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Atmospheric Neutrino and Proton Decay Results in Super-Kamiokande

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Abstract. Super-Kamiokande (SK) is a 50 kiloton water Cherenkov detector aiming for the detection of several physics such as solar, atmospheric, astrophysical neutrinos, proton decay, WIMP dark matter, etc. It has been running over 20 years since 1996, and achieved several remarkable outcomes in the field of the particle and astrophysics, one of which is the discovery of the neutrino oscillation, bringing the Nobel Prize in physics 2015. SK still accumulates a large number of neutrino events, and simultaneously the physic target and its sensitivity are extended along with the improvement of the analysis method, such as event reconstruction and background rejection. One of the strong motivations for the atmospheric neutrino oscillation measurement is to measure the mass ordering (hierarchy) between ν_2 and ν_3 . The atmospheric neutrino is sensitive to the mass hierarchy with help of the matter effect which is given when passing through the Earth. We have performed a detailed analysis to discriminate small signature of the mass hierarchy due to the matter effect. Proton decay is a direct signature anticipated by the grand unified theory (GUT) which is the physics beyond the standard model. Though the major decay modes and GUT models are excluded by the past searches, the efforts to search a glimpse of the proton decay signal are being continued with better event reconstruction and analysis method. In this paper the recent results of the atmospheric neutrino measurement and proton decay search using the most updated dataset taken until 2017 spring are described.

1. Introduction

Cosmic rays, such as proton and Helium, interacts with the atmosphere when they enter the Earth, and produces many secondary particles. The atmospheric neutrinos are produced as their decay products. The energy spectrum of the atmospheric neutrino follows the power-law shape and extends up to several 100 TeV though it becomes softer below several GeV by the cutoff effect due to the geomagnetic field. Since the atmospheric neutrino can easily penetrate the Earth, the surface detector observes the atmospheric neutrinos in all directions. The path length to the detector from the production point depends on the zenith angle direction, ranging from several 10 km for downward-going direction to $\sim 13,000$ km for upward-going direction. The atmospheric neutrinos are affected by the neutrino oscillation driven by the atmospheric mass (Δm_{32}^2) below several 10 GeV depending on the energy and the path length.

The Super-Kamiokande (SK) detector [1] has been observing atmospheric neutrinos from the beginning of the experiment in 1996. SK is a water Cherenkov imaging detector located in Gifu prefecture of Japan. The detector size is about 40 meter in the height and the diameter. The total (fiducial) volume is 50 (22.5) kiloton. About 11000 20-inch photo-multipliers (PMTs) are placed in grid on the inner detector wall, and about 1800 8 PMTs in outer detector for the



veto. SK has been running almost 20 years from 1996. So far it has been accomplished several remarkable achievements especially in neutrino physics. For example, in 1998 the neutrino oscillation has been discovered by observing the deficit of the upward-going muon neutrino, bringing the Nobel Prize in Physics 2015. The observation of the atmospheric neutrino by SK covers the wide energy range from $O(100 \text{ MeV})$ to $O(1 \text{ TeV})$. The neutrino flavor (ν_e or ν_μ) is reconstructed by the particle identification algorithm using the Cherenkov image pattern with excellent performance. There are four experimental phases; the first phase, SK-I, began with the original configuration of 40% photo coverage. We lost about half of PMTs due to accident. SK-II ran with 20% photo coverage. After full recovery in 2005, SK-III start with 40% coverage again. The front-end electronics are upgraded in SK-IV.

Proton decay is predicted by Grand Unified Theory (GUT), which is beyond Standard Model physics. Also it provides the method for baryon asymmetry Universe. There are many GUT predictions, for example, SU(5), SO(10), SUSY GUT, and the major decay modes, such as $p \rightarrow e^+ \pi^0$ and $p \rightarrow \nu K^+$ are predicted. Super-K is the world leading experiment in proton decay. Many decay modes have been explored so far; anti-lepton plus meson [2, 3], ν plus K [4], and others such as di-nucleon, n-n bar oscillation, etc. The lifetime limits which Super-K has published exceeds by 1-2 orders larger compared to other experiments. This time we have updated the result of $p \rightarrow \nu K^+$ search based on the analysis described in [4].

2. Oscillation Analysis

There are many opportunities to study neutrino oscillation especially three flavor mixing in the atmospheric neutrinos. As known well, the disappearance of muon neutrino are caused by $\nu_\mu \rightarrow \nu_\tau$ oscillation driven by Δm_{32}^2 and θ_{23} . In addition, due to non-zero θ_{13} mixing angle, the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation is expected, which provides many interesting information such as neutrino mass hierarchy, leptonic CP phase (δ_{CP}), and θ_{23} octant.

