# Studies of Multi-Nucleon Processes at T2K

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# Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$S_{23} = \sin(\theta_{23})$, $C_{13} = \cos(\theta_{13})$, etc.

Three neutrino flavors can oscillate in to each other via the PMNS mixing matrix

- Matrix characterized by three independent mixing angles ($\theta_{12}$,$\theta_{13}$, $\theta_{23}$) and one CP-violating phase, $\delta_{CP}$
- Two mass splittings have been measured: $|\Delta m^2_{21}|$ and $|\Delta m^2_{32}|$

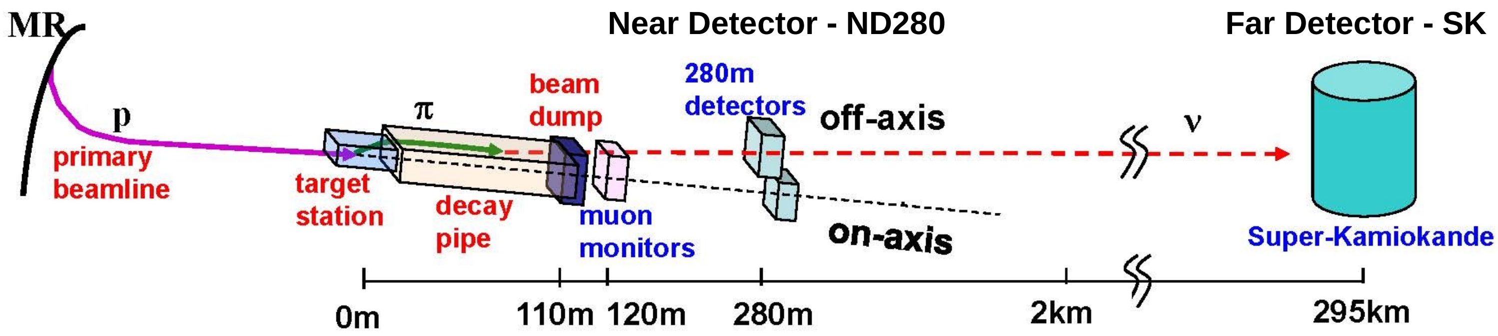
| Parameter | best-fit ($\pm 1\sigma$) | $3\sigma$ |
|---|---|---|
| $\Delta m^2_{21}$ [$10^{-5}$ eV $^2$] | $7.54^{+0.26}_{-0.22}$ | $6.99 - 8.18$ |
| $\lvert\Delta m^2\rvert$ [$10^{-3}$ eV $^2$] | $2.43 \pm 0.06$ $(2.38 \pm 0.06)$ | $2.23 - 2.61$ $(2.19 - 2.56)$ |
| $\sin^2\theta_{12}$ | $0.308 \pm 0.017$ | $0.259 - 0.359$ |
| $\sin^2\theta_{23}$, $\Delta m^2 > 0$ | $0.437^{+0.033}_{-0.023}$ | $0.374 - 0.628$ |
| $\sin^2\theta_{23}$, $\Delta m^2 < 0$ | $0.455^{+0.039}_{-0.031}$, | $0.380 - 0.641$ |
| $\sin^2\theta_{13}$, $\Delta m^2 > 0$ | $0.0234^{+0.0020}_{-0.0019}$ | $0.0176 - 0.0295$ |
| $\sin^2\theta_{13}$, $\Delta m^2 < 0$ | $0.0240^{+0.0019}_{-0.0022}$ | $0.0178 - 0.0298$ |
| $\delta/\pi$ ($2\sigma$ range quoted) | $1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$ | $(0.00 - 0.16) \oplus (0.86 - 2.00)$ |
| | | $((0.00 - 0.02) \oplus (0.70 - 2.00))$ |

PDG 2014

Want to measure $\sin^2(\theta_{23})$ more precisely.

