New 2-ring ν_e CC1π^+ samples at the T2K Far Detector

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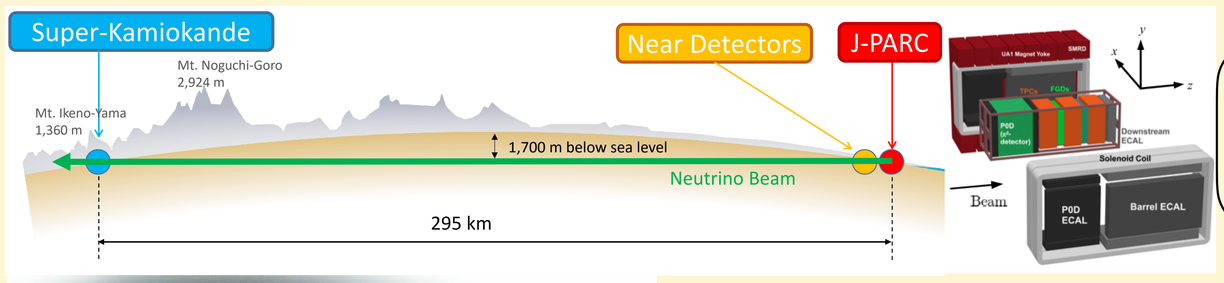
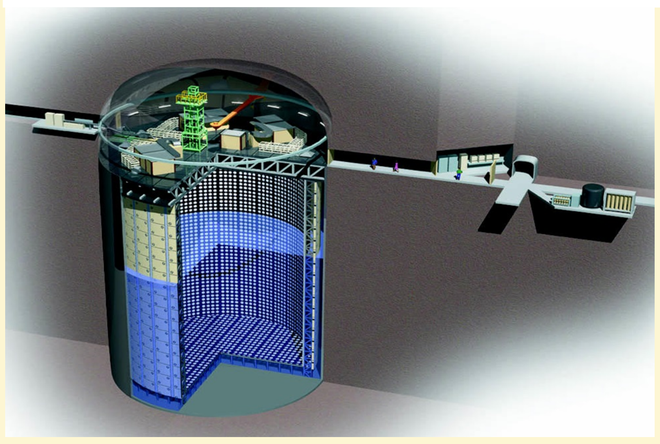


The Tokai-to-Kamioka (**T2K**) experiment in Japan is a long-baseline neutrino experiment that studies neutrino oscillations with a neutrino beam peaked around **0.6 GeV**.



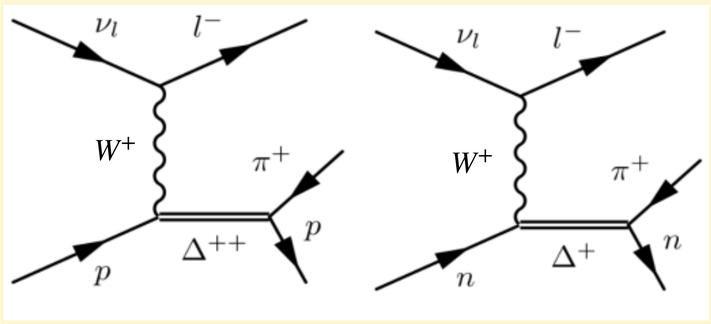
- One of T2K's main physics goal is to measure leptonic CP violating phase (δ_{CP}).
- Probability of $\nu_e/\bar{\nu}_e$ appearances from T2K's $\nu_\mu/\bar{\nu}_\mu$ beam are sensitive to this parameter.
- Currently, our constraints on δ_{CP} are limited mainly due to ν_e statistics, and this study aims to increase ν_e statistics by adding a new sample at Super-Kamiokande (SK), T2K's far detector.
- Along with the increase in statistics, this sample can also pave way to constrain systematic error parameters such as high energy cross-section parameters and detector systematics.

At T2K's neutrino beam energies, ν_e signal events come from these dominant interactions [1]:

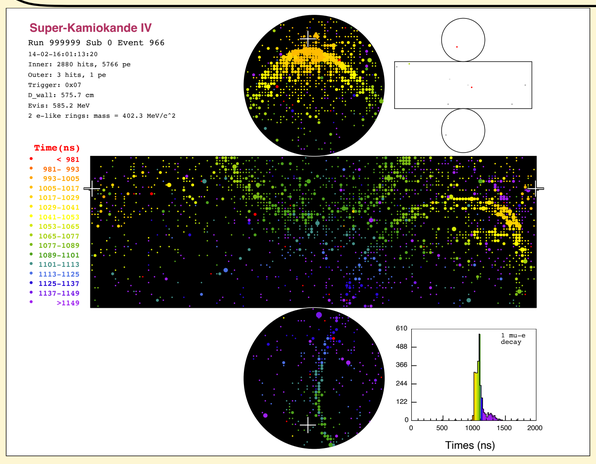
1. Charged Current Quasi-Elastic (CCQE) interaction (1 e^--like ring)
2. Charged Current single π^+ production (CC1π^+) (1 e^--like ring **+ 1π^+-like ring if π^+ momentum is above Cherenkov threshold** along with a decay electron from $\pi^+ \to \mu^+ \to e^+$ decay)

In its previous **oscillation analysis** [2], T2K used only one-ring $\nu_e/\bar{\nu}_e$ samples:

1. $\nu_e/\bar{\nu}_e$ CCQE sample
2. ν_e CC1π^+ samples where π^+ is **below** Cherenkov Threshold.