When neutrino propagates through the matter, the effective neutrino mass is known to be changed by the effect of the additional potential caused by the forward scattering with electrons in matter. Accordingly, neutrino oscillation probability is changed depending on the neutrino energy and electron density. Especially in multi-GeV region, the resonant-like enhancement of $\nu_\mu \rightarrow \nu_e$ oscillation is expected. The neutrino mass hierarchy could be proved by the atmospheric neutrino via such enhancement.

The three flavor oscillation fit to the atmospheric neutrino data is performed. To reduce the uncertainties due to other oscillation parameters such as Δm_{32}^2 , θ_{23} , θ_{13} and maximize mass hierarchy sensitivity, several constraints from other experiments are employed in the fit; $\sin^2 \theta_{13}$ value is constrained from reactor neutrino experiments. Also the constraints from T2K public data are included as an additional χ^2 , which is calculated using the published T2K data and our modeled expectation based on SK analysis. The fit is done with both normal hierarchy and inverted hierarchy assumptions, respectively, and the minimum χ^2 in each fit are compared to test mass hierarchy hypothesis. Fig. 1 shows χ^2 difference as a function of oscillation parameters, Δm_{32}^2 , $\sin^2 \theta_{23}$, δ_{CP} . The χ^2 value becomes slightly smaller for normal hierarchy case; the difference is $\Delta\chi^2 = 5.2$, corresponding to the significance of about 2σ level. The best-fit values of $\sin^2(\theta_{23})$ and δ_{CP} are 0.55 and 4.89, respectively.

3. Tau Appearance

The establishment of the appearance of the oscillation-driven ν_τ is crucial to verify three-flavor oscillation scheme. However the detection of tau is challenging because tau production rate is much lower than ν_μ and ν_e interactions due to higher energy threshold of the tau production (3.5 GeV). Also the signal events are affected by many background; the background rate is

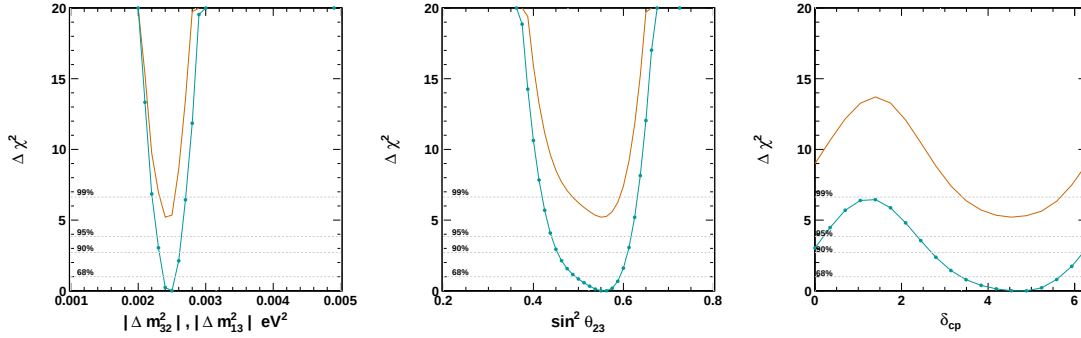


Figure 1. χ^2 difference ($\Delta\chi^2$) from the best fit point in the oscillation fits to Super-Kamiokande atmospheric neutrino sample. The fit is performed under the assumptions of normal (green) and inverted (orange) mass hierarchies. The figures show $\Delta\chi^2$ value as a function of $|\Delta m^2_{32}|$ or $|\Delta m^2_{13}|$ (left), $\sin^2 \theta_{23}$ (middle), δ_{CP} (right), respectively.

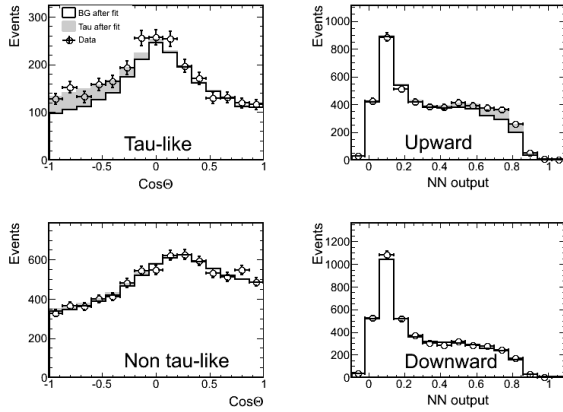


Figure 2. Zenith angle distributions (left) and neural network classifier output (right) in tau appearance analysis. The left upper (lower) figure shows the zenith angle distribution of tau-like (non-tau-like) events, with the fitted expectation of the tau signal (shaded) overlaid on the background events. The right upper (lower) figure shows the neural network output of the selected events in the upward-going (downward-going) sample.

about two order higher before the selection cut. In previous analysis [5] the tau signal has been detected in 3σ level. We have updated by increasing the data statistics for further confirmation of the tau appearance.

