Recent results from Super-Kamiokande
~ atmospheric neutrino ~

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for the Super-Kamiokande collaboration
Super-Kamiokande detector

50000 tons  Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground

Operation started in Apr. 1996.

Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.
Super-Kamiokande detector

History of the SK detector

- SK-I
  - April 1996
  - ~ June 2001
  - 11146 ID PMTs
    - (40% coverage)

- SK-II
  - October 2002
  - ~ October 2005
  - 5182 ID PMTs
    - (19% coverage)

- SK-III
  - June 2006
  - ~ September 2008
  - 11129 ID PMTs
    - (40% coverage)

- SK-IV
  - September 2008
  - ~ running
  - Electronics Upgrade
Physics in Super-Kamiokande

**Neutrino oscillation**
- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

**GUT**
Proton decay
\[ p \rightarrow e^+ + \pi^0 \]
\[ p \rightarrow K^+ + \bar{\nu} \]

**New physics**
- WIMP search
- n-\(\bar{n}\) oscillation
- dinucleon decay etc....

**Neutrino astrophysics**
- Super nova burst neutrino
- Super nova relic neutrino
Neutrino mixing parameter measurements

Normal hierarchy

\[ \Delta m_{32}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-3} \text{(eV/c}^2)^2 \]

\[ |\Delta m_{32}^2| \\ ~2.5 \pm 0.2 \times 10^{-3} \text{(eV/c}^2)^2 \]

Inverted hierarchy

\[ \Delta m_{21}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-3} \text{(eV/c}^2)^2 \]

\[ |\Delta m_{32}^2| \\ ~2.5 \pm 0.2 \times 10^{-3} \text{(eV/c}^2)^2 \]

\[ \sin^2 \theta_{12} \sim 0.305 \pm 0.013 \]

\[ \sin^2 2\theta_{13} = 0.098 \pm 0.013 \]

Remaining questions

1) \( \theta_{23} \) is really \( 45^\circ \) or \( < 45^\circ \) or \( > 45^\circ \)?

Current uncertainty of \( \sin^2 \theta_{23} \) is still large \( \sim 10\% \) level

\[ \sin^2 \theta_{23} = 0.514 \pm 0.055 \quad (\text{T2K 2014}) \]

2) CP is violated or not ( \( \delta = 0 \) or not )?

3) Mass hierarchy \( \sim \) which is heavier? ( \( \Delta m_{32}^2 > 0 \) or \( < 0 \)?)
Neutrino oscillation probability $\sim \nu_\mu$ to $\nu_e$ oscillation

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2S_{13}^2S_{23}^2 \cdot \sin^2 \Delta_{31}$$

$\theta_{13}$ Leading term

$$+ 8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$- 8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$+ 4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2 + S_{12}^2S_{23}^2S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2 \Delta_{21}$$

$$- 8C_{13}^2S_{13}^2S_{23} \cdot \frac{a}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+ 8C_{13}^2S_{13}^2S_{23} \cdot \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31}$$

For anti neutrinos,

$$a \rightarrow -a, \ \delta \rightarrow -\delta$$

Now, $\theta_{13}$ is known to be (quite) large.

There are chances to observe the contributions from mass hierarchy and CPV ($\delta$)!
Recent results from Reactor & T2K

$\nu_e$ appearance clearly observed in T2K

Allowed region of $\delta_{CP}$ for each $\sin^2 2\theta_{13}$

Reconstructed $\nu$ energy

Data
Best fit
No oscillation

Extracted $\sin^2 2\theta_{31}$ is slightly larger than the ones from reactor experiments

$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ (normal hierarchy)
$0.170^{+0.044}_{-0.037}$ (inverted hierarchy)

Indication of non-zero $\delta_{CP}$?
Characteristics of atmospheric neutrino

Primary cosmic ray (p, He..)

Generation height 10~30 km

Atmospheric ν energy spectrum

Atmospheric neutrino energy spectrum
Peaked at ~ several hundreds of MeV, Extended > TeV

Neutrino travel length from ~ 10 km to 13,000 km

Zenith angle corresponds to travel length of neutrinos.
Atmospheric neutrino ~ event topology in SK

