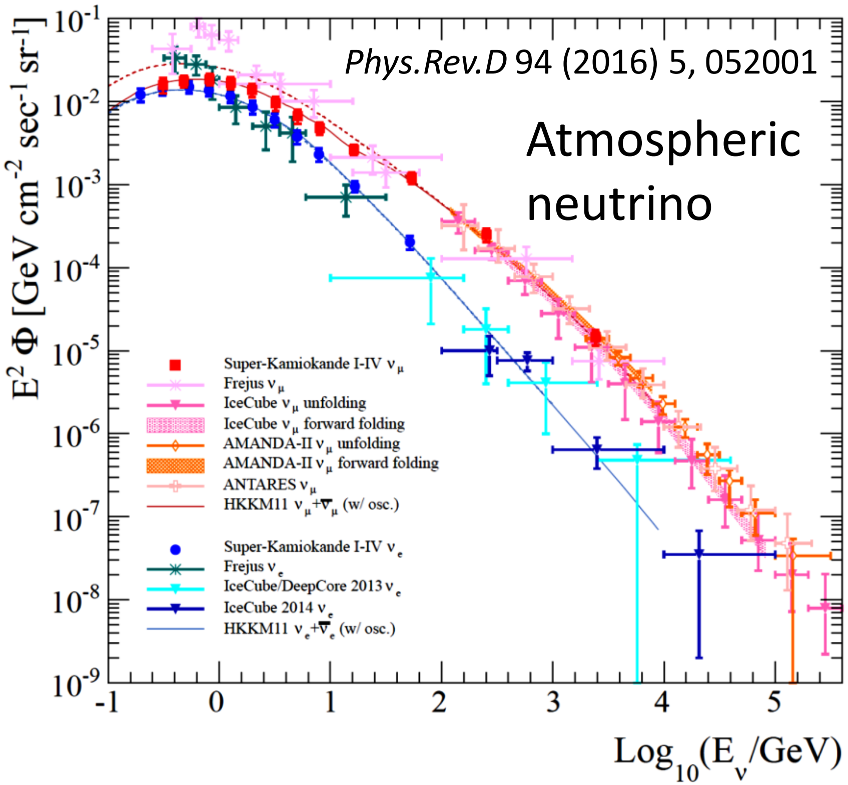
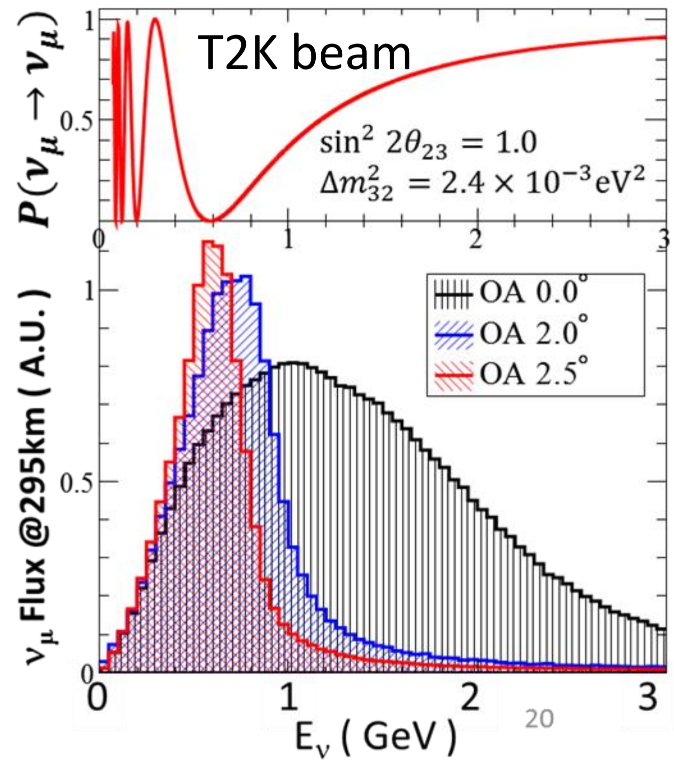
Recent status of NEUT and future development plan for the current and future neutrino and proton decay experiments

Yoshinari Hayato

Introduction ~ atmospheric and T2K neutrino beam

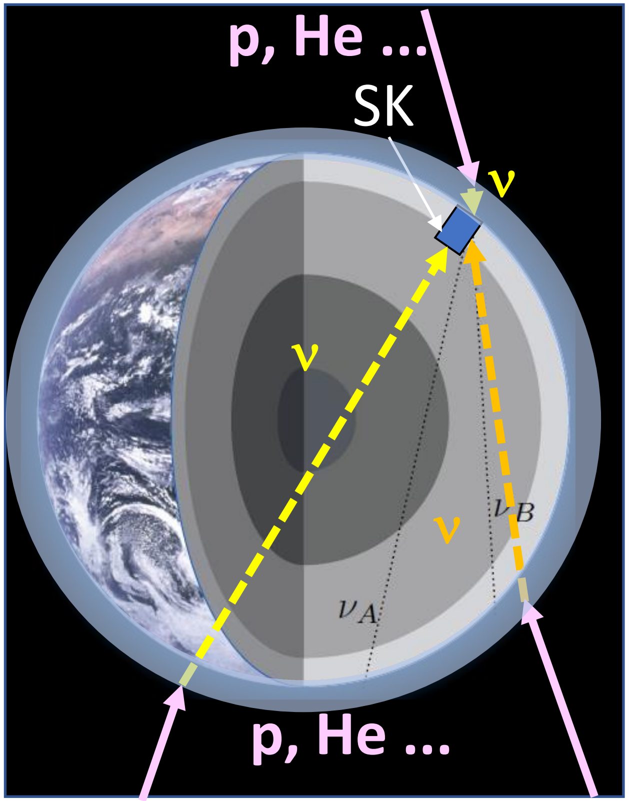
- The energy of atmospheric neutrino spans from ~100 MeV to TeV.
- The energy of accelerator neutrino spans from ~100 MeV to GeV.

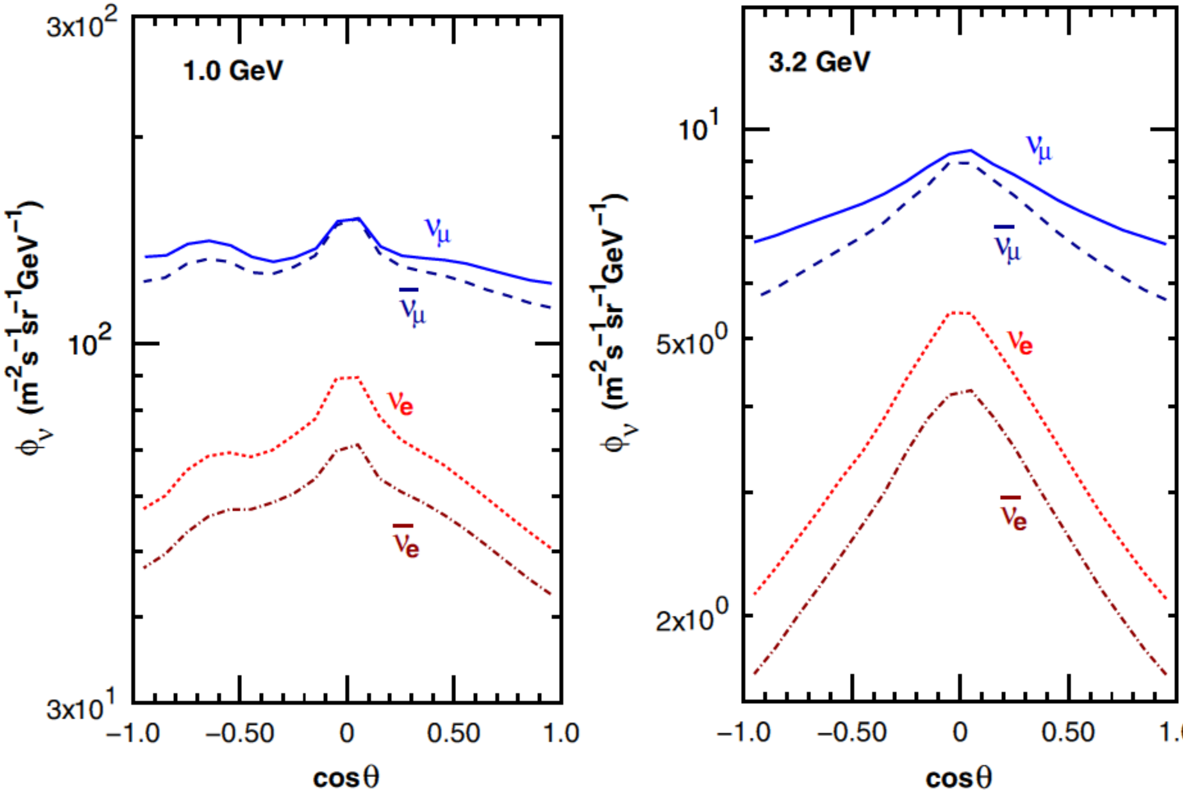




Neutrino interactions around a few to several hundreds of MeV is crucial in T2K.
A few GeV and above is also important for the atmospheric neutrino studies and nucleon (proton) decay searches.

Atmospheric neutrino observation





Minimum travel distance ~ thickness of the air -> 10 ~ 30km

Maximum travel distance ~ diameter of the earth -> 13,000 km

Travel distance of neutrino has good correlation with its zenith angle.

➡ Possible to study neutrino oscillation with observed energy (momentum) and zenith angle.

