PROCEEDINGS OF SCIENCE

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

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Tokai to Kamioka (T2K) is an accelerator long baseline experiment that measures the neutrino oscillation parameters by observing ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance from a ν_μ ($\bar{\nu}_\mu$) beam. The experiment has both near and far detectors situated at 280 m and 295 km respectively from the beam production target. The far detector Super-Kamiokande where ν and $\bar{\nu}$ interact is a water Cherenkov detector. The dominant interactions at 0.6 GeV where T2K flux peaks are charged current quasi–elastic which result in single ring events. The next largest charged current interaction at T2K energy is resonant 1π production. The addition of charged current $\nu_\mu 1\pi^+$ samples to the T2K analysis is expected to improve the precision on $\sin^2\theta_{23}$ and $|\Delta m^2{}_{32}|$. Studies on the selection of ν_μ charged current $1\pi^+$ like events accumulated in forward horn current operation corresponding to a proton on target of 1.9663×10^{21} are performed. The estimation of systematic uncertainty is important in the studies of sensitivity to neutrino oscillation parameters. One source of uncertainty is the impact of shortcomings in the detector model on the event selection. In our study, far detector systematic uncertainty is estimated via a fit to atmospheric neutrinos events collected in Super-Kamiokande, using a Markov Chain Monte Carlo Framework. We present the selection of ν_μ charged current $1\pi^+$ multi–ring events and the process of estimation of detector systematic uncertainty.

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1. Introduction

The far detector of T2K experiment [1] is Super–Kamiokande (SK) [2], where we observe the oscillated beam ν and $\bar{\nu}$. At 0.6 GeV, where T2K flux peaks, the quasi elastic interactions are the most dominant and the resonant single pion production is the second most dominant. Previously [3] only 5 samples from the far detector were used in T2K oscillation analysis. These are single ring μ and e–like samples in both ν and $\bar{\nu}$ modes (charged current quasi–elastic); single ring e–like sample with 1–decay electron in ν mode only (charged current ν_e resonance interactions with π^+ below the Cherenkov threshold). A new multi–ring ν_μ charged current $1\pi^+$ like sample is added for the first time in T2K oscillation analysis this year [4] making the number of far detector samples 6. Far detector systematics is updated with the new samples. To estimate the SK detector systematics for T2K events, a fit to the atmospheric neutrino data collected in SK, is performed using a Markov Chain Monte Carlo (MCMC) framework. Sections.2 and 3 of this proceeding describe the selection of the new sample and estimation of far detector uncertainty.

2. Selection of multi–ring ν_μ charged current $1\pi^+$ events

The multi–ring (MR) ν_μ charged current $1\pi^+$ sample corresponds to the resonance interactions $\nu_\mu\ p \to \mu^- p\pi^+$ and $\nu_\mu\ n \to \mu^- n\pi^+$. Since SK only detects particles that are above Cherenkov threshold, only the rings from μ^- and π^+ (if above Cherenkov threshold) will be observed. The signal topologies for this new sample have rings from (i) $1\mu^- + 1\pi^+$ and 1 (μ^+ absorbed before its decay) or 2 decay electrons and (ii) $1\mu^-$ with 2 decay electrons (π^+ is below the Cherenkov threshold). The schematic of this event is shown in Fig. 1(a). This sample is selected only from the ν mode runs of T2K Runs 1–10,with an forward horn current proton on target (FHC POT) of 1.9663×10^{21}, based on cuts optimised by maximizing the figure of merit (FOM): $S/\sqrt{S+B}$, where S and B are the number of signal and background events. Pre–selections ensure that the selected events are independent of the single ring μ–like events and are fully contained within the inner detector (ID). The events should have 1 or 2 decay electrons and distance of their vertices from the nearest ID wall $\geq$ 200 cm. Two cuts based on the log–likelihoods of the different fit hypotheses provided by the T2K event reconstruction software are applied next.

A 2–dimensional (2–D) cut in the plane of $\ln(L_{\pi\pi}/L_e)$ vs $p^{min}_{\pi\pi}$, where $L_{\pi\pi}$ and L_e are the likelihoods for 2–ring $\pi^+\pi^+$ and 1–ring e hypotheses respectively; $p^{min}_{\pi\pi}$ is the smaller momentum of the momenta of the two rings in $\pi^+\pi^+$ hypothesis. This cut rejects 1–ring events with real electrons and multi–ring events (say π^0 like events) with overlapping rings reconstructed as a 1–ring electron–like event. Then a 1–D cut is applied as in Fig.1(c), on $\ln L_{BO2R}/L_{\pi\pi}$, where L_{BO2R} is the best likelihood from other 2–ring fits with ee, $e\pi^+$ and π^+e hypotheses. This reduces the background from multi–ring events with electrons. For the 1–decay electron sub–sample alone, an additional cut on the sum of the energy loss by two rings in the $\pi^+\pi^+$ fit that is required to be larger than 300 MeV is applied as shown Fig. 1(d).

The neutrino energy E^{rec}_ν is reconstructed using the final state μ^- kinematics and $\Delta^{+(+)}$ mass of 1232 MeV/c^2. The selection efficiency and purity for the $1\mu^- + 1\pi^+$ topology with 1 (2) decay electron(s) are ~83% (~93%) and ~30% (~48%) respectively, whereas for the $1\mu^-$ topology with 2 decay electrons they are ~96% and ~18% respectively.

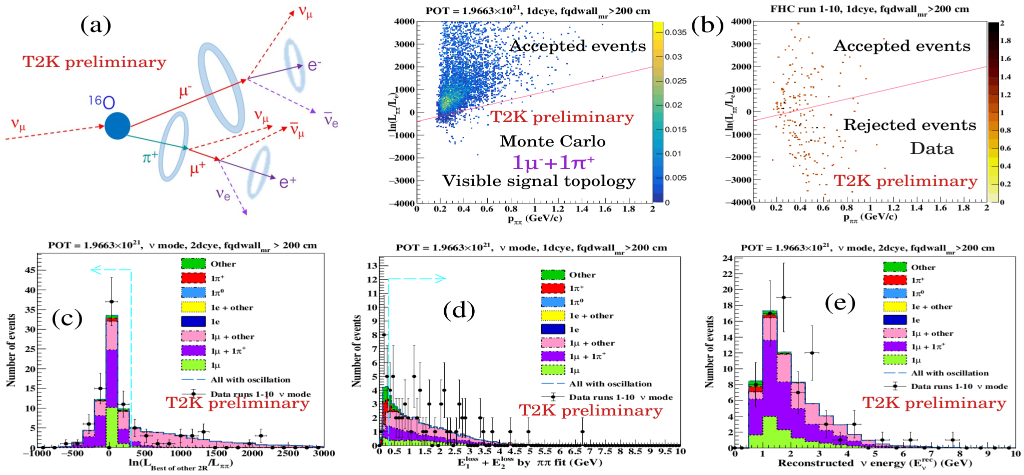

Figure 1: (a) Schematic of a multi–ring ν_μ charged current $1\pi^+$ event. (b) (Left) The number of accepted Monte Carlo events from the signal topology; (right) the number of accepted and rejected ν mode data events from Runs 1–10. (c) 1–D cut to reject other multi–ring events with e–like rings. (d) Cut to reject neutral current π^+ background to 1 decay electron sub–sample. (e) E_ν^{rec} (GeV) for 2–decay electron sub–sample.

3. Estimation of far detector systematic uncertainties using atmospheric neutrino fit

The mis-modeling of SK detector can introduce systematic uncertainties on T2K selection variables, leading to the migration of events from one sample to the other. Since T2K does not have a control sample to estimate these errors, a fit to the atmospheric $\nu + \bar{\nu}$ data collected during 2519.9 days of SK-4 operation period, is performed. The atmospheric neutrino events are divided into 8 categories depending on particle identification and the number of decay electrons as: 1 ring e–like with 0 or 1 decay electron; 1 ring μ-like and multi–ring events with 0,1 or 2 decay electrons. For each of these samples, the shape distributions of the T2K selection variables (including those for multi–ring ν_μ charged current $1\pi^+$) are fitted using a Markov Chain Monte Carlo framework.

The uncertainties on the selection variables are parametrized as: $L^i_{jk} \rightarrow \alpha^i_{jk} L^i_{jk} + \beta^i_{jk}$, for the i^{th} T2K selection variable, j^{th} final state visible topology and k^{th} visible energy bin. The smear (α) and shift (β) affect the shape of the distributions. For the nominal case, $\alpha = 1, \beta = 0$, whereas $\alpha > (<)1$ widens (narrows) and $\beta > (<)0$ shifts the distribution to the right (left) as shown in Fig. 2(a). The atmospheric neutrino fit gives us the allowed range of α and β - which is used to create the final detector covariance matrix. In the fit, prior constraints are applied to the $1\mu^- + 1\pi^+$ final state visible topology in the Monte Carlo, via a χ^2 map constructed using a hybrid $\mu^-\pi^+$ sample.

The hybrid data (MC) sample is constructed by merging the hits from an atmospheric single ring μ–like data (MC) event and single π^+ generated using particle gun in the SK detector simulation framework, such that the kinematics of μ^- and π^+ match that of a true T2K MC event with $1\mu^- + 1\pi^+$ topology. The χ^2 map is constructed by smearing and shifting the hybrid MC and comparing it with the hybrid data and is input to the fit. The posterior predictive of the distributions indicate how good the fit is, which is shown in Fig. 2(b). The posteriors of α, β from the different samples, topologies and visible energy bins are used as inputs to construct the detector covariance matrix.

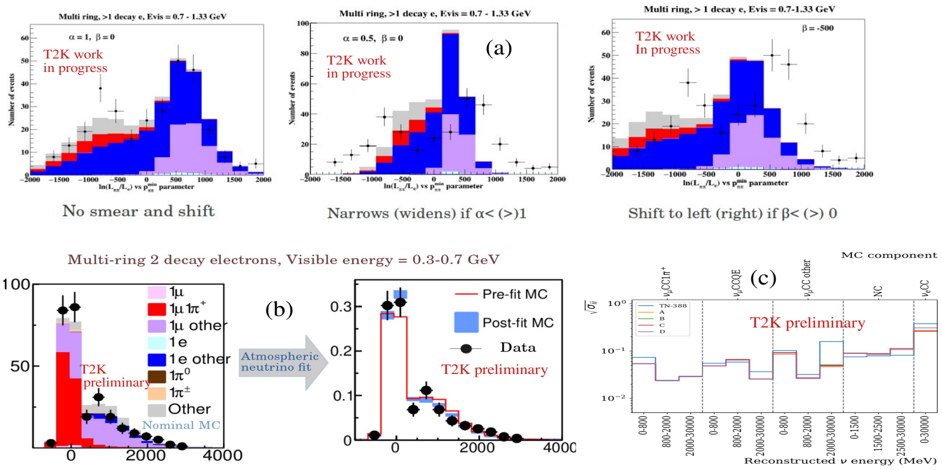

Figure 2: (a) The effect of smear α and shift β on the shape distribution of one of the T2K selection variables for multi–ring ν_μ charged current $1\pi^+$ events in the visible energy bins 0.7–1.33 GeV for a the multi–ring atmospheric neutrino sample with > 1 decay electron. (b) (Left) Comparison of data and MC before the fit for one of the selection variables; contributions to MC from various final state topologies are also seen; (right) comparison of the posterior predictive distribution with the pre–fit MC and data. (c) Diagonal elements of the covariance matrix for multi–ring events. The different lines correspond to the results from running the MCMC fit with different step sizes.

The diagonal elements of this matrix, corresponding to the multi–ring events are shown in Fig. 2(c).

4. Summary

A new charged current multi–ring $\nu_\mu 1\pi^+$ sample from ν mode data of T2K Runs 1–10 was selected and the far detector systematics including these events were estimated using a fit to the atmospheric neutrino data collected in SK.

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