Study of neutrons produced in neutrino interactions with a water target at T2K

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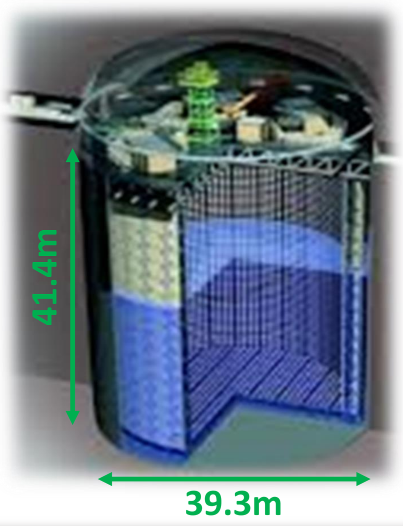
1. T2K experiment

- A long-baseline neutrino oscillation experiment in Japan [1]
- Primarily $\nu_\mu/\bar{\nu}_\mu$ 2.5° off-axis beam produced at J-PARC with peak energy of ~0.6 GeV
- Measurement of the beam neutrinos with the near detector complex located at 280 m and the Super Kamiokande (SK) far detector 295 km away from the beam source
- Have collected data for both ν- and ν̄-mode beam

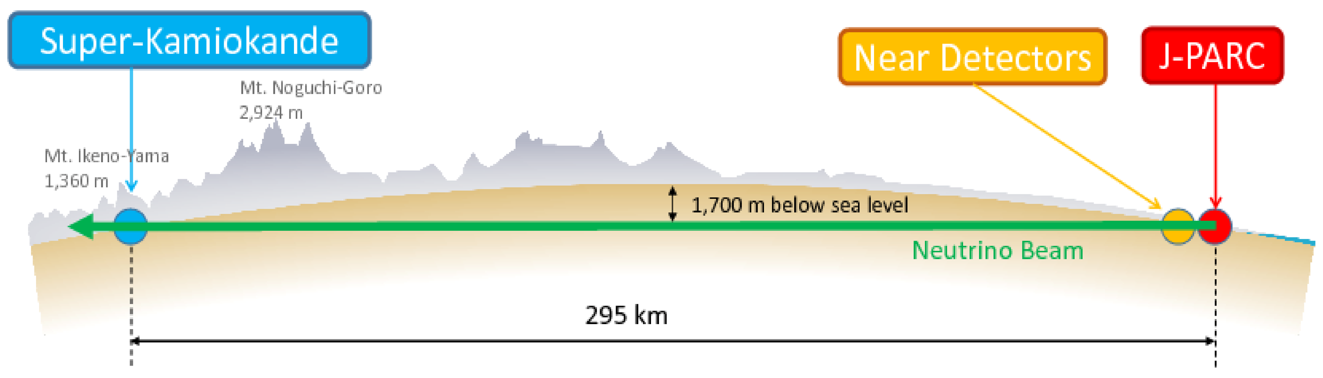
Runs1-8 Protons On Target (POT)

ν-mode	14.73×10^{20}	ν̄-mode	7.56×10^{20}

Super (SK) *Kamiokande*



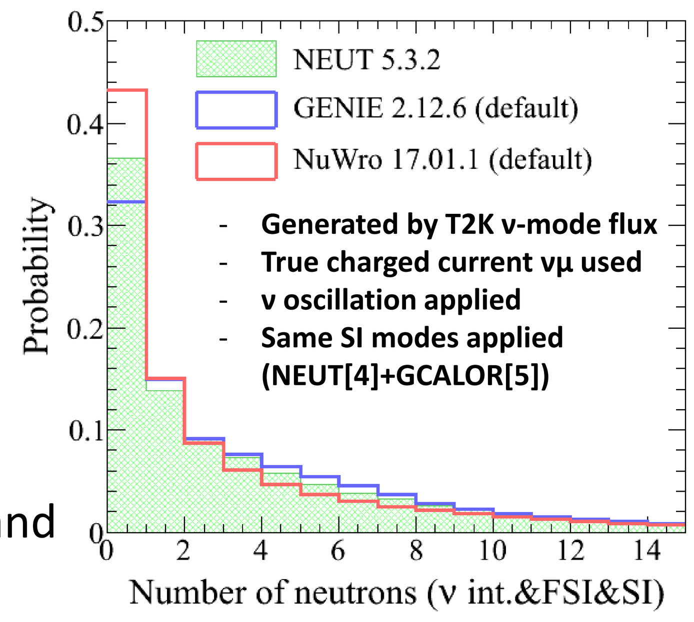
- 50 kton water Cherenkov detector
- 2700 m.w.e. overburden in Kamioka mine
- >11,000 20-inch PMT in the inner detector for Cherenkov ring imaging