Neutrino oscillation studies using atmospheric ν

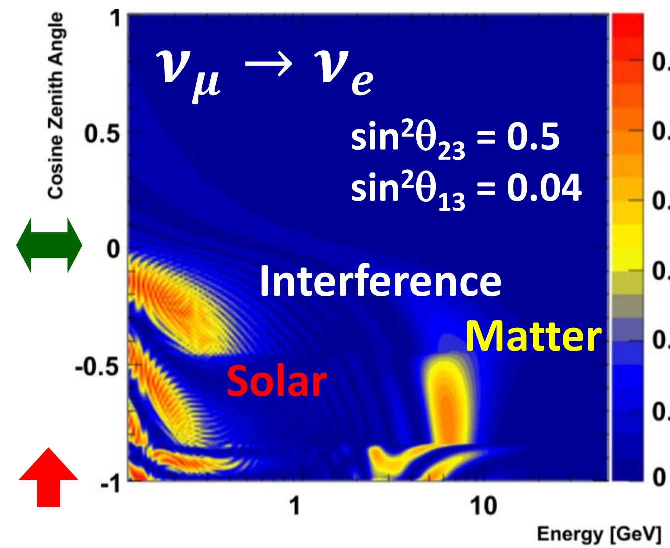
Possibility in observing small distortion in ν_e

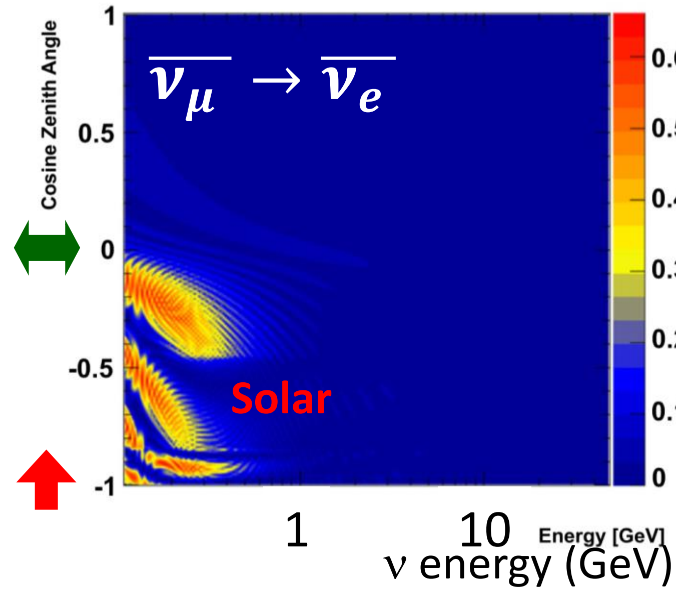
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \leftarrow \text{Matter effect}$$
$$+\Delta_2(\Delta m_{12}^2) \quad \leftarrow \text{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m_{12}^2, \delta) \quad \leftarrow \text{Interference}$$

- Matter effect ~ from mass hierarchy
  Possible enhancement in **several GeV**
  passed through the earth core
  One of the flavors (ν_e or $\overline{\nu_e}$) shows this enhancement.
- Solar term ~ from θ_{23} octant degeneracy
  Possible ν_e enhancement in sub-GeV
- Interference
  CP phase could be studied.

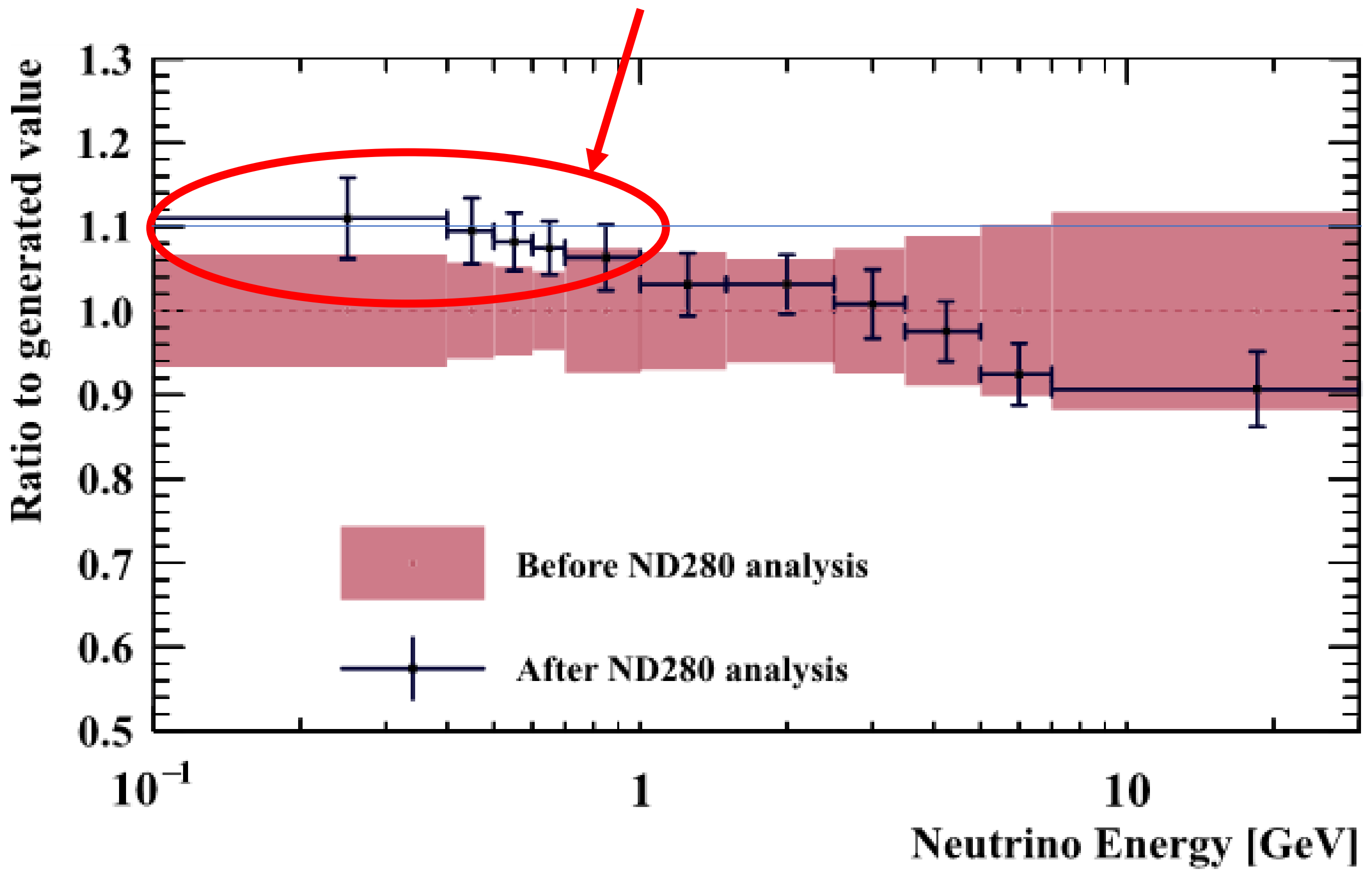
Normal hierarchy





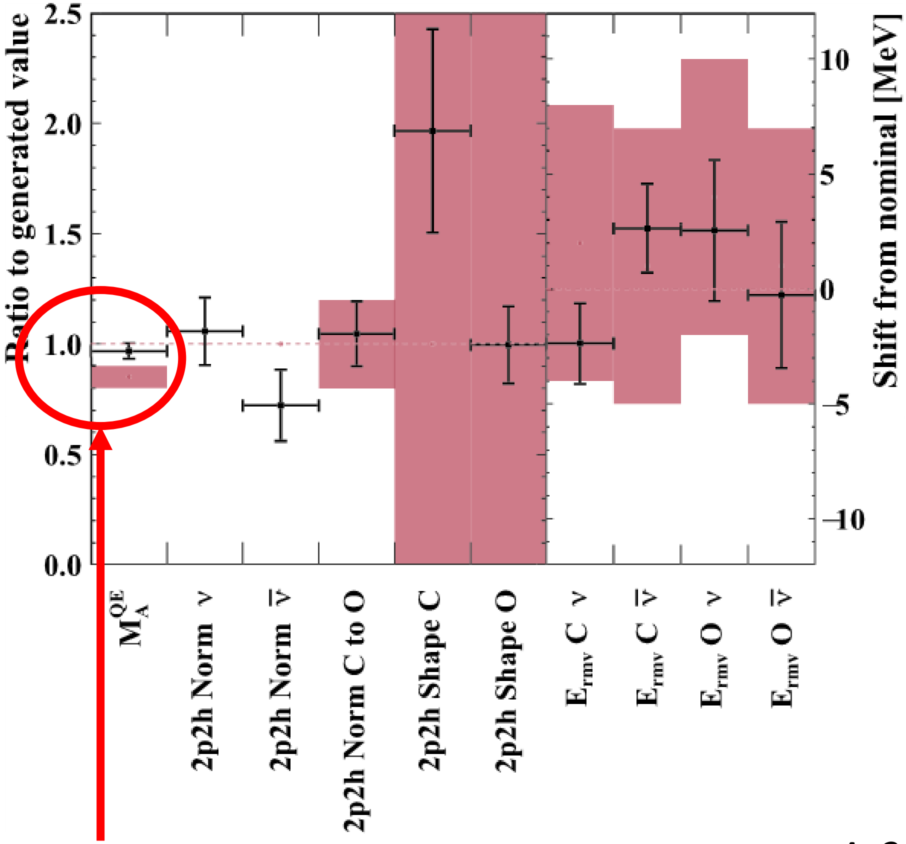
Observation in T2K; neutrino flux and interaction rate

