

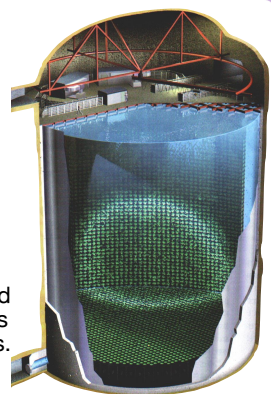
Sterile neutