Recent results from atmospheric neutrino analysis at Super-Kamiokande

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Abstract. The atmospheric-neutrino sample at Super-Kamiokande is sensitive to all neutrino oscillation parameters. Our recent analyses focus on the sub-dominant effects which includes unknown parameters. The upper limit to θ_{13} is set to be $\sin^2\theta_{13} < 0.066$ (< 0.122) at 90% confidence level in case of the normal (inverted) mass hierarchy. We confirm our sample has the sensitivity to the CP phase, δ_{CP}. The mass hierarchy test also is performed. CPT violation in the neutrino oscillation is tested with the atmospheric-neutrino sample. However, our result suggests the CPT conservation.

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SUPER-KAMIOKANDE

Super-Kamiokande (SK) is one of the leading experiments which investigates neutrino (ν) oscillation. The SK detector is a multipurpose ν detector which measures atmospheric-ν, solar-ν, and those from supernovae. It has been operated since 1996. The first observation of ν oscillation was made with the atmospheric-ν analysis at this experiment in 1998. There are four periods in the SK experiment. The number of active PMTs in each run period are 11146 (SK-I), 5182 (SK-II), and 11129 (SK-III, IV). The difference between SK-III and IV is the readout electronics. In September 2008, the new readout electronics called QBEE (namely QTC-Based Electronics with Ethernet)[1] was installed and the SK-IV operation was started. Here, I report the results of the oscillation analyses with SK-I, II, III data.

TWO FLAVOR ANALYSIS

In the atmospheric-ν sample, the effect of the oscillation parameters θ_{23} and Δm^2_{23} are dominant and appear in its ν_μ flux. The two flavor analysis, which considers only this dominant effect of the ν oscillation, is performed. The live times for analyzed data are 1489, 799, and 518 days for SK-I, II, and III, respectively.

The allowed region of this analysis is shown in Figure 1. Two kinds of studies named the zenith angle analysis and the L/E analysis are shown. They are consistent with each other. The Δm^2_{23} region of the L/E analysis is slightly better than that of the zenith angle analysis. Our results are consistent also with results from MINOS[2] and K2K[3]. The best limit to θ_{23} is set by our experiment while that for Δm^2_{23} is set by MINOS. The one dimensional allowed region is shown in Table 1.

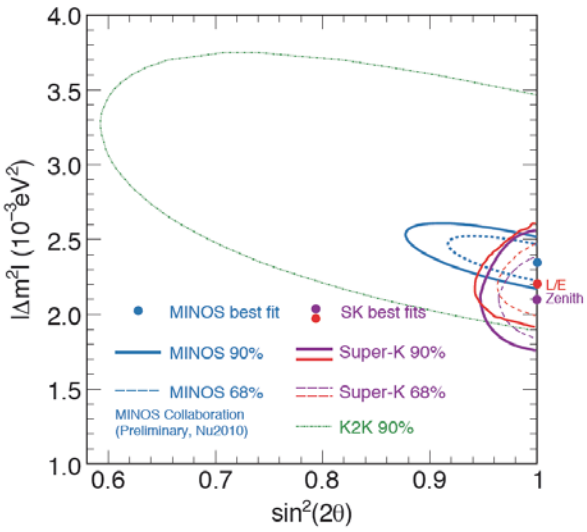

FIGURE 1. Contour plot for the allowed region of $\sin^2 2\theta_{23}$ and Δm^2_{23}. The purple (red) point, dash line, and solid line show the best fit point, 68% C.L. limit, and 90% C.L. limit for the zenith angle (L/E) analysis, respectively. The results from MINOS[2] (blue) and K2K[3] (green) are also shown.

TABLE 1. Allowed regions of Δm^2_{23} and $sin^2 2\theta_{23}$. The results from both the zenith angle analysis and the L/E are shown, respectively.

Analysis	Δm^2_{23} (eV^2)	$sin^2 2\theta_{23}$
Zenith	$2.11^{+0.11}_{-0.19} \times 10^{-3}$	> 0.96 (90% C.L.)
L/E	$2.19^{+0.14}_{-0.13} \times 10^{-3}$	> 0.96 (90% C.L.)

FULL THREE FLAVOR ANALYSIS

In case we consider matter effects[4], an interesting behavior appears in the atmospheric-ν_e flux. The ν_e flux is

slightly deformed by effects of the Δm^2_{12}, θ_{12}, θ_{13}, and δ_{CP} parameters. We evaluate the θ_{13} and δ_{CP} parameters, which are still unknown, from the precise study of the ν_e flux. During the analysis, the Δm^2_{12} and $\sin^2\theta_{12}$ are set to be 7.66×10^{-5} eV^2 and 0.304[5]. The effects of those uncertainties are taken into account in the systematic errors. The oscillation fitting with four free parameters, Δm^2_{23}, θ_{23}, θ_{13}, and δ_{CP}, is performed to the same data set as two flavor analysis.