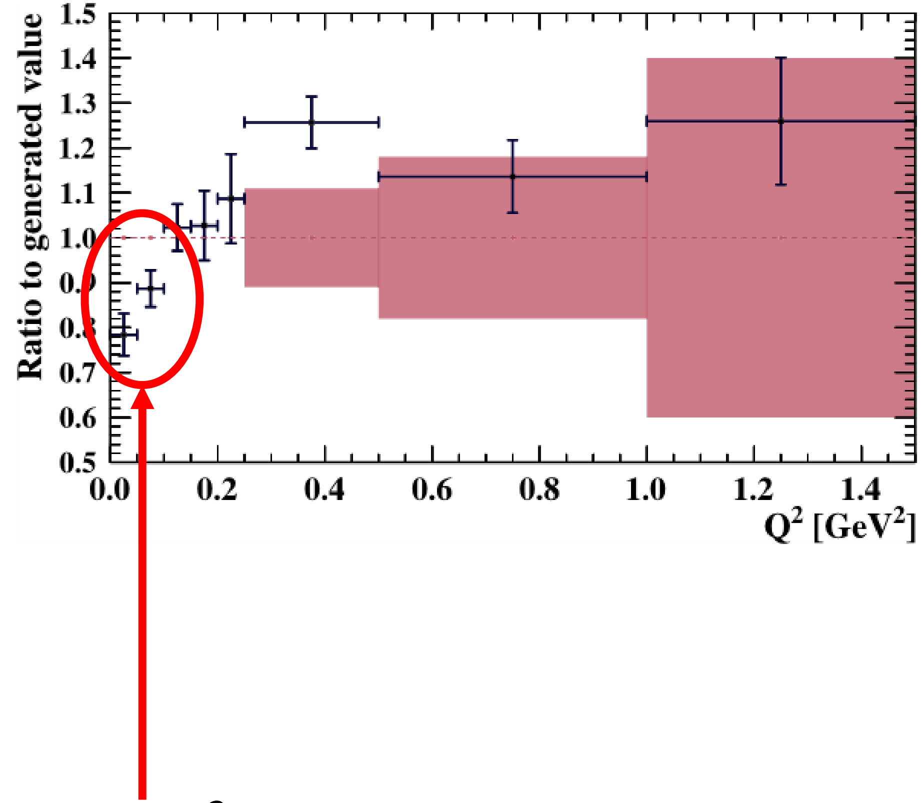
Even with the "reweighted" neutrino interaction model, flux below 1 GeV needs to be increased by 8 ~ 11%.



Necessary enhancement is larger than the "prior" obtained by our neutrino flux prediction, including hadron production uncertainties.

Observation in T2K; CCQE interaction





Favored CCQE M_A was ~1.2 GeV/c^2.
(NEUT uses M_A = 1.2GeV/c^2 by default but the fitting nominal was set to 1.05 GeV/c^2 and thus, the center of the pink band is ~0.8).

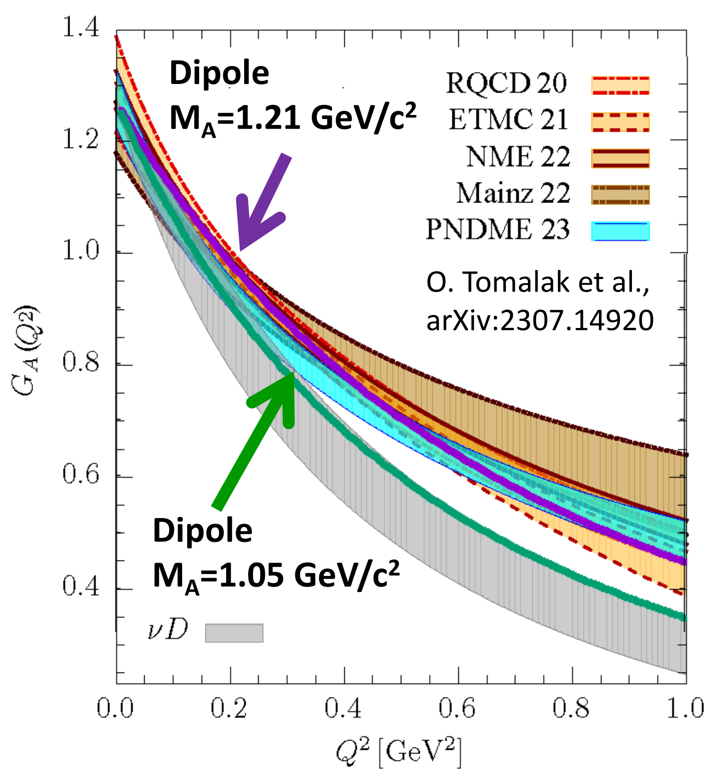
Low q^2 suppression is observed.
(T2K uses spectral function CCQE model in NEUT but this does not have special suppression treatment.)

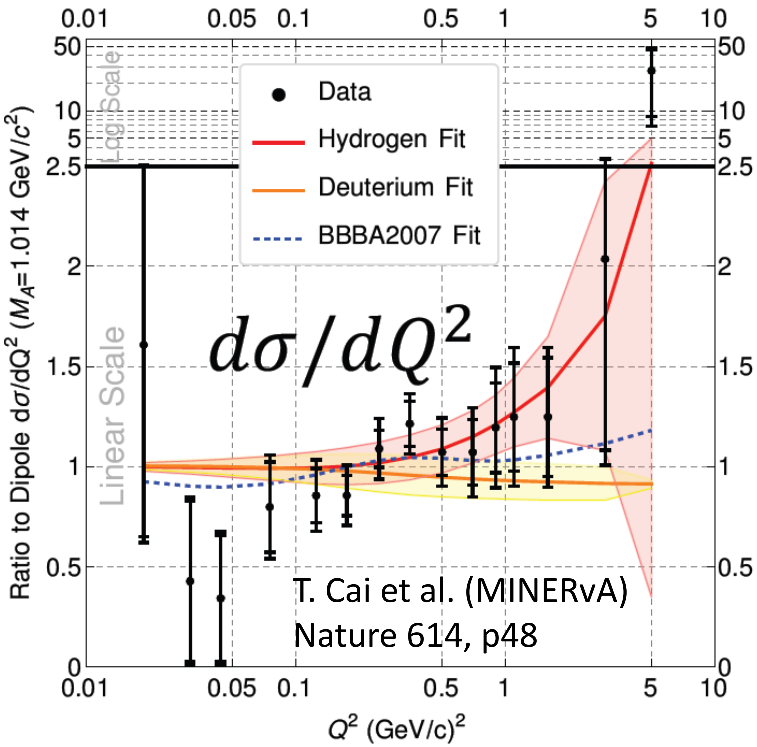
Recent development; CCQE

Axial vector form factor (dipole) $F_A(q^2) = -\frac{1.276}{(1-(q^2/{M_A}^2))^2}$

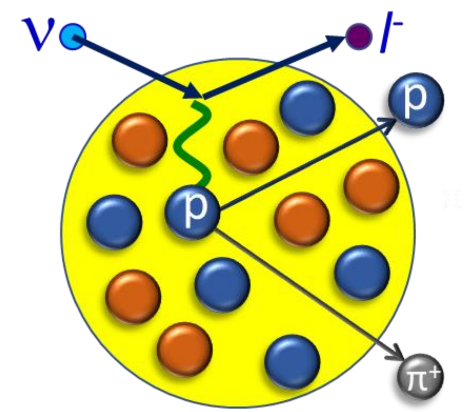
Recent lattice QCD (LQCD) results suggest the larger M_A from bubble chamber data fit and non-dipole.

MINERvA measured ds/dQ^2 of $\overline{\nu_\mu}\,\mathrm{p} \rightarrow \mu^+\mathrm{n}$ scattering. Enhance in the large Q^2.





Observation in Ninja and T2K; CC π prod.



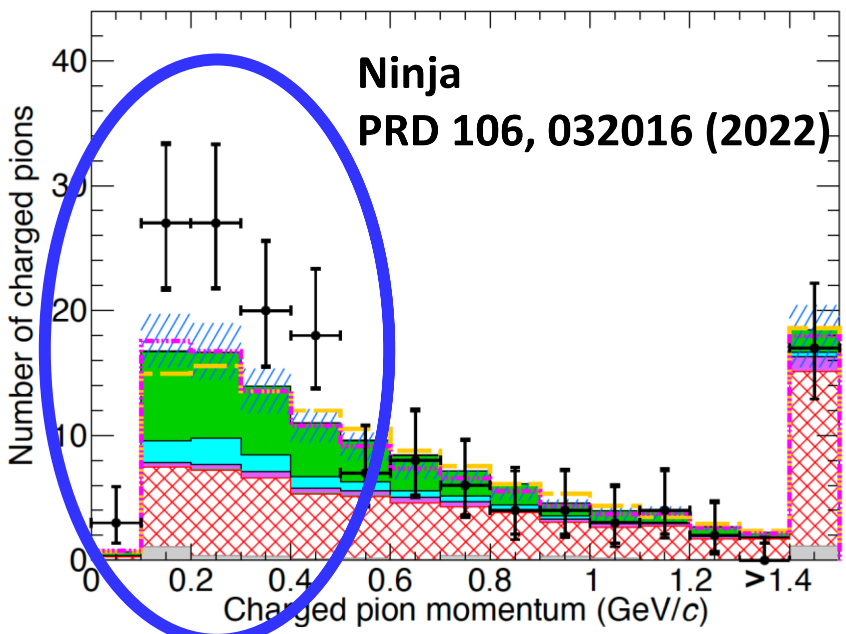
Single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