2. Neutrons produced in ν interactions on water

- Observed neutrons are expected to be useful for future precise oscillation analyses [2] and have been utilized for proton decay searches [3].
- These analyses need a precise Monte Carlo (MC) simulation to predict neutron multiplicity for ν interactions on water.
- Different MC predictions due to uncertainties on :
  - **ν-nucleon interactions in nuclear medium**,
  - **hadronic-final state interactions in nucleus (FSI)**, and
  - **secondary interactions in detector medium (SI)**

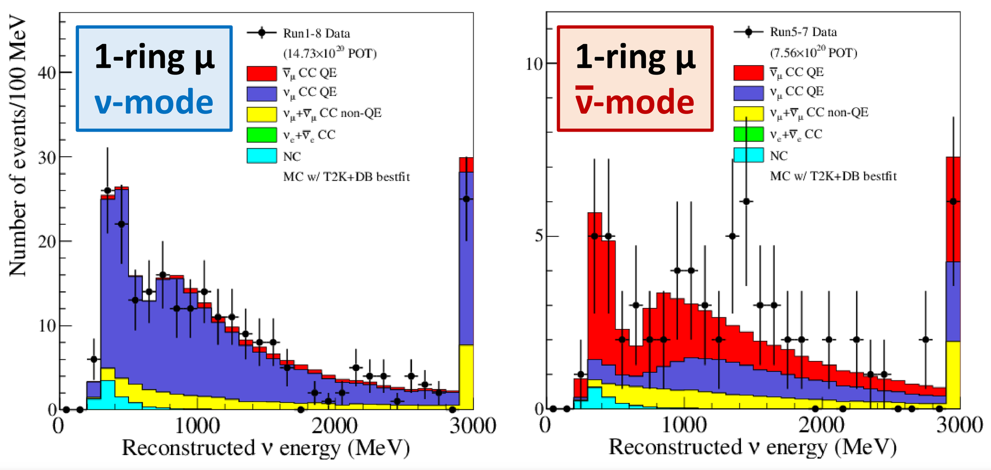
Neutron multiplicity for ν interactions on water



- No measurements of the neutron multiplicity have yet been published.

3. Goals of this study

- There are single-Cherenkov ring muon (**1-ring μ**) samples in the SK, which has been used in the T2K ν oscillation analyses.
- Neutrons associated with ν interactions on water can be studied using the samples.
- Aim to achieve :
  1. **Measurement of mean neutron multiplicity** and
  2. **Compare the measurement results with theoretical models via MC predictions**.

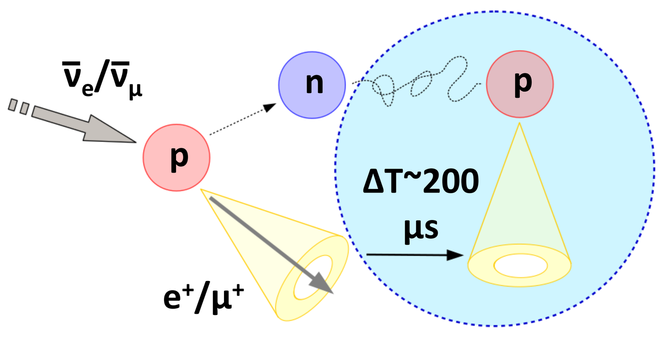


4. Neutron tagging at SK

- *Neutron capture*

- Neutrons produced in water are quickly thermalized and then are predominantly captured on a free proton via the reaction :

$$n + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$$

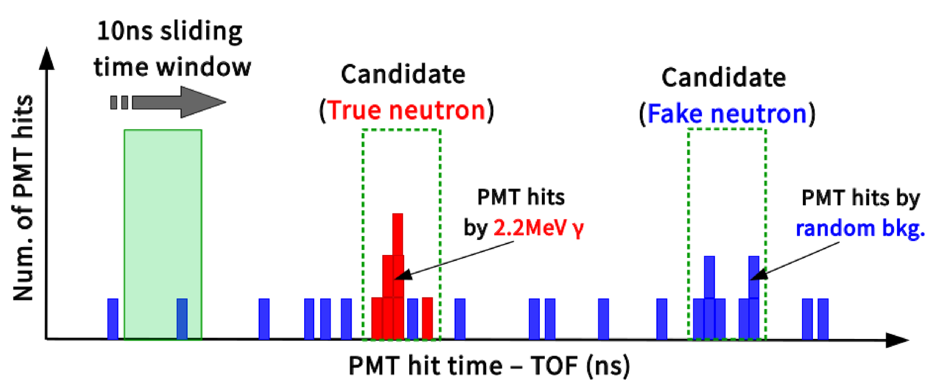


- *Tagging algorithm*

- There are two steps to tag neutrons.

