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Atmospheric Neutrino Results from Super-Kamiokande

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Recent results of the Super-Kamiokande atmospheric neutrino analysis are presented. Super-Kamiokande has measured the flux of atmospheric neutrinos with energies from 100 MeV to 10 TeV, and measured the east-west effect to 8.0 (6.0)σ for electron (muon) neutrinos. The search for tau neutrino appearance from neutrino oscillations has resulted in a 4.6σ deviation from the hypothesis of no tau neutrino appearance. Super-Kamiokande data have a weak preference for normal mass hierarchy ($\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$) including the constraints from the reactor neutrino experiments, and the preference is strengthened ($\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$) after including constraints from the T2K experiment.

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1. Introduction

Atmospheric neutrinos are a natural source of neutrinos, which are produced by the interactions of primary cosmic rays with nuclei in upper atmosphere. The energies of atmospheric neutrinos at Super-Kamiokande (Super-K) have a span of 5 orders of magnitude, and the path-length varies between 10 km and 13,000 km. The large sample collected over 20 years provides an opportunity to measure the atmospheric neutrino fluxes and to investigate neutrino oscillations. Recent atmospheric neutrino results from Super-K related to these topics are presented below.

Super-K is a 50 kiloton water Cherenkov detector located at a depth of 1,000 meters in Japan. The detector is optically separated into an inner detector (ID), which is viewed by 11,146 20 inch photomultiplier tubes (PMTs), and an outer detector (OD), which is viewed by 1,885 8 inch PMTs. The PMTs collect photon produced by Cherenkov radiation via charged particles passing through the water in the detector, and the collected photons are used to reconstruct the neutrino interactions.

Super-K has been in operation since 1996, and has collected 5,326 days of atmospheric neutrino data over four run periods, SK-I (1996-2001), SK-II (2002-2006), SK-III (2006-2008) and SK-IV (2008-present). During the SK-I, SK-III, SK-IV periods, the ID was instrumented with 40% PMT coverage, while the coverage was 20% during the SK-II period. In 2008, the electronics were upgraded. The SK-IV period denotes the data taken after the upgrade of the electronics[1]. The neutrino events are categorized into three types, full contained (FC), partially contained (PC) and upward-going muons (UPMU), based on the event topology.

2. Measurement of atmospheric neutrino flux

Super-K recently published a direct measurement of atmospheric neutrino flux[2], with energy spectra measured in the range of 100 MeV to 10 TeV. Fig.1 shows the Super-K-measured neutrino fluxes as a function of the neutrino energy, and the ratio of data to oscillated HKKM11 model prediction[3], which calculates the atmospheric neutrino flux by Monte Carlo simulations. The measured fluxes are consistent with oscillated HKKM11 model prediction.

Super-K previously measured the directional asymmetry of the neutrino flux (5σ for electron neutrino and 2σ for muon neutrino), known as the east-west effect[4], with a 45 kton·yr exposure of the detector. The asymmetry is caused by the deflection of comic rays in the earth's geo-magnetic field. A parameter is defined to show the azimuthal asymmetry,

$$A = \frac{n_{east} - n_{west}}{n_{east} + n_{west}} \tag{2.1}$$

where n_{east} (n_{west}) is the number of east-going (west-going) single-ring events in the Super-K dataset. The new measurement showed the asymmetry with a significance of 8.0 (6.0)σ for electron (muon) neutrinos, using SKI-IV data spanning 20 years. Fig. 2 shows the A parameter as a function of reconstructed energy and zenith angle for single ring e-like and μ-like events in the Super-K data and Monte Carlo (MC) simulations.

3. Search for tau neutrino appearance from neutrino oscillations

In the three-flavor neutrino oscillation model, neutrinos produced in a specific lepton flavor can change to a different flavor during propagation. Tau neutrino appearance is expected in atmospheric

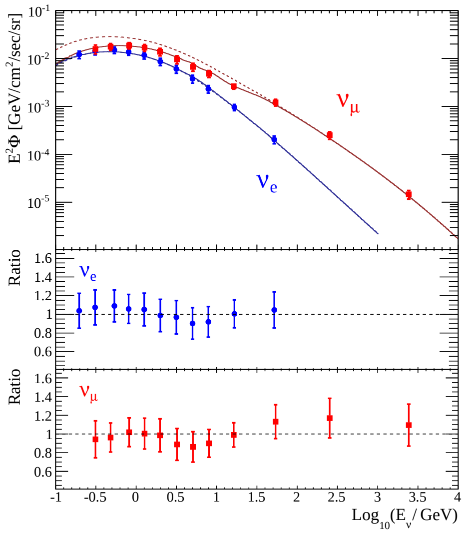

Figure 1: The measured the atmospheric electron neutrino (blue) and muon neutrino (red) fluxes as a function of the neutrino energy. The HKKM11 model predictions are also shown in solid (with oscillation) and dashed (without oscillation) lines. The lower part shows the ratio of data to HKKM11 model prediction[3]. Adapted from [2].