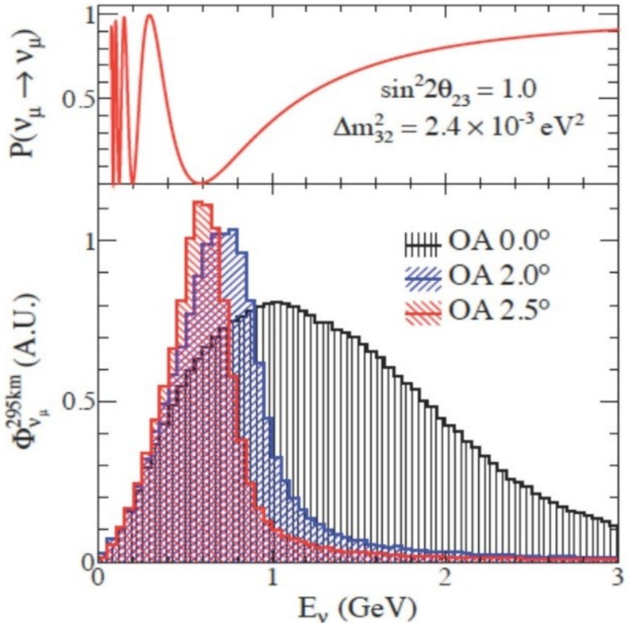
Want to know if $\delta_{CP}$ is non-zero.

# T2K (Tokai to Kamioka)




The T2K experiment is an off-axis long baseline neutrino oscillation experiment.

- High intensity muon neutrino beam is directed from J-PARC to the Super-Kamiokande (SK) detector at an angle of 2.5 degrees from the beam axis.
- Off-Axis angle creates a narrow neutrino energy band.
- Observe characteristic deficit of muon neutrino events at the far detector (SK) to detect oscillation of muon disappearance.

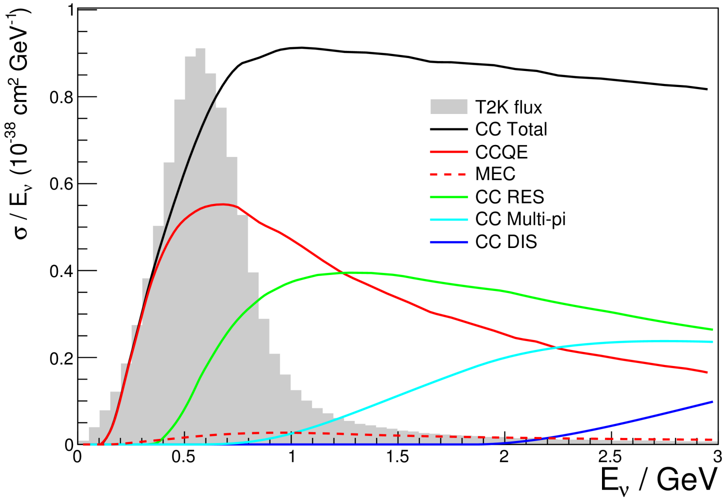


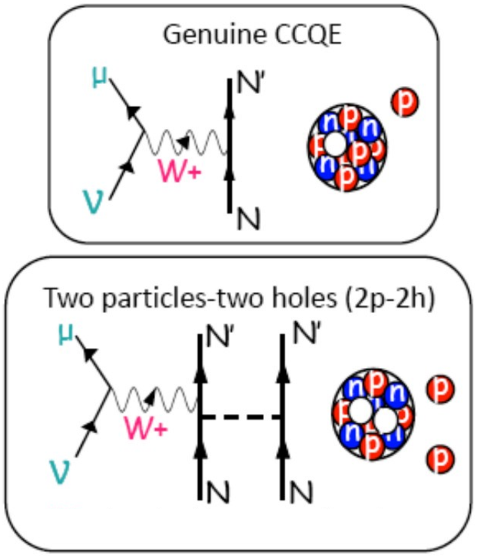

PRD 88, 032002 (2013)

# Neutrino Cross Sections

At the energy band of T2K, neutrino – nucleus interactions are predominately Charged Current Quasi-Elastic (CCQE)

- Contains a significant CC Resonant piece
- Contains other interactions such as multi-nucleon processes




Picture by M. Martini

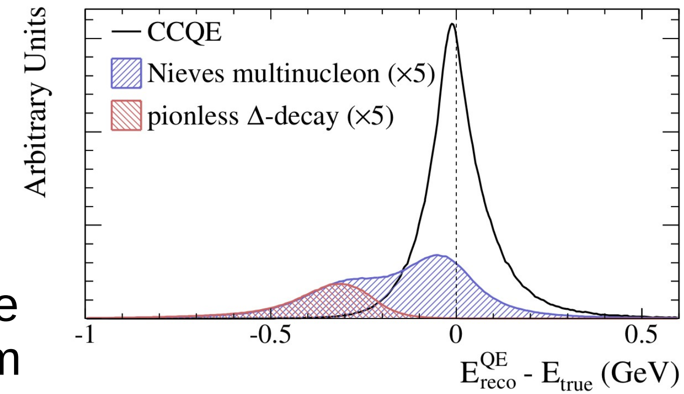
What are multi-nucleon processes? The incident neutrino can interact with two (or more) nucleons at the same time instead of just one.

- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)

# Multi-Nucleon Processes

These multi-nucleon processes can produce several different effects such as:

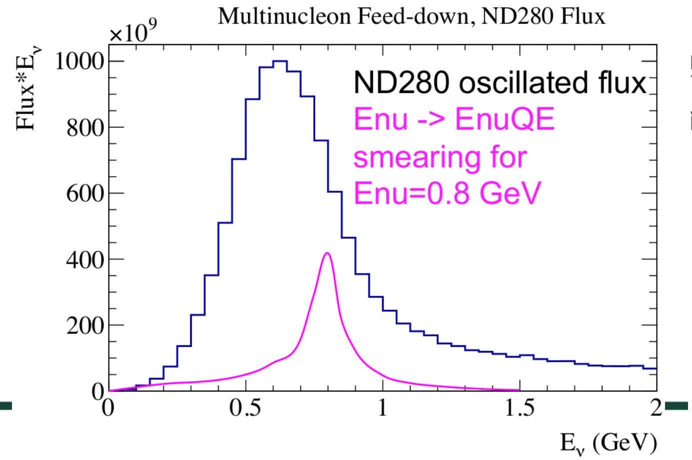
- Enhancement of number of events
- Biasing of reconstructed neutrino energy

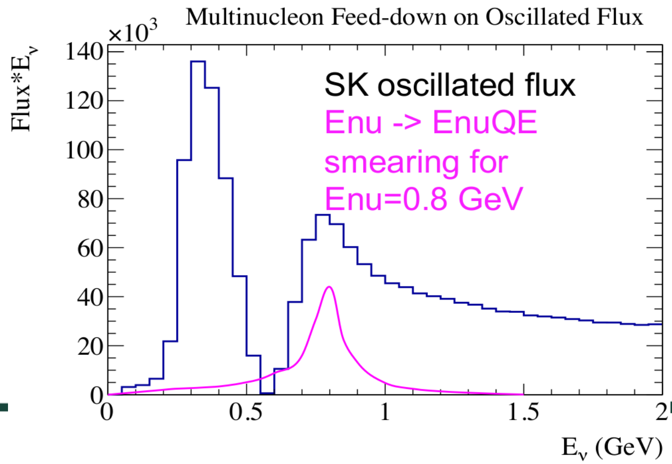



T2K collab PRL 112, 181801 (2014)

The smearing of reconstructed energy can cause neutrino events to feed down in the flux spectrum for muon neutrino disappearance.

These feed down events can overlap with the oscillation dip and change the extracted oscillation parameters.



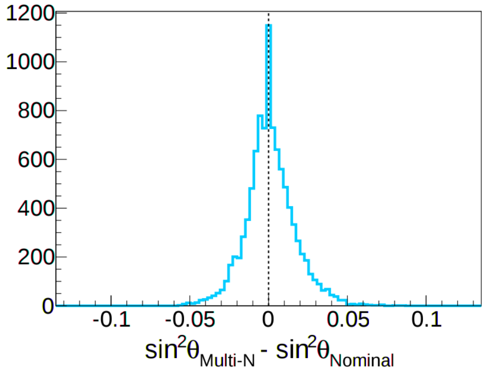
# Oscillation Measurements

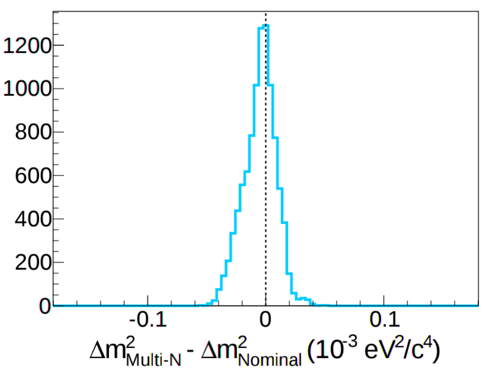
Multi-nucleon processes can bias oscillation parameters such as $\theta_{23}$ and $|\Delta m^2_{32}|$

