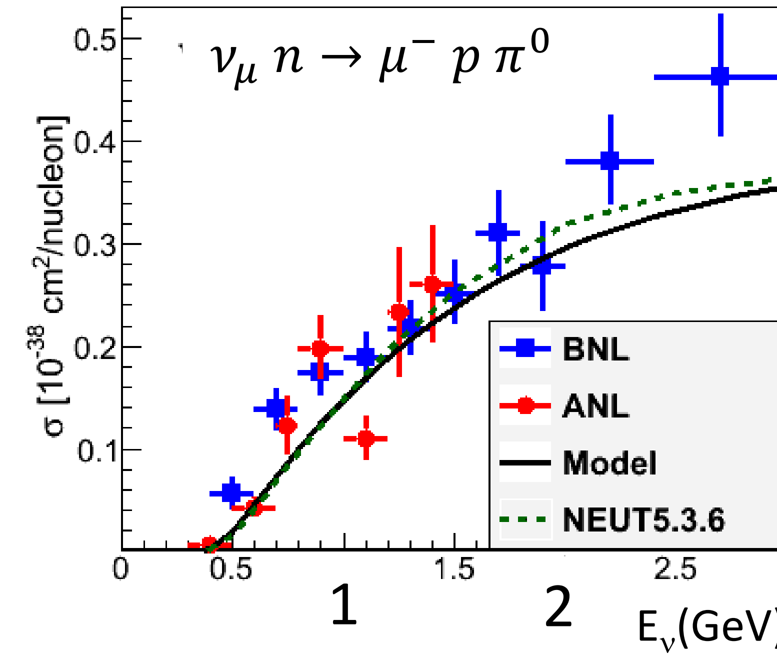
Single pion production ~ recent development in Neut

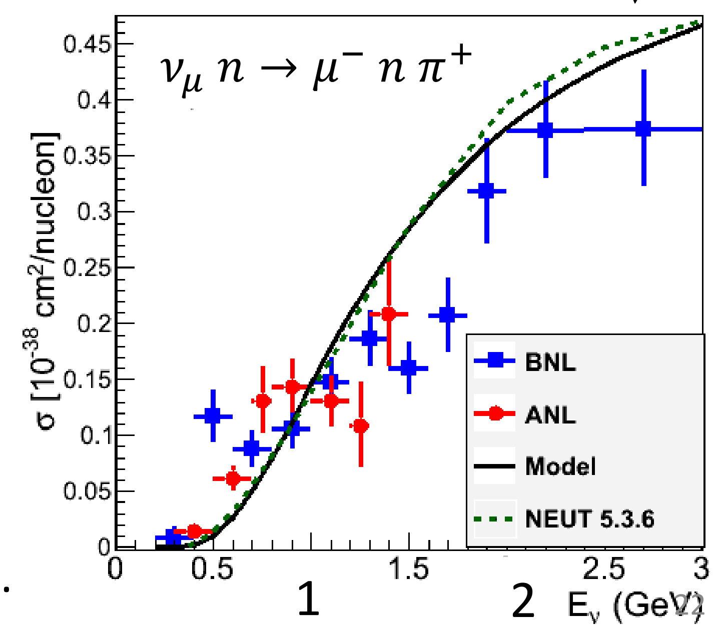
New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Interaction cross-sections

10^{-39}(cm^2) $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$ (W < 2GeV/c^2)







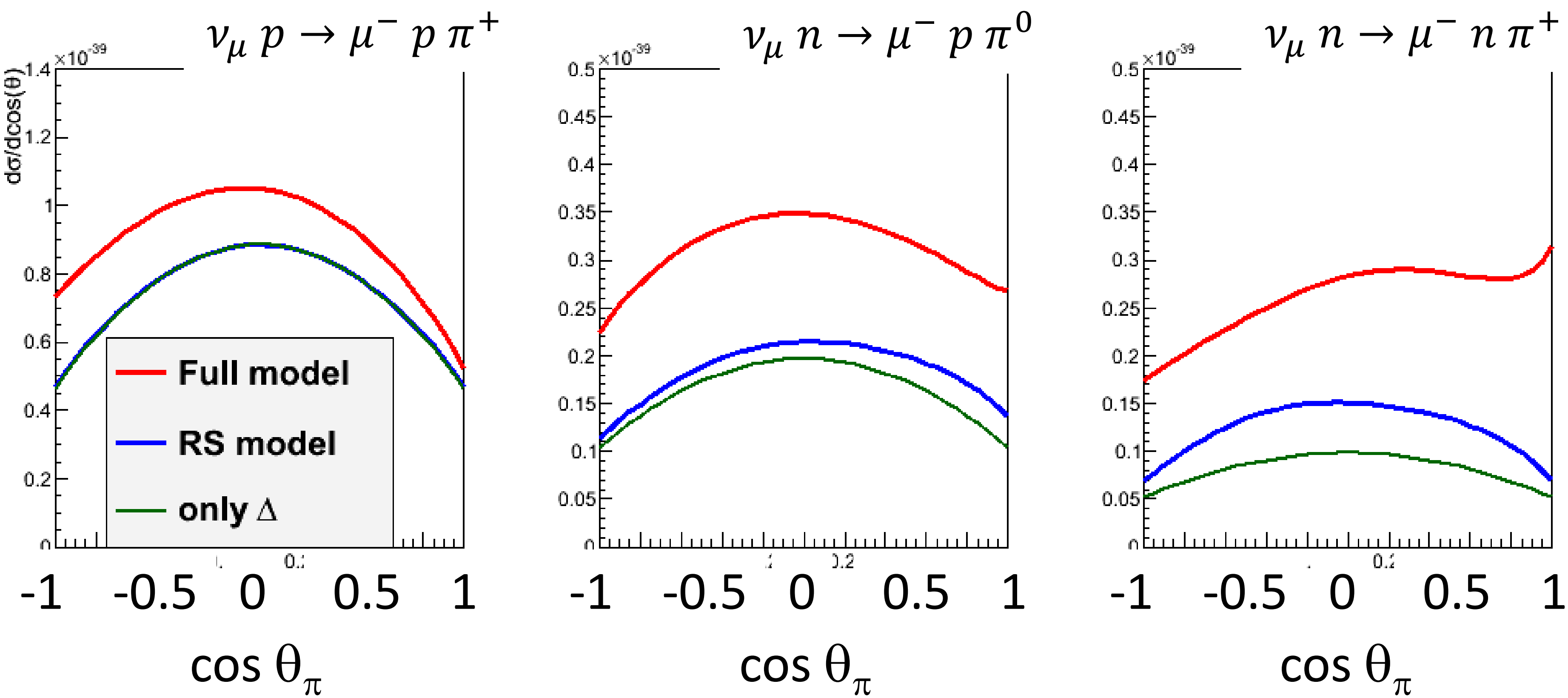
Figures by M. Kabirnezhad,
ANL & BNL data is reanalyzed by C. Wilkinson et al.

Single pion production ~ recent development in Neut

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

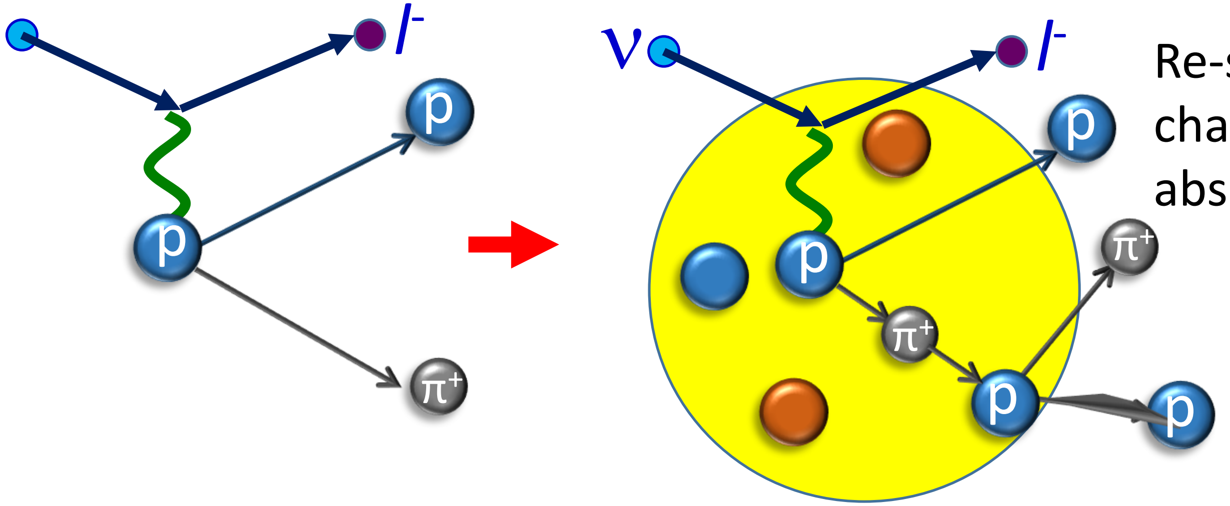
Angular distribution of π in the Adler frame