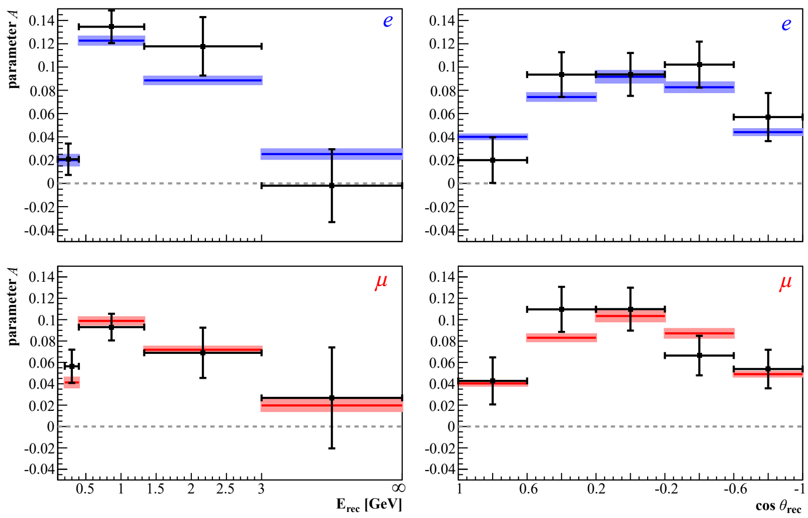

Figure 2: The A parameter (representing the azimuthal asymmetry) as a function of reconstructed energy (left) and cos zenith angle (right) for single-ring e-like (blue) and μ-like (red) events in the Super-K data (points) and MC (boxes). Adapted from [2].

neutrinos, which consists mostly of electron and muon neutrinos at production. Super-K performed a search for charged-current tau neutrino events with a neural network algorithm. Details of the neural network are described in [5]. The analysis performed a 2D unbinned maximum likelihood fit of data against the PDFs built from MC,

$$Data = PDF_{BG} + \alpha \times PDF_{tau} + \sum \varepsilon_i \times PDF_i \tag{3.1}$$

where PDF_{BG}, PDF_{tau} and PDF_i are 2D likelihoods built from MC for the background, tau signal and the systematic errors induced by shifting the error by 1σ, respectively. In the fit, the magnitude of each systematic error is constrained with a Gaussian function centered at 0 with a width equal to 1. Fig. 3 shows the 2D likelihood distribution for signal and background constructed with MC. The fitted α parameter in the normal neutrino mass hierarchy assumption is 1.47 ± 0.32, corresponding to a significance of 4.6σ deviation from 0. Fig. 4 presents the zenith angle distribution of tau-like events for background and tau signal in both simulation and data in SKI-IV.

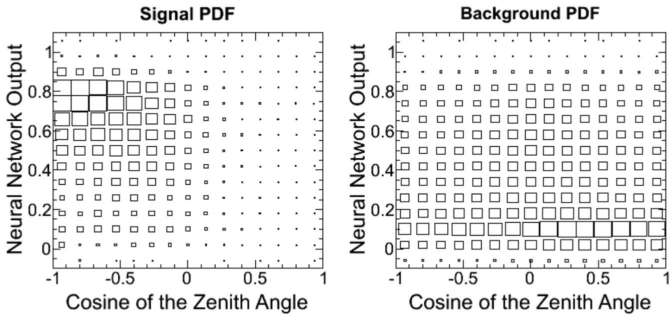

Figure 3: 2D likelihood distribution as a function a cos zenith angle and neural network output for tau signal (left) and background (right) built with MC.

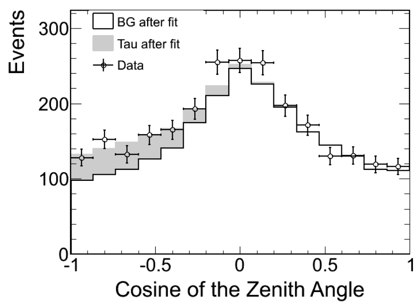

Figure 4: The zenith angle distribution of tau-like events (events with neural network likelihood larger than 0.5) for background (white), tau signal (gray) in simulation and data (cross) in SKI-IV.