1. Primary selection

- Search for neutron candidates by finding PMT hits clusters due to 2.2 MeV γs.



2. Neural network (NN) selection

- Efficient removal of fake neutrons from the neutron candidates.
- Use 16 input variables to characterize PMT hits cluster of each neutron candidate.

Basic performance

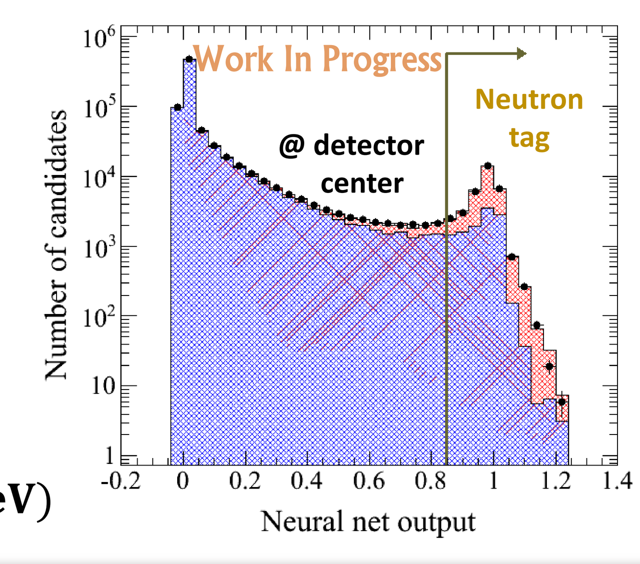
Work In Progress

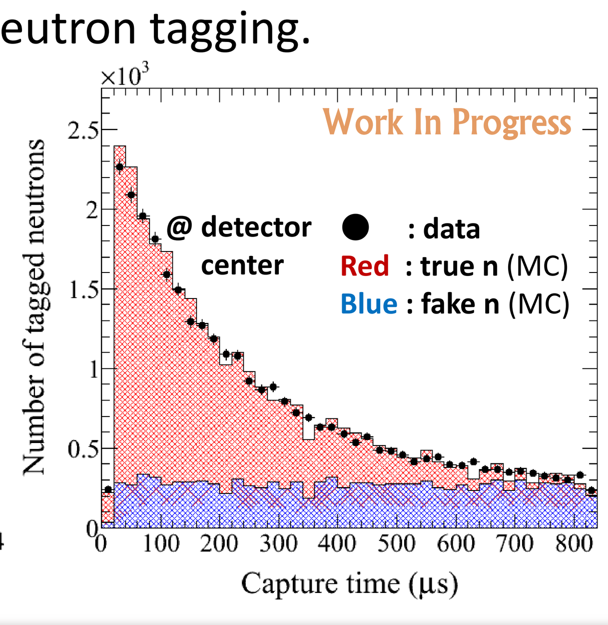
	Neutron tagging efficiency (%)	Number of fake neutrons /event
Primary	33.1	4.56
NN	21.2	0.018

- *Neutron calibration*

- Am/Be + BGO calibration has been done to study the neutron tagging.

$$\alpha + {}^{9}\text{Be} \rightarrow {}^{*12}\text{C} + n$$
$$\rightarrow {}^{12}\text{C} + n\ (4.4\text{MeV})$$