T2K ND280 neutrino flux



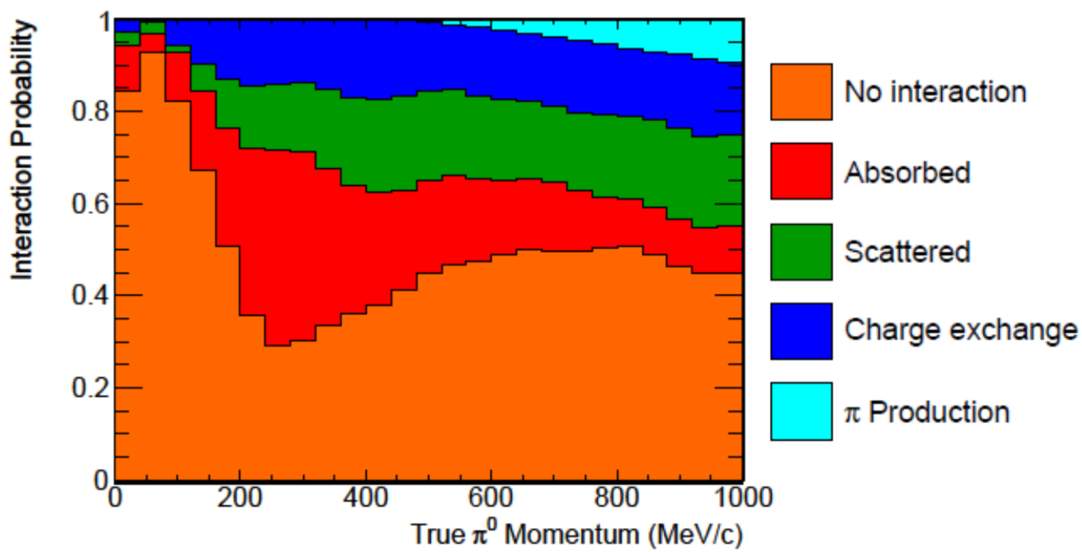
Pion interactions in nucleus

Interaction probability of π from O(1GeV) ν interactions is so large and easily scattered or absorbed in nucleus.



Re-scattering, charge exchange, absorption etc..

Interaction probability of π^0 produced in Oxygen. (Simulation : Neut)



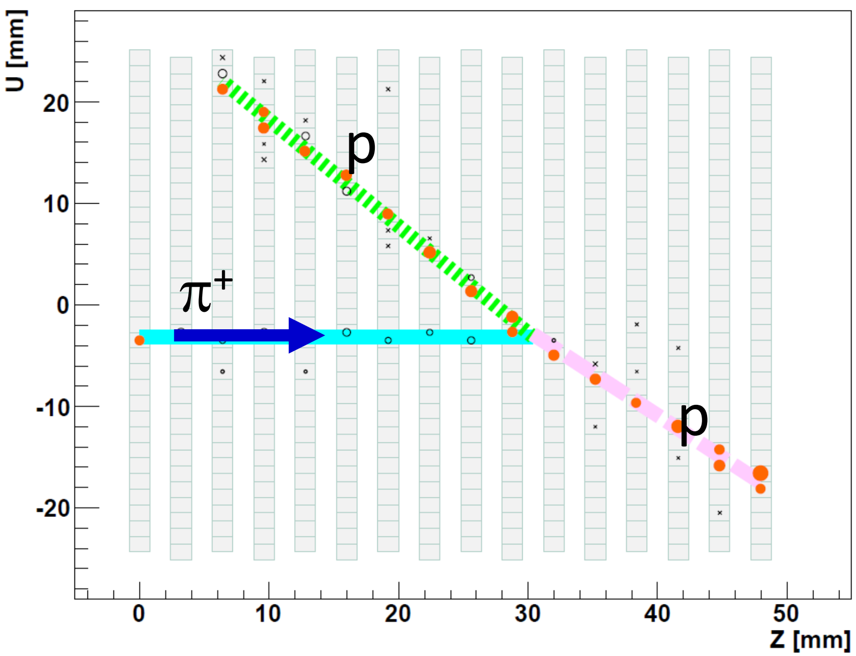
Nuclear effects ~ pion interaction in nucleus