SK's strategy for tau appearance is to discriminate signal events in which tau decays into hadrons since the event topologies are relatively different from background. The discrimination algorithm using neural net (NN) has been utilized with the inputs of various reconstruction variables of signal and background events. The discrimination of the signal events are performed effectively using two dimensional PDFs of NN output and the zenith angle direction; tau signal appears in the area of the upward direction and the large NN output while the background events distributes in all directions and small NN output. The number of the tau events are estimated by the fit using the combined PDFs of signal and background with normalization parameter (α); $PDF_{BG} + \alpha \times PDF_{SIG}$, where $\alpha=1$ means the observed events are consistent with the expectation while $\alpha=0$ corresponds to no tau appearance. Fig. 2 shows the zenith angle distribution of events with large NN output ($NN>0.5$). The observed CC ν_τ events is estimated to be 338.1 ± 72.7 events while the expectation is 224.5 events which corresponds to 4.6σ significance with normal hierarchy (NH) assumption. The significance is increased to 5.0σ for inverted hierarchy case.

The large ν_τ sample offers the opportunity to measure the charged current (CC) ν_τ cross section in the energies of $3.5 \sim 70$ GeV. The flux averaged cross section is measured to be

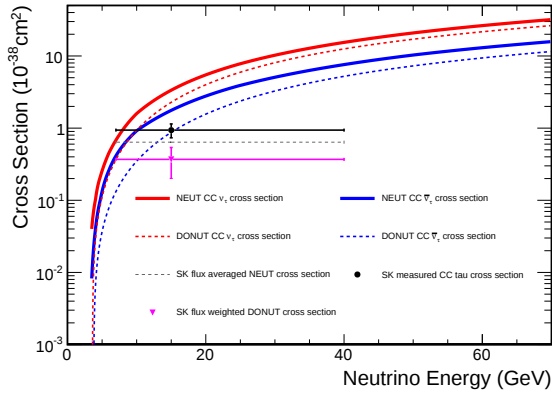


Figure 3. Measured flux-averaged charged-current tau neutrino cross section (black point), scaled DONUT measurement (magenta), together with theoretical differential cross sections (ν_τ in red and $\bar{\nu}_\tau$ in blue), flux-averaged theoretical cross section (dashed gray). The horizontal bar of the measurement point shows the 90% range of tau neutrino energies in the simulation.

$(0.94 \pm 0.20) \times 10^{-38} \text{cm}^2$ while the expectation is $0.64 \times 10^{-38} \text{cm}^2$ (Fig. 3), which is consistent with prediction within 1.5σ . Also the expectation based on the measurement of DONUT experiment, which is scaled down to SK sensitive energy by using the energy dependence of the theoretical cross section, is compared and found to be smaller than our measurement.

4. Search for $p \rightarrow \nu K^+$

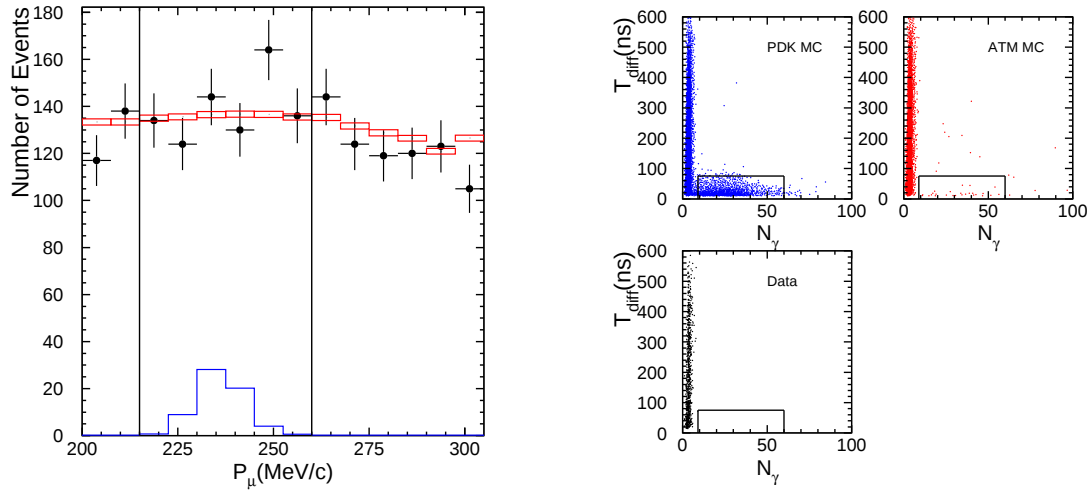
Two analyses are performed depending on K^+ decay channel produced by $p \rightarrow \nu K^+$; one is that K^+ decays into ν plus μ^+ (single μ^+ mode), and another is K^+ decays into $\pi^0 \pi^+$. The basic strategy of the event selection for single μ^+ mode is to select single-ring muon events accompanied with the following μ - e decay signal and the prompt 6 MeV gamma signal from excited oxygen nuclei. This μ - e - γ three-fold coincidence enables the significant reduction of the background events while keeping the moderate signal efficiency. Fig. 4 shows the distributions of selection cuts by the reconstruct muon momentum and the prompt gamma observables. In $\pi^0 \pi^+$ mode, $\pi^0 \rightarrow 2\gamma$ decay events are selected by the reconstructed mass, and the faint activity due to π^+ in the opposite side of π^0 direction is required (Fig. 5). As a result, no candidate events are observed for both decay modes for 349 kton-year exposure of SK 1-4 data, corresponding to 8×10^{33} years lower limit of lifetime limit in 90% CL.