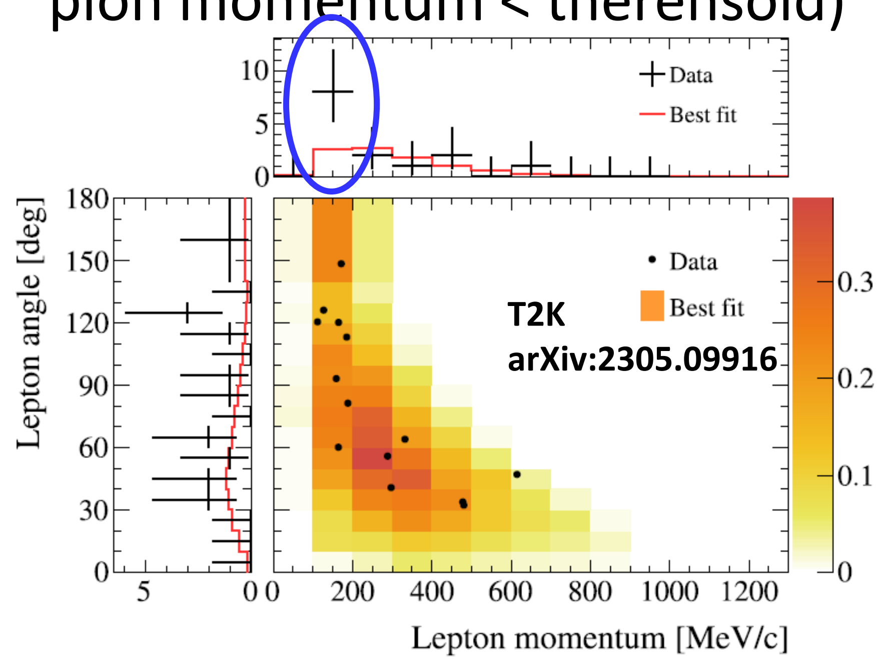
Discrepancies between the observation and simulation results

Low-momentum charged pion events excess in the data

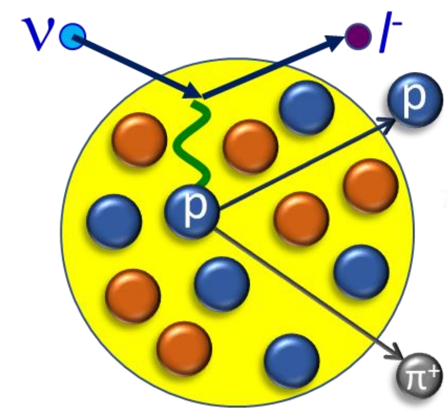
($\bar{\nu} + Fe$@Ninja)



Low-momentum lepton + pion events excess in the data (e-like 1 ring with decay-e@SK = pion momentum < therehsold)



Observation in Ninja and T2K; CC π prod.



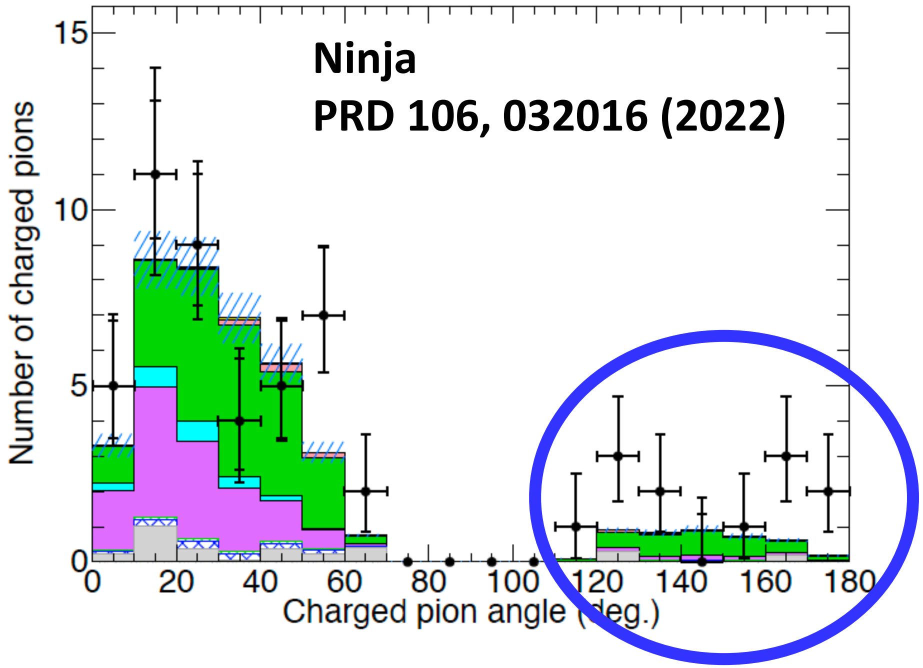
Single π production

$$\nu + N \rightarrow l^{-}(\nu) + N' + \pi$$

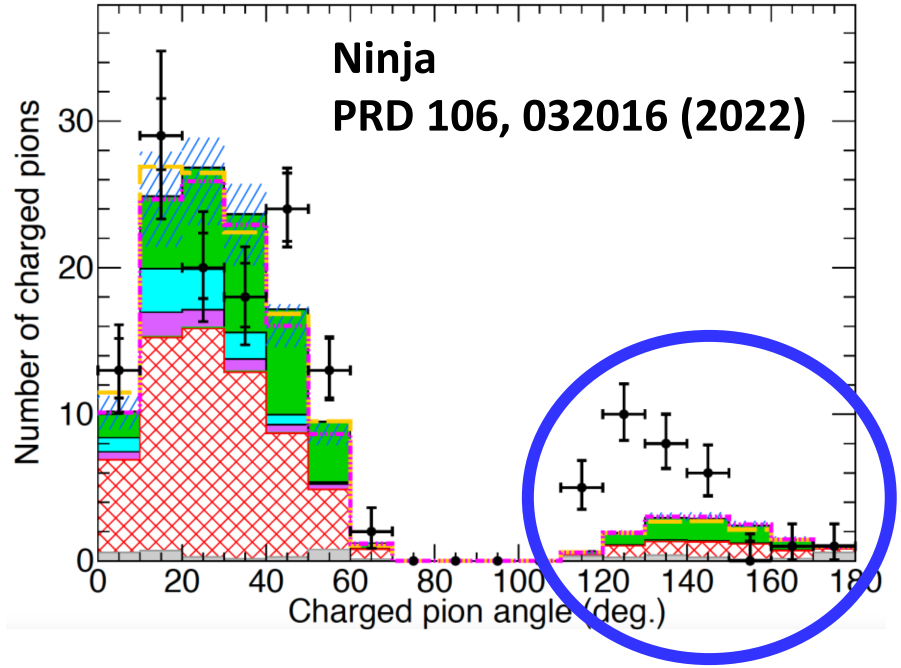
Discrepancies between the observation and simulation results

Larger # of charged pions in the backward direction.

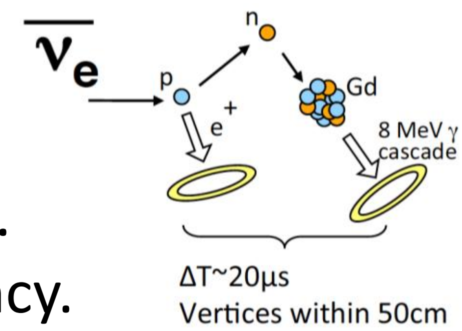
$(\nu + Fe$@Ninja)



$(\bar{\nu} + Fe$@Ninja)



Observation in SK; neutron multiplicity

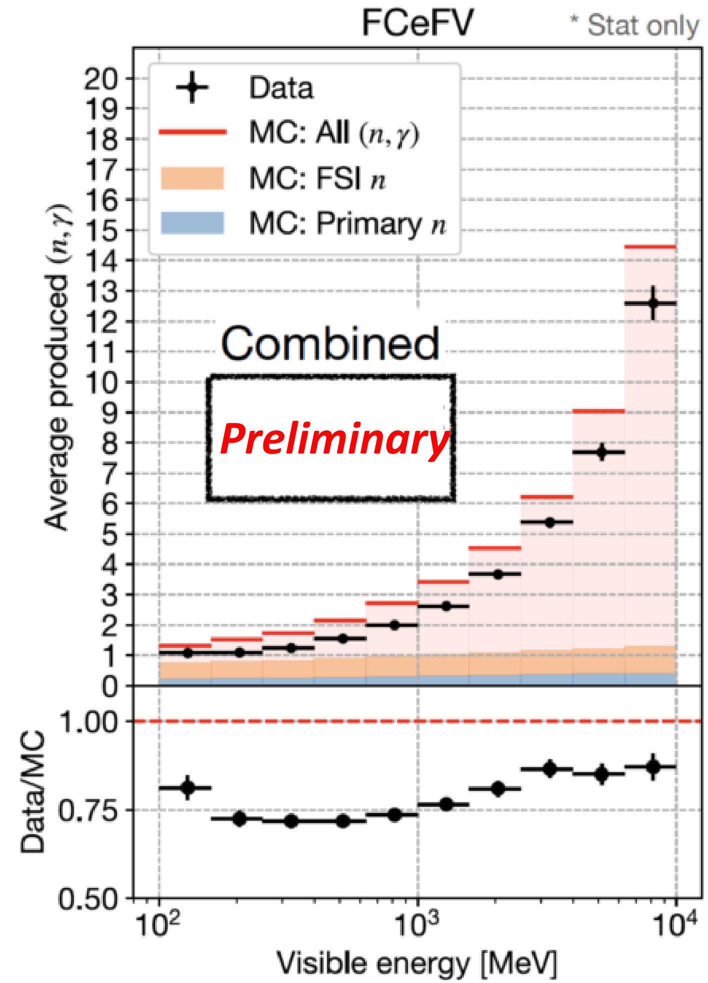


Super-Kamiokande loaded Gd to the water.