### Fully Contained (FC)
- Average energies
  - FC: ~ 1 GeV
  - PC: ~ 10 GeV
  - UpMu: ~ 100 GeV

### Partially Contained (PC)

### Upward-going Muons (Up-\(\mu\))
Atmospheric neutrino ~ Analysis samples in SK

**Fully Contained (FC)**
- Zenith angle distribution of each sample

**Partially Contained (PC)**

**Upward-going Muons (Up-μ)**

- In total 19 analysis samples (classified by ν flavors, event topologies, energies, ...)
- Fit to the data in bins of cosθ_{zenith} and momentum
- Dominated by ν_{μ} → ν_{τ} oscillations
- Interested in sub-dominant contributions
  - Three-flavor effects, Sterile Neutrinos, LIV, ...
Neutrino oscillation studies using atmospheric $\nu$

**Evidence for $\nu_\tau$ Appearance at Super-K**

**Zenith Distribution**

Search for events $\sim$ hadronic decay of $\tau$ lepton
Multi-ring e-like events $\sim$ mostly DIS interactions

Actual event selection performed by neural network
Total efficiency $\sim$ 60%

Negligible primary $\nu_\tau$ flux
$\sim$ $\nu_\tau$ must be oscillation-induced

*Expected only in upward-going*

\[ \beta = 0 : \text{no} \ \nu_\tau \]

\[ \text{Data} = \alpha (\gamma) \times bkg + \beta (\gamma) \times \text{signal} \]

<table>
<thead>
<tr>
<th>Result</th>
<th>Background $\pm$</th>
<th>DIS $\gamma$ $\pm$</th>
<th>Signal $\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I+II+III</td>
<td>0.94 $\pm$ 0.02</td>
<td>1.10 $\pm$ 0.05</td>
<td>1.42 $\pm$ 0.35</td>
</tr>
</tbody>
</table>

180.1 ± 44.3 (stat) +17.8-15.2 (sys) events
$\sim$ 3.8 $\sigma$ excess (Expected 2.7 $\sigma$ significance)
Neutrino oscillation studies using atmospheric $\nu$

High statistics atmospheric neutrino data

~ Possibility in observing small distortion in $\nu_e$

- **Matter effect** ~ from mass hierarchy
  Possible $\nu_e$ enhancement in several GeV passed through the earth core

- **Solar term** ~ from $\theta_{23}$ octant degeneracy
  Possible $\nu_e$ enhancement in sub-GeV

- **Interference**
  CP phase could be studied.

### Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \approx \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)$$

- **Matter effect**
- **Solar term**
- **Interference**

![Diagram showing $\nu_e$ flux ratio and different effects](image)
Neutrino oscillation studies using atmospheric $\nu$

**Expected Sensitivity**

Hierarchy Sensitivity (True: NH)

As a function of the true value of $\sin^2 \theta_{23}$, this plot shows the ability to reject the inverted mass hierarchy hypothesis assuming the normal hierarchy.

Owing to the broad energy spectrum and baseline, atmospheric neutrino has sensitivity to the mass hierarchy.

However, sensitivity to the mass hierarchy has rather strong relation with the other oscillation parameters.

As a function of the true value of $\sin^2 \theta_{23}$, this plot shows the ability to reject the inverted mass hierarchy hypothesis assuming the normal hierarchy.
Neutrino oscillation studies using atmospheric $\nu$

**Changes and Updates to Oscillation Analyses**

1775 days of SK-IV data: 4581.4 days total (282.2 kton·yrs)

Addition of a new analysis sample

- Fully contained Multi-Ring $e$-like
- “other” = not-$\nu_e$ & not-$\bar{\nu}_e$

### Multi-Ring e-like Sample Purities

<table>
<thead>
<tr>
<th>Purity</th>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$-like</td>
<td>72.2%</td>
<td>8.3%</td>
<td>3.2%</td>
<td>16.1%</td>
</tr>
<tr>
<td>$\bar{\nu}$-like</td>
<td>75.0%</td>
<td>6.5%</td>
<td>2.8%</td>
<td>15.6%</td>
</tr>
<tr>
<td>other</td>
<td>30.9%</td>
<td>33.4%</td>
<td>5.1%</td>
<td>30.5%</td>
</tr>
</tbody>
</table>

Improved systematic error treatments

- Updates to cross-section, FSI, detector systematics, $2p-2h$ (MEC)
Neutrino oscillation studies using atmospheric $\nu$

$\theta_{13}$ **Fixed** Analysis (NH+IH) SK Only

$\theta_{13}$ fixed to PDG average

uncertainty is included as a systematic error

**Preliminary**

Offset in these curves shows the difference in the hierarchies
Neutrino oscillation studies using atmospheric $\nu$

$\theta_{13}$ Fixed Analysis (NH+IH) SK Only

Normal hierarchy favored

but $\chi^2_{IH} - \chi^2_{NH} = -0.9$

Not a significant preference

Previous results (2013 Summer) favored inverted hierarchy by $\Delta \chi^2 \sim 1.5$

