NEUTRON PRODUCTION IN NEUTRINO-NUCLEUS INTERACTION

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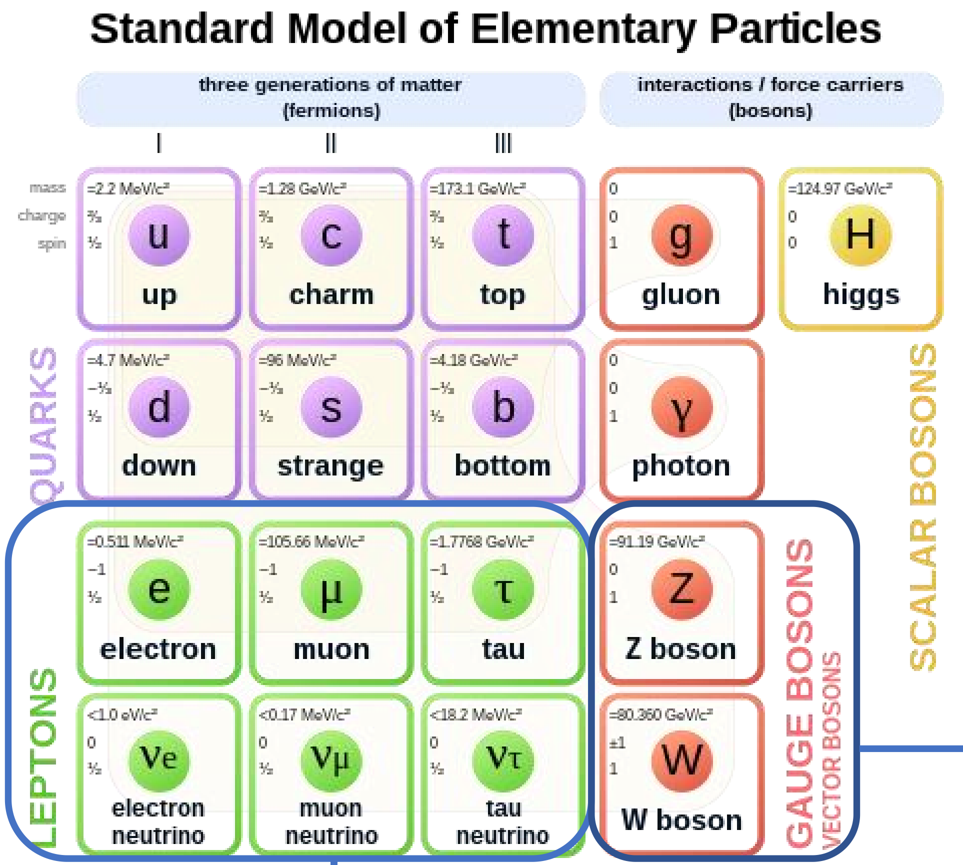
MPA Retreat 2024

Neutrinos - "Ghost" Particles



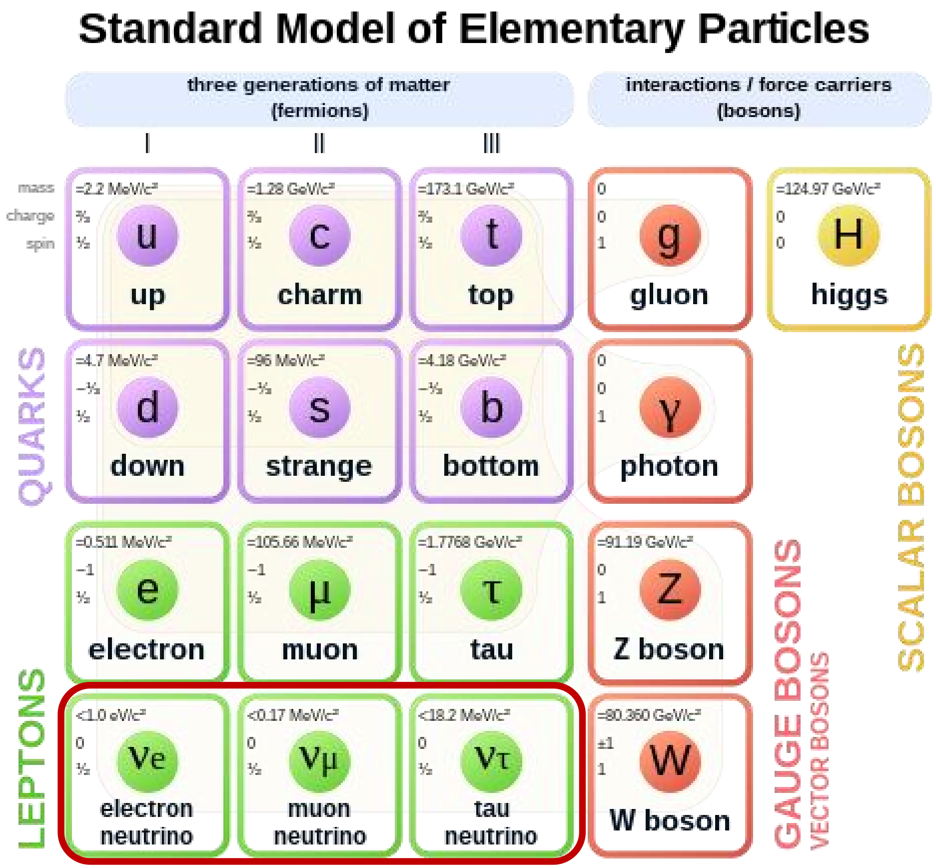
Neutrinos are electrically neutral spin 1/2 particles, which interact only via weak interaction.

About 100 trillion neutrinos pass through our body every second.

Force carriers of weak interaction, and hence, neutrino-nucleus interaction.

Leptons do not interact via strong interaction.

Neutrinos have mass

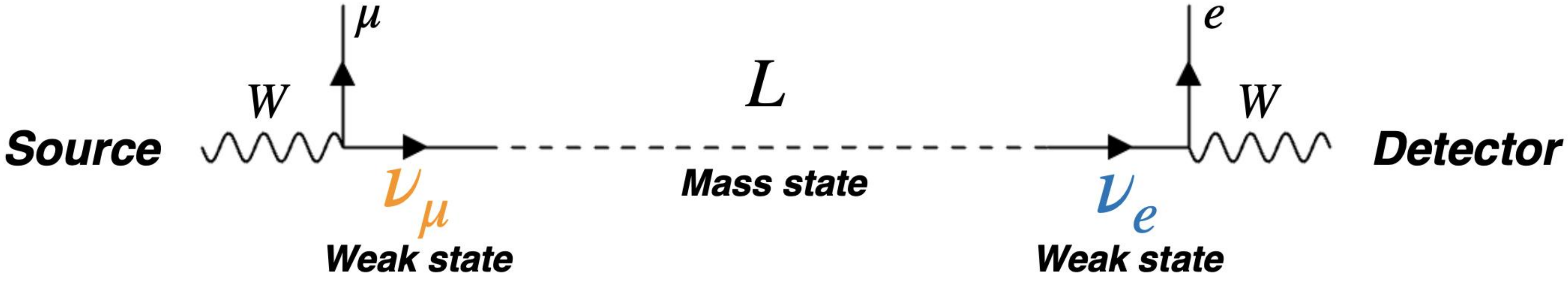


Neutrinos were believed to be massless.

Various experiments since 1960s have hinted at and shown that neutrinos have mass.

The basis of this is neutrino oscillations.

Neutrino Oscillations



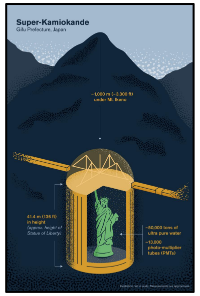
- Neutrinos produced in a specific flavor state (ν_μ) with energy E

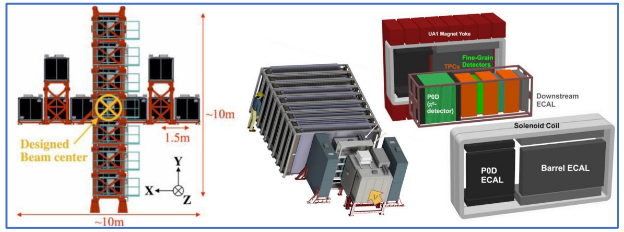
- Oscillation probability depends on:
  - ➢ Neutrino energy
  - ➢ Travelling distance ("baseline")
  - ➢ PMNS mixing parameters
  - ➢ Difference between mass states

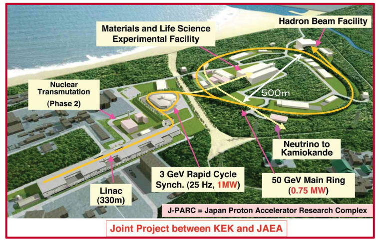
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

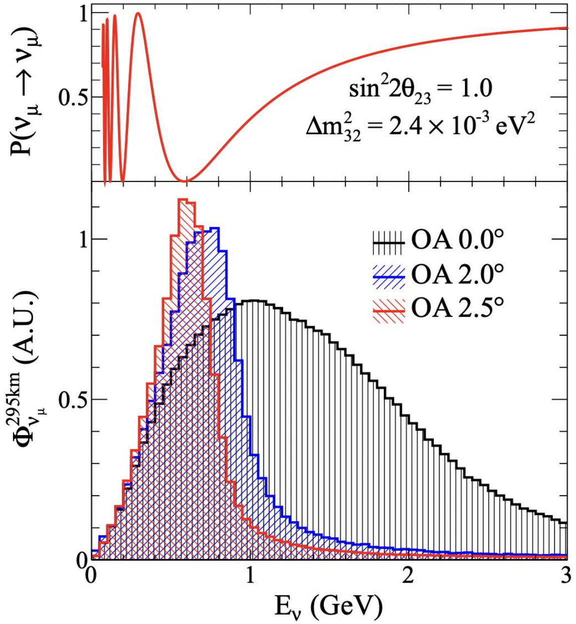
Parameters in PMNS matrix
$(\theta_{23}, \theta_{13}, \theta_{12}, \delta_{CP})$

The T2K Experiment

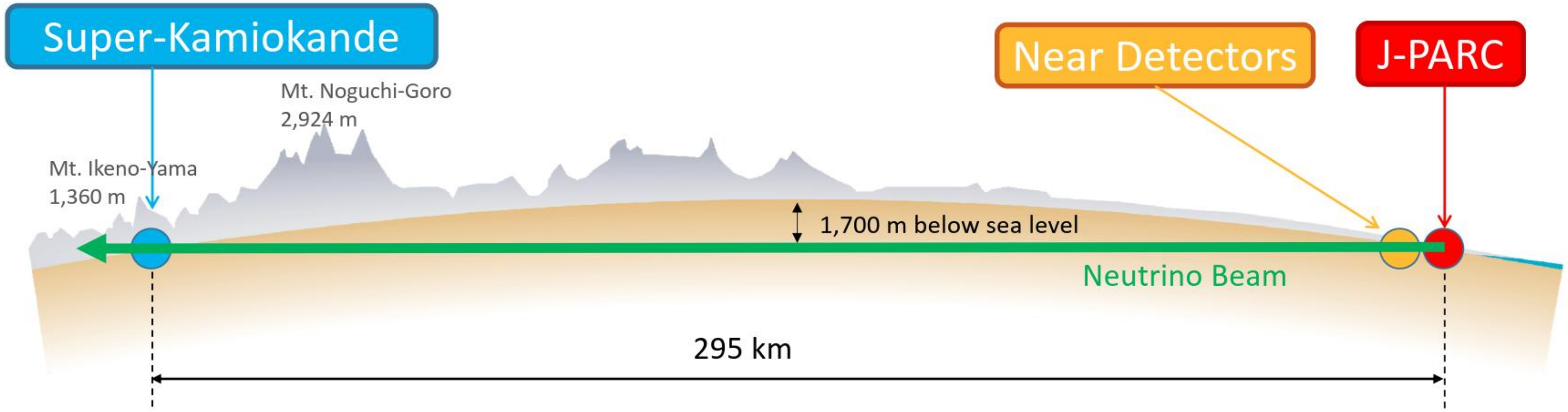






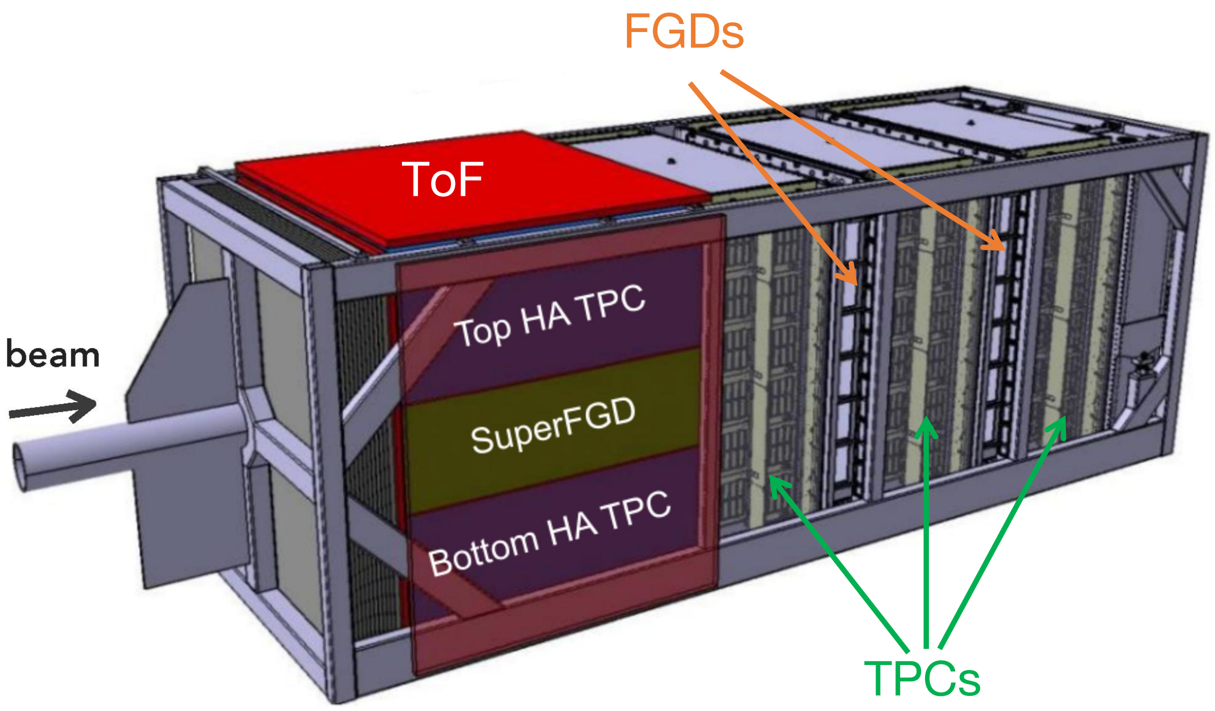


https://arxiv.org/pdf/1211.0469.pdf



- Long-baseline experiment (295 km)
- Near detectors (ND280, INGRID, WAGASCI-BabyMIND) at 280m from J-PARC
- E_ν peaks at 0.6 GeV at ND280 (2.5° off-axis)

Near Detector ND280 Upgrade



- Super-FGD is made of about 2 million scintillator cubes
- It provides a position resolution of about 1 cm and timing resolution less than 1 ns
- HA-TPC provides better reconstruction of particles traveling at higher angles
- TOF, with timing resolution around 150 ps, along with SFGD can differentiate between incoming and outgoing particles

Event Rate Calculation

Number of ν_e events at Super-Kamiokande

$$N(E_{reco}) = \int dE_{true} P(\nu_\mu \to \nu_e)(E_{true}) \sigma(E_{true}) \Phi(E_{true}) S(E_{true}, E_{reco})\, \epsilon(E_{true})$$

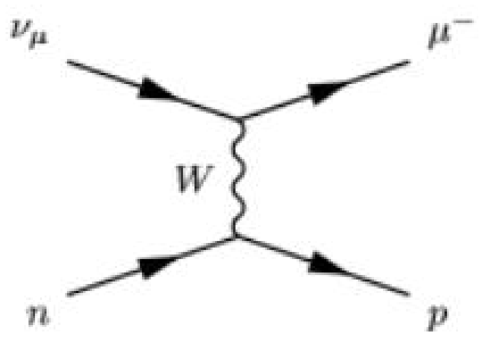
$N(E_\nu)$ = Event rate
$P(\nu_\mu \to \nu_e)(E_\nu)$ = Oscillation probability
$\sigma(E_\nu)$ = Interaction cross-section
$\Phi(E_\nu)$ = Neutrino flux
S(E_{true} , E_{reco}) = Smearing matrix
$\epsilon(E_\nu)$ = Detector efficiency

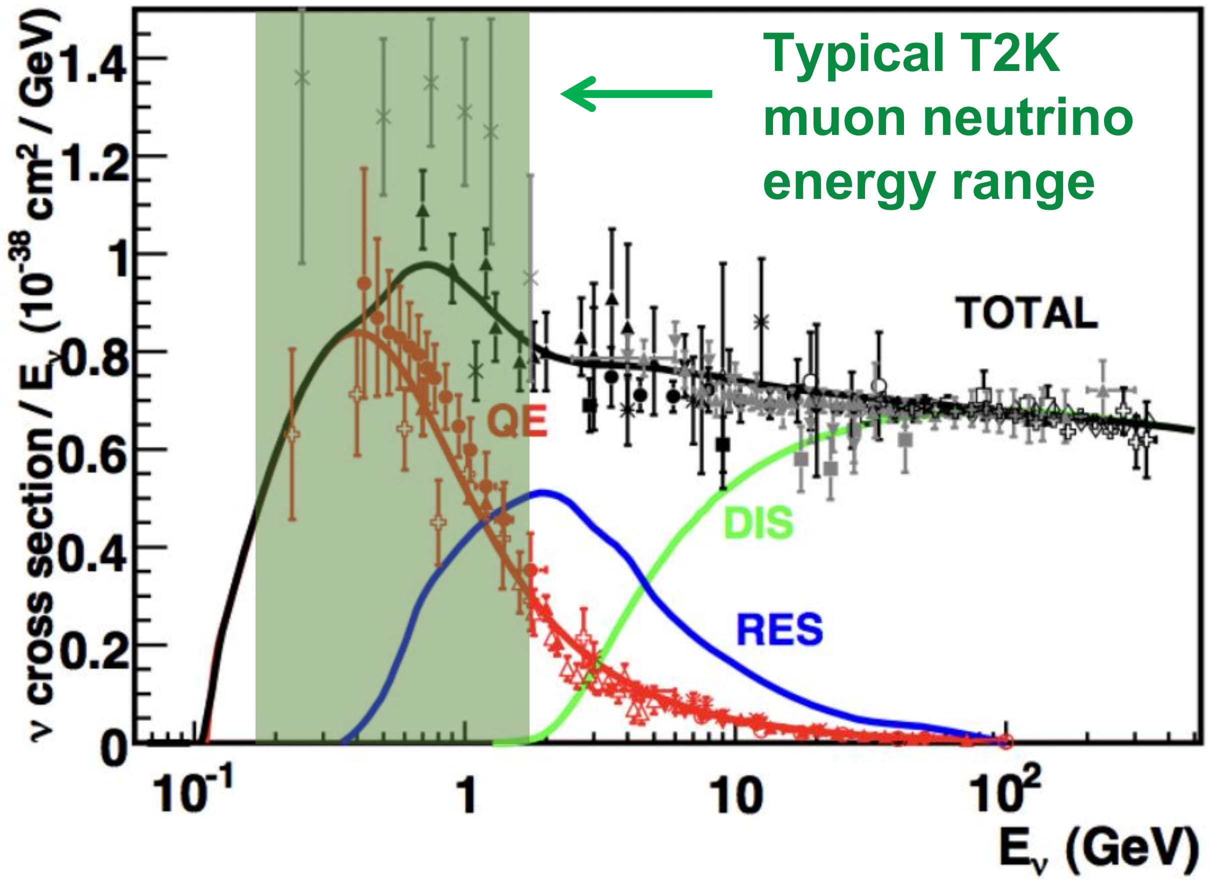
Reconstructed energy can be different from true energy