- Gd captures neutron and emit 8 MeV γ cascade.
- SK can detect γ emitted from Gd at high efficiency.

In 2020, concentration was 0.01%
(~50% n captured by Gd)
and now 0.03 % (~75% n captured by Gd)
from 2022.

Observed # of neutrons is **smaller** than predicted.
Similar tendencies were observed with the pure water phase (SK IV) atmospheric and T2K data.
(Pure water phase neutron detection efficiency was ~25%.)



Latest status of NEUT

Released a new version (5.6.4) recently

New model and existing model improvements

- Single pion production

  Dynamical couple channel (DCC) model

  S. X. Nakamura, et al., Phys. Rev. D 92, 074024 (2015).

  Pion distributes uniformly in the Adler frame with current version.

- Deep (Shallow) inelastic scattering

  Proper treatments of neutral current DIS/SIS

  Multiple pion multiplicity models (for Multi-pion mode)

  Newer Bodek-Yang correction

- Final state interaction of K and η

  Improved descriptions

- CCQE-like 2p2h

  Treat additional nuclei using extra/interpolation

- New radiative correction

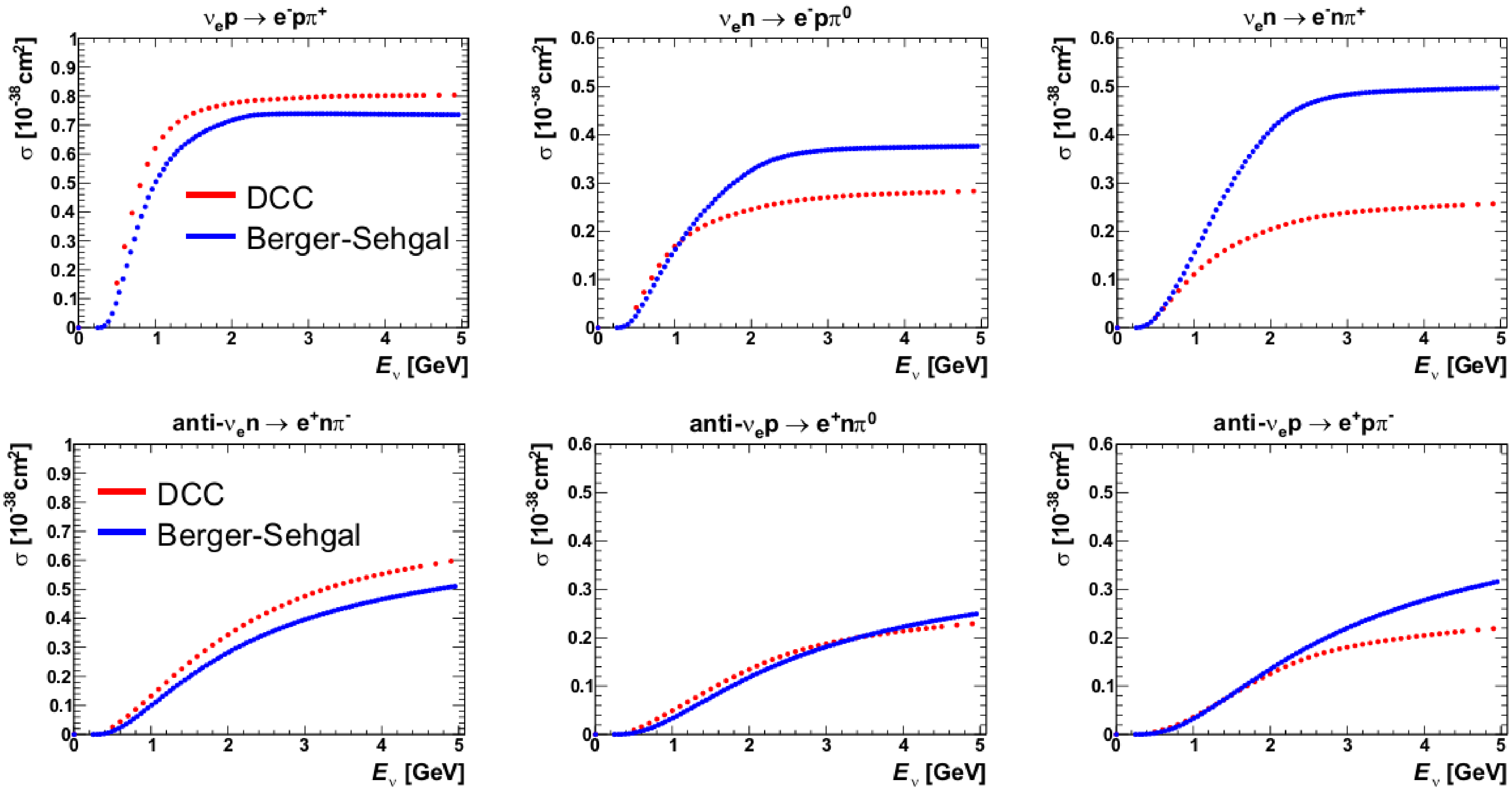
  γ emission together with charged lepton.

Single pion model comparisons

Total cross-section

K. Yamauchi

Large differences were found, and differences depend on the channel and neutrino flavor (neutrino and anti-neutrino.)



Single pion model comparisons

K. Yamauchi

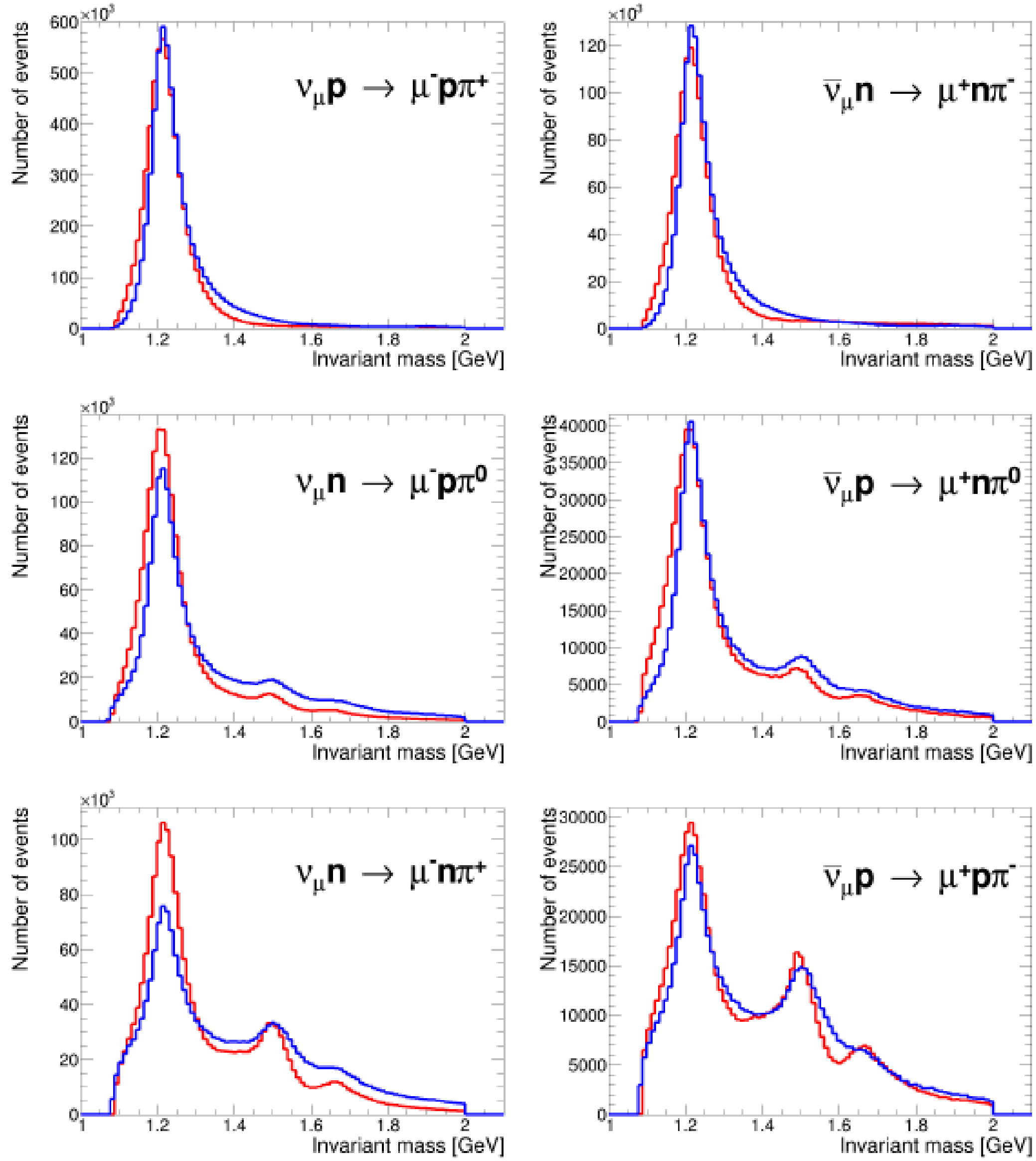
Intermediate resonance mass distribution seems to be quite different.