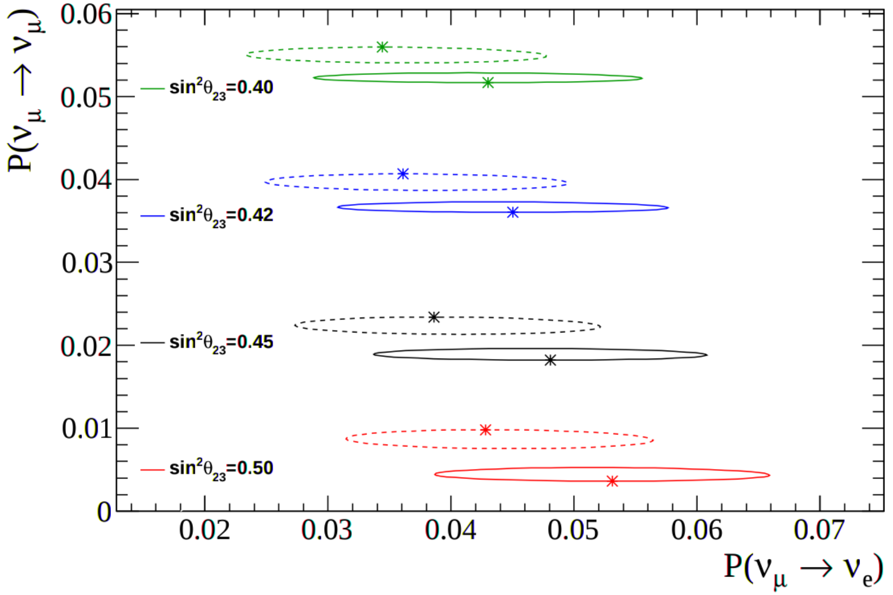
Changes in $\sin^2(\theta_{23})$ can change the muon neutrino disappearance probability and thus effect the measurement of $\delta_{CP}$ .

The variation of $\sin^2(\theta_{23})$ is currently estimated at the 3% level, which will become important as measurement precision improves.

Phys. Rev. D 91, 072010 (2015)




Solid (dashed) line for normal (inverted) hierarchy. Changes in $\delta_{CP}$ by moving along the contour. All other oscillation parameters fixed.

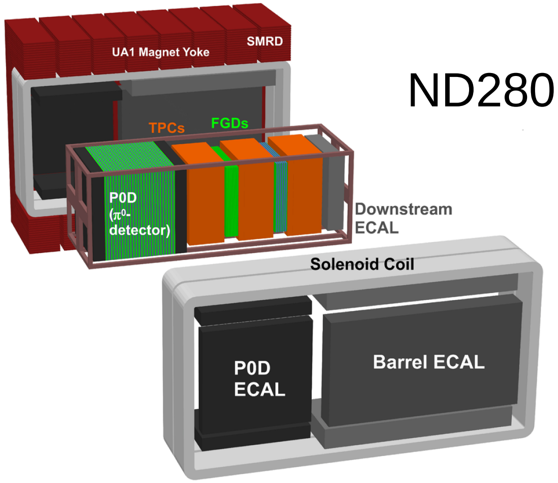
# Near and Far Detectors

Multi-nucleon processes can produce different effects depending on the flux and phase space.

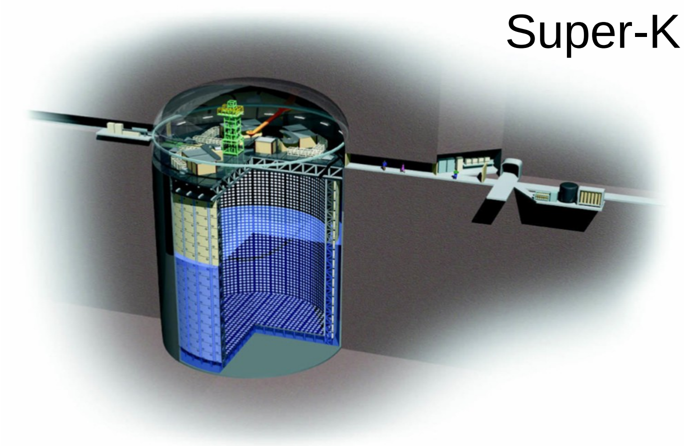
The near (ND280) and far (SK) detector have both different fluxes and measure different regions of phase space with separate efficiency.

- ND280 is a mostly forward detector
- Super-K is a $4\pi$ detector

So how do multi-nucleon processes differ between the near and far detector taking into account the differences?