Neutrino-nucleus interaction models

Neutrino-Nucleus Interactions

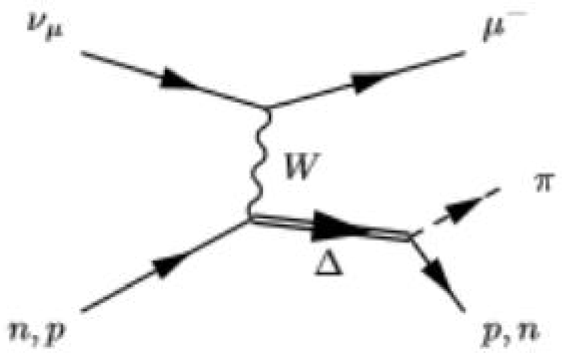
Quasi-Elastic Scattering (CCQE)



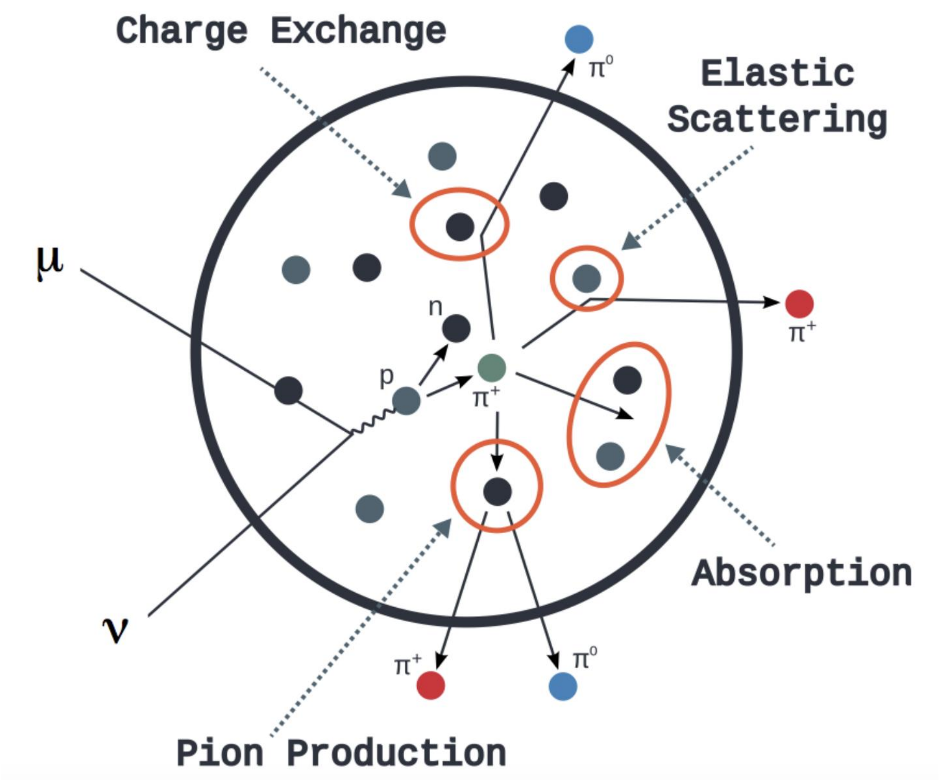


https://publications.anl.gov/anlpubs/2012/06/73380.pdf

Delta Resonance



Final State Interactions (FSI)



- Particles produced after neutrino-nucleus interaction can undergo FSI.
- This makes identification of specific interactions in detector difficult.
- Identifying topology is a better choice as it reduces model dependence.

Some topologies:

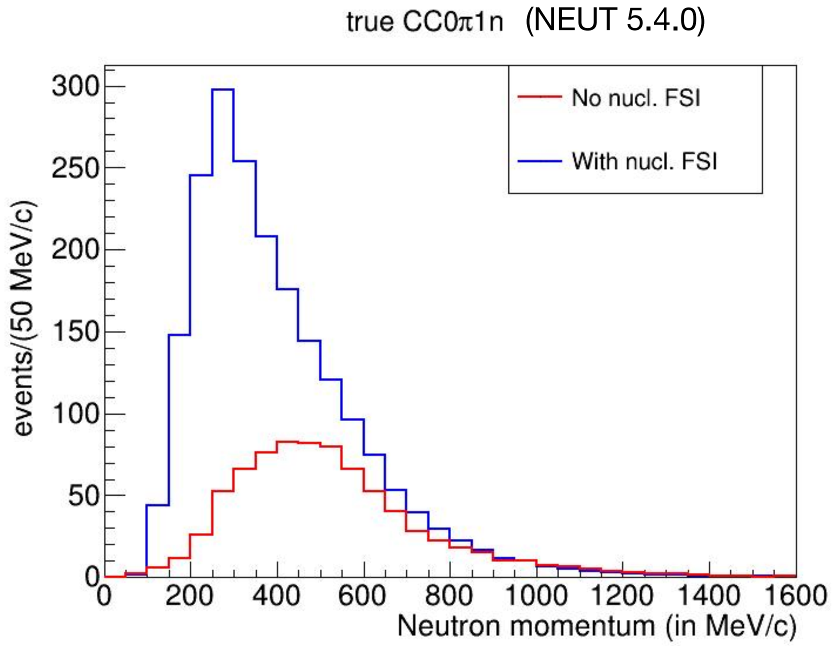
CC0π, CC1π, CC-multi π, **CC0π1n, CC0π0p1n, CC0π0pNn**

Interactions in CC0π1n Topology

CCQE ($\nu_\mu n \to \mu^- p$) : With FSI
2p2h ($\nu_\mu nn \to \mu^- np$) : With or without FSI
($\nu_\mu np \to \mu^- pp$) : With FSI
Delta resonance : With or without FSI

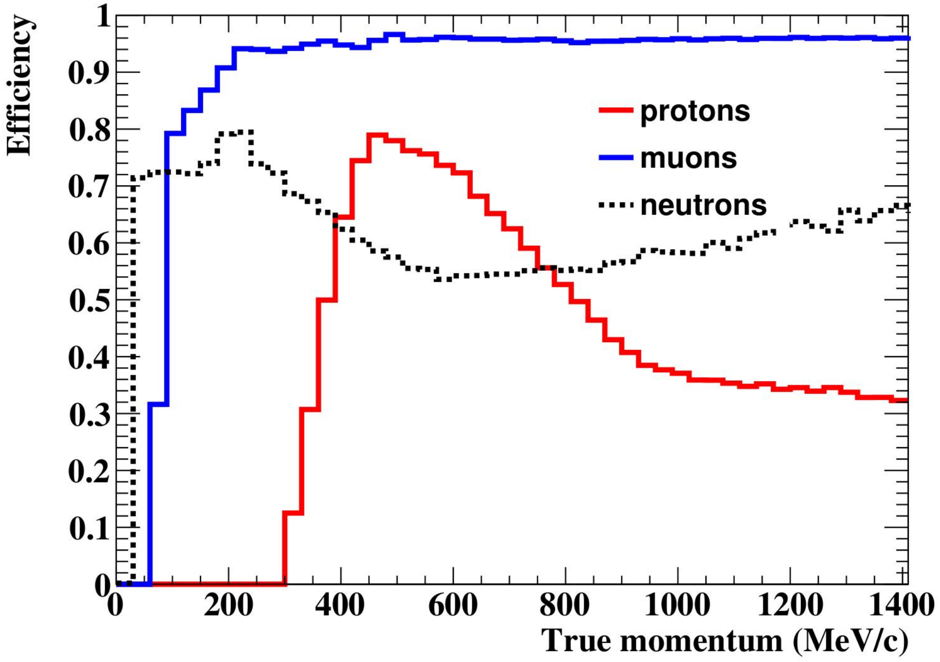
Type of interaction	% in CC0π1n (before FSI*)	% in CC0π1n (after FSI*)
CCQE	0%	58.98%
2p2h	50.33%	23.62%
Delta res.	48.59%	17.07%
Others	1.08%	0.33%

*FSI turned ON or OFF here is Nucleon FSI



- Large increase in events due to CCQE undergoing FSI
- CC0π1n topology can be used to test FSI models

Momentum based Cuts (Detector-based)

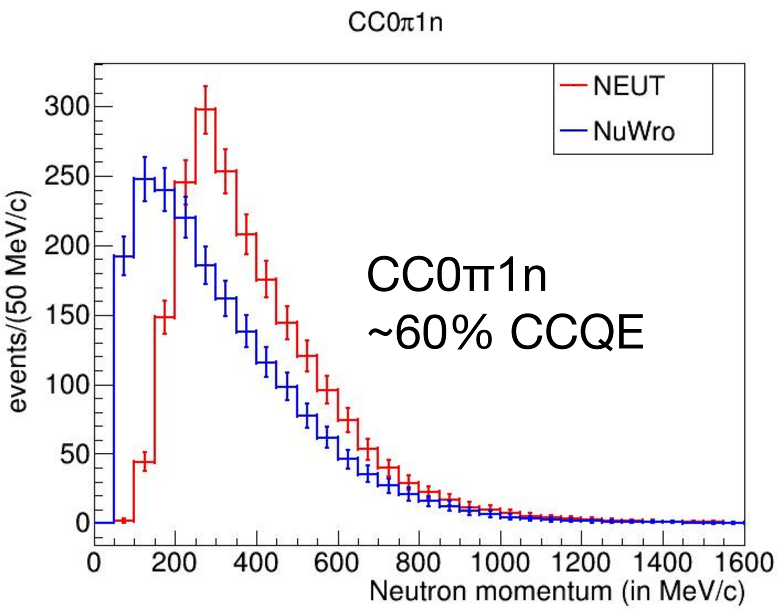


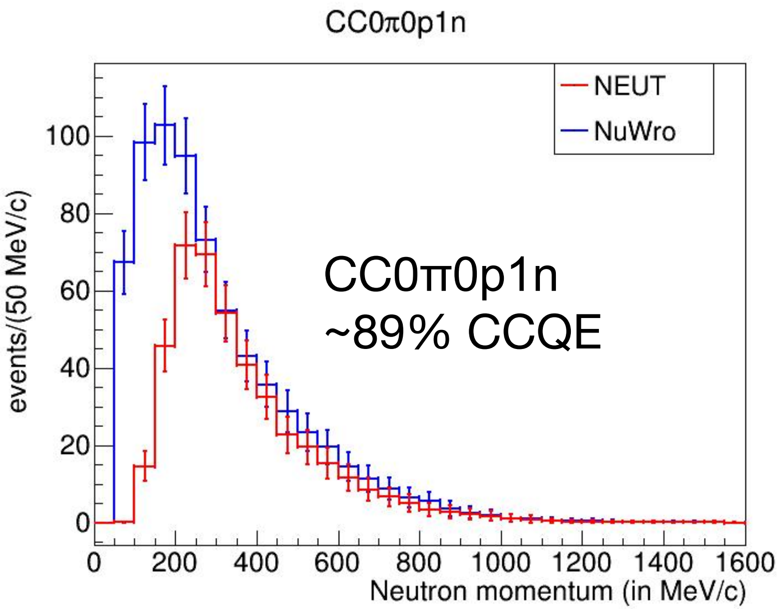
Phys Rev. D 105, 032010 (2022)

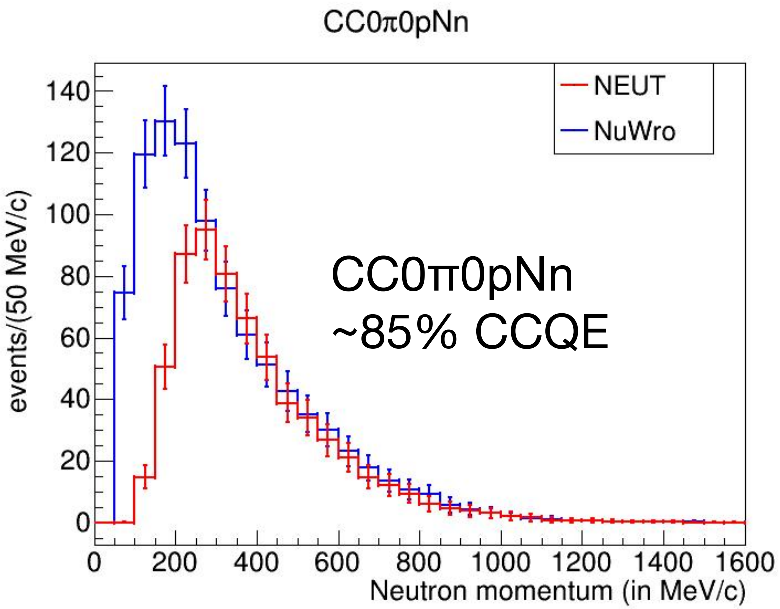
Momentum-based cuts:

- $p_\mu > 50$ MeV/c
- $p_n > 50$ MeV/c
- $p_p < 300$ MeV/c (in CC0p topology)

Comparison between NEUT and NuWro

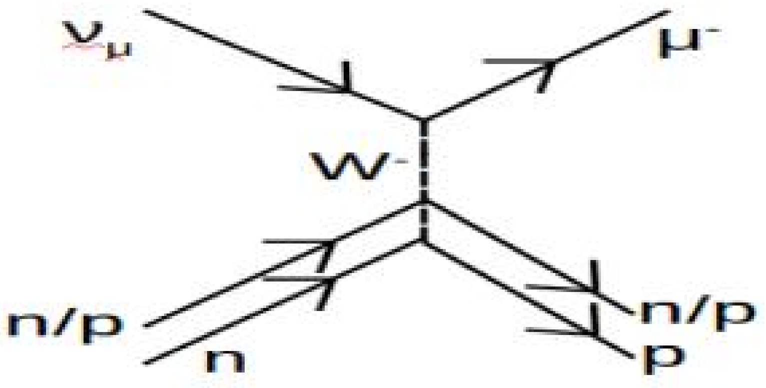






- All the CCQE events enter these topologies through FSI only.
- NEUT 5.4.0 and NuWro 19.02.1 have same CCQE models.
- These topologies can differentiate between FSI models in NEUT and NuWro using T2K data.

Neutron events in 2p2h



$$\nu_\mu nn \to \mu^- np$$

$$\nu_\mu np \to \mu^- pp$$

- Different models such as SuSAv2 and Valencia model 2p2h differently. Ref: Phys. Rev D 101, 033003 (2020)
- One of the difference is in number of nn/np initial state pairs.
- This affects the number of events with neutrons in the final state, i.e. affects topologies CC0π0n and CC0πNn.
- Since protons deposit more energy in general, this also effects the deposited energy distribution.

Neutrons in antineutrino interactions

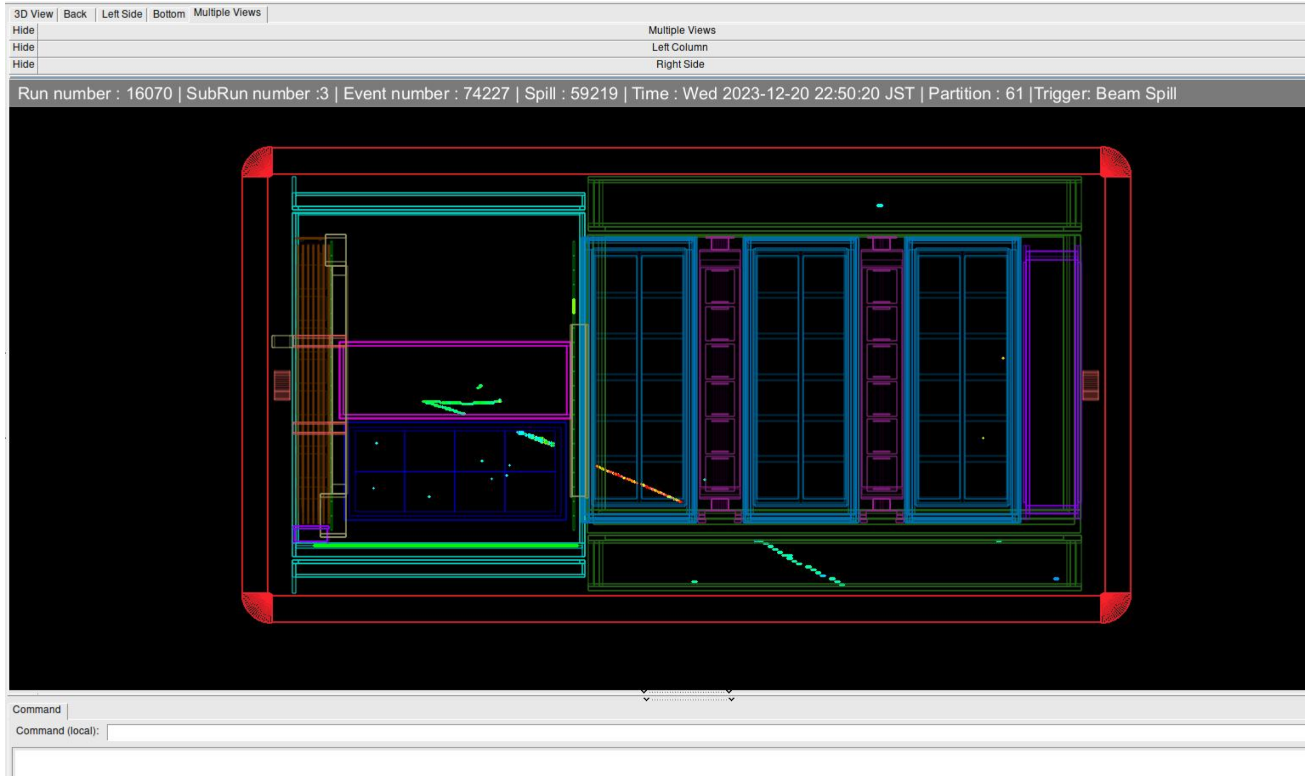
Detecting neutrons is extremely important to measure antineutrino interaction cross-sections.

Some interactions:

CCQE ($\overline{\nu}_\mu p \rightarrow \mu^+ n$) (dominant interaction)
2p2h ($\overline{\nu}_\mu np \rightarrow \mu^+ nn$)
($\overline{\nu}_\mu pp \rightarrow \mu^+ np$)
Delta resonance : With or without FSI

Modeling antineutrino cross-sections is connected to understanding CP violation (neutrinos and antineutrinos oscillate at the same rate or not).

NEUTRON SELECTION (IN PROGRESS)



A track with muon signature

A blip/cluster away from the interaction vertex

Distance of the cluster from the vertex

Timing of the cluster (to remove photon candidates, background)

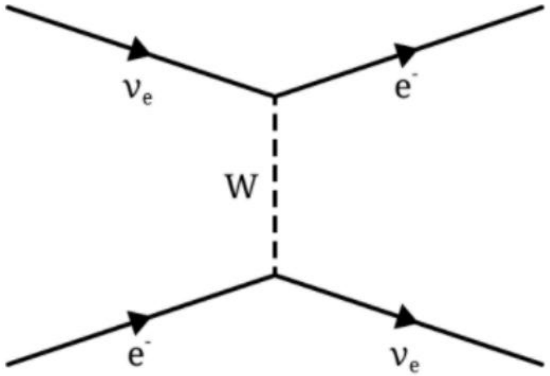
Summary

- ND280 upgrade has made **reconstruction of particles with shorter tracks** or smaller energies even better.
- Using CC0π1n and CC0π0p1n/Nn topologies, **60 to 90% of CCQE purity** is achievable.
- These topologies can be instrumental in **testing FSI models** since CCQE in these topologies enters **only through FSI**.
- Neutrons are important to test 2p2h models and measure antineutrino cross-sections too.
- Neutron selection is the next step and its development is in progress.

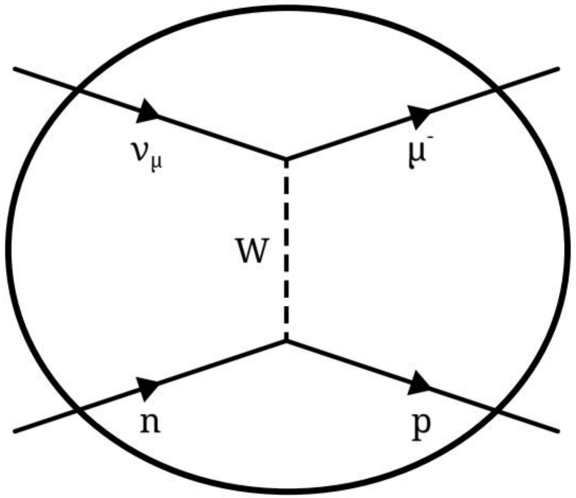
Thanks for your attention!

Backup

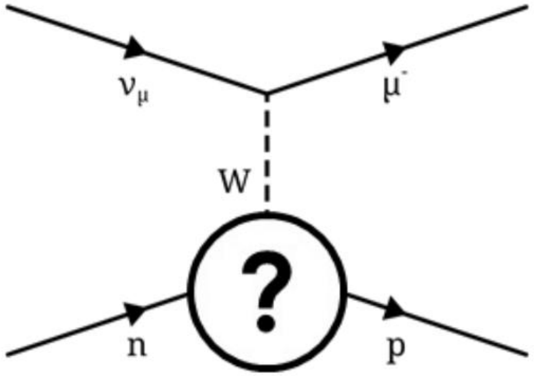
Interaction Modeling



Point-like: Masters homework problem



Nucleon: mostly harmless

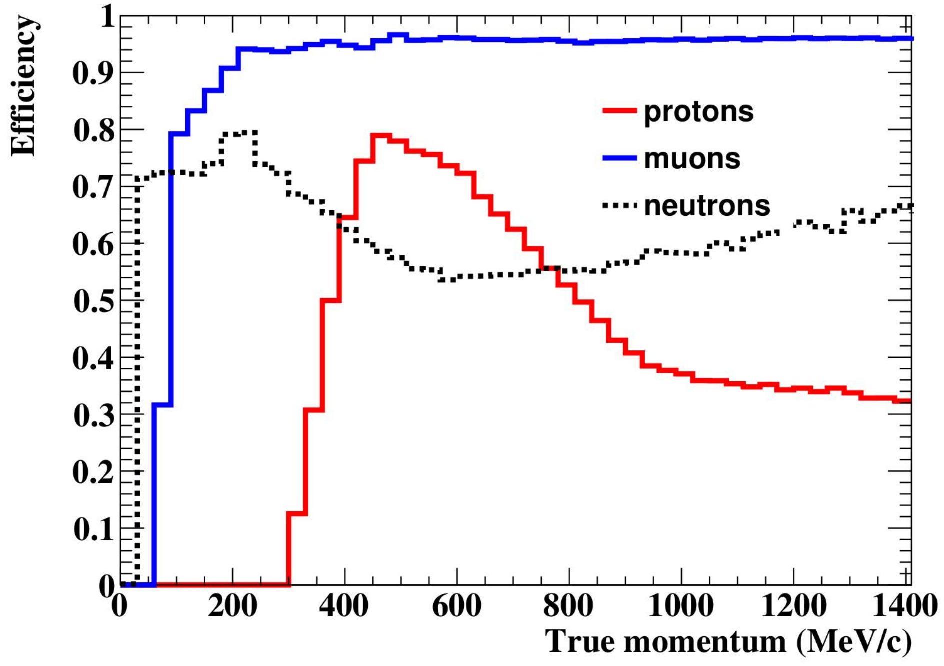


Nucleus: very hard

- Nuclear effects (Fermi motion, Pauli blocking, nucleon-nucleon correlations)
- Final State Interactions

S. Dolan, NuSTEC Summer School 2024

CUTS AND SCALING



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Momentum-based cuts:

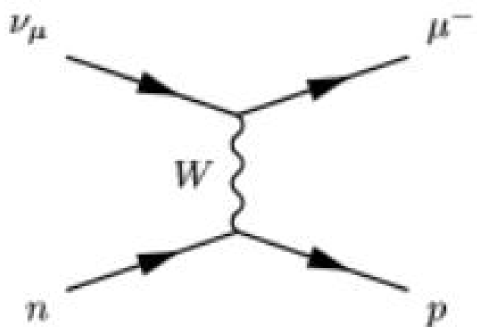
- muon momentum > 50 MeV/c
- neutron momentum > 50 MeV/c
- proton momentum < 300 MeV/c (in CC0p topology)

Scaling:

- Scaled to 2E20 PoT (corresponding to Dec 2023 run)
- 50% scaling of events (based on comparison between NEUT 5.4.0 and values given in arXiv for CC0π topology)

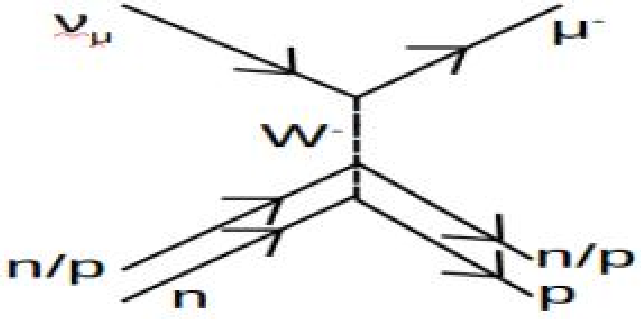
NEUTRINO-NUCLEUS INTERACTIONS

Quasi-Elastic Scattering (CCQE)



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

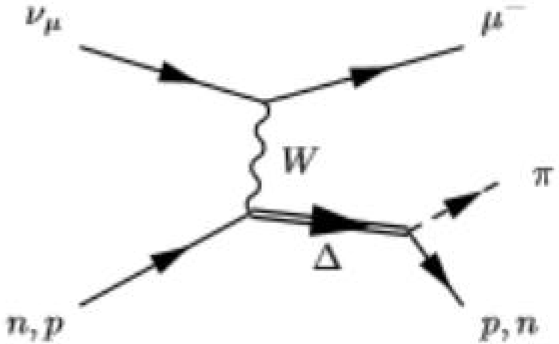
Two-particle two-hole process (2p2h)



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

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

Delta Resonance



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

$$\rightarrow \mu^- \pi^0 p$$

$$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- \pi^+ p$$

PONTECORVO- MAKI-NAKAGAWA-SAKATA (PMNS) MATRIX

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & \text{PMNS} & \\ & \text{matrix} & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix} P \, . \end{aligned}$$

- PMNS matrix describes mixing between flavour states and mass states
- Six parameters in PMNS matrix