The allowed regions for the Δm^2_{23}, $\sin^2\theta_{13}$, and δ_{CP} are in Figure 2. Since the matter effect appears only ν (anti-ν, $\bar{\nu}$) in the normal (inverted) mass hierarchy case, the results assuming two hierarchies become different. They are shown in the separate figures. One dimensional results for all parameters are summarized in Table 2. The resultant Δm^2_{23} and θ_{23} are consistent with those from the two flavor analysis. This means the Δm^2_{23} and θ_{23} parameters are robust to the matter effect and the two flavor oscillation scheme is a good approximation for the neutrino oscillation in the atmospheric-ν sample. The best fit value of θ_{13} is 0.006 (0.044) for the normal (inverted) mass hierarchy. These non-zero signals are not significant when we consider their uncertainties. Then, the 90 % confidence level (C.L.) limit of $\sin^2\theta_{13}$ <0.066 (0.122) is set in case of the normal (inverted) hierarchy. No significant constraint to δ_{CP} can be made from this analysis. However, we can conclude atmospheric-ν sample has sensitivity to δ_{CP} and our non-zero result might be the sign of the CP violation in the ν oscillation.

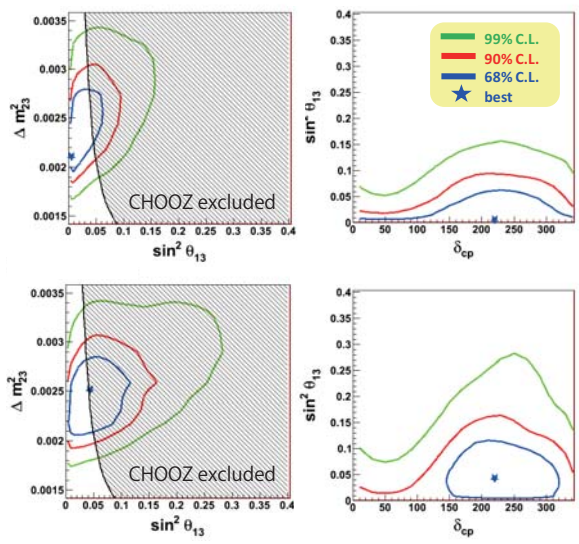

FIGURE 2. Allowed region for full three flavor analysis. The upper two figures are in case of the normal mass hierarchy and lowers are that of the inverted mass hierarchy. Our results are shown in the colored lines. The 90 % C.L. CHOOZ limits[6] also are shown in the hatched regions.

TABLE 2. Resultant parameters for the full three flavor analysis in both mass hierarchy cases.

(Normal) Parameters	Best Fit	90% C.L. Bound
Δm^2_{23}	2.11×10^{-3}eV^2	$[1.88, 2.75]\times10^{-3}$eV^2
$\sin^2\theta_{23}$	0.525	[0.406, 0.629]
$\sin^2\theta_{13}$	0.006	<0.066
δ_{CP}	220 degree	-

(Inverted) Parameters	Best Fit	90% C.L. Bound
Δm^2_{23}	2.51×10^{-3}eV^2	$[1.98, 2.81]\times10^{-3}$eV^2
$\sin^2\theta_{23}$	0.575	[0.426, 0.644]
$\sin^2\theta_{13}$	0.044	<0.122
δ_{CP}	220 degree	[121.4, 319.1] degree

MASS HIERARCHY TEST

The ν mass hierarchy can be discussed within the full three flavor analysis performed in the previous section. We determine the minimum χ^2 values of 469.94 and 468.34 when the normal and inverted mass hierarchies are assumed in the fit, respectively. The χ^2 distribution as a function of $\sin^2\theta_{13}$ is shown in Figure 3. The results suggest the inverted mass hierarchy is slightly favored. Although the difference, $\Delta\chi^2 = 1.6$, is not significant, we conclude the mass hierarchy can be tested with the SK's atmospheric-ν sample in the future.

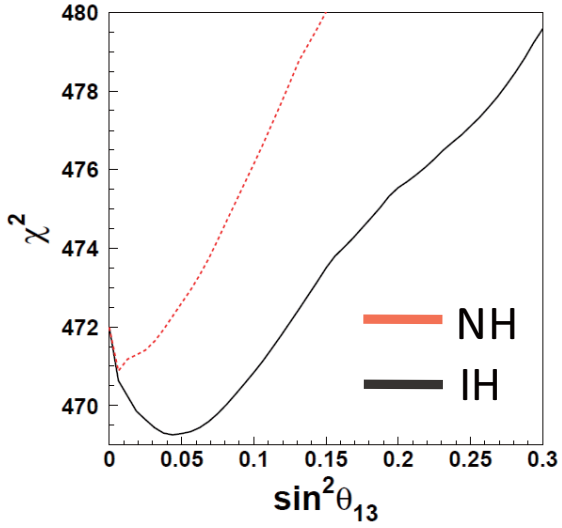

FIGURE 3. The χ^2 distribution as a function of $\sin^2\theta_{13}$. The normal (red) and inverted (black) mass hierarchy cases are shown together.