$\nu\ p \rightarrow l^-\ p\ \pi^+$ and $\bar{\nu}\ n \rightarrow l^+\ n\ \pi^-$ are quite similar because Δ resonance dominates.

However, peak position is slightly different.

Other than these channels, strengths of each resonance are quite different.

Pion momentum distribution could be different.



Multi-pion and DIS updates (fixes and improvements)

Corrected NC Multi-pi production cross-section

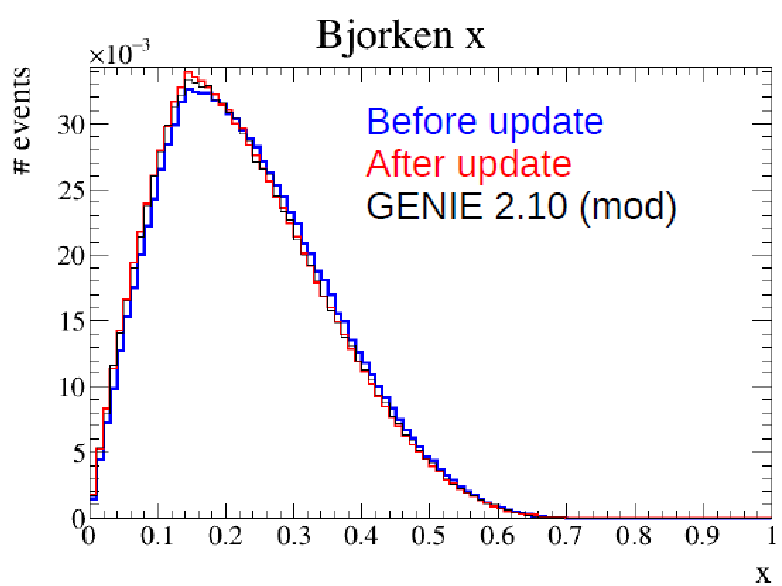
(Previous versions used simple scaling to CC.)

Old neut (5.4.x and before) used essentially the CC model with a different outgoing lepton mass.

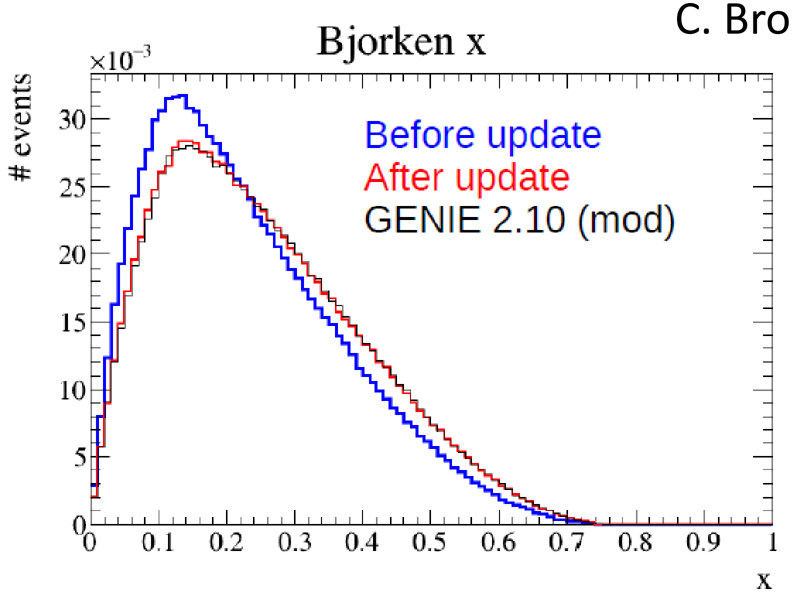
New version (5.6.x)

- use Z0 propagator instead of W for NC
- use proper structure functions (eq 16.18 of PDG2011)

2 GeV numu on free n



2 GeV numubar on free n



C. Bronner

Current issues of NEUT

1. NEUT requires CERNLIB(*)
   1. PYTHIA5.7 in CERNLIB (neutrino scattering)
   2. PDF library in CERNLIB
   3. Mathematical and kinematics utility functions
   4. Configuration (CARD) file access library
2. Old style FORTRAN (FORTRAN77 with extension)
   1. Extensively used COMMON (and EQUIVALENT).
   2. Sometimes, variables are not defined (declared).
3. Custom data formats
   1. Requires the custom ROOT class library or ZBS (based on ZEBRA in CERNLIB) functions to access ouptuts.

→ Not easy for people to use NEUT.

(*) CERN resumed to distribute CERNLIB (only among the CERN users at this moment) as a part of the “data preservation” efforts.
NEUT is known to work with the latest releases (2022 and 2023.)

Future direction of NEUT (NEUT6)

1. Minimize dependence on CERNLIB
    1. PYTHIA5.7 in CERNLIB (neutrino scattering)
    2. PDF library in CERNLIB
2. Support nuHEPMC event data format
3. New configuration card format
4. Restructure and modernize the code
    1. Improve interoperability with C/C++ (Fortran 2008)
    2. Appropriate definitions of variables
    3. CMake build system
5. Simple API to introduce new models by theory groups.
6. Simple API to access total and differential cross-sections.
7. Simple API to generate an “event” for given neutrino.

The alpha version of NEUT6 is under testing.

Planning to release in 2024.

Necessary improvements of NEUT physics models

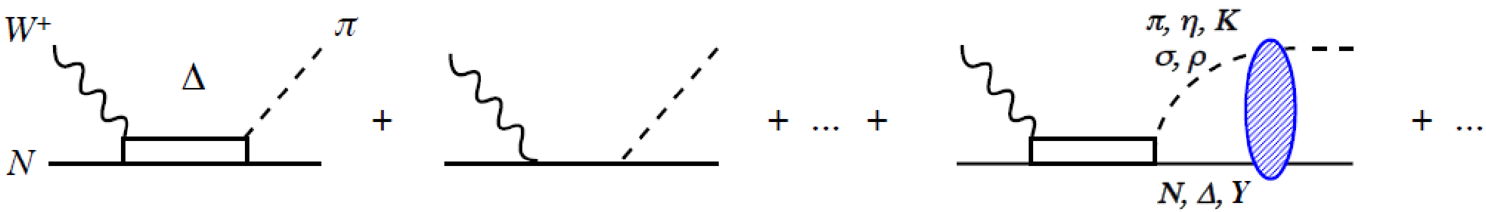
1. New improved QE/2p2h model
   1. SuSAv2 + RMF (with G. Megias et al.)
   2. Local Fermi-gas model (especially NCQE)
   3. Low energy (<100MeV) QE model
2. Meson production
   1. DCC model with full pion kinematics and other channels (with T. Sato)
   2. MK single pion model (with M. Kabirnezhad)
3. Nuclear de-excitation and neutron emission
   1. Use output of TALYS (with S. Abe)
4. Hadron (pion and nucleon) final state interactions in nucleus
   1. nucleon (neutron) emission after FSI
5. Electron scattering for validation
   1. DCC model of electro-pion production (with T. Sato)
   2. SIS/DIS (rather straightforward)

Fin.

backup

DCC (Dynamical coupled-channel) model

Define a Hamiltonian, which includes resonance and meson-Baryon states. The parameters are determined using pi-N and gamma-N experimental data.
Extensively tested with e-N or the other scattering data.



Developed through analyzing $\gamma^{(*)}N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ data (~25,000 data pts.)

→ Extended to $\nu N \rightarrow l^- X \quad (X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma)$

Unique features

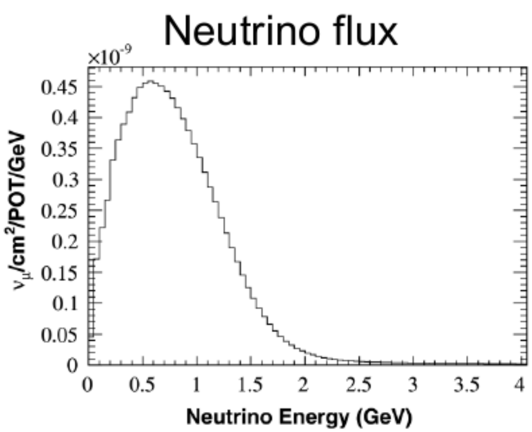
- Hadronic rescattering and channel-couplings are taken into account
  ← requirement from the unitarity
- Interference among resonant and non-resonant mechanisms are under control within the model