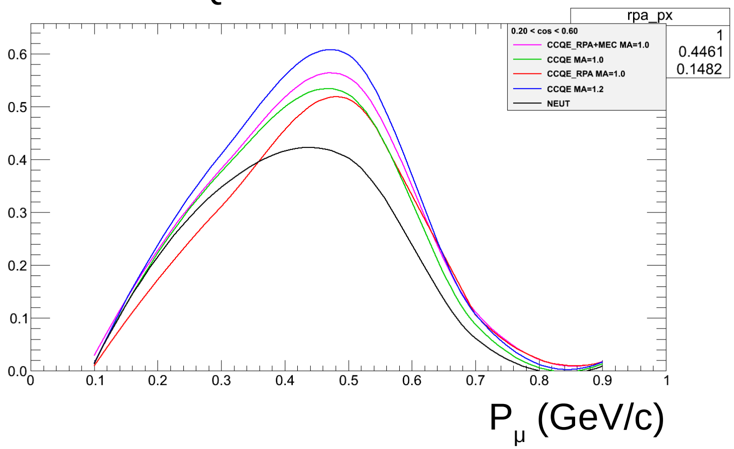

ND280



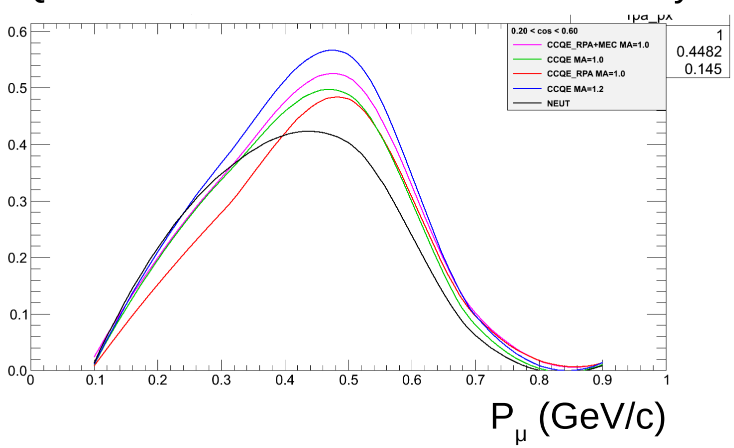
Super-K

# Meson Exchange Current

CCQE Cross Section




CCQE Cross Section with ND280 Efficiency




The process of an incident neutrino exciting two nucleons at the same time is commonly referred as meson exchange current (MEC).

MEC contributions also contain a process known as pion-less delta decay.

Studied the amount of MEC at both the near and far detector to see how they differ.

Quantified the amount of MEC in the CCQE cross section for muon neutrinos by integrating across the entire phase space.

$$\int \mathrm{d}\sigma_{MEC} = \int \mathrm{d}\sigma_{(CCQE+RPA+MEC)} - \int \mathrm{d}\sigma_{(CCQE+RPA)}$$

# Meson Exchange Current

**Muon Neutrino**

| Frac: | UnOsc Flux | ND280 Eff | Osc Flux | SK Eff |
|---|---|---|---|---|
| MEC | +0.154 | +0.151 | +0.180 | +0.177 |
| PDD | +0.073 | +0.070 | +0.083 | +0.083 |

**Muon Anti-Neutrino**

| Frac: | UnOsc Flux | ND280 Eff | Osc Flux | SK Eff |
|---|---|---|---|---|
| MEC | +0.241 | +0.240 | +0.265 | +0.274 |
| PDD | +0.090 | +0.091 | +0.11 | +0.114 |

$$\frac{\int \mathrm{d}\sigma_{MEC}}{\int \mathrm{d}\sigma_{CCQE}}$$

Table represents the total fraction of MEC present in the CCQE cross section for different incident flux and different detector efficiency.

The pion-less delta decay (PDD) piece of the MEC component is listed separately.

The fraction of MEC differs between detectors by 14 to 17% of the total for neutrinos, while differing 13 to 14% for anti-neutrinos.

The PDD differs by about 16 to 18% for neutrinos, 21 to 26% for anti-neutrinos.

# Conclusions

The T2K experiment currently uses measurements by the near detector combined with theoretical models to predict the amount of MEC at the far detector.

The results of these studies show that in the extrapolation from the near to far detector, some consideration must be made for the differences between the detectors.

The current level of uncertainty placed on the amount of MEC at the far detector is 100%.

The results also indicate that the extrapolation from near to far detector also may carry an uncertainty on the order of 20%.

Multi-nucleon processes are an interesting part of neutrino – nucleus cross sections and many improvements have been made in the past several years.