Results from old p – A experiments have large uncertainties

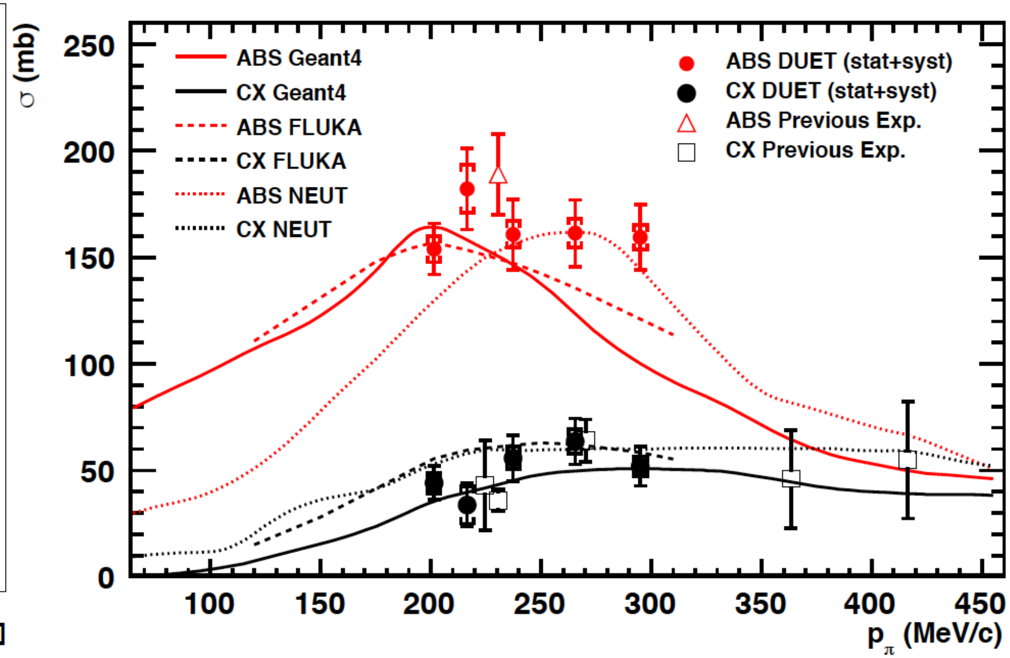
DUET experiments measured

absorption & charge-exchange cross-sections.

Absorption candidate events



Phys.Rev. C95 (2017) 045203



Almost back to back protons are observed after absorption.

(Correlated pair nucleon absorbed π^+ ?)

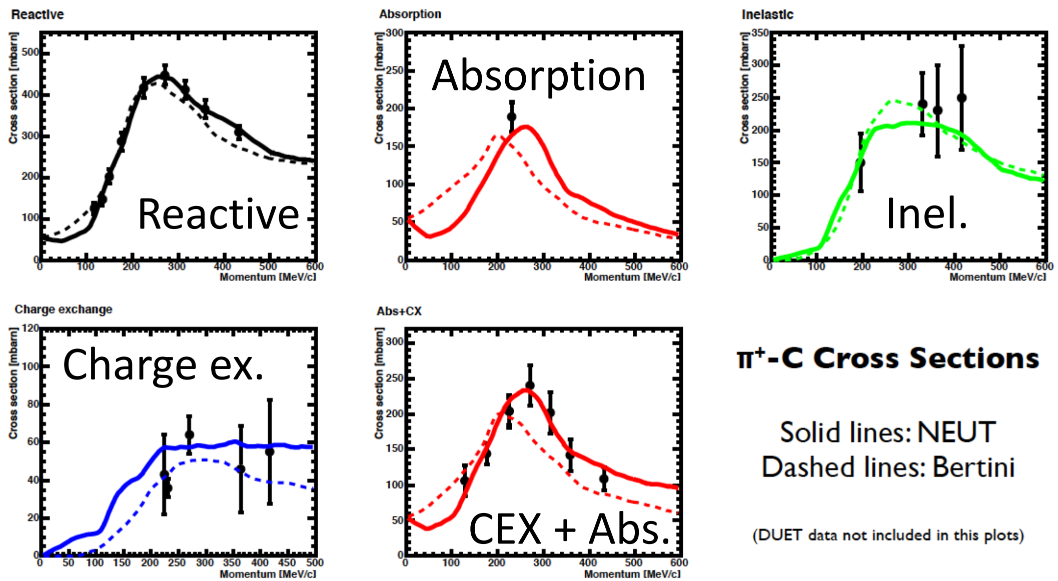
Errors got smaller.