S. X. Nakamura, H. Kamano, and T. Sato, Phys. Rev. D **92,** 074024 (2015).

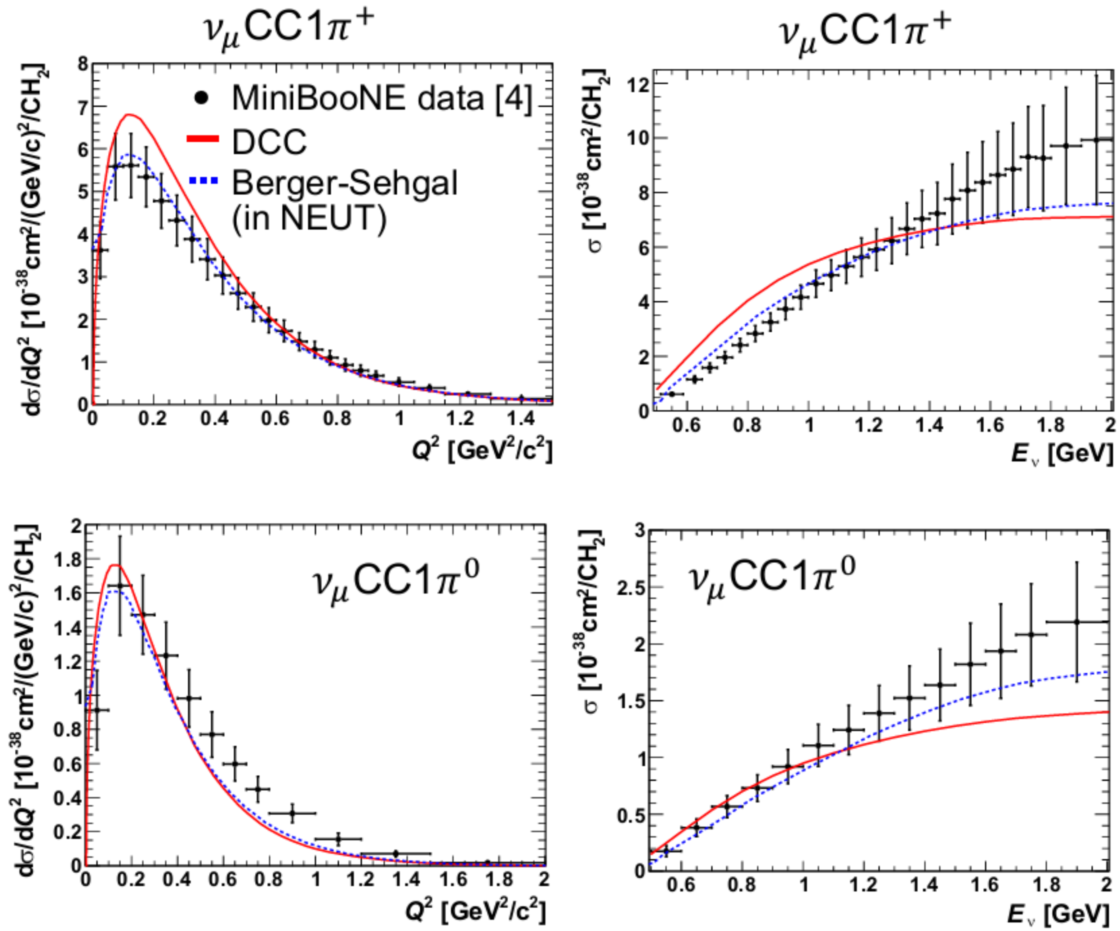
Single pion model comparisons

Comparisons with experimental data

Berger-Sehgal model (in NEUT) seems to give better agreement.
(Form factors and parameters of Berger-Sehgal model
were tuned to bubble chamber data in in NEUT.)



K. Yamauchi



Multi-pion and DIS updates (fixes and improvements)

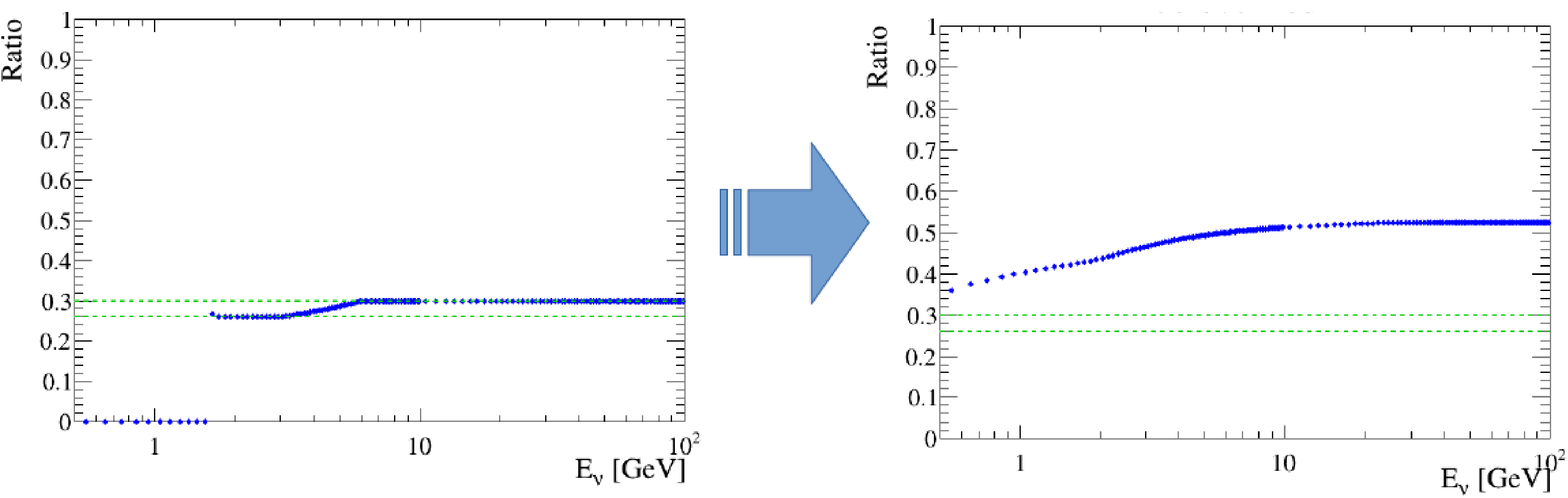
Corrected NC DIS cross-section

(Previous versions used simple scaling to CC.)

Old neut (5.4.x and before) applied a factor to CC ones from Rev. Mod. Phys. 53, 211 (1981)

Now computing them by integrating d2σ/dxdy correctly.

<u>Example</u>: ratio σ_{NC}/σ_{CC} for interactions of ν_e on protons, low W DIS mode



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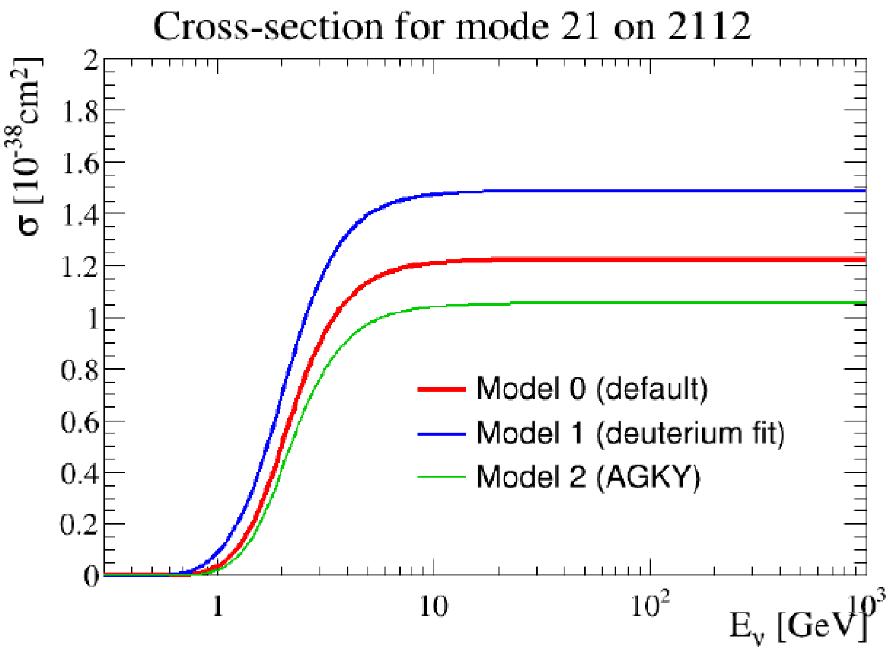
Multi-pion and DIS updates (fixes and improvements)

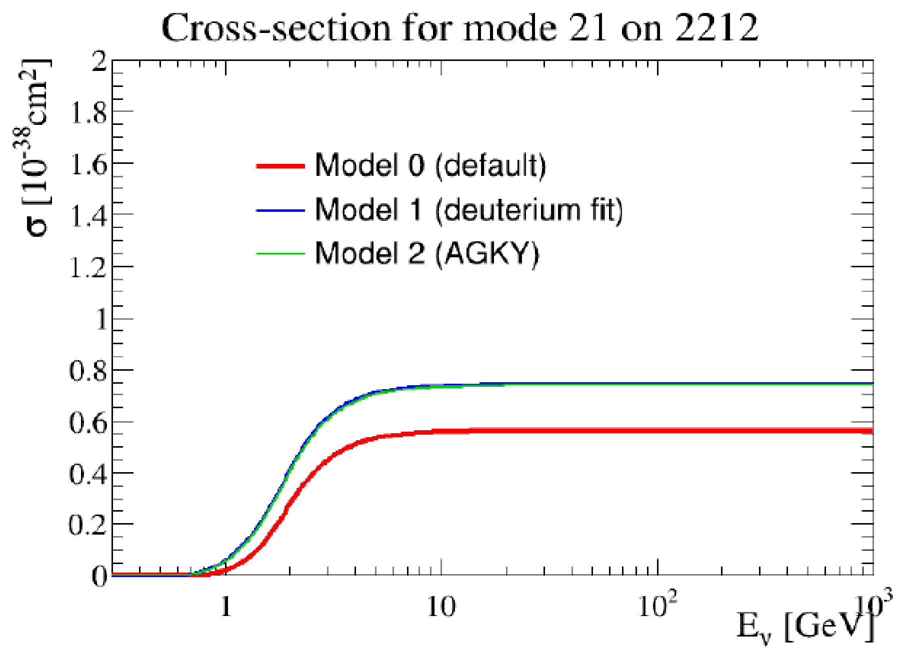
Alternative pion multiplicity parametrization (for SIS)

To generate "multi-pion" (# of π > 1) events with W < 2 GeV/c^2,
We use the custom code based on the experimental data.
Three multiplicity functions are provided.