5. Nominal MC predictions

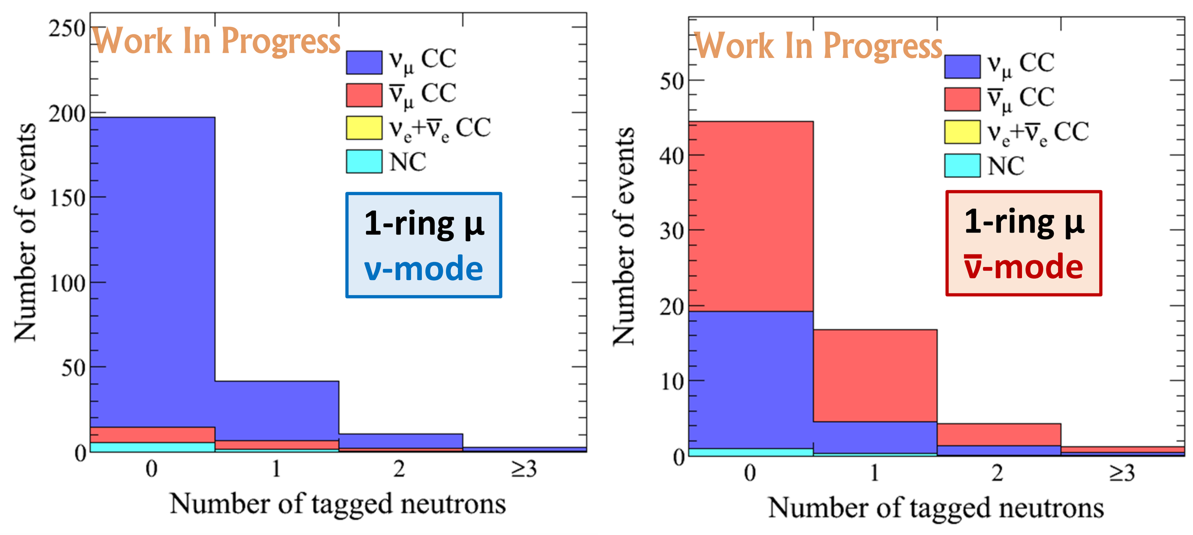
- MC predictions for the tagged neutrons of the **1-ring μ samples**.
- The processes of neutron production in the MC were simulated by NEUT [4] v5.3.2 and GCALOR [5].