  $(\boldsymbol{\theta_{23}}, \boldsymbol{\theta_{13}}, \boldsymbol{\delta_{CP}}, \theta_{12}, \ \alpha_1, \alpha_2)$

  ↑

  T2K is sensitive to these three parameters

$$P_{\mathrm{Majorana}} = \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- CP phase (or "Dirac phase") δ_{CP}: a measure of asymmetry between neutrino and antineutrino oscillations

- Majorana phase (α_1, α_2): Plays a role in neutrinoless double beta decay but not in neutrino oscillations

Definition of χ^2

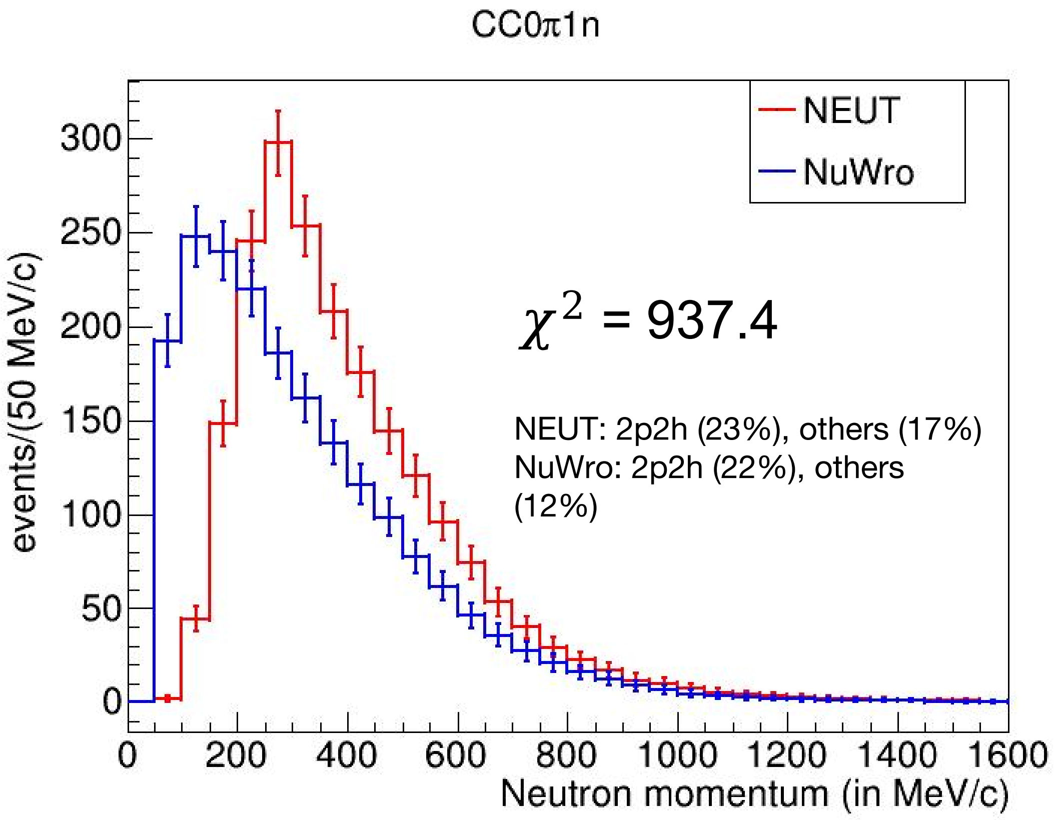
$\chi^2 = \sum_i \frac{(neut_i - nuwro_i)^2}{\sigma_i^2}$, i is the bin number

$\sigma^2_{neut(i)} = neut_i$, $\sigma^2_{nuwro(i)} = nuwro_i$

$$\sigma_i^2 = \frac{\sigma^2_{neut(i)} + \sigma^2_{nuwro(i)}}{2} = \frac{neut_i + nuwro_i}{2}$$

uncertainty = square root of bin content (i.e., statistical uncertainties)

CC0π1n (pneut > 50 MeV/c, pmu > 50 MeV/c)



χ^2 = 937.4

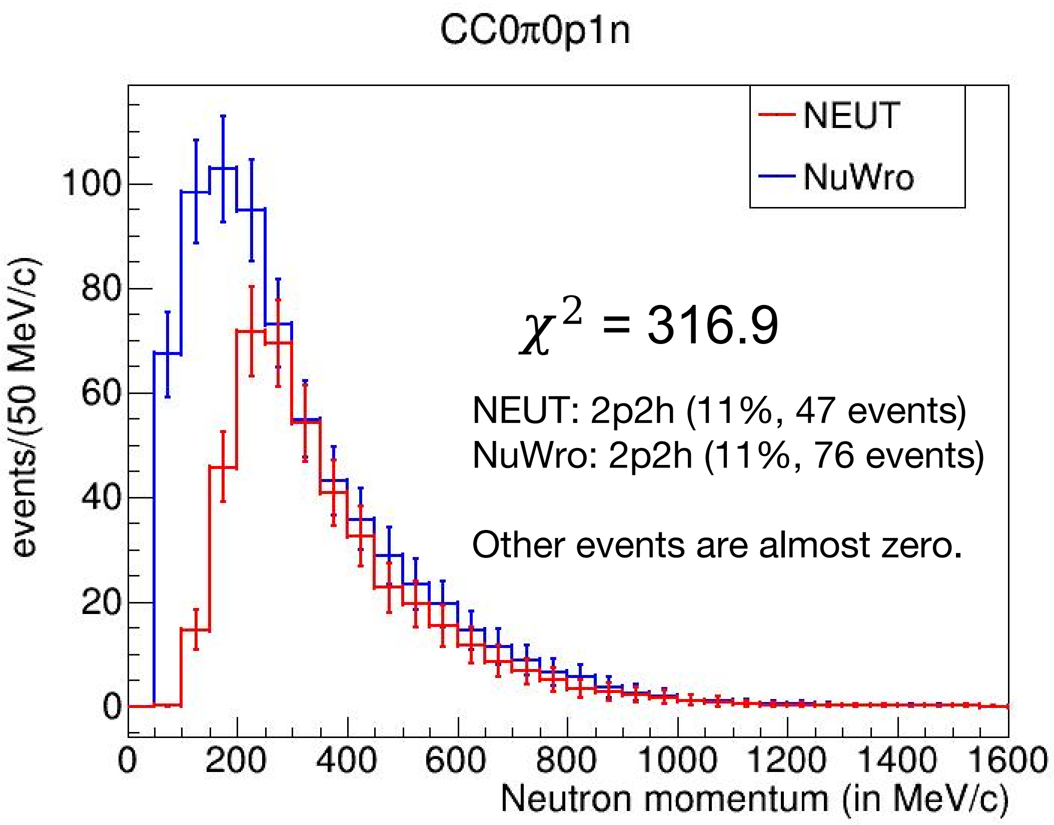
NEUT: 2p2h (23%), others (17%)
NuWro: 2p2h (22%), others (12%)

Entries in the table: total number of events (% of QE, number of QE events)

Topology (χ^2)	NEUT 5.4.0	NuWro 19.02.1
CC0pi1n (937.4)	2019.05 (59.15% QE, 1194.32)	1928.79 (65.43% QE, 1261.98)
CC0pi0p1n (316.9)	431.34 (88.95% QE, 383.68)	700.52 (89.07% QE, 623.98)
CC0pi0pNn (399.4)	628.81 (84.93% QE, 534.03)	935.20 (85.04% QE, 795.28)

The difference here is primarily due to FSI.

CC0π0p1n (pprot < 300 MeV/c, pneut > 50 MeV/c, pmu > 50 MeV/c)



χ^2 = 316.9

NEUT: 2p2h (11%, 47 events)
NuWro: 2p2h (11%, 76 events)

Other events are almost zero.

Entries in the table: total number of events (% of QE, number of QE events)