Driven by excess of upward-going e-like consistent with the effects of $\theta_{13}$

Primarily in SK-IV data

New multi-ring e-like sample also pulls the fit towards the NH

Fit for $\theta_{13}$ now weakly favors $\theta_{13} > 0$

Rejection of $\delta_{cp} \sim 60^\circ$ driven by excess in Sub-GeV electron events

Constraint is consistent with sensitivity
Neutrino oscillation studies using atmospheric $\nu$

Introduction of External Constraint

Constraints from the other experiments,
( especially, $\Delta m^2$ and $\sin^2 \theta_{23}$ ),
make it possible to improve sensitivity to mass hierarchy.

Fit the T2K $\nu_\mu$ and $\nu_e$ data sets
with SK atmospheric neutrino data.

Use publicly available T2K information and results.

Simulate T2K using SK tools
( not a joint result of the T2K and the SK collaborations )
Neutrino oscillation studies using atmospheric $\nu$

$\theta_{13}$ Fixed SK + T2K $\nu_\mu$, $\nu_e$ (External Constraint) Normal Hierarchy

$\Delta \chi^2$ vs $|\Delta m^2_{32}|$ MeV$^2$

$\sin^2 \theta_{23}$ vs $\Delta m^2_{23}$ for $\theta_{13}$ = 0.025

$\Delta m^2_{32}$ vs $\delta_{cp}$

<table>
<thead>
<tr>
<th>Fit (543 dof)</th>
<th>$\chi^2$</th>
<th>$\theta_{13}$</th>
<th>$\delta_{cp}$</th>
<th>$\theta_{23}$</th>
<th>$\Delta m^2_{23}$ (x10$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK + T2K (NH)</td>
<td>578.2</td>
<td>0.025</td>
<td>4.19</td>
<td>0.55</td>
<td>2.5</td>
</tr>
<tr>
<td>SK + T2K (IH)</td>
<td>579.4</td>
<td>0.025</td>
<td>4.19</td>
<td>0.55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

$\chi^2_{IH} - \chi^2_{NH} = -1.2$ (-0.9 SK only)

$\sin \delta_{cp} = 0$ is still allowed at (at least) 90% C.L. for both hierarchies.
Neutron tagging ~ For further improvements ~

Effective neutron tagging make it possible to
1) discriminate $\nu$ and $\bar{\nu}$ interactions more efficiently
2) reduce background of proton decay

- Electronics in SK-IV store all PMT hits for 500 $\mu$sec after a neutrino-like trigger.
- Search for the 2.2 MeV gamma from $p(n,\gamma)d$
  Actual search is performed with a neural network (16 variables)
- Data and MC show good agreement on atmospheric neutrino sample

### 2.2 MeV $\gamma$ Selection

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>20.5%</td>
</tr>
<tr>
<td>Background / Event</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Sterile neutrino oscillations in atmospheric neutrino

Sterile Neutrino searches at SK
Independent from
the sterile $\Delta m^2$ and
the # of sterile neutrinos.

$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}$

\[ |U_{\mu4}|^2 \]
Induces a decrease in event rate of
$\mu$-like data of all energies and zenith angles

\[ |U_{\tau4}|^2 \]
Shape distortion of angular distribution
of higher energy $\mu$-like data

Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande
K. Abe et al., PHYSICAL REVIEW D 91, 052019 (2015)
Sterile neutrino oscillations in atmospheric neutrino

Assuming sterile neutrinos experience vacuum oscillation, ( = turning off sterile matter effects ), while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$

\[
\begin{align*}
P_{ee} &= P_{ee}^{(3)}, \\
P_{e\mu} &= (1 - |U_{\mu 4}|^2) P_{e\mu}^{(3)}, \\
P_{\mu e} &= (1 - |U_{\mu 4}|^2) P_{\mu e}^{(3)}, \\
P_{\mu\mu} &= \left(1 - |U_{\mu 4}|^2\right)^2 P_{\mu\mu}^{(3)} + |U_{\mu 4}|^4
\end{align*}
\]

Suppression due to existence of sterile $\nu$

*) Infinite width for same L/E $\sim \nu_e$ CC matter effects

\[|U_{\mu 4}|^2 = 0.0058\]
Sterile neutrino oscillations in atmospheric neutrino

Sterile vacuum oscillation

Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande

\[
|U_{\mu 4}|^2 < 0.041 \text{ at } 90\% \text{ C.L. (})^*
\]

SK-I~IV data (4438 days)

\((*)\) Limit is valid for \(\Delta m_{41} > 0.1 \text{ eV}^2\)
Summary

$\nu_\tau$ appearance

$180.1 \pm 44.3$ (stat) $+$17.8-15.2 (sys) events ($3.8\sigma$)

Three-Flavor neutrino oscillation analysis

Using data from SKI to IV (4538 days),

$\sim1 \sigma$ preference for the NH, and second octant

Neutron tagging

Data taken with SK-IV electronics,

we developed new “neutron tagging” analysis tools.