Expected number of ν events and tagged n for Runs1-8 POT

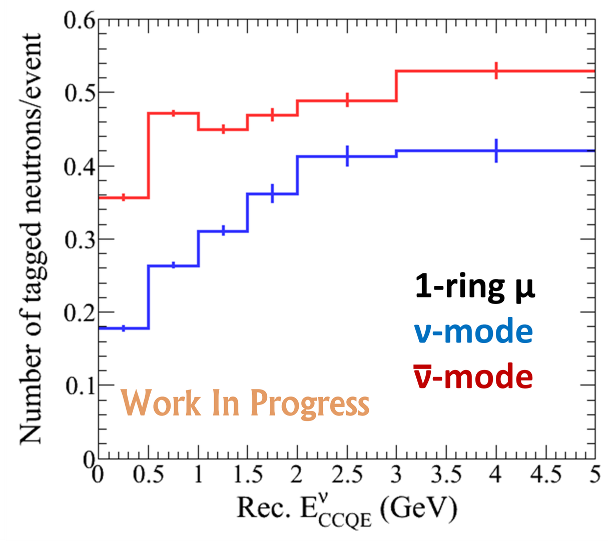
Work In Progress

	Number of ν events	Number of tagged n
ν-mode	252.8	70.4
ν̄-mode	67.1	29.3

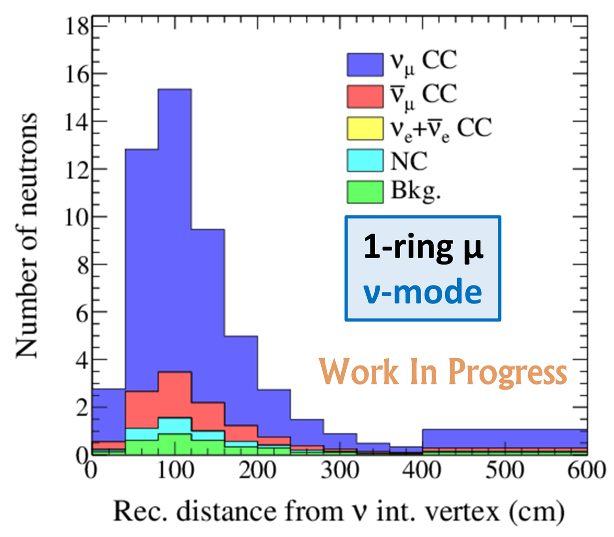
Tagged neutron multiplicity

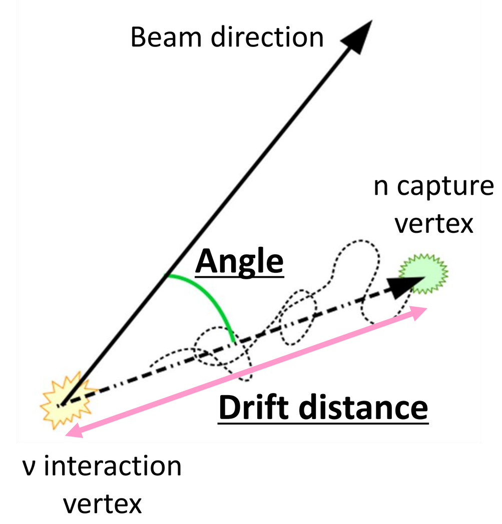


Mean tagged n multiplicity

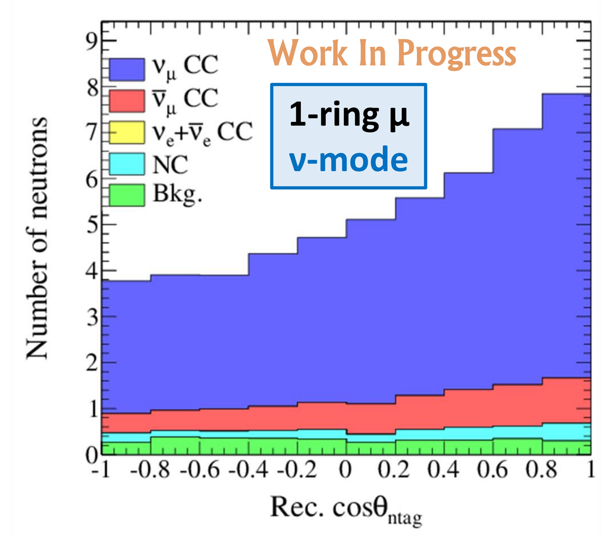


Reconstructed drift distance





Reconstructed angle

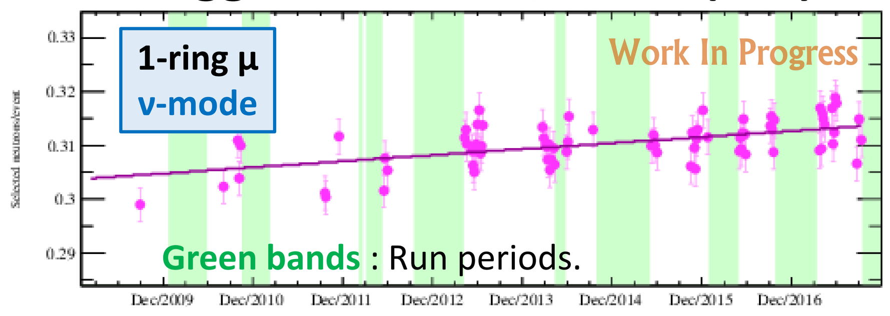


6. Ongoing works

- *SK time variations on neutron tagging*

- Several time varying effects have been observed.
  - **PMT gain increase**
  - **water transparency**
  - **non-uniform water quality**
- Impacts of the time variations in this study have been studied.

Time variation of tagged neutrons/event (MC)



- *Estimation of possible model uncertainties*

- To compare the measurement results with theoretical models, several sources of systematic uncertainties in the current MC predictions are under study, such as **FSI/SI for π, p, and n.**

- *Modification of the current neural network*

- Some input variables used in the current NN are explicitly model dependent such as **the distance between the neutrino interaction and the neutron capture**, which we hope to measure in this study.
- Alternative MC samples produced by different ν event generators will be used to study model dependence after modifying the current NN.

7. Summary

- Neutrons produced in ν interactions on water can be studied for both ν and ν̄ by utilizing the T2K ν- and ν̄-mode data.
- MC expectations related to tagged neutrons were presented.
- Precise estimation of time-dependent effects at SK are needed, and are currently under study.
- The measurement will be done once the ongoing works are completed.

References

[1] K. Abe et al., Nuclear Instruments and Methods, vol. A 569, (106).
[2] Teppei Katori and Marco Martini 2018 J. Phys. G: Nucl. Part. Phys. 45 013001.
[3] K. Abe et al., Phys. Rev.D 96, 012003 (2017)
[4] Y. Hayato, Acta Phys.Polon.B40, 2477 (2009).
[5] C. Zeitnitz and T. A. Gabriel, In Proc. of International Conference on Calorimetry in High Energy Physics, Tal-lahasse, FL, USA, February 1993.