Multi-ring charged current $\nu 1\pi^+$ samples and the estimation of detector systematic uncertainties at T2K far detector

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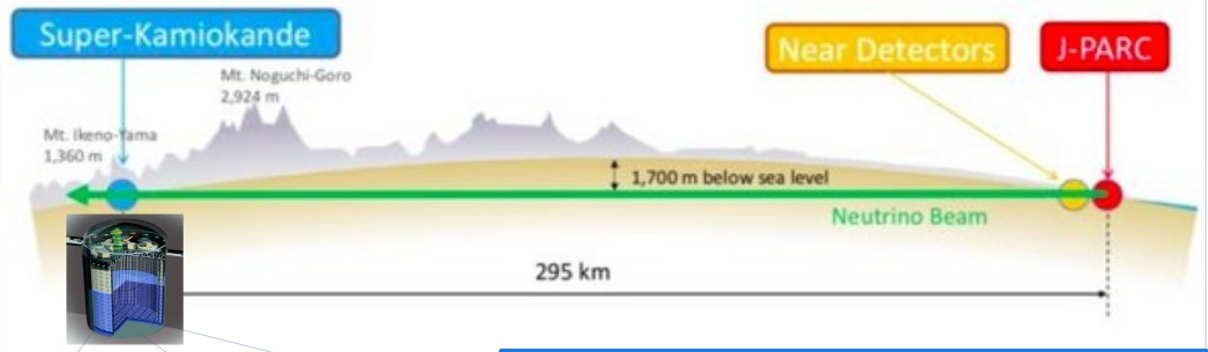
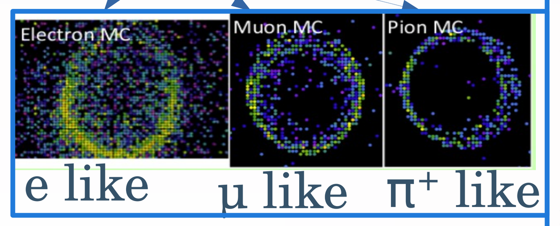
INTRODUCTION



- T2K experiment measures neutrino oscillation parameters via the observation of disappearance of ν_μ ($\bar{\nu}_\mu$) and appearance of ν_e ($\bar{\nu}_e$) from a ν_μ ($\bar{\nu}_\mu$) beam using near and far detectors.
- In the far detector Super-Kamiokande (SK) ν_l & $\bar{\nu}_l$ interaction products produce Cherenkov rings.



- Most dominant interaction at T2K flux peak: Charged Current Quasi Elastic (CCQE) interaction of ν and $\bar{\nu}$: $\nu_l + n \rightarrow l^- + p$; $\bar{\nu}_l + p \rightarrow l^+ + n$.
- Second dominant channel - Resonant single pion production: **3 charged current resonant single pion production channels**

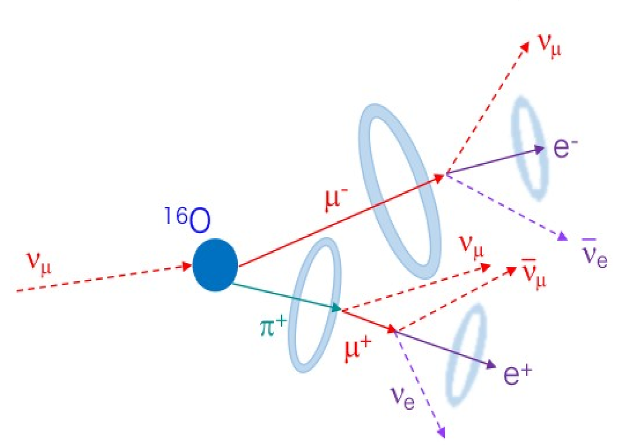
$$\nu_l\, p \rightarrow l^-\, p\, \pi^+ \,;\; \bar{\nu}_l\, p \rightarrow l^+\, p\, \pi^-$$
$$\nu_l\, n \rightarrow l^-\, n\, \pi^+ \,;\; \bar{\nu}_l\, n \rightarrow l^+\, n\, \pi^-$$
$$\nu_l\, n \rightarrow l^-\, p\, \pi^0 \,;\; \bar{\nu}_l\, p \rightarrow l^+\, n\, \pi^0$$

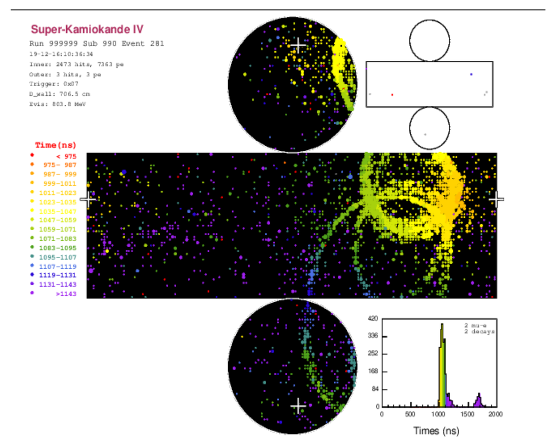
Event samples currently used in T2K analyses
- 1 ring μ–like and e–like events (CCQE) in both ν and $\bar{\nu}$ modes
- 1-ring e-like with 1 decay electron only in ν mode (ν_e CC1π+ sample with π+ below Cherenkov threshold)

- A maximum likelihood reconstruction algorithm **fiTQun** reconstructs the events at SK.
- Depending on the charge profile, various event topology hypotheses (e-, μ-, and π+- like) and their likelihood functions are formed.
- Position, time, direction, momentum and energy loss of tracks are reconstructed.
- Multi-ring hypotheses are tested by sequentially adding e-like and π+ like rings.
- The expected charge of 1-ring hypotheses are summed up to 6 rings.

- This study : To add CC 1π+ dominant sample in ν mode, to improve event statistics and hence the constraints on neutrino oscillation parameters θ_{23}, $|\Delta m^2_{32}|$ and δ_{CP}.

Charged Current $\nu_\mu 1\pi^+$ events





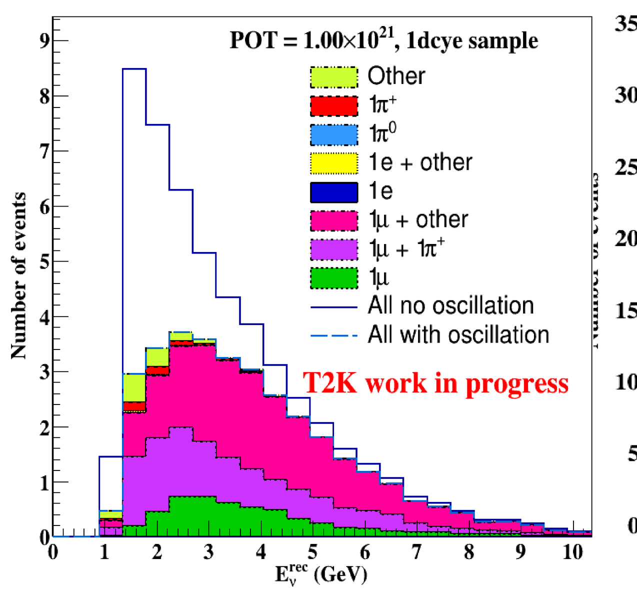
- Inclusion in oscillation analysis is expected to improve the sensitivity to θ_{23} and $|\Delta m^2_{32}|$.
- Events are selected for neutrino mode running only.
- Two sub-categories of events with 1 and 2 decay electron(s).
- Selection is optimized based on a simple figure of merit **S/√(S + B)**, where S = signal and B = background.

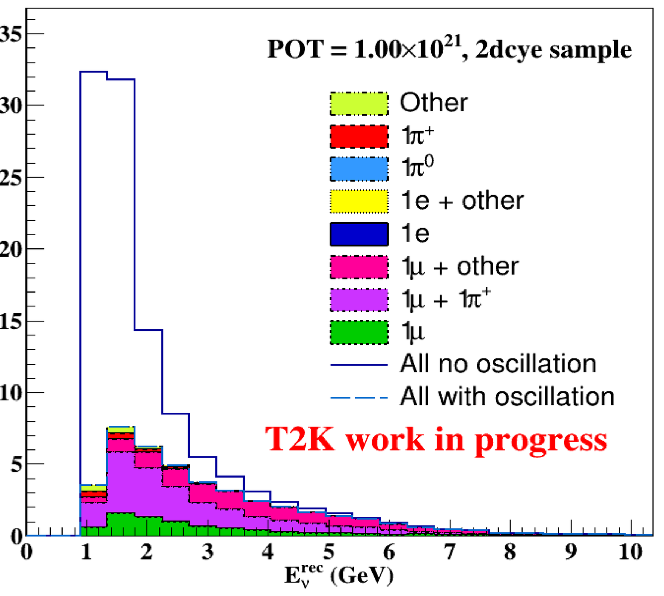
1.00×10^{21} POT	ν_μ CCQE	ν_μ CC1π+	ν_μ CC other	$\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$CC	NC	Signal Purity
1R μ like	143.34 (Signal)	18.41	7.45	11.43	0.05	5.49	76.99%
Signal Efficiency	83.84%						
MR 1 decay e	8.93	11.15 (signal)	9.26	2.38	0.088	1.83	33.14%
Signal efficiency		52.02%					
MR 2 decay e	2.85	23.97 (signal)	11.86	0.732	0.011	1.76	58.20%
Signal efficiency		86.28%					

T2K work in progress

Selection efficiency* and purity† of ν_μ signal events in neutrino mode with a POT of 1.00 X 10^{21}.

- Cuts on fiducial volume, number of decay electrons, ratios of log likelihoods of $\pi^+\pi^+$ hypothesis vs e-like and best of other 2-ring hypotheses are applied.
- For 1 decay electron sample an extra cut on the sum of the energy loss of two rings by fiTQun 2-ring $\pi^\pm\pi^\pm$ is applied to remove NC1π ± background.



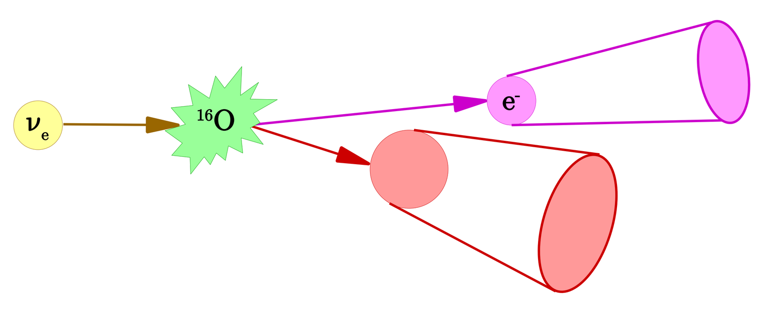


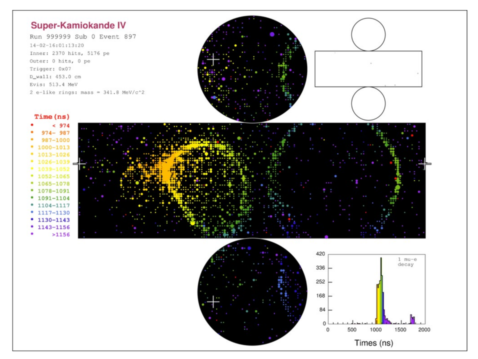
1 decay electron sample   2 decay electron sample

Reconstructed neutrino energy (GeV) after all cuts

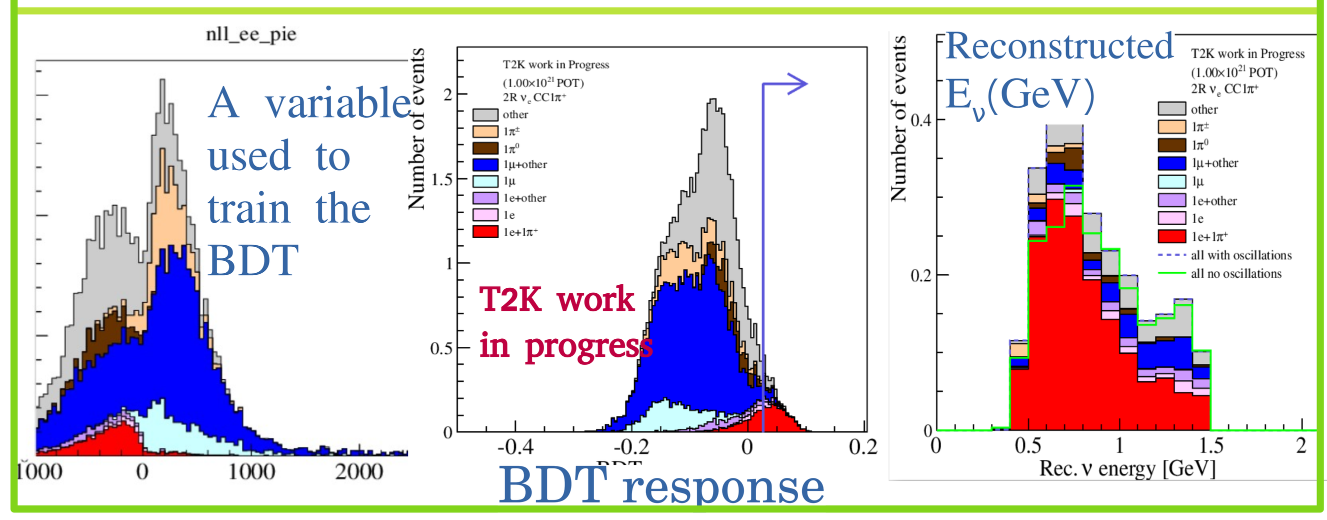
- Signal efficiency* is calculated with respect to the events passing the fully contained and fiducial volume cuts.
- Signal purity† is the fraction of signal events passing the final selection cut, out of all events passing the same cut.

Charged Current $\nu_e 1\pi^+$ events





- Inclusion in oscillation analysis will improve the sensitivity to leptonic δ_{CP}. A 12% increase in ν_e signal events is predicted.
- Event selection involves cuts on reconstructed variables and a cuts from training a **Boosted Decision Tree (BDT)** on Monte Carlo (MC) events.
- Pre-BDT cuts: events have to be in the fiducial volume of SK and should have 1 decay electron from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$.
- Reconstructed ν energy should be < 1.5 GeV. BDT uses likelihood ratios of different ring hypotheses and reconstructed kinematic variables from various fits.



1.00×10^{21} POT	ν_e CCQE	ν_e CC1π+	ν_e CC other	$\bar{\nu}_e$ CC	$\nu_\mu+\bar{\nu}_\mu$ CC	NC	Signal purity
Existing 1 ring elike 0 dcye sample	39.892 (signal)	3.347	0.884	0.482	0.201	2.771	83.85%
Signal efficiency	76.65%						
MR e like BDT sample	0.027	1.647	0.134	0.007	0.328	0.388	65.07%
Signal efficiency		9.64%					

T2K work in progress

Selection efficiency* and purity† of ν_e signal events in neutrino mode with a POT of 1.00 X 10^{21}.

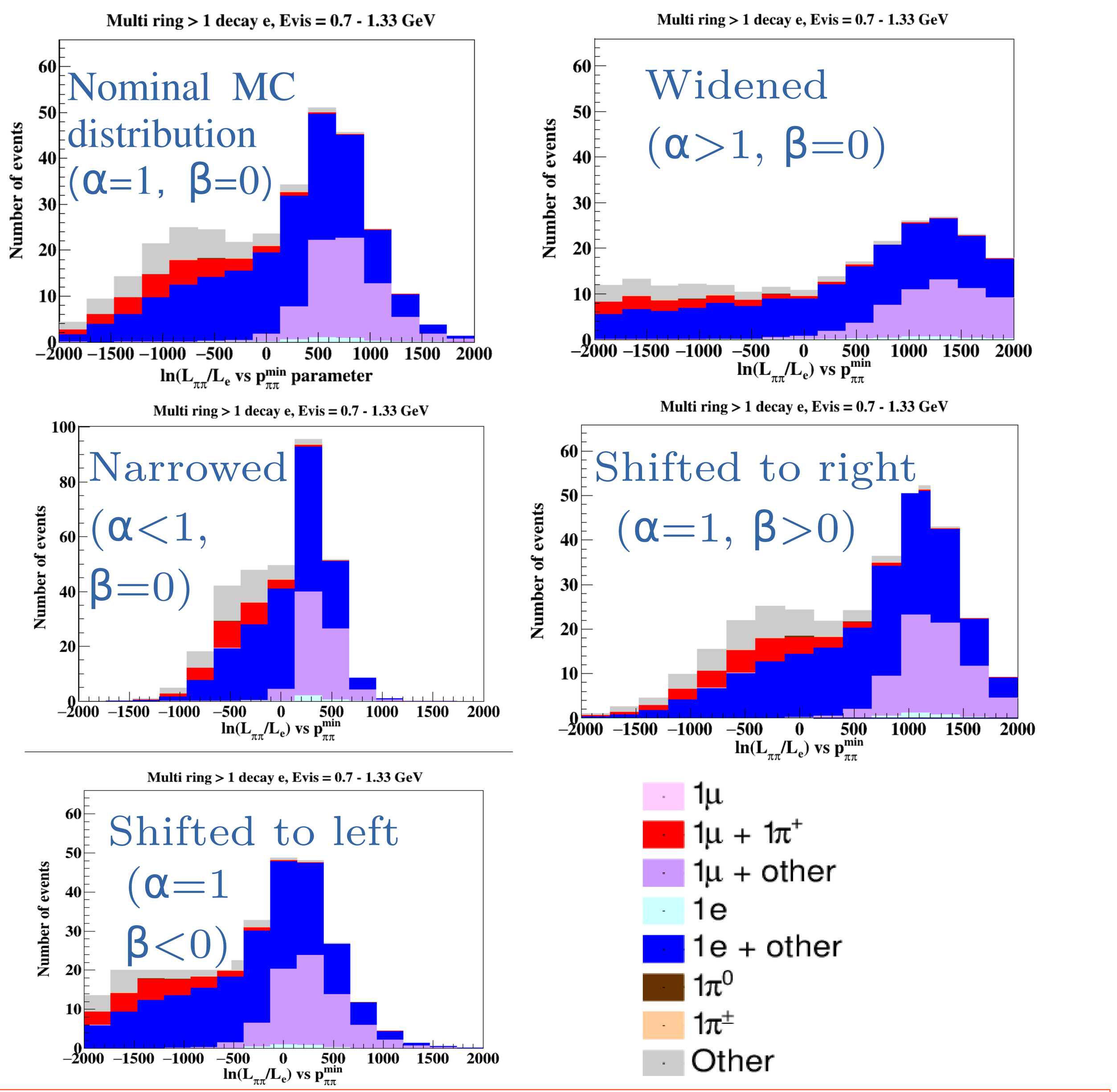
Estimation of detector systematic uncertainties

- Due to the lack of control samples for the events at T2K energies, detector systematic uncertainties for T2K events are estimated using atmospheric neutrino events in the far detector.
- Detector systematic errors are parametrised as:

$$L^i_{jk} \rightarrow \alpha^i_{jk} L^i_{jk} + \beta^i_{jk}$$

L^i → fiTQun reconstructed variables,
j → visible final state,
k → visible energy bin,
(α, β) are the smear and shift parameters respectively.

- α and β affect the shapes of the distributions of the fiTQun reconstructed variables.
- A Markov Chain Monte Carlo (MCMC) based analysis is used to obtain the posteriors of α and β corresponding to the different selection variables for different final state topologies in various visible energy bins.



Effect of smear and shift in the Evis bin 0.7 – 1.33 GeV, on the distribution of the ππ/e separation variable for the sample with mulit-rings and more than 1 decay electrons.

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References:
1. Tomoyo Yoshida, *"A study of single charged-pion production events at Super-Kamiokande induced by charged-current interaction of T2K-beam muon Neutrinos"*, PhD Thesis, 2020.
2. Trevor Towstego, *"Development of a multi-ring sample at the T2K far detector"*, Poster NEUTRINO 2020
3. Shimpei Tobayama, *"An Analysis of the Oscillation of Atmospheric Neutrinos"*, PhD Thesis, 2010

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