Topology (χ^2)	NEUT 5.4.0	NuWro 19.02.1
CC0pi1n (937.4)	2019.05 (59.15% QE, 1194.32)	1928.79 (65.43% QE, 1261.98)
CC0pi0p1n (316.9)	431.34 (88.95% QE, 383.68)	700.52 (89.07% QE, 623.98)
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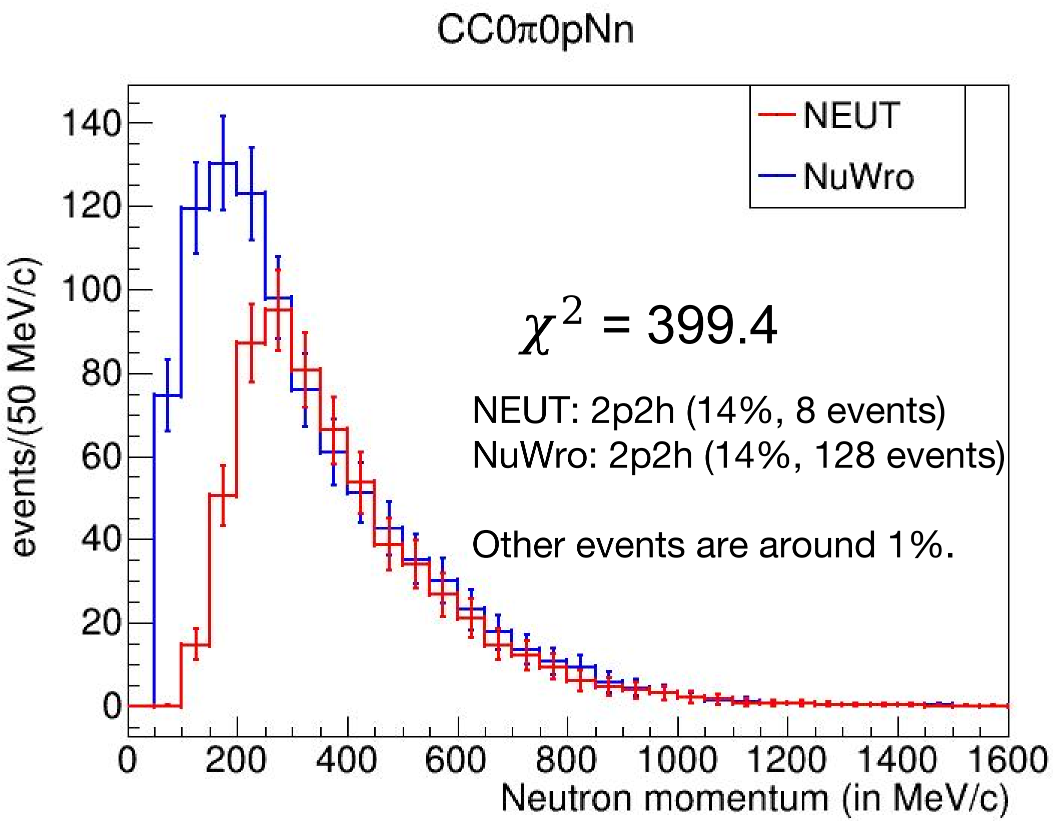
CC0π0pNn (pprot < 300 MeV/c, pneut > 50 MeV/c, pmu > 50 MeV/c)



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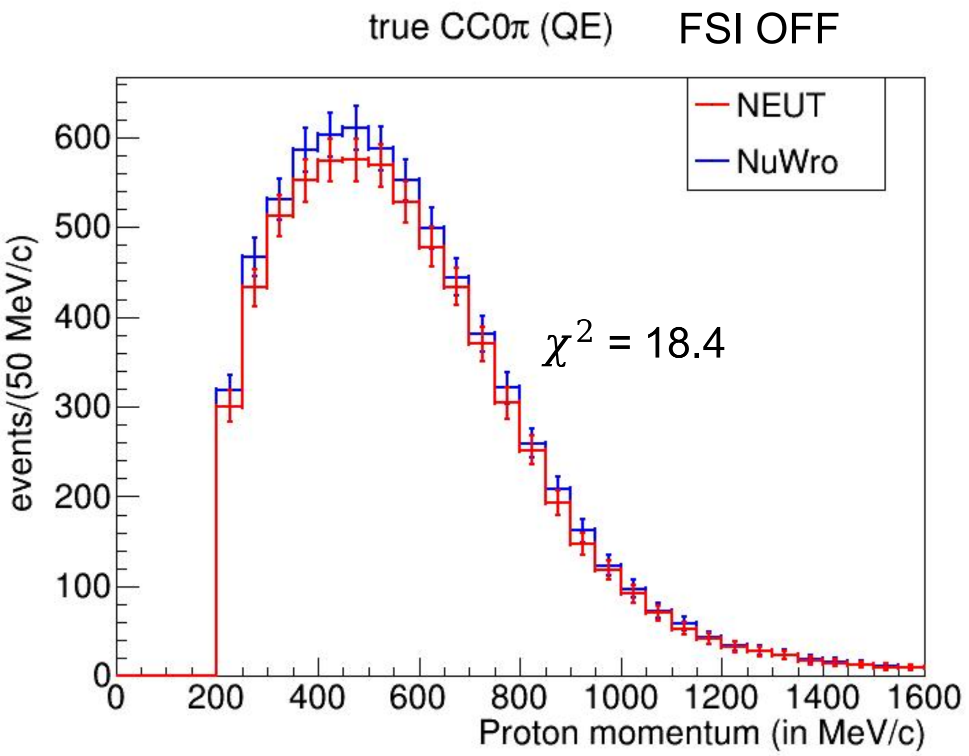
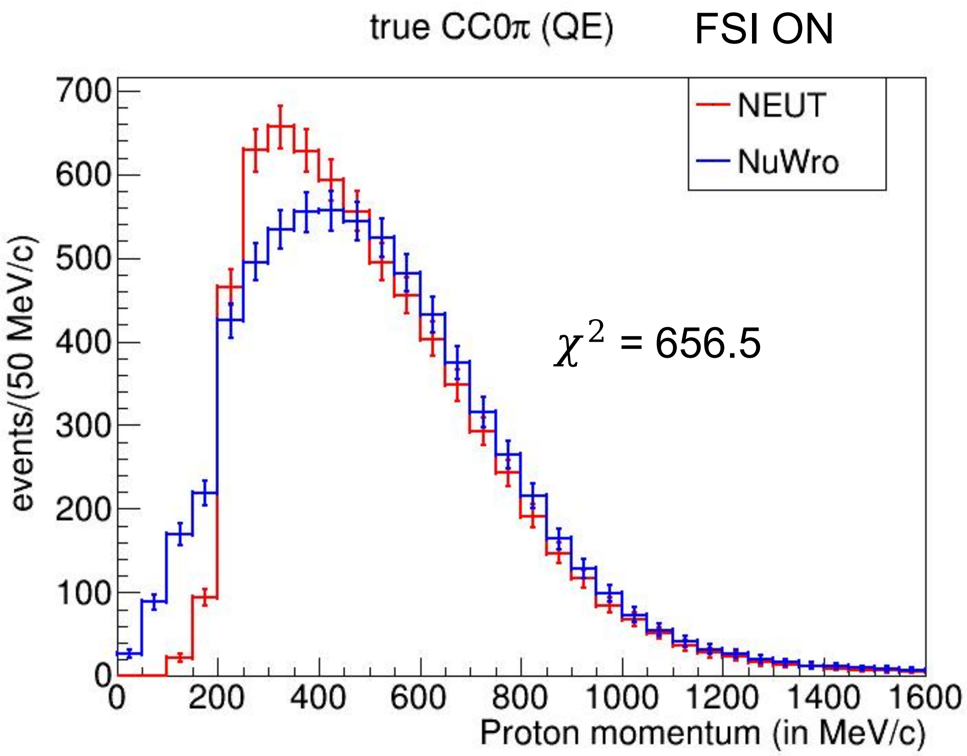
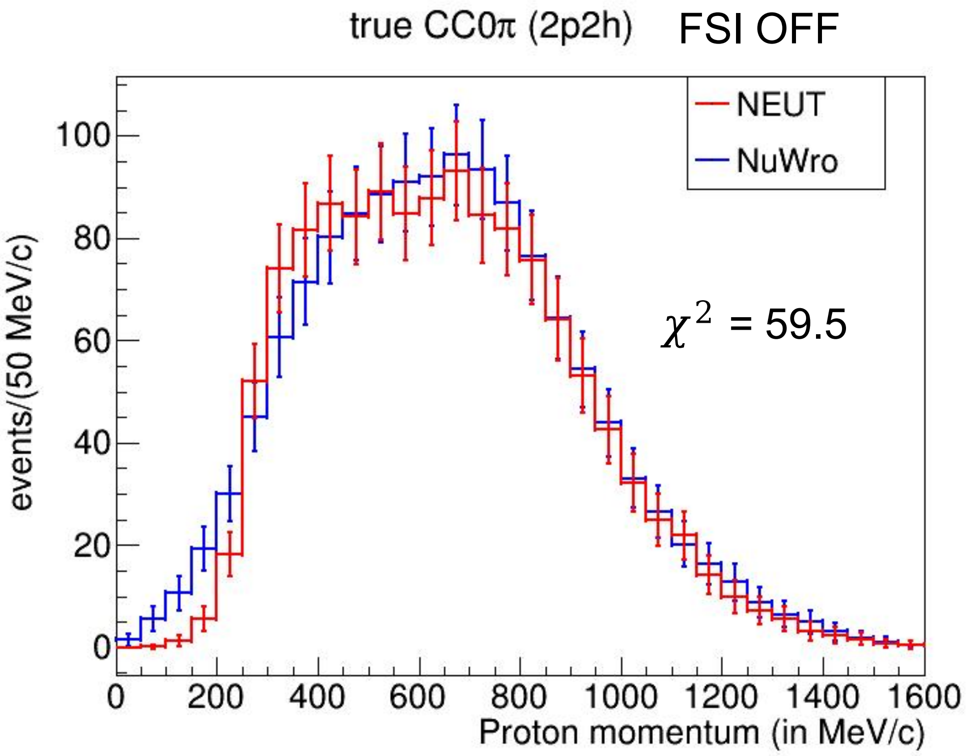
The difference here is primarily due to FSI.