SEARCH FOR CPT VIOLATION

CPT violation was recently suggested by MINOS[2] and MiniBooNE[7]. They compared two flavor analysis results and reported the discrepancy between samples in ν-beam and $\bar{\nu}$-beam operation modes. The atmospheric-ν sample has same Δm^2 region as MINOS so that we can examine their result.

The statistical evaluation is performed since the SK detector cannot distinguish ν and $\bar{\nu}$ on an event by event. The ν to $\bar{\nu}$ ratios of the cross section and the original ν flux have dependence on their energy. SK's oscillation fitting is applied to sub-samples divided by the scattered lepton momenta. Therefore, the oscillations of both ν and $\bar{\nu}$ can be determined, separately.

The oscillation fit to the atmospheric-ν data is implemented with the two flavor scheme and four free parameters. Two parameters are for the ν oscillation and two others are for the $\bar{\nu}$ oscillation. The one dimentional allowed region at 90 % C.L. is summarized in Table 3. The resultant oscillation parameters for both ν and $\bar{\nu}$ are consistent with each other and they are also consistent with the result of our two flavor analysis. There is no evidence of CPT violation in the atmospheric-ν oscillation. The allowed region for $\bar{\nu}$ oscillation parameters is shown and compared with the MINOS result in Figure 4. Although our result suggests CPT conservation, there is no discrepancy between MINOS's and our results since their allowed region is partially included in our allowed region.

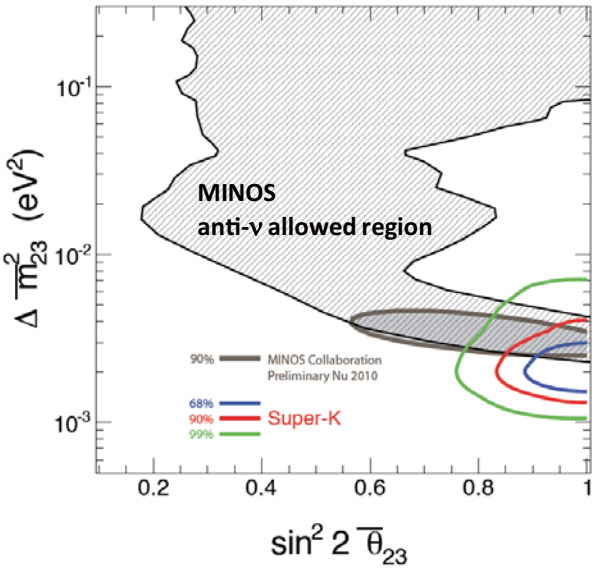

FIGURE 4. Allowed region of the $\bar{\nu}$ oscillation. The allowed region of the SK's $\bar{\nu}$ oscillation is shown with colored lines. The MINOS's 90 % C.L. limit for the ν (black line) and $\bar{\nu}$ (hatched region) oscillations[2] also are shown.

TABLE 3. Oscillation parameters

Parameters	Best Fit	90% C.L. Bound
Δm^2	2.1×10^{-3}eV^2	$[1.8, 2.7] \times 10^{-3}$eV^2
$\Delta \bar{m}^2$	2.0×10^{-3}eV^2	$[1.5, 3.1] \times 10^{-3}$eV^2
$\sin^2 2\theta$	1.0	$[0.92, 1.0]$
$\sin^2 2\bar{\theta}$	1.0	$[0.88, 1.0]$

CONCLUSION

We performed the study of sub-dominant effects of the neutrino oscillation in the atmospheric-ν flux. These effects are caused by the matter effect with the oscillation parameters, Δm^2_{12}, θ_{12}, θ_{13}, and δ_{CP}. We determine the 90 % C.L. limit of $\sin^2\theta_{13} < 0.066$ (0.122) in case of the normal (inverted) mass hierarchy. We confirm SK's atmospheric-ν data has sensitivity to δ_{CP}.

The mass hierarchy test is performed by comparing the minimum χ^2 values of the oscillation fitting assuming either normal or inverted mass hierarchies. They are slightly different and the inverted mass hierarchy case is favored. The difference is not significant. However, we conclude our data can be used to determine the mass hierarchy in the future.

CPT violation in the ν oscillation is tested with SK's atmospheric-ν data. The MINOS result can be examined since our data has the same Δm^2 region. The oscillation fit with the two flavor scheme and four free parameters is performed. The resultant oscillation parameters for both ν and $\bar{\nu}$ are consistent with each other. Our result suggest the CPT conservation.

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