Efficiency $\sim 20.5\%$

Will be used for atmospheric neutrino oscillation analyses

and proton decay search.

No indication of oscillations into sterile neutrinos

For 3+N models $|U_{\mu 4}|^2 < 0.041$ at 90% C.L.
fin.
Neutrino oscillation studies using atmospheric $\nu$

Searching for Three-Flavor Effects: Oscillation probabilities

Resonant oscillations between 2-10 GeV (Multi-GeV region) for $\nu$ or $\bar{\nu}$ depending upon MH,
No oscillations from downward-going neutrinos above $\sim$5 GeV
No oscillations above 200 GeV ,
No $\nu_\mu \rightarrow \nu_e$ appearance above $\sim$20 GeV,
Expect effects in most analysis samples, largest in upward-going $\nu_e$
Neutrino oscillation studies using atmospheric $\nu$ oscillation Effects on Analysis Subsamples

$P(\nu_\mu \rightarrow \nu_\mu)$

Ratio to two-flavor oscillations

$\sim 100 \text{ km}$

$\sim 10,000 \text{ km}$
Neutrino oscillation studies using atmospheric $\nu$

**Oscillation Effects on Analysis Subsamples**

\[ P(\nu_\mu \rightarrow \nu_e) \]

Ratio to two-flavor oscillations

\[
\begin{align*}
\delta_{\text{cp}} &= 3\pi/2 \\
\delta_{\text{cp}} &= \pi/2
\end{align*}
\]

Appearance effects are roughly halved for the inverted hierarchy.
<table>
<thead>
<tr>
<th>FC</th>
<th>Sub-GeV</th>
<th>1-ring</th>
<th>e-like</th>
<th>0 decay electron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 decay electron</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>π⁰ like</td>
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<td></td>
<td></td>
<td></td>
<td>μ-like</td>
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<td></td>
<td></td>
<td>1 decay electron</td>
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<td></td>
<td>2 decay electron</td>
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<tr>
<td>Multi-GeV</td>
<td>1-ring</td>
<td>e-like</td>
<td></td>
<td>0 decay electron</td>
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<td>with decay electron</td>
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<td></td>
<td></td>
<td>μ-like</td>
<td>νₑ- like</td>
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<tr>
<td></td>
<td>multi-ring</td>
<td>e-like</td>
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<td>̅νₑ- like</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>others</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>μ-like</td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric neutrino ~ Analysis samples in SK

PC
   OD stopping
   OD through going

Up-going m
   Stopping
   Through going showering
   Through going non-showering
Sterile neutrino oscillations in atmospheric neutrino

Assuming $\theta_{13} = \theta_{12} = 0$,

$$P_{\mu\mu} = \left(1 - |U_{\mu 4}|^2\right)^2 (1 - \sin^2(2\theta_m) \sin^2(E_m L)) + |U_{\mu 4}|^4,$$

$$E_m^2 = \left(\frac{\Delta^2_{32}}{4E}\right)^2 + A_S^2 + 2A_{32}A_S \cos(2\theta_{23} - 2\theta_s),$$

$$\sin\theta_m = \frac{A_{32} \sin(2\theta_{23}) + A_S \sin(2\theta_s)}{E_m}, \quad A_S = \left(\frac{|U_{\mu 4}|^2 + |U_{\tau 4}|^2}{2}\right)$$

**$\mu$ survival probability**

$$|U_{\mu 4}|^2 = 0.0018, \quad |U_{\tau 4}|^2 = 0.33$$

**Suppression**

**Sterile matter effect**
of freedom. We limit $|U_{\tau 4}|^2$ to less than 0.18 at 90% and less than 0.23 at 99%. These limits are independent of the new $\Delta m^2$ above 0.1 eV$^2$ (see Appendix B 3). The contours in $|U_{\tau 4}|^2$ vs $|U_{\mu 4}|^2$ can be seen in Fig. 5. The $|U_{\mu 4}|^2$ best fit point and limit are discussed in the next section in the analysis which focuses on that parameter.