4. Three flavor neutrino oscillation

Recent reactor experiments measured a finite value for the mixing angle θ_{13} [7]. Due to the large value of θ_{13}, matter effects induces a resonant enhancement of $\nu_\mu \to \nu_e$ for upward-going neutrinos passing through the core and mantle of the planet. The enhancement depends on both neutrino mass hierarchy and the CP violation phase δ_{CP}[6]. Super-K performed a full three flavor neutrino oscillation analysis with the atmospheric neutrino sample, in which the sub-leading effects are taken into account. In the analysis, θ_{23}, Δm_{23}, and δ_{cp} are fitted simultaneously, while θ_{13} are constrained to the recent reactor neutrino measurements. The best-fit information for this fit is summarized in Table. 1. One dimensional $\Delta\chi^2$ distributions for the oscillation parameters are shown in Fig. 5. Normal hierarchy (NH) is preferred, $\chi^2_{NH} - \chi^2_{IH} = -4.3$, by Super-K atmospheric neutrino data. Toy Monte Carlo samples were generated with the assumption of either normal or inverted hierarchy to test the significance of the preference. The probability of having $\Delta\chi^2$ smaller than -4.3 is 0.45 in the NH assumption, and is between 0.007 ($\sin^2(\theta_{23})$=0.4) and 0.031 ($\sin^2(\theta_{23})$=0.6) in the IH assumption. In addition, a model of the T2K experiment's ν_e appearance[8] and ν_μ disappearance[9] samples were built with the atmospheric neutrino MC and simulation framework. Both model samples were fit together with the Super-K atmospheric neutrino samples to include T2K's constraints into the fit. By including the T2K constraints, the preference for normal hierarchy is slightly stronger (χ^2_{NH}-χ^2_{IH} = -5.2). The best fit information of this fit is also summarized in Table. 1.

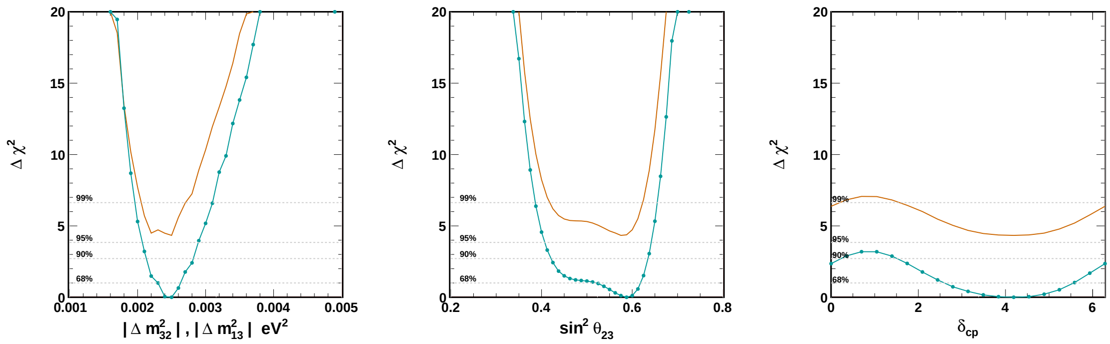

Figure 5: Constraints on neutrino oscillation parameters from the SKI-IV atmospheric neutrino data. Orange line denotes the result in the IH assumption, which has been offset from the NH result, shown in blue, by the difference of their $\Delta\chi^2$.

Fit	Δ^2_{min}	δ_{CP}	$\sin^2\theta_{23}$	$\Delta m^2_{23,13}[eV^2]$
SK NH	571.7	4.19	0.59	2.5×10^{-3}
SK IH	576.0	4.19	0.58	2.5×10^{-3}
SK+T2K NH	639.6	4.89	0.55	2.4×10^{-3}
SK+T2K IH	644.8	4.54	0.55	2.5×10^{-3}

Table 1: Summary of best-fit information for fits assuming the normal or inverted hierarchy with the SK neutrino data only (517 d.o.f.) or with constraint from T2K (585 d.o.f.).

5. Conclusion

Using the large atmospheric neutrino sample, Super-K has precisely measured the atmospheric neutrino flux with energies between 100 MeV and 10 TeV, and observed the east-west effect in both muon neutrinos (6.0σ) and electron neutrinos (8.0σ). The search for tau neutrino appearance has yielded a significance of 4.6σ deviation from no tau appearance hypothesis. Atmospheric neutrino data have a preference for normal hierarchy (χ^2_{NH}-χ^2_{IH}=-4.3), and the preference is slightly strengthened after including constraints from the T2K experiment (χ^2_{NH}-χ^2_{IH}=-5.2).

Acknowledgments

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