Cross-section for $\nu_\mu + n \to \mu^- + N + \mathrm{n}\pi$
(N: nucleon, n > 1, W < 2GeV)



Cross-section for $\nu_\mu + p \to \mu^- + N + n\pi$
(N: nucleon, n > 1, W < 2GeV)



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Multi-pion and DIS updates (fixes and improvements)

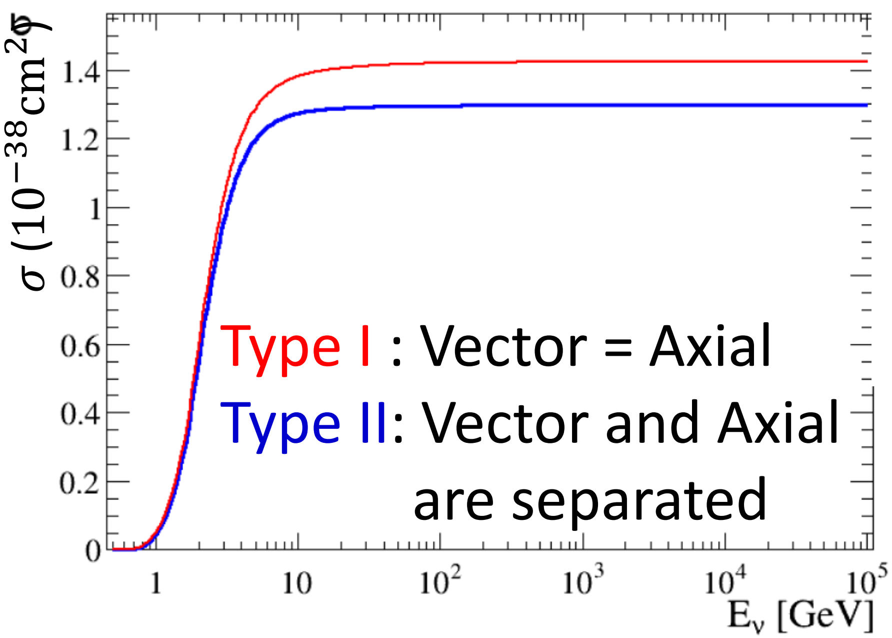
Multi-pion (SIS) and DIS updates

Newer Bodek-Yang correction is implemented. (arXiv: hep-ph:2108.09240v2)

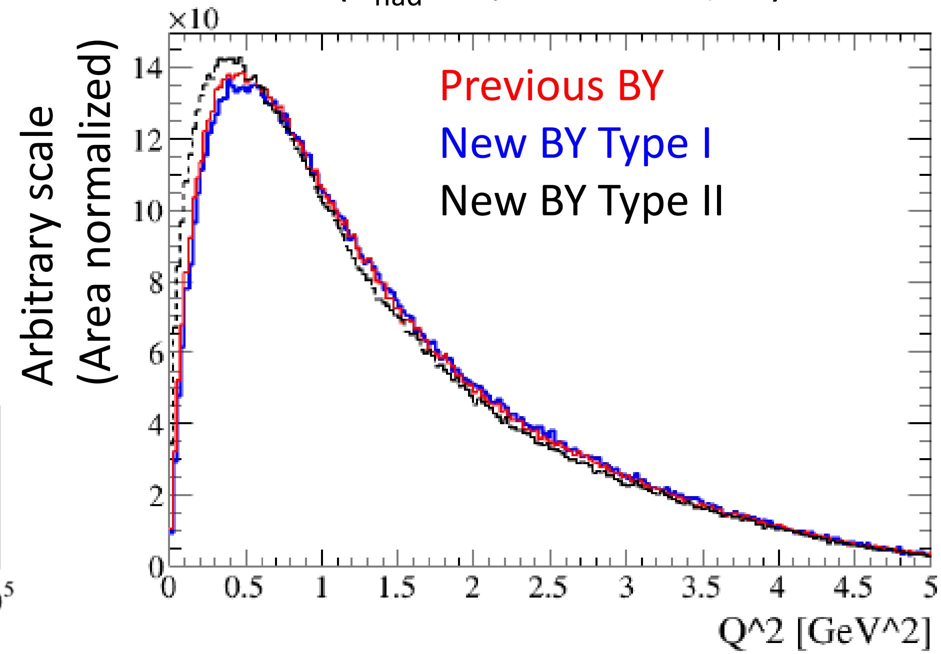
value of K^{axial}_{val}, introduction of K_{LW}^{ax},

increased sea quark and antiquark contributions

Cross-section for $\nu_\mu + n \rightarrow \mu^- + N + \mathrm{n}\pi$
(N: nucleon, n > 1, W < 2GeV/c²)



Q^2 for 4 GeV ν_μ on water,
(n_{had} > 1, W < 2GeV/c2)



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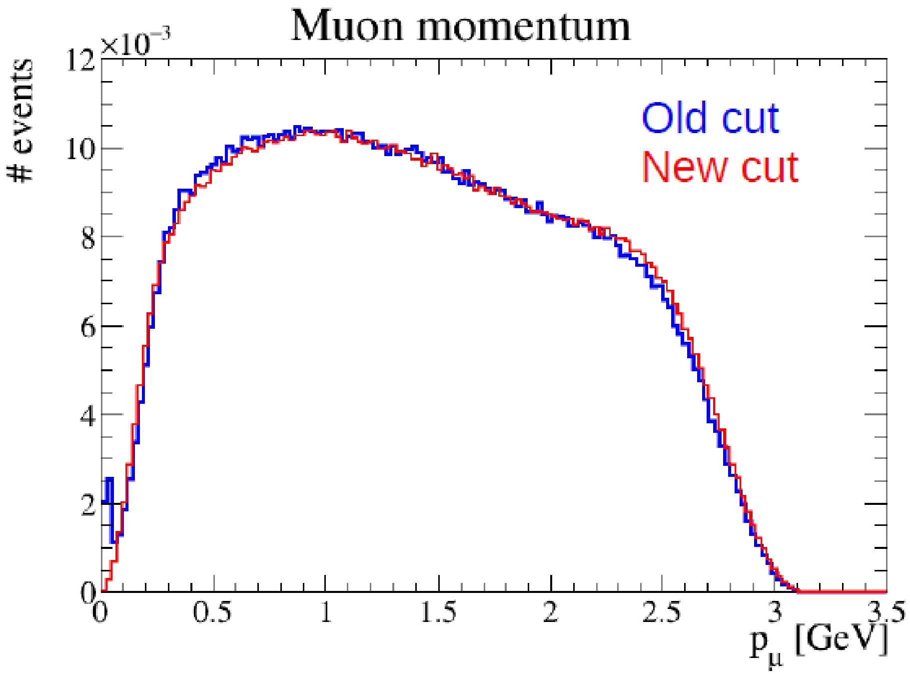
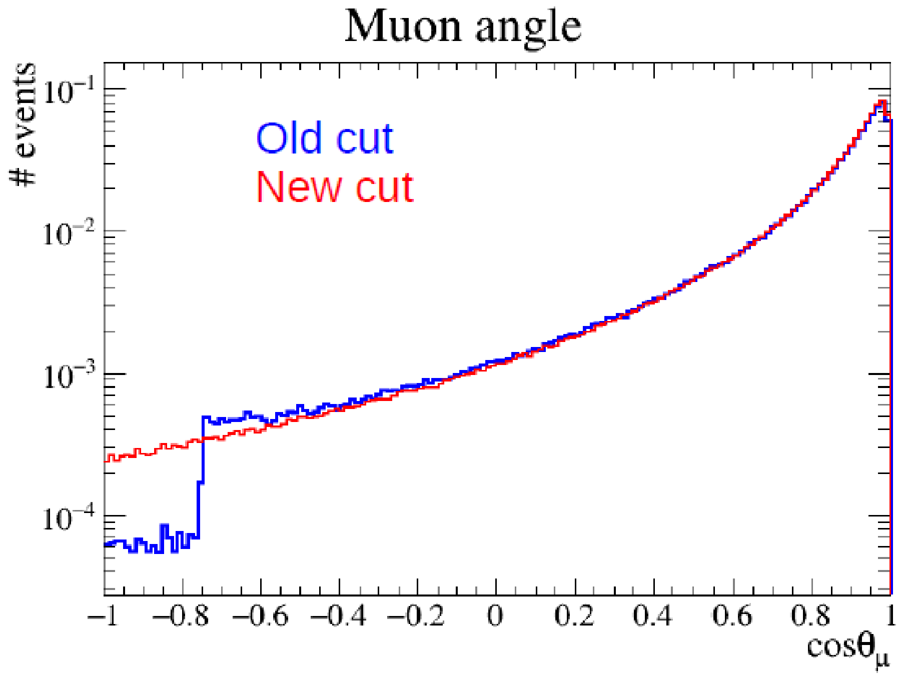
Multi-pion and DIS updates (fixes and improvements)

Fixed an issue coming from the implementation of PYTHIA.

In PYTHIA, most 2→2 processes have divergent cross-sections for $z=\cos(\theta_{RF}) \rightarrow \pm 1$. Previously, $\cos(\theta_{lab})>-0.75$ cut was applied.
A cut $|\cos(\theta_{RF})|>0.999$ removes problematic features better.





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