Feynman diagrams for the ν_e CC1π^+ interaction



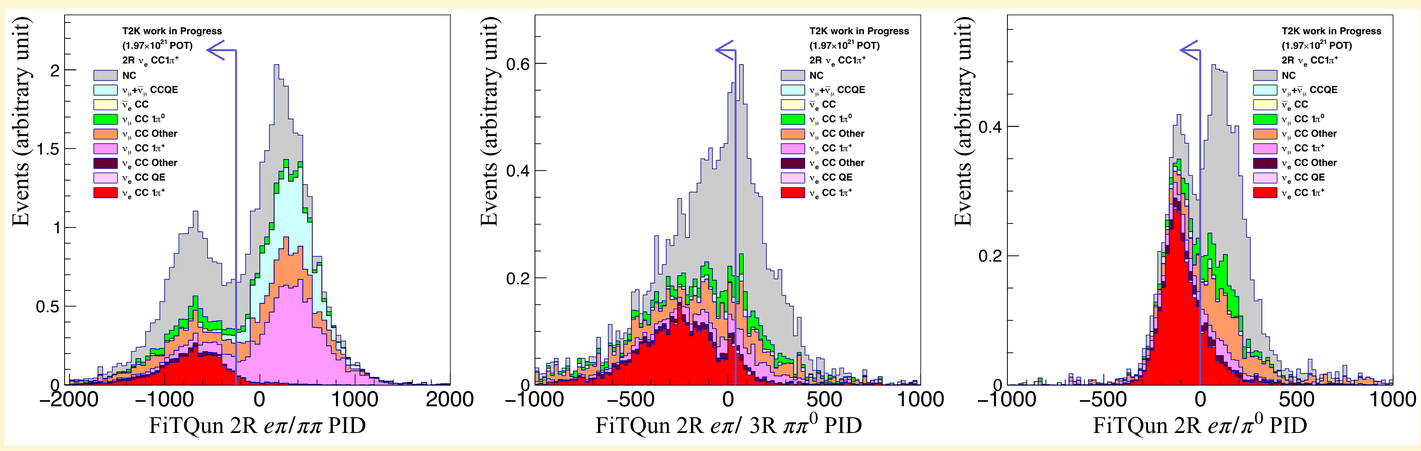
Event display of a 2-ring ν_e CC1π^+ event at SK

This study is aimed at adding a **2-ring ν_e CC1π^+** sample where the π^+ is **above** Cherenkov threshold, hence adding to the ν_e statistics.

- The topology of this event at SK would have one e-like and one π^+-like rings, whose information is obtained from kinematic variables and likelihoods generated by the reconstuction software.
- The reconstruction software tests various particle hypotheses using a maximum-likelihood algorithm based on **charge** and **time** information from SK's **PMT**s and performs single or multi-ring fits on each event. Output from this is then used to develop selection cuts.

Selection Cuts:

1. Event should be fully contained in SK's inner detector's fiducial volume
2. Reconstruction software finds two Cherenkov rings
3. Event should contain one decay electron
4. Reconstructed neutrino energy must be less than 1.25 GeV
5. Reject 2-ring ν_μ CC1π^+-like events
6. Reject 3-ring ν_μ CC1π^0-like events
7. Reject 2-ring NCπ^0-like events



T2K work in progress: Study performed on T2K Monte Carlo with 1.97×10^{21} protons on target (POT), equivalent to the first 10 runs at T2K.

Note: $\bar{\nu}_e$ CC1π^- events are excluded from selections since the π^- produced in CC1π^- interaction will mostly get absorbed by the positively charged nucleus.

Cut	ν_e CCQE	ν_e CC1π^+	ν_e CC$_{other}$	$\bar{\nu}_e$ CC	$\nu_\mu/\bar{\nu}_\mu$ CCQE	ν_μ CC1π^+	ν_μ CC1π^0	ν_μ CC$_{other}$	NC
1. FCFV	96.65	30.1	24.61	4.95	292.1	138.36	345.04	30.32	270.33
2. N Rings = 2	5.79	7.34	4.84	0.83	23.2	42.88	48.85	6.36	125.09
3. 1 dcy electron	0.2	4.49	1.73	0.11	14.73	19.62	21.31	4.22	17.4
4. $E_\nu^{recon.} < 1.25$	0.05	3.35	0.45	0.01	6.59	10.14	5.95	1.94	14.55
5. 2Rν_μ rejection	0.05	3.09	0.41	0.01	0.33	1.05	2.3	1.19	7.82
6. 3Rν_μ rejection	0.04	2.81	0.31	0.01	0.21	0.61	1.54	0.76	4.27
7. π^0 rejection	0.02	2.31	0.15	0.01	0.14	0.34	0.41	0.21	0.67
Rem. Eff. wrt. 2.	0.35%	**31.47%**	3.10%	1.20%	0.60%	0.79%	0.84%	3.30%	0.54%

Events selected : 4.26
Total signal events : 2.31
Signal purity : **54.23%**
Signal efficiency : **31.47%**

Conclusion:

- Selection of a new 2-ring ν_e CC1π^+ sample at T2K far detector is being studied. Since ν_e appearance measurement is sensitive to leptonic CP violation, an increase in ν_e statistics can improve T2K's sensitivity to δ_{CP}, and also improve constraints systematic error parameters.
- Inclusion of this sample increases the ν_e CC1π^+ statistics by $\sim 25\%$.
- A neural network based classification will be applied to further improve signal purity and efficiency in the next step of the analysis.
- After this, systematic uncertainties arising from this sample will be estimated and studies on sensitivity to neutrino oscillation parameters will be performed.

[1] J.A. Formaggio and G. P. Zeller, *Rev. Mod. Phys.* **84**, 1307 (2012)
[2] K. Abe *et al. Phys. Rev. D* **103**, 112008 (2021)

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