Tune parameters with these new results.

Nuclear effects ~ pion interaction in nucleus

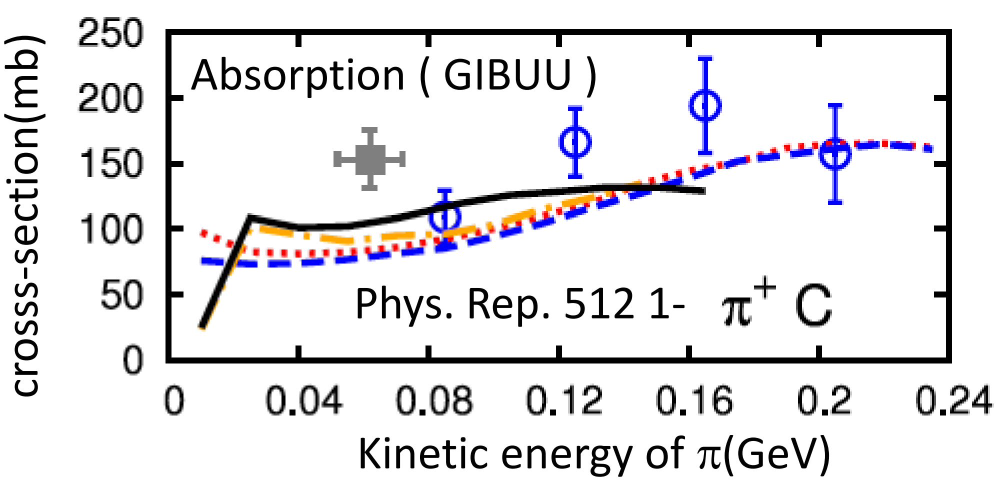
Various tuning of pion interactions are on-going.

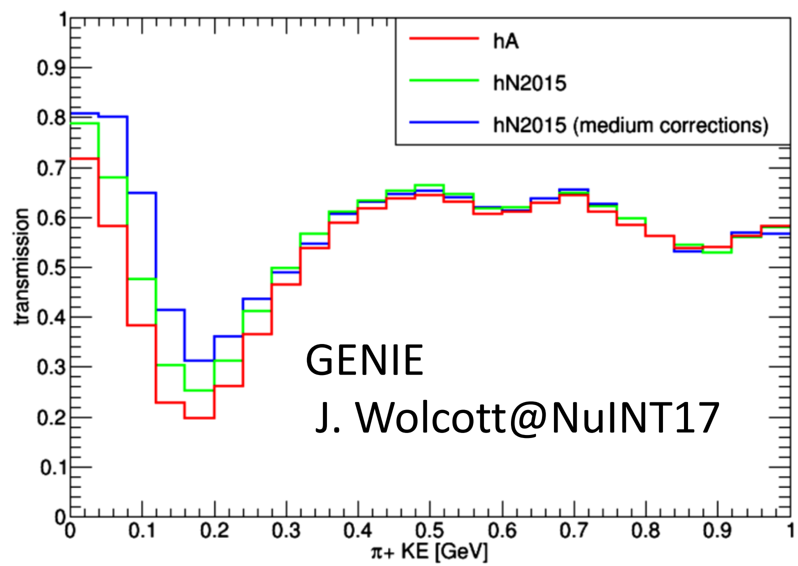
Some of the works are also used to improve detector simulations.



Neut cascade with GEANT4

E. Pinzon & M. Yu (@ NuINT17)





Summary

Many developments and improvements have been made.
Recent experiments provide high precision data sets.
Multi-nucleon interaction became important.
However, the new data sets are not so easy to reproduce.

In order to understand the CCQE and multi-nucleon scatterings,
further detailed information on hadrons are necessary.

Not only the total sum (available energy or vertex activity)
but geometrical distributions of hadron energy deposit
may be useful.

Nucleon re-scattering is getting important
to reduce the systematic uncertainties.

Sophisticated hadron transport, like one in GIBUU may be necessary.

Fin.