Atmospheric Neutrino Results from Super-Kamiokande

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For The Super-Kamiokande Collaboration
Super-Kamiokande

- Super-K is a 50 kton water Cherenkov detector with 22.5 kton of fiducial volume at 2,700 m.w.e underground.
- The detector is optically separated into ID and OD.
- Excellent in detection of atmospheric neutrinos.
- 20 years since the start of data taking in 1996, >47,000 atmospheric neutrino events.
- A Nobel prize winning experiment!

Four Run Periods:
Atmospheric neutrinos in SK

Event categories

~13,000 km

~10 km

cosmic rays

\( \pi^\pm, K^\pm \)

\( \nu^u \)

\( \nu^e \)

\( \nu^e \)

\( \nu^\mu \)

Full contained

Partially contained

Upward muon

ICHEP 2016
Atmospheric neutrinos in SK

Sub-GeV to more than 10 TeV neutrino energy.
Atmospheric neutrinos measurement in SK

SK measures the flux of atmospheric neutrino with energy of sub-GeV to ~10 TeV. The measurement is consistent with model prediction.

With the large sample, SK can test the effects on atmospheric neutrino flux of geo-magnetic field, solar activity, etc.
Atmospheric neutrinos measurement in SK

Cosmic rays are mostly positive charged.

SK observes clear azimuthal dependence for both μ-like (6.0σ) and e-like (8.0σ) samples due to the effect of geo-magnetic field, and no significant solar modulation of atmospheric neutrino flux.

Fitted α as degree of solar modulation, α=0: no correlation, 1:expected

arXiv:1510.08127
Neutrino oscillations at Super-K

Leading effect is $\nu_\mu$ disappearance ($\nu_\mu \rightarrow \nu_\tau$).
$\nu_\tau$ appearance from neutrino oscillations could be detected by charged current $\nu_\tau$ interaction in SK.
Tau neutrino appearance in SK

- Tau lepton production is rare in SK due to 3.5GeV energy threshold of charged-current $\nu_{\tau}$ interaction.
- Multiple light-producing particles from tau decay.
- Neural network(input variables in backup) to select hadronic tau decay events.

 Tau lepton decays in $\sim 10^{-13}$s, tau lepton track is undetectable in SK detector.
Tau neutrino appearance in SK

\[ \alpha = 1.47 \pm 0.32 \] preliminary

compared to simulation

\( (4.6\sigma \text{ from } 0) \) assuming NH

Sensitivity at \( \alpha = 1: \ 3.3\sigma \)
SK1-4 0.33 Mtyr data and MC

3 flavor oscillation at best fit and reactor $\theta_{13}$ for MC.
Neutrino oscillations at Super-K

Leading effect is $\nu_\mu$ disappearance.
Sub-leading effects help to resolve $\theta_{23}$ octant, $\delta_{CP}$ and mass hierarchy.
Neutrino oscillations at Super-K

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

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

Oscillation probability has dependence on $\sin^2 \theta_{23}$

Ratio to two-flavor oscillations shown. Multiple samples used in the analysis.

More $\nu_e$ at $\pi < \delta_{CP} < 2\pi$.

Matter effect and large $\theta_{13}$, $\nu_e$ enhanced at NH.
SK oscillation analysis-θ₁₃ constrained

• θ₁₃ is constrained at PDG average, uncertainty is included as a systematic error.

• Δχ² = χ²_{NH} - χ²_{IH} = -4.3 (-3.1 of sensitivity)

• The p-value of obtaining Δχ² of -4.3 or less is 0.031 (sin²θ₂₃=0.6) and 0.007 (sin²θ₂₃=0.4) in IH hypothesis. Under NH hypothesis, the p-value is 0.45 (sin²θ₂₃=0.6).

| Fit (517 dof) | χ² | sin²θ₁₃ | δ_CP | sin²θ₂₃ | |Δm²_{32}|| eV² |
|---------------|----|---------|------|---------|-------------|----------------|
| SK (IH)       | 576.0 | 0.0219 | 4.2  | 0.58    | 2.5x10⁻³    |
| SK (NH)       | 571.7 | 0.0219 | 4.2  | 0.59    | 2.5x10⁻³    |
Oscillation analysis with constraint from published T2K data

$\Delta \chi^2 = -5.2$ (-3.8 of sensitivity for SK best, -3.1 for combined best)

The p-value of obtaining $\Delta \chi^2$ of -5.2 is 0.024 ($\sin^2 \theta_{23} = 0.6$) and 0.001 ($\sin^2 \theta_{23} = 0.4$). Under NH hypothesis, the p-value is 0.43 ($\sin^2 \theta_{23} = 0.6$).
Summary

• Measurement of atmospheric neutrino flux of energies from sub-GeV to 10 TeV.
• Tau neutrino appearance with significance of 4.6σ.
• Normal hierarchy preferred by $\Delta \chi^2 = -5.2$, p-value is between 0.024 ($\sin^2 \theta_{23} = 0.6$) and 0.001 ($\sin^2 \theta_{23} = 0.4$) in IH hypothesis.
• Weak preference of second octant and $\delta_{CP}$ near $3/2\pi$.
• More analyses in SK, indirect WIMP search in poster session.
Super-Kamiokande Collaboration

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14 University of Hawaii, USA
15 Imperial College London, UK
16 KEK, Japan
17 Kobe University, Japan
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34 University of Tokyo, Japan
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36 Dep. of Phys., University of Toronto, Canada
37 TRIUMF, Canada
38 Tsinghua University, China
39 University of Washington, USA

~150 collaborators
39 institutions
8 countries
Backups
Seasonal variation

No seasonal variation is seen as expected.
Tau analysis

Seven input variables to neural network. Fit result for different samples, signal/BG MC scaled by fit result.
Fitted systematic errors in tau analysis

Fitted deviation in unit of $\sigma$ of systematic errors

Fitted value of systematic terms, distributed around 0.

\[
\text{error}_{\text{fit}} = \text{mean} - \text{sigma}_{\text{input}} - \text{sigma}_{\text{fit}}
\]
Paper fit update of tau analysis

![Graphs showing distributions of events in different categories: Tau-like, Non-Tau-like, Upward, Downward, with signal fractions and background projections.]

**Tau fraction**: $1.37 \pm 0.23^{+0.13}_{-0.11}$, the significance is $5.1\sigma$. 
Improved MH sensitivity with T2K constraint

$\Delta \chi^2$ Wrong Hierarchy Rejection

- NH
  - SK+T2K
  - SK only

- IH
  - SK+T2K
  - SK only

$\delta_{CP}$ Uncertainty
p-value for MH preference

SK analysis with T2K constraint.
MH preference in sub-samples

Δχ² = χ²_{IH} - χ²_{NH}
Hierarchy preference in sub-samples

\[ \Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} : +0.35 \]

Multi-Ring e-like $\nu_e$ 

Multi-GeV e-like $\nu_e$ 

Multi-Ring others 

$-2.97$

Multi-GeV e-like $\nu_e$ 

$-2.18$

Multi-Ring e-like $\nu_e$ 

$-0.92$
Indirect WIMP search

Search for an excess of neutrinos from galaxy, sun or earth (shown in the plot).

Indirect Dark Matter Searched with Super-Kamiokande
Poster by K. Frankiewicz

Preliminary sensitivity result of 90% CL limits for background only scenario for WIMP decay in earth core.