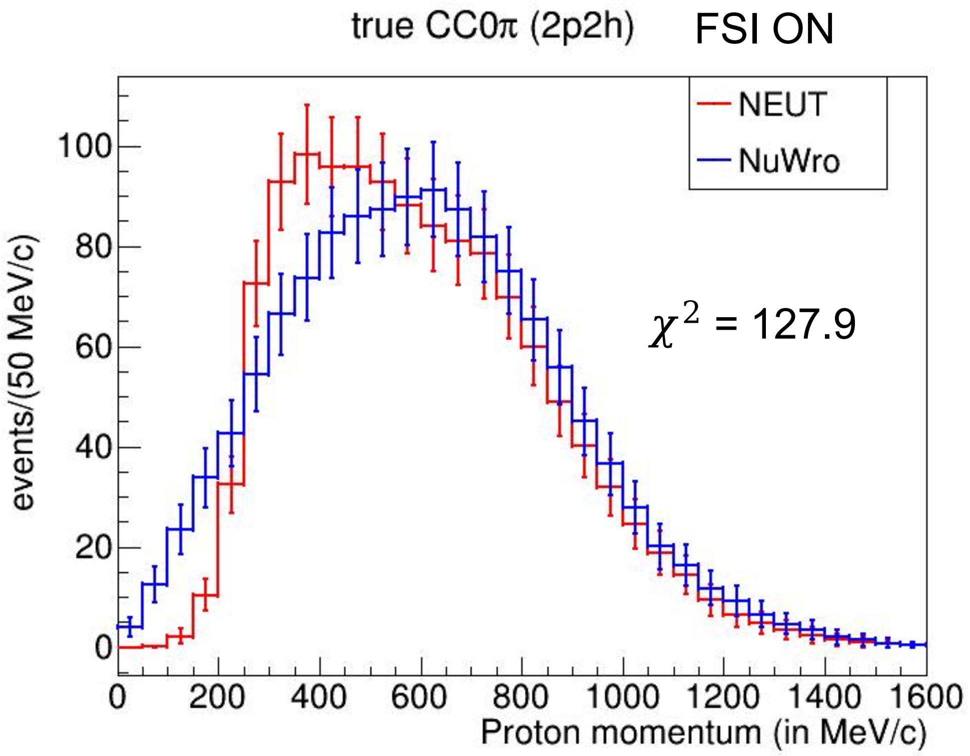
True CC0π (QE)


true CC0π (QE)
FSI OFF
NEUT
NuWro
χ^2 = 18.4
events/(50 MeV/c)
Proton momentum (in MeV/c)

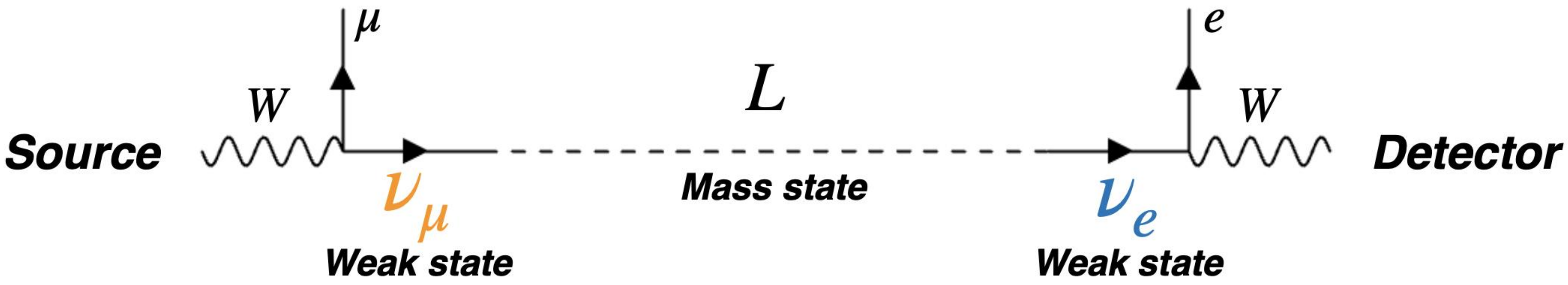

true CC0π (QE)
FSI ON
NEUT
NuWro
χ^2 = 656.5
events/(50 MeV/c)
Proton momentum (in MeV/c)

True CC0π (2p2h)





Neutrino Oscillations

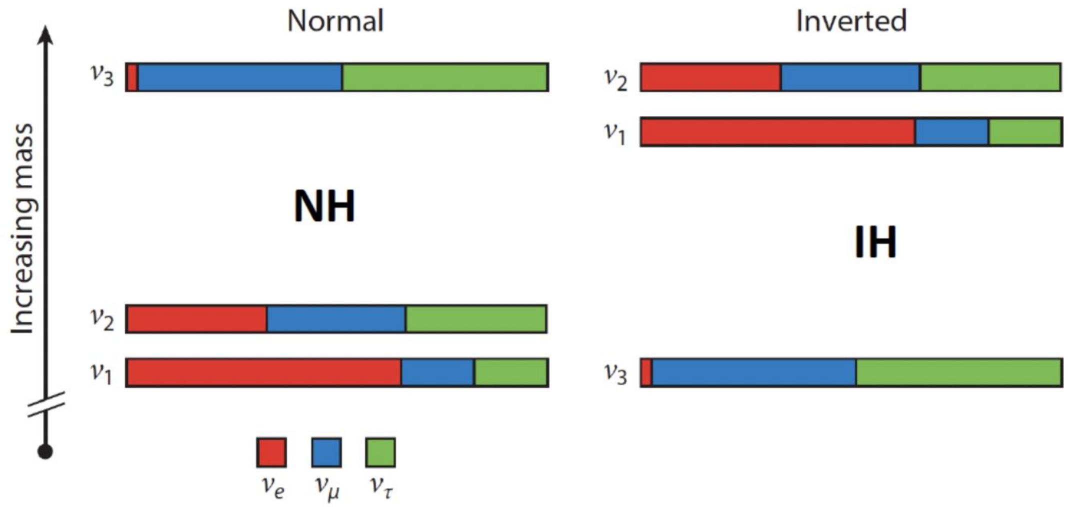


- Neutrinos produced in a specific flavor state (ν_μ) with energy E
- After traveling a distance L,

  ν_μ decrease in number $\Longrightarrow$ ν_μ disappearance
  ν_e increase in number $\Longrightarrow$ ν_e appearance

- Sensitivity to maximum oscillation depends on L/E

Neutrino Mass Ordering



https://arxiv.org/pdf/1610.05533.pdf

MINERvA Multi-Neutron Results

2p2h dominant selection

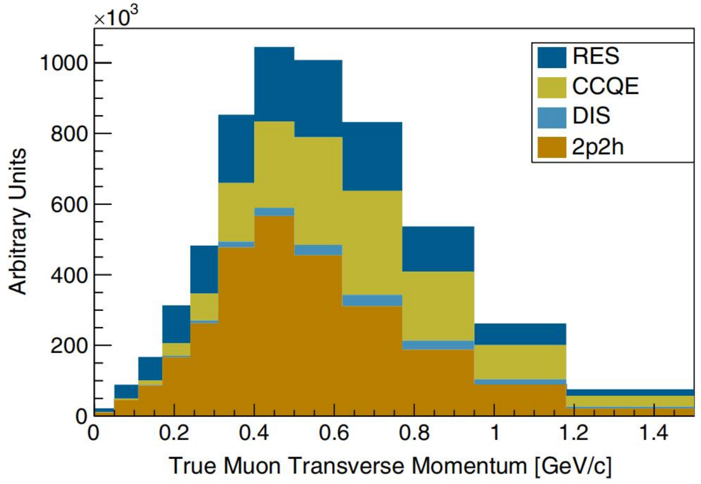


FIG. 1. Multineutron antineutrino interactions with $E_{\text{available}}$ less than 100 MeV predicted by the main MINERvA Monte Carlo model, MnvTunev1, stacked by the interaction mode GENIE used to produce them. 2p2h and QE processes dominate across the full $p_{T\mu}$ range studied.

[Phys. Rev. D 108, 112010 (2023)]

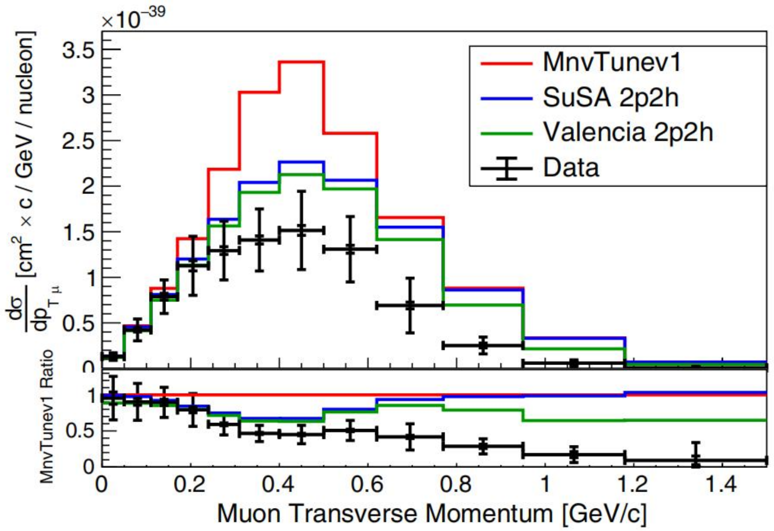


FIG. 9. Cross section for an antineutrino to produce multiple neutrons in the final state and no more than 100 MeV of available energy. The black data points are the result extracted from data using MnvTunev1 MC. Inner error bars show statistical uncertainty, and outer error bars show the full uncertainty on each data point. The colored lines are cross section predictions from various MC models available as reweights of MINERvA MC. The bottom panel shows the ratio of each cross section to MnvTunev1. The data points in this figure are included in Table I in Appendix A. Table II provides the covariance matrix between these data points.

There is a discrepancy between data and MC.

Sensitivity to 2p2h and FSI.

In the high momentum region, 2p2h contributions are expected to be small.

FSI could be a driving factor and needs to be explored.