5. Concluding Remarks

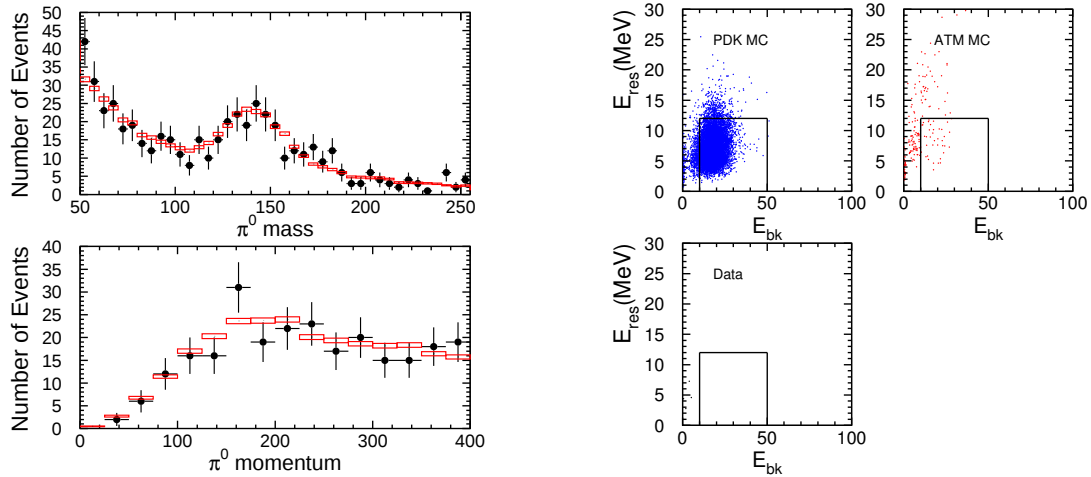
Atmospheric neutrino provides us the opportunity to investigate three flavor mixing scheme in various ways. The oscillation probability of $\nu_\mu \rightarrow \nu_e$ channel is expected to be enhanced by the matter effect for neutrinos which transverse inside the Earth. Thanks to mass hierarchy dependence of $\nu_\mu \rightarrow \nu_e$ resonance oscillation in multi-GeV region, atmospheric neutrino neutrino is sensitive to mass hierarchy. According to the oscillation fit result to the observed data with reactor and T2K constraints, SK data weakly prefers normal hierarchy. The significance of the tau appearance signal has been improved to 4.6σ mainly due to the increase of the exposure time. The larger ν_τ cross section than the prediction is measured though still consistent with theory. The proton decay is an unique method to probe GUT theory. Super-Kamiokande has been contributing to explore the possibility of the beyond Standard Model physics. The search of $p \rightarrow \nu K^+$ decay mode has been updated. There are no candidate events observed from the searches of two K^+ decay modes. The lower lifetime limit has been improved to 8.0×10^{33} years.

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**Figure 4.**

Left figure: momentum distributions of single muon events in the search of $p \rightarrow \nu K^+$ via K^+ decaying into ν plus μ^+ for proton decay MC (blue histogram), data (points with error bar), atmospheric MC (red histogram). Right figure: distributions of timing difference versus number of hits for prompt gamma in $p \rightarrow \nu K^+$ analysis for proton decay MC (blue), atmospheric MC (red), and data (black).

**Figure 5.**

Left figure: reconstructed π^0 mass and momentum distributions for data (points with error bar) and atmospheric MC (red histogram). Right figure: E_{res} versus E_{bk} distributions for proton decay MC (blue), atmospheric MC (red), and data (black), where E_{res} corresponds to the residual visible energy defined as energy not associated with the π^0 nor the π^+ , and E_{bk} the visible energy backward of reconstructed π^0 direction. In the analysis selection criteria of $E_{res} < 12$ MeV and $10 < E_{bk} < 50$ MeV are required.

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