PROCEEDINGS OF SCIENCE

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

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The Tokai-to-Kamioka (T2K) experiment is a long-baseline accelerator neutrino experiment in Japan that measures the leptonic CP-violating phase δ_{CP} by studying ν_e appearance from the ν_μ beam at T2K's far detector, Super-Kamiokande (SK). The near detector (ND280) stands 280 metres, and SK stands 295 km away from the beam production target. SK is a 50 kton water-Cherenkov detector that observes Cherenkov rings from charged particles produced in neutrino interactions with water. Both single and multi-ring samples for ν_μ at SK are used in T2K's latest oscillation analyses, while for ν_e, only single-ring samples are used. Charged current single π^+ (CC1π^+) events form the second most dominant signal events in ν_e appearance studies, of which events with π^+ below Cherenkov threshold are used in the latest analysis (1 e-like ring and a decay electron signature). The addition of the sample with π^+ above the Cherenkov threshold, consisting of an e-like ring and a π^+-like ring can increase the statistics of ν_e events and thus our sensitivity to δ_{CP}. In this proceeding, cuts-based selection of these 2-ring ν_e CC1π^+ events will be discussed.

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1. The T2K experiment and its far detector

The T2K experiment [1] in Japan studies neutrino oscillation by observing $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance from a $\nu_\mu(\bar{\nu}_\mu)$ beam that peaks at 0.6 GeV. It is the world's first neutrino experiment that uses an off-axis setup to deliver a beam that has a narrow spread of energies at the near detector (ND280), located 280 m from the beam source and the far detector (SK [2]), located 295 km from the beam source. The off-axis method ensures maximum $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$ oscillation at 295 km and also reduces the high energy unoscillated background events, both which are crucial for neutrino oscillation studies.

A beam of protons accelerated to 30 GeV is impinged on a graphite target, producing hadrons (mainly pions) that decay to neutrinos in a decay volume, generating a sub-GeV neutrino beam. Being a accelerator-based neutrino source, by switching the polarity (of the current) of the beam magnetic horns, which are used to select and collimate hadrons, either neutrino (forward horn current, FHC) or antineutrino (reverse horn current, RHC) dominated beam can be produced.

T2K's far detector, SK, is a 50-kiloton water Cherenkov detector equipped with ~12,000 PMTs which allow for e/μ discrimination from Cherenkov ring imaging [2]. Particle identification and kinematics are inferred from the properties of the Cherenkov ring: e/γ produces blurry-edged rings while μ/π produces sharper rings.

One of T2K's main physics goals is to measure the leptonic CP violating phase δ_{CP} which is a parameter in the neutrino mixing matrix. This matrix relates neutrino mass states with the flavour states. Measurement of this parameter can shed light on the observed matter-antimatter asymmetry in the universe. T2K's constraints on δ_{CP} are currently limited due to ν_e statistics, and this study is aimed at increasing the statistics by adding a multi-ring ν_e sample at SK.

2. New multi-ring sample at SK

At 0.6 GeV, neutrinos interact mainly through charged-current (CC) quasi-elastic (QE) interactions, with a subdominant contribution coming from the CC single-pion production (CC1$\pi^\pm$) [3]. The latter only gains prominence when T2K runs in the FHC mode since, in the case of RHC, the π^- produced will mostly get absorbed by the positively charged nucleus. The topology of a ν_ℓ CCQE interaction is a single ℓ-like ring at SK where $\ell = e/\mu$. In the case of CC1π^+ interactions, depending on whether the π^+ is above or below its Cherenkov threshold, an additional π^+-like ring is also visible with the ℓ-like ring. Regardless of the Cherenkov threshold, a CC1π^+ interaction is accompanied by a delayed signal of the decay electron coming from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay, which is useful to tag the π^+.

T2K's latest oscillation analysis uses $\nu_e, \bar{\nu}_e$ CCQE, $\nu_\mu, \bar{\nu}_\mu$ CCQE, 1-ring ν_e CC1π^+ (π^+ below Cherenkov threshold) and multi-ring ν_μ CC1π^+ samples at SK. In this study, a cuts-based selection of ν_e CC1π^+ events with a visible π^+-like ring (see Figure 1) is developed. This sample can increase ν_e statistics, and along with it, possibly increase T2K's sensitivity to δ_{CP}. Estimation of systematic uncertainties of cut parameters used in the selection can further track down any (anti)correlations between these cut parameters and those used in the selection of other samples.

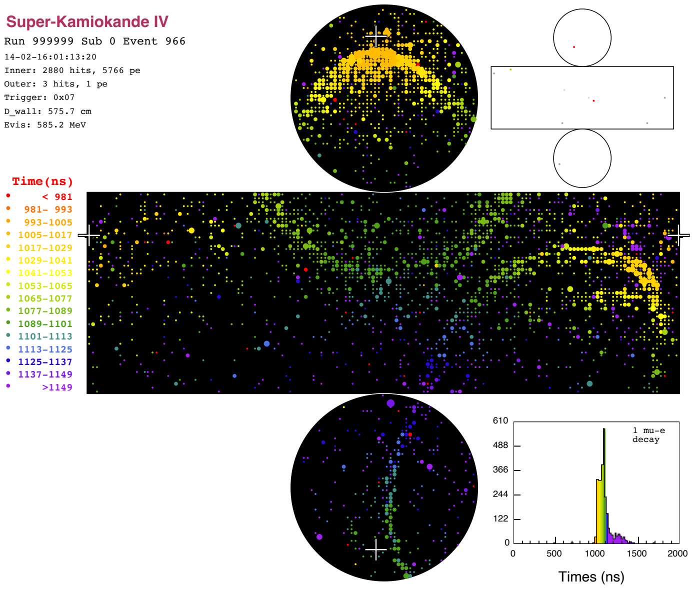

Figure 1: SK event display of a multi-ring ν_e CC1π^+ event, from T2K Monte Carlo simulation.

3. Selection cuts and efficiency

The cuts were developed using kinematic variables and likelihood ratios generated by SK's reconstruction software. Events of interest were demanded to be in SK's fiducial volume with minimal activity in its outer detector. They should have two visible rings, and one delayed decay electron signal. To cut off intrinsic beam ν_e, an upper cap of 1.25 GeV gets applied to the reconstructed neutrino energy. Cuts based on likelihood ratios between signal-like and background-like event hypotheses were developed and optimized by performing a grid scan over the cut parameter space. The cut parameters were chosen such that they returned the highest $S/\sqrt{S+B}$ value, where S = signal events and B = background. The selection was applied on T2K Monte Carlo weighted to be equivalent to the 10 runs of T2K's data taking.

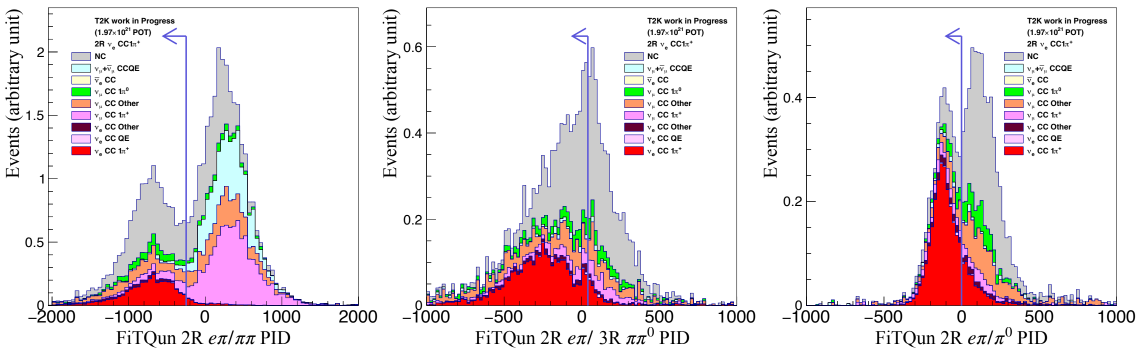

Figure 2: Likelihood-ratio based selection cuts aimed at removing the major backgrounds. The red histogram shows the signal ν_e CC1π^+ events

The main backgrounds to this sample were identified to be multi-ring ν_μ CC events, and multi-ring neutral-current (NC) events (see Figure 2). In terms of final state topology, the signal is represented as $e\pi$ and the likelihood ratio between $e\pi$ hypothesis and $\pi\pi$, $\pi\pi^0$, π^0 hypotheses provided a great signal-background separation, hence they were used as the three likelihood ratio cuts.

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 CCπ^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. NRings = 2	5.79	7.34	4.84	0.83	23.2	42.88	48.85	6.36	125.09
3. Ndcye = 1	0.2	4.49	1.73	0.11	14.73	19.62	21.31	4.22	17.4
4. E_ν^{rec} ¡ 1.25 GeV	0.05	3.35	0.45	0.01	6.59	10.14	5.95	1.94	14.55
5. $e\pi/\pi\pi$ LLH	0.05	3.09	0.41	0.01	0.33	1.05	2.3	1.19	7.82
6. $e\pi/\pi\pi^0$ LLH	0.04	2.81	0.31	0.01	0.21	0.61	1.54	0.76	4.27
7. $e\pi/\pi^0$ LLH	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%**	3.1%	1.2%	0.6%	0.79%	0.84%	3.3%	0.54%

Table 1: Event reductions along the selection cuts. After applying the likelihood ratio cuts, a signal purity of ~54% was obtained. The remaining efficiency was calculated with respect to the second cut, as those correspond to true 2-ring ν_e CC1π^+ events. LLH stands for log likelihood.

2-ring ν_e CC1π^+ events were selected with a purity of ~ 54% and an efficiency of ~ 31.5% (see Table 1).

4. Summary

A new multi-ring sample at SK is being developed, aimed at selecting ν_e CC1π^+ events, which are the second most dominant ν_e events after ν_e CCQE events. The ν_e appearance is sensitive to measuring leptonic CP violation and increasing ν_e statistics can improve T2K's sensitivity to δ_{CP}. The cuts-based selection of multi-ring ν_e CC1π^+ events show an increase of total ν_e CC1π^+ events by ~ 48.67% and total ν_e statistics by ~ 4.1%.

The next step in this analysis is to estimate SK detector systematic uncertainties associated with the variables used in this selection cut, followed by sensitivity studies on neutrino oscillation parameters upon including this sample. Additionally, to make the best use of T2K data, and for better signal-background separation as compared to cuts-based selections, a neural-network-based classification is planned to be developed.

References

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