Possible contribution from Ninja & WAGASCI

Yoshinari Hayato (Kamioka, ICRR, Univ. of Tokyo)

CCQE-like events

Genuine CCQE + Multi-Nucleon (2p2h) interactions

1) # of observed CCQE-like events is larger than expected.

   10 ~ 20% for E_ν below or around 1 GeV.

   Super-Kamiokande atmospheric ν, (K2K: no official results), MiniBooNE, MINOS, T2K

2) Observed # of forward going lepton is much smaller

   SK, K2K, MiniBooNE, MINOS, T2K, MINERvA, NOvA, MicroBooNE

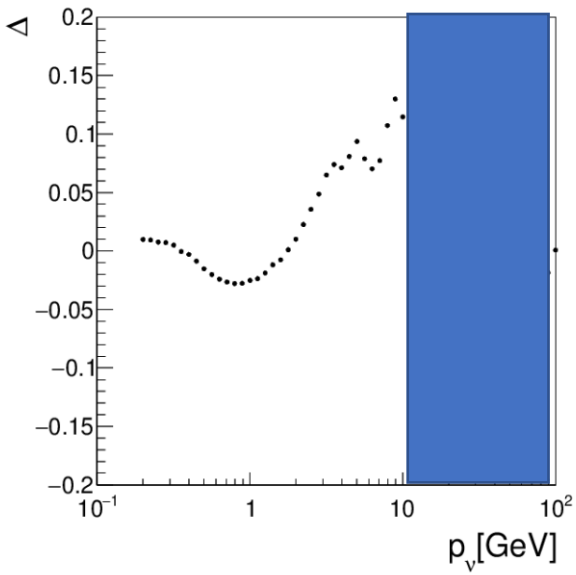
Neutrino flux prediction (hadron production)?
Inappropriate description of CCQE?
Existing of CCQE-like interactions?

Atmospheric neutrino flux

K. Sato and his colleagues use
the accelerator data to re-calculate
atmospheric neutrino flux and
try to estimate errors.

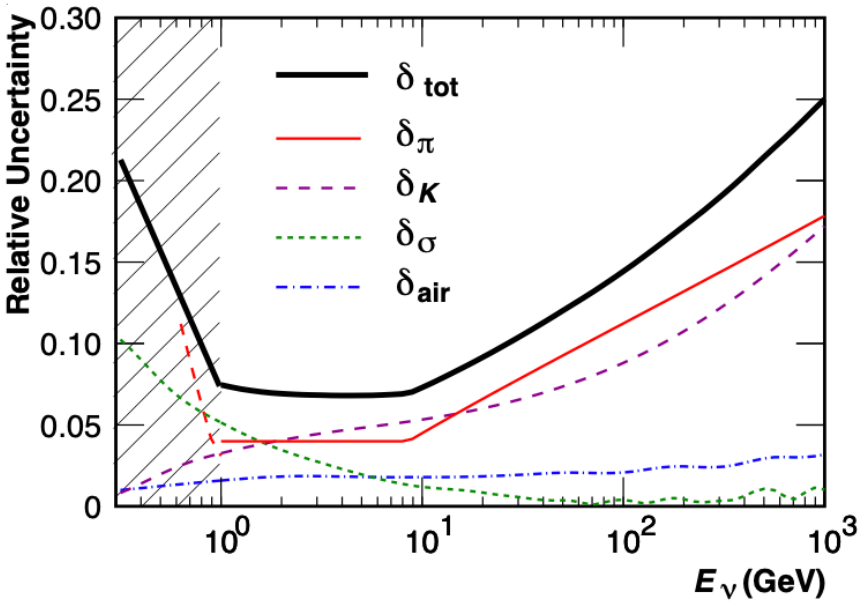
K. Sato et. al. (JPS 2020 Sep.)

[New method]/[Honda flux]

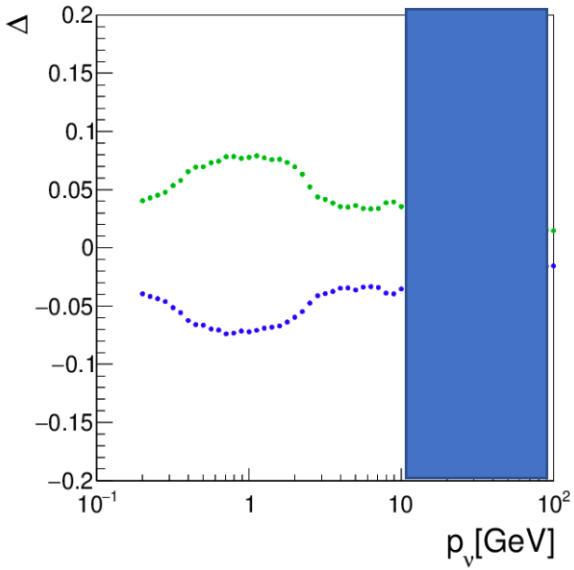


uncertainty of ATMNC flux

[M. Honda et. al, PRD75, 043006(2007)]



Error from the hadron production data



Flux correction factors from the T2K near detector fit

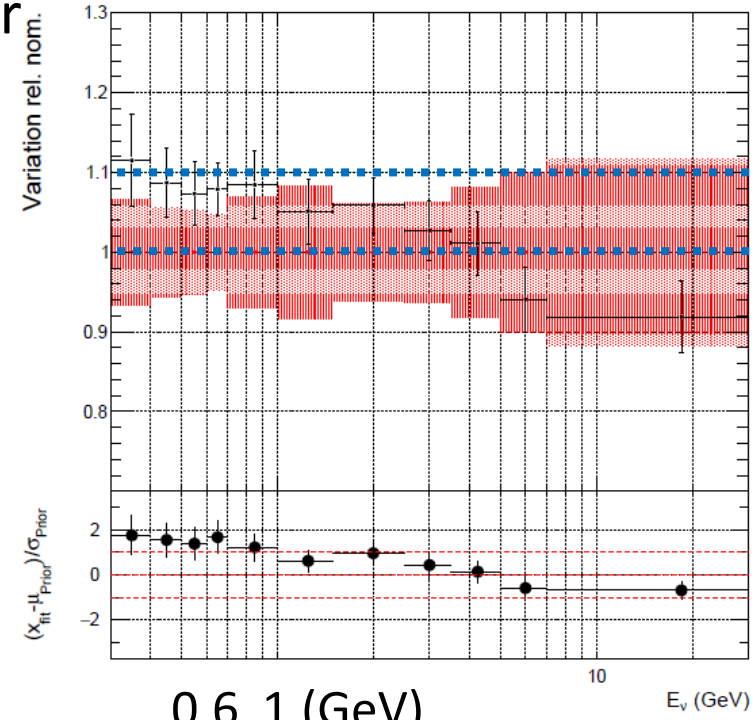
Fluxes need to be increased by 5 ~ 10% below 2GeV.

Correction factor

1.1

1.0

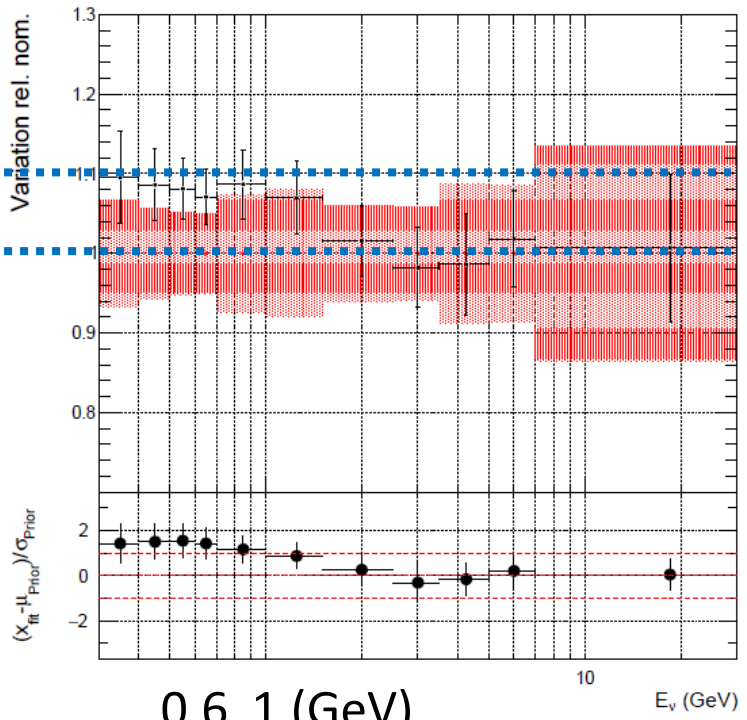
FHC ν_μ



0.6 1 (GeV)

Neutrino energy

RHC $\overline{\nu_\mu}$

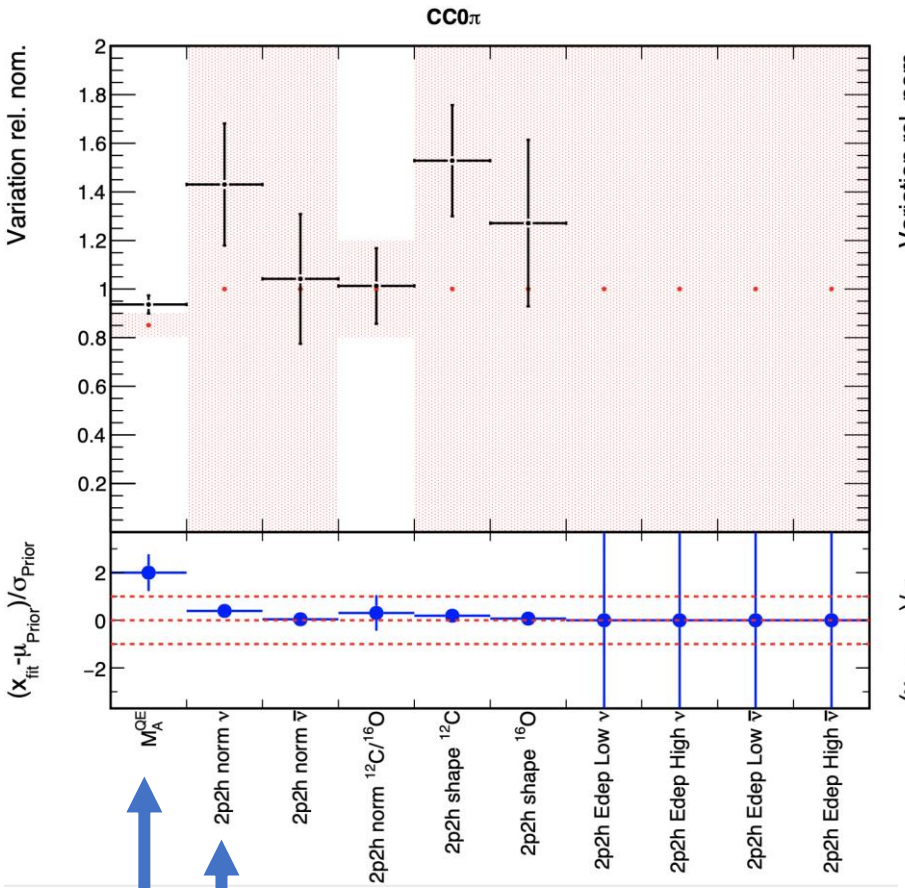


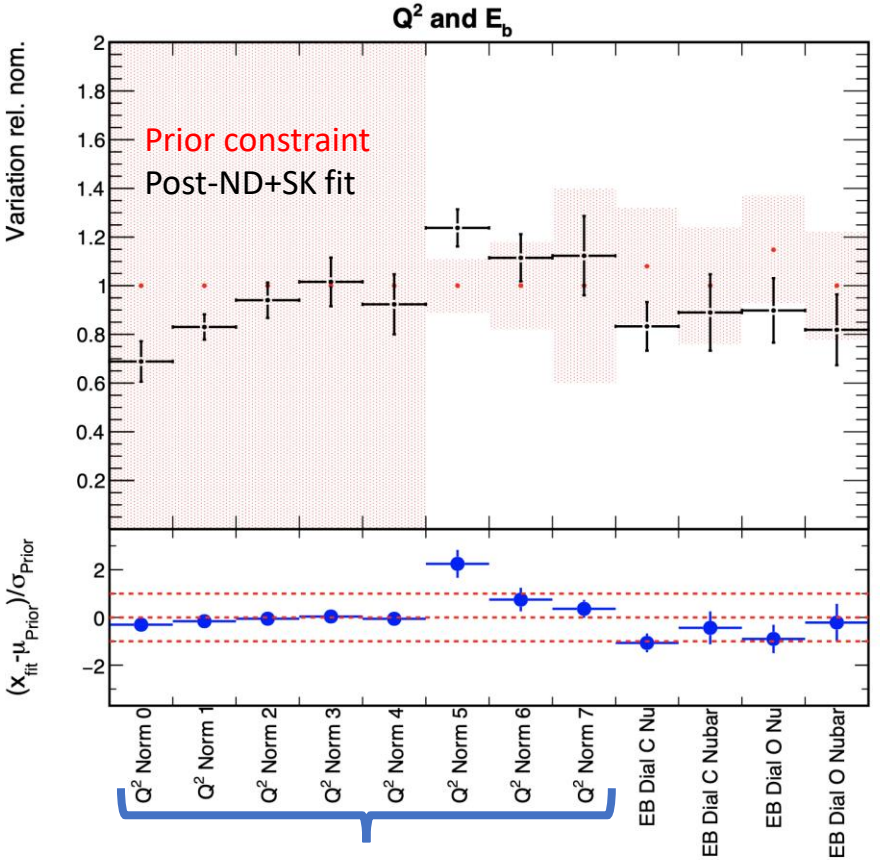
0.6 1 (GeV)

Neutrino energy

Model “correction” factors from the T2K near detector fit

Predicted σ(CCQE + MEC) is smaller than the data.





Need large Q^2 suppression

2p2h need to be increased by ~40%

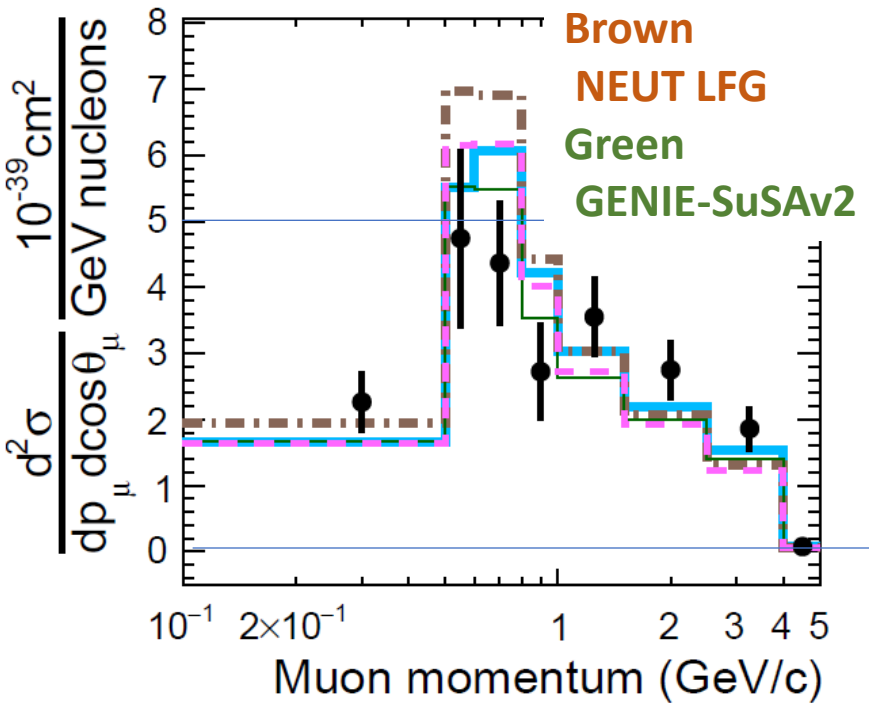
$M_A \sim 1.21$ x 0.95 GeV/c^2 (Spectral function model)

CCQE + 2p2h : Nuclear dependence (Carbon and Oxygen)

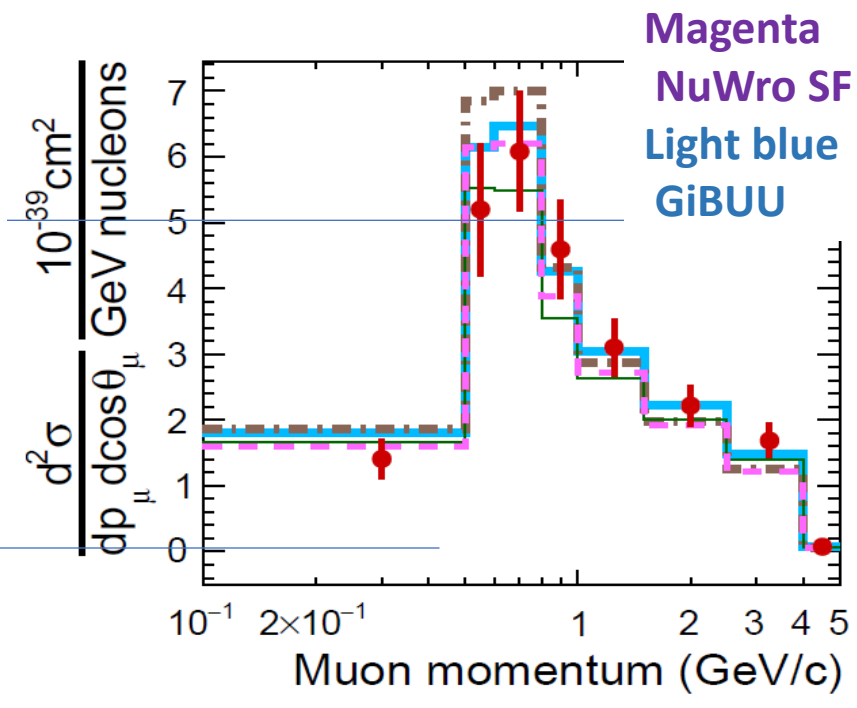
Cross-section measurement using the "T2K CC 0π sample"

Phys. Rev. D 101, 112004

Oxygen $0.93 < \cos\theta_\mu < 1$



Oxygen $0.93 < \cos\theta_\mu < 1$



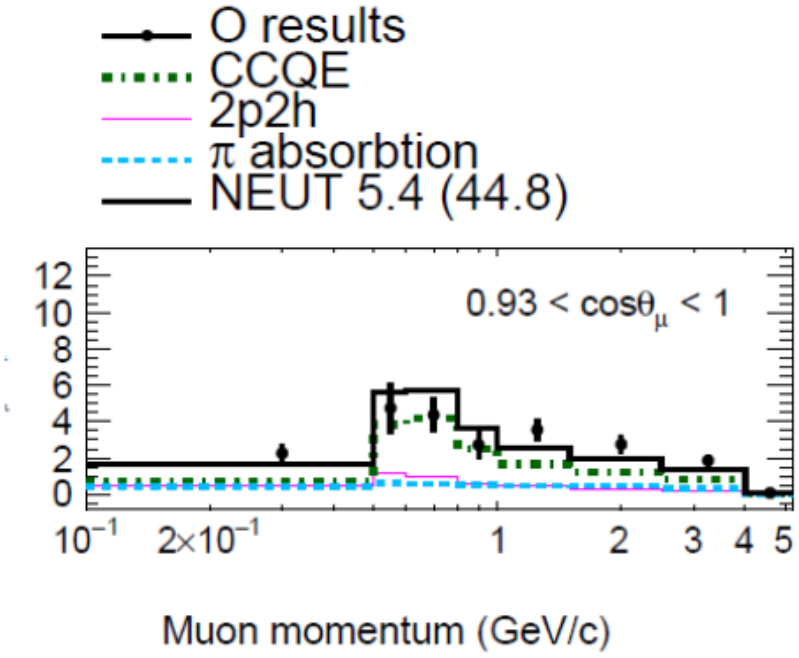
Stronger forward suppression observed in the Oxygen sample?
(Most of the models give not so significant difference.)

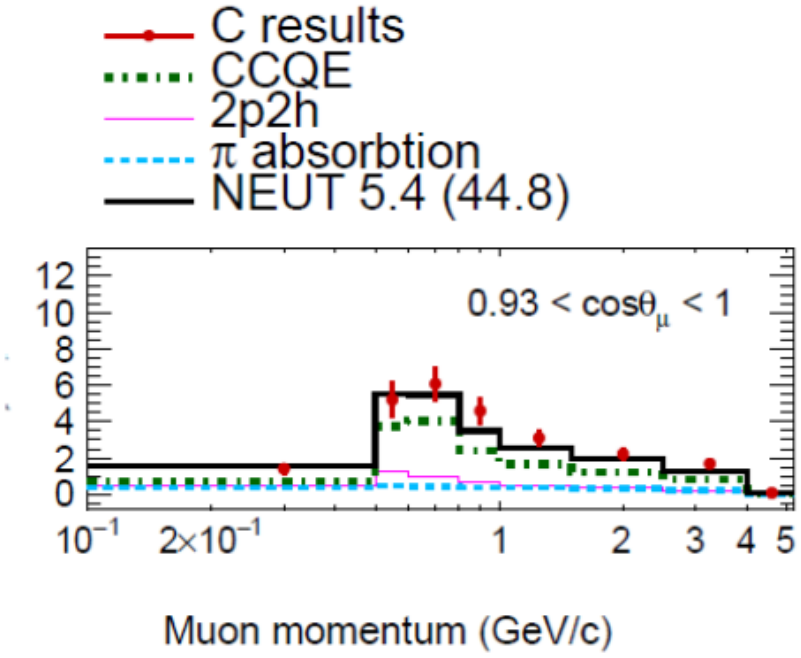
CCQE + 2p2h : Nuclear dependence (Carbon and Oxygen)

Cross-section measurement using the "T2K CC 0π sample"

Phys. Rev. D 101, 112004

According to the simulation model prediction,
contribution from 2p2h is rather small for this sample.

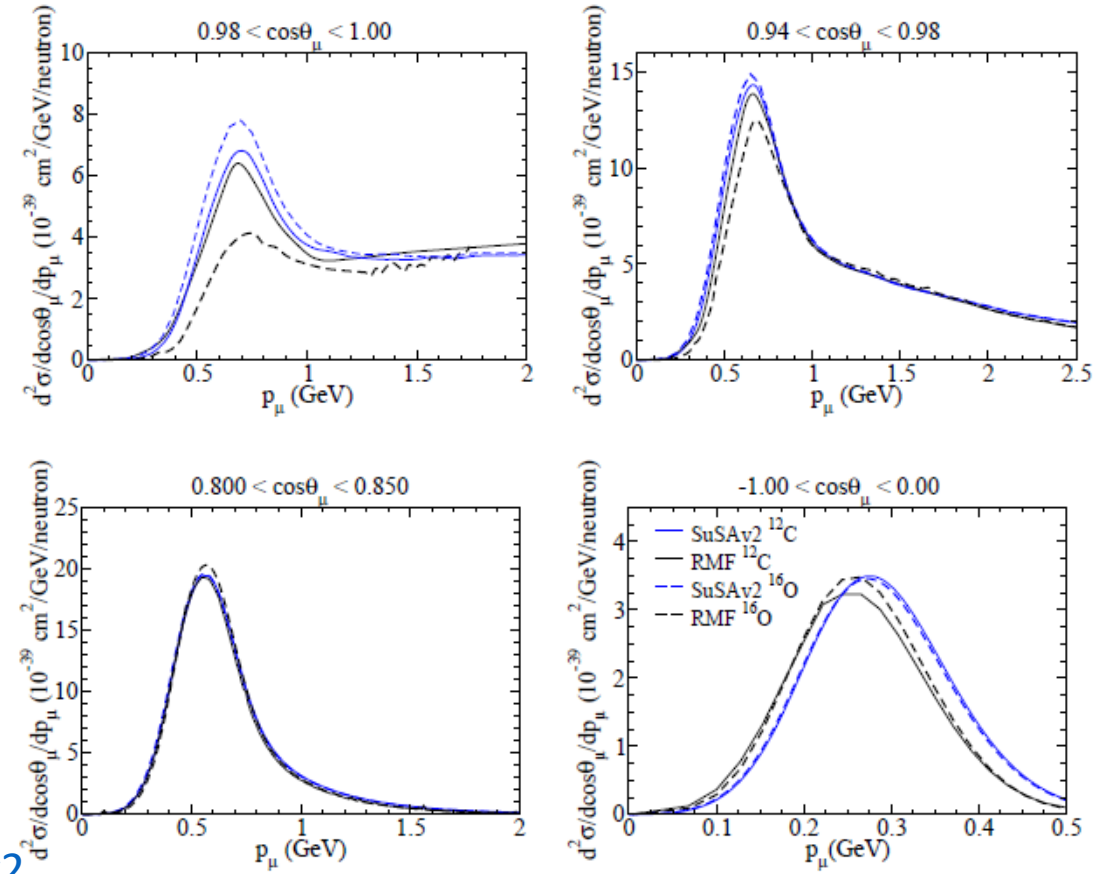




CCQE + 2p2h : difference of the nuclear dependences between two models (T2K flux, SuSAv2 and Relativistic Mean Field)

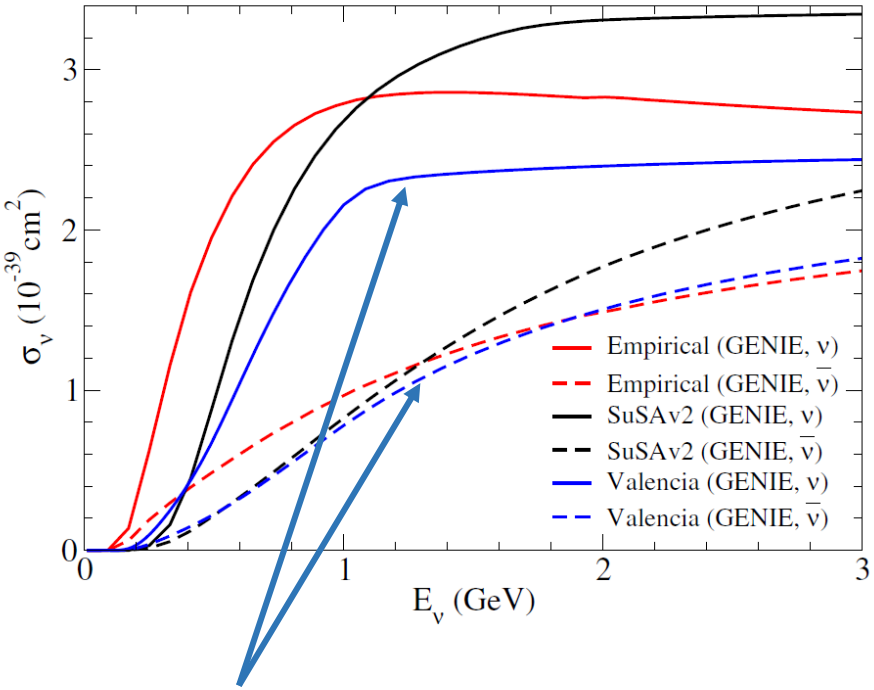
RMF shows larger difference in the very forward region, $\cos\theta > 0.98$ ($\theta < 11.5$ degree).

RMF expected to have better reproducibility in small q^2 (forward) angle region.

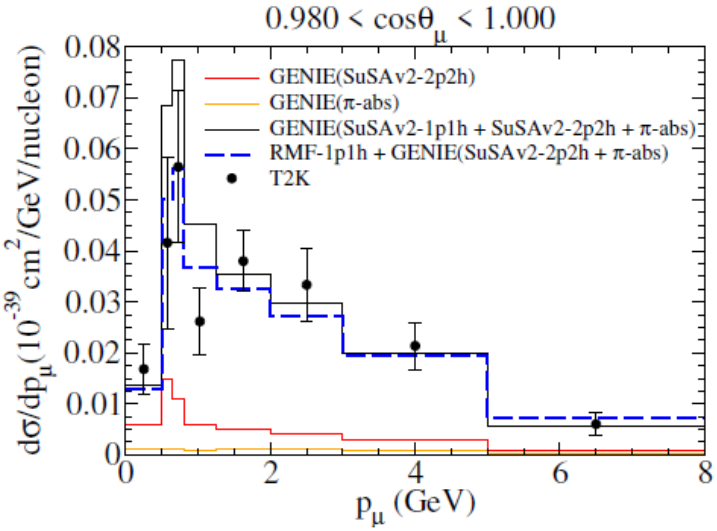


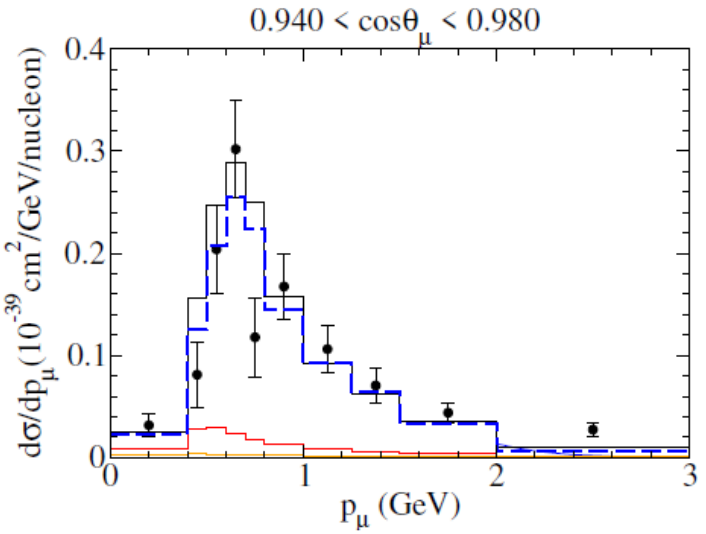
https://arxiv.org/abs/1912.10612v2

CCQE + 2p2h : Difference between models
Valencia vs SuSAv2 (using GENIE)



Valencia 2p2h(MEC) model
(This plot is generated using GENIE.
NEUT also uses the Valencia model.)





CCQE-like cross-section from MicroBooNE (Liquid Argon detector)

arXiv:2006.00108v2 [hep-ex]

1) Strong suppression in very forward region.

$$\cos\theta_\mu > 0.8$$

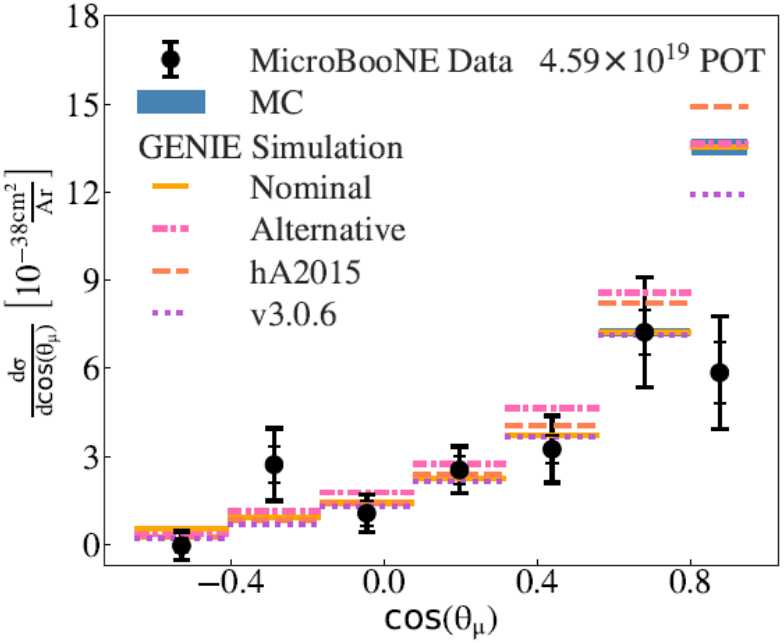
2) 100 MeV/c < p_μ

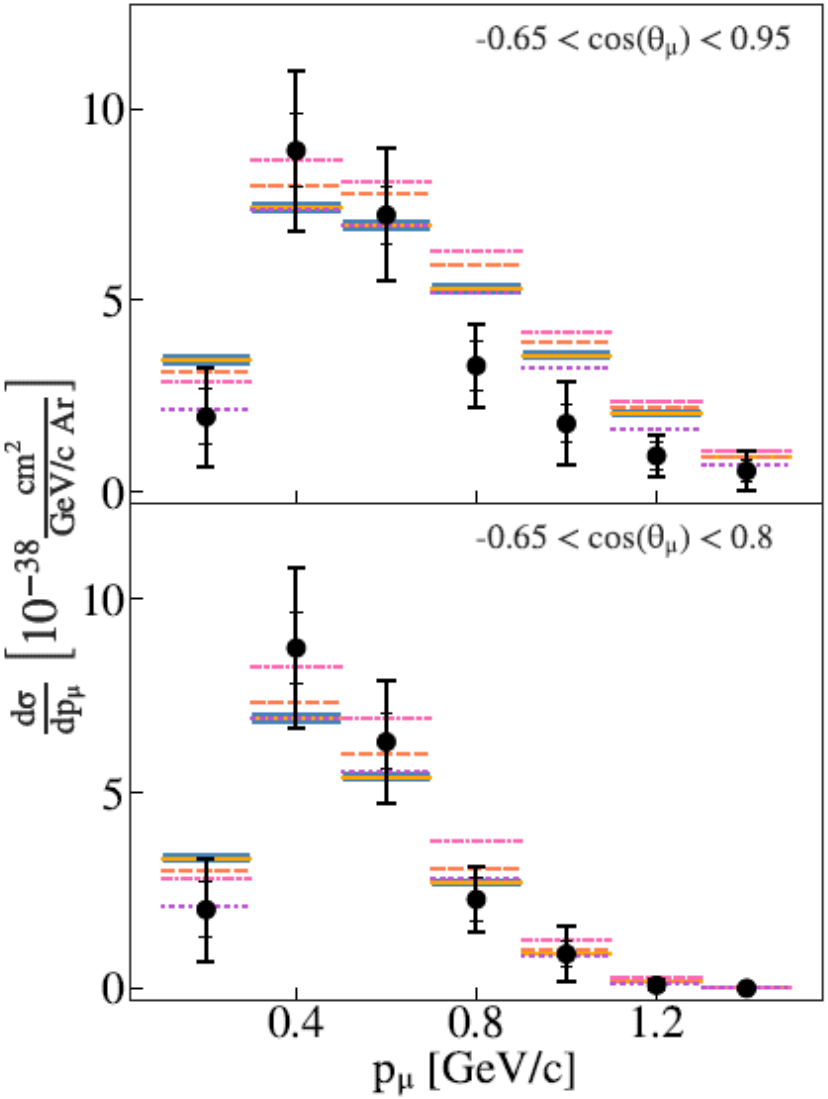
300 MeV/c < p_p < 1000 MeV/c

$-0.65 < \cos\theta_\mu < 0.95$

$0.15 < \cos\theta_p$

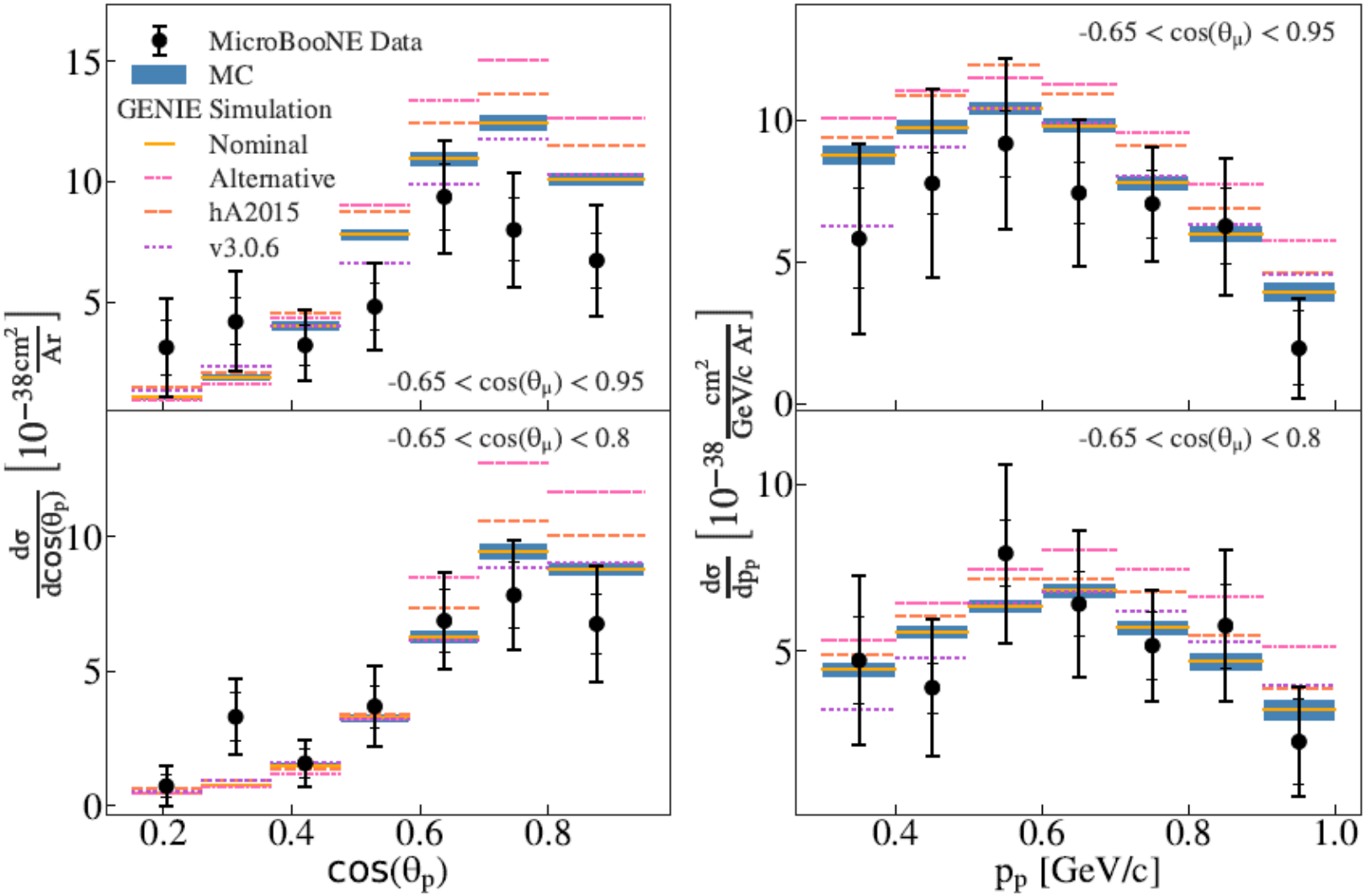
3) Cross-section is consistent with prediction.





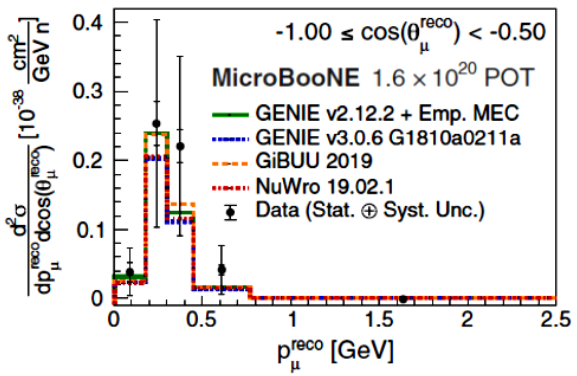
CCQE-like cross-section from MicroBooNE (Liquid Argon detector)

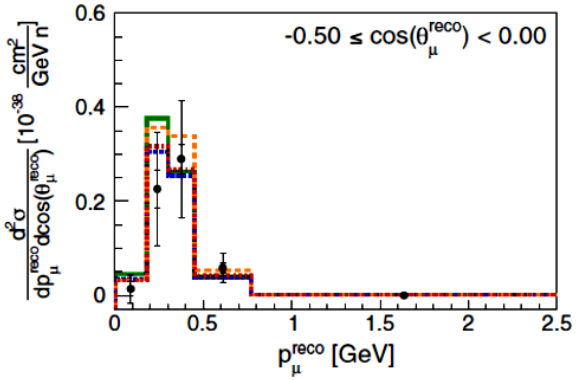
arXiv:2006.00108v2 [hep-ex]

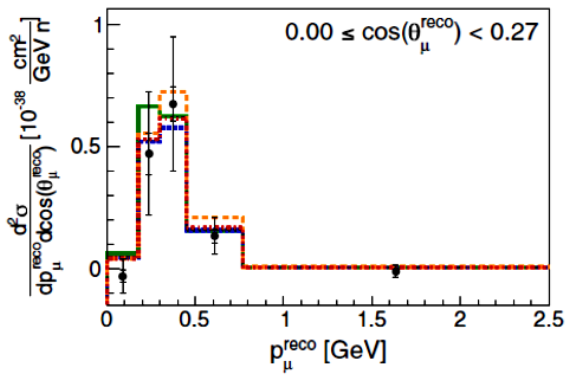


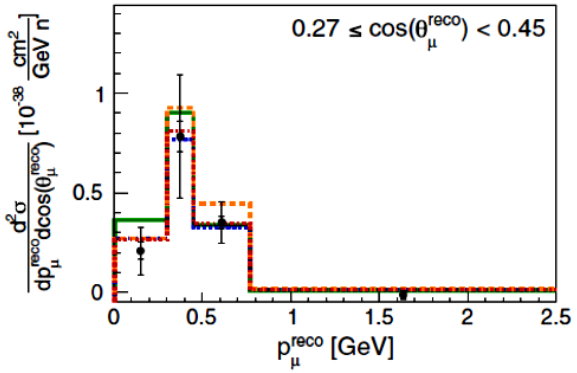
CC Inclusive cross-section from MicroBooNE (Liquid Argon detector)

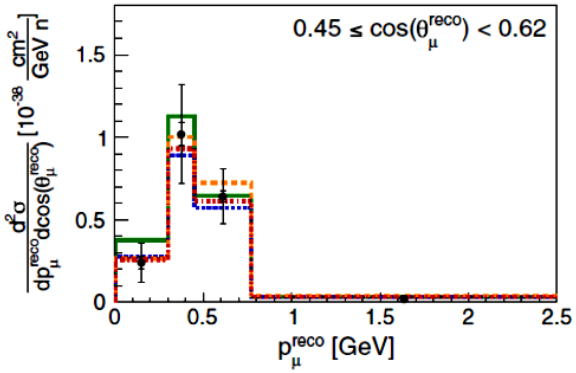
Phys. Rev. Lett. 123, 131801 (2019)

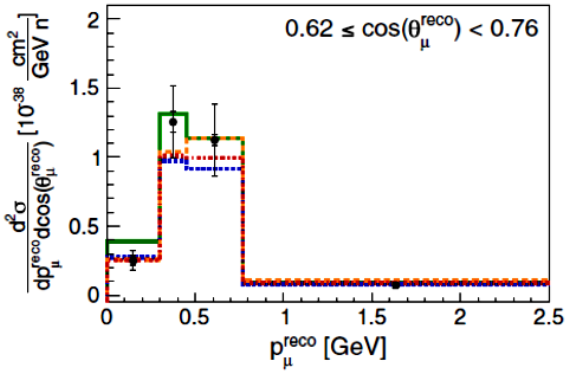


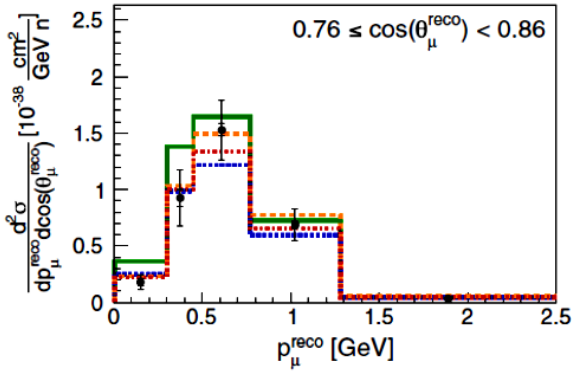


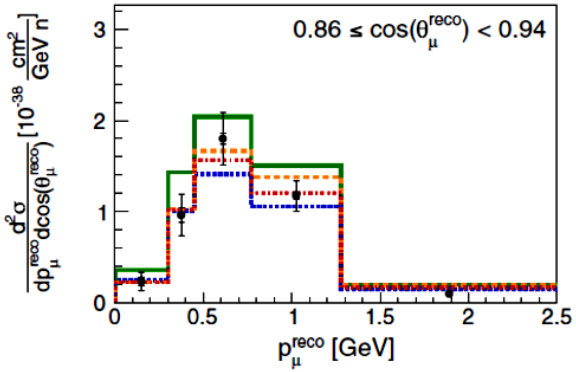


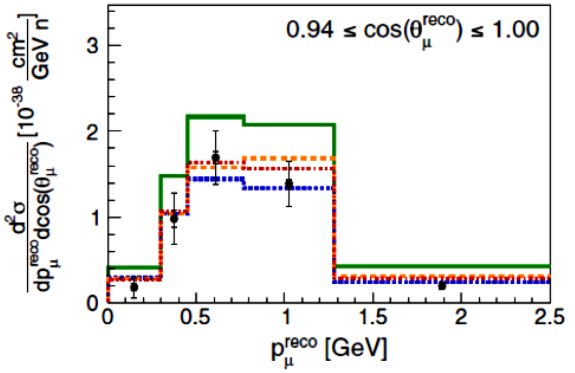










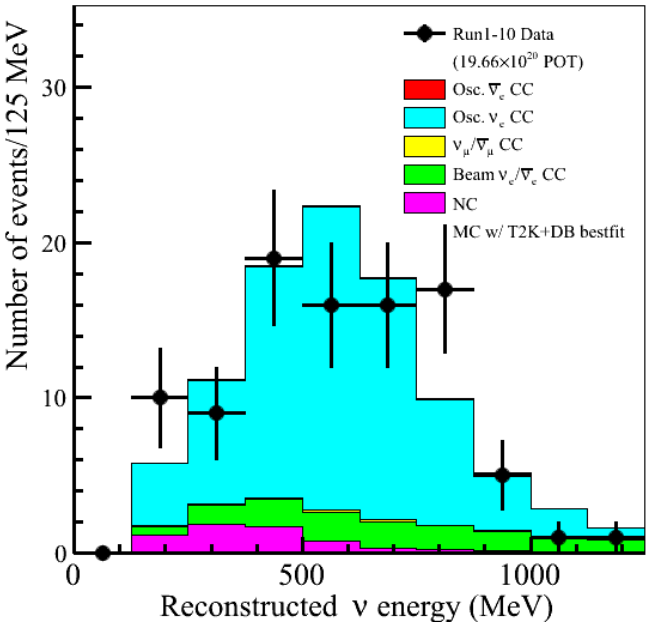


Importance of pion production

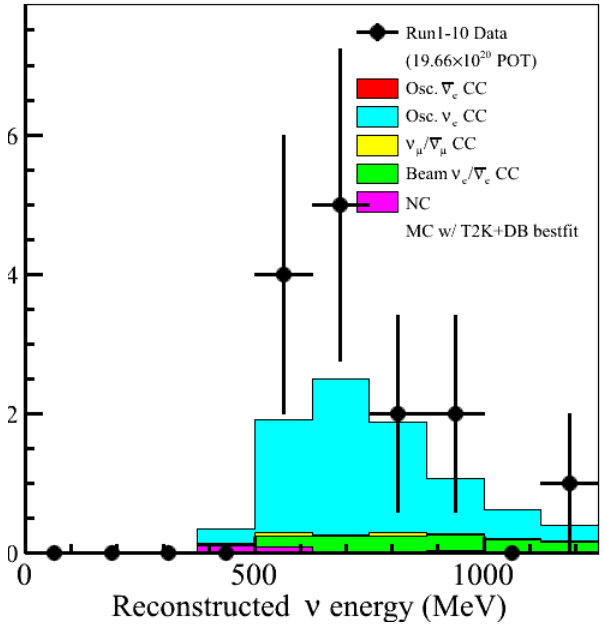
Since 2017, T2K stated using CC 1 π production to search for the appearance of ν_e

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e sample
93 events



ν_e (e^- + π^+) sample
14 events



Importance of neutrino pion production

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

Understanding the cross-section of $1\pi^+$ production
and the momentum distribution of π^+ become important.

Whether π^+ is observed as a ring or not (in SK)
is one of the major sources of the systematic error.
T2K is considering to use "2-ring" sample.
(e^- and π^+rings with 1 decay electron)

1) pion momentum distribution from neutrino-nucleon interaction,
2) momentum distribution of nucleon, and
3) change of the momentum of pion
from the re-scattering in nucleus (FSI).

Importance of neutrino pion production

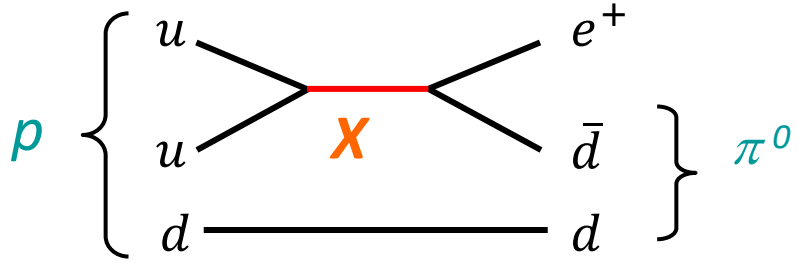
Proton decay search ~ signal and background ~

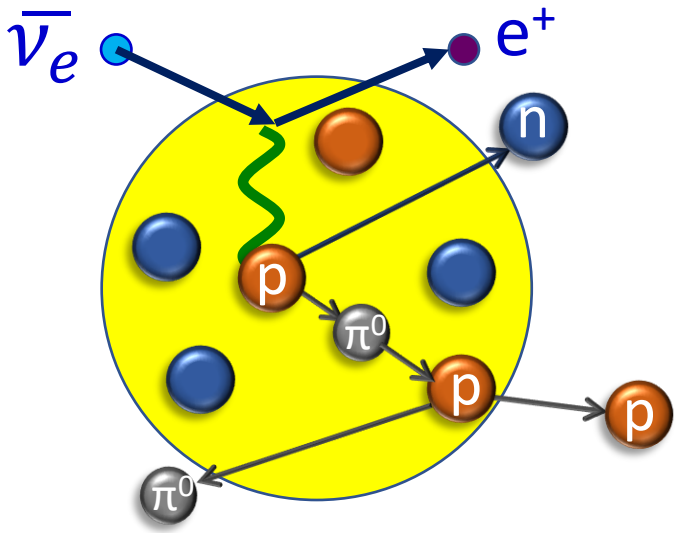
Proton decay signal

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

Background (example)

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





Background atmospheric neutrino events could be rejected if neutrons are tagged.

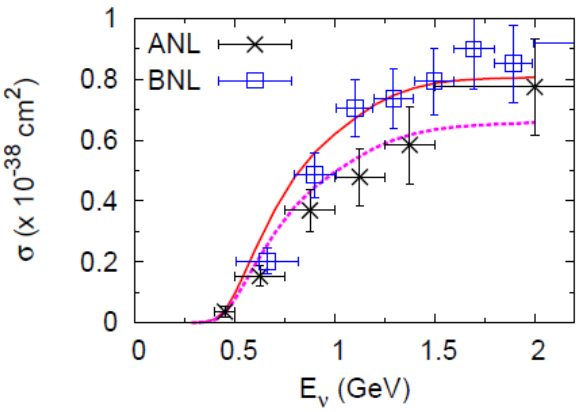
In the water, neutron is captured by hydrogen (~ 200 μs) and emit 2.2 MeV γ ray.

$$n + p \rightarrow d + \boldsymbol{\gamma}$$

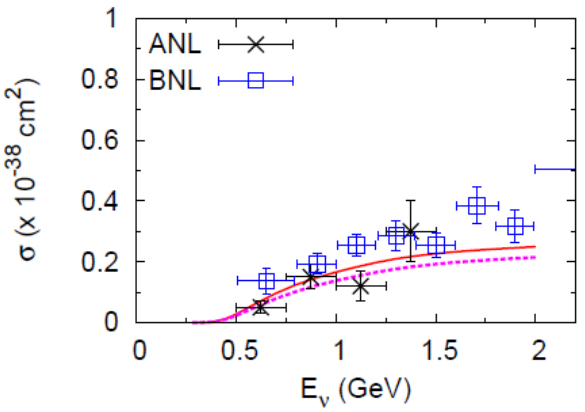
Importance of neutrino pion production

Results from the DCC model (Sato-Nakamura) are shown in red-solid lines

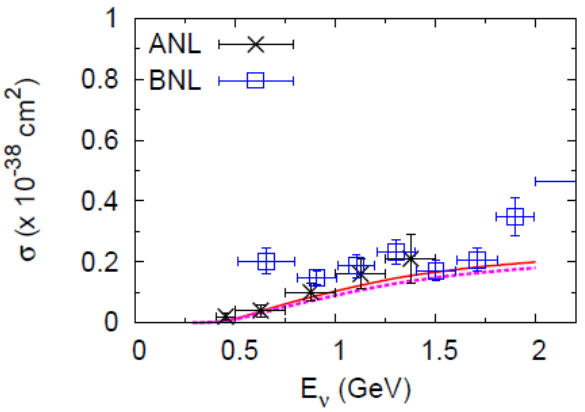
$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$



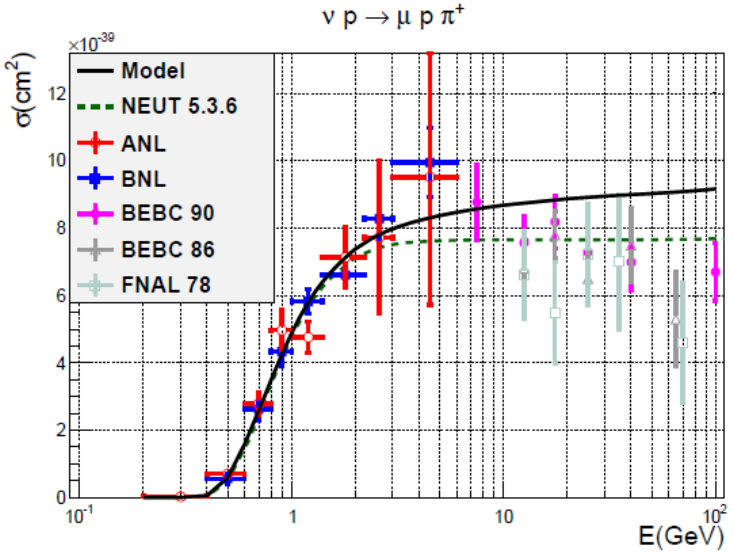
$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$

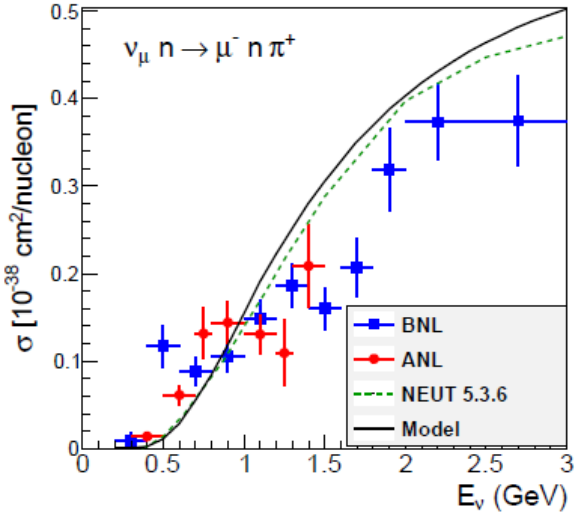


$\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$



Results from the MK model (M. Kabirnezhad) are shown in red-solid lines





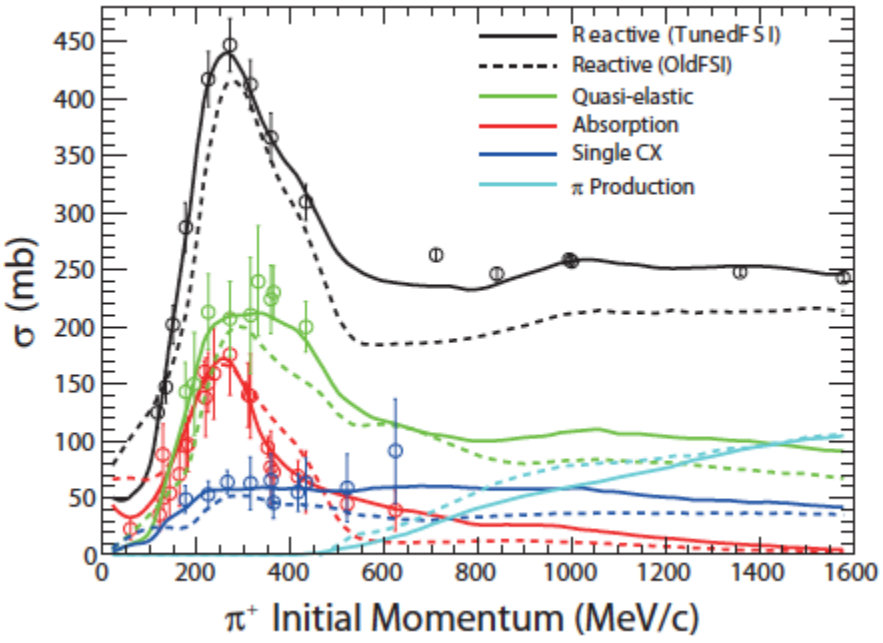
Importance of neutrino pion production

One of the major sources of inefficiency

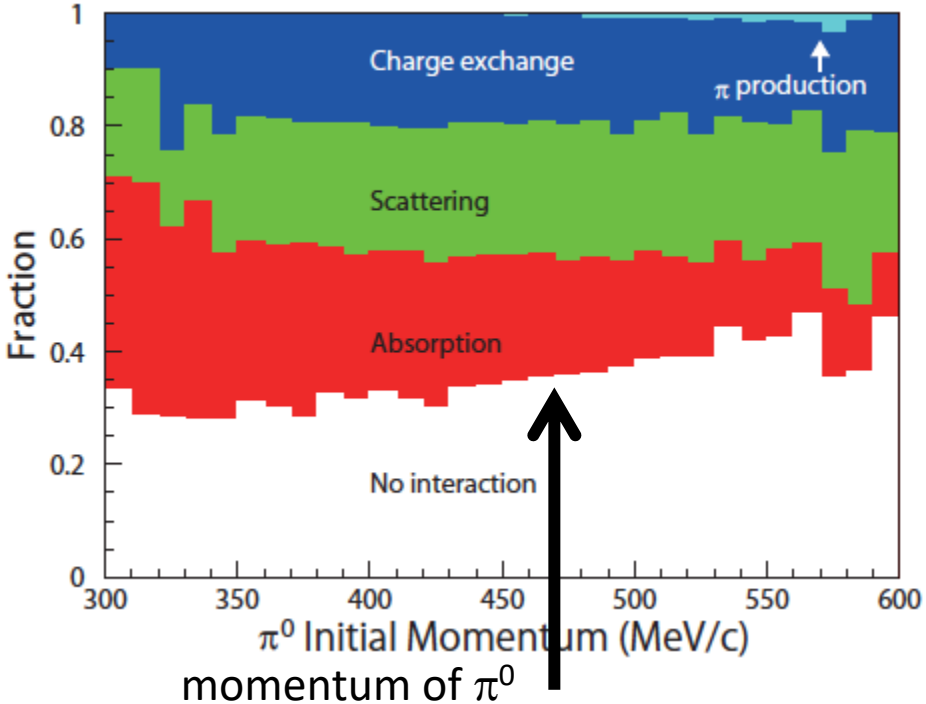
π interaction in Oxygen (before escaping from ^{16}O)

- charge exchange ($\pi^0 \rightarrow \pi^{\pm}$)
- inelastic scattering ~ change momentum and direction of π^0

π^+ interaction cross-section on carbon



π^0 interaction probability in ^{16}O

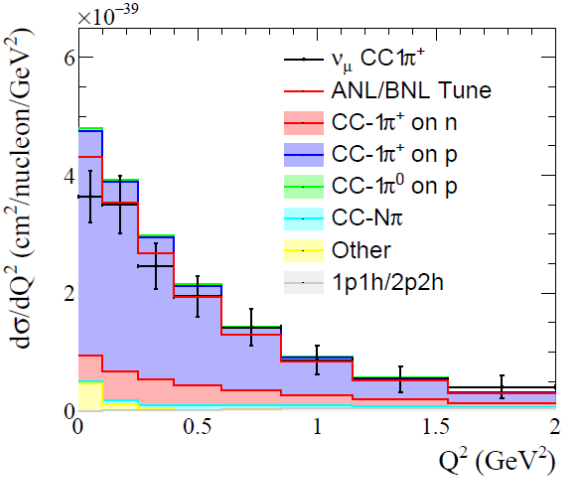


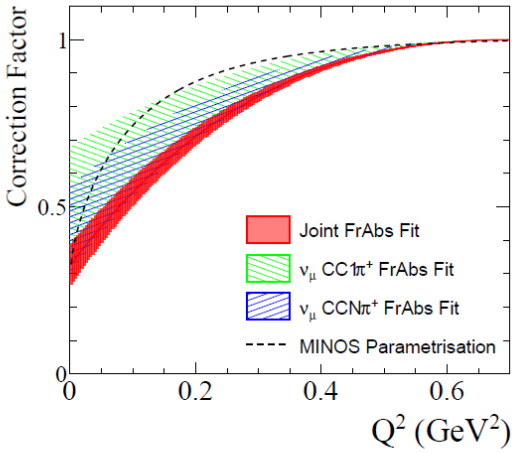
momentum of π^0

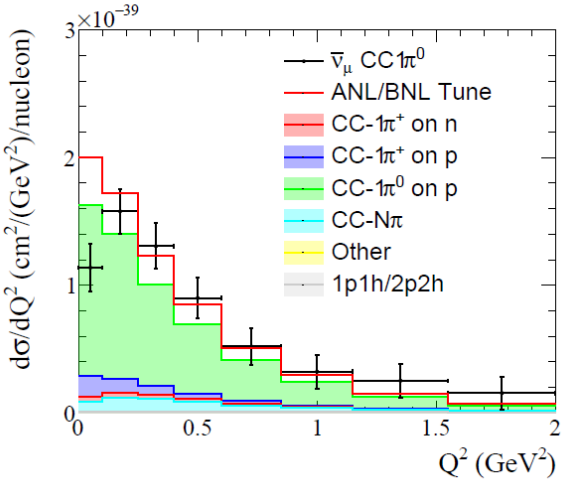
(from stationary proton's decay)

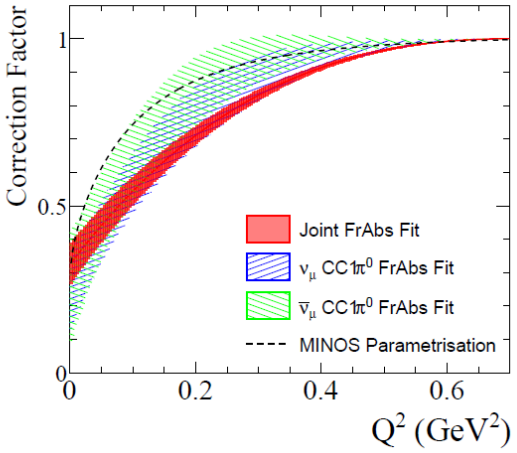
Importance of neutrino pion production

Forward (small q^2) suppression in Minerva data









This kind of large suppression is not observed in T2K-ND280 data.

Energy dependent effect?

Summary

- Some of the experiments observed larger # of CCQE-like events.
- This excess is comparable (or slightly lager than) the upper limit of the recent flux uncertainty in T2K and SK.
- Recent MicroBooNE experiment reported the consistent results with the prediction.
- Almost all the recent experiments find strong suppression in the forward going muons, likely small q^2.
- Proton information is expected to give us some “insight”.
- There are some new models of CCQE and CCQE-like (2p2h) interactions. Need to be implemented in NEUT.
- Some experiments also observed strong forward μ suppression in the CC 1π production. But T2K does not. Energy dependence?
- CC 1π interactions are getting more important.
- Important to evaluate new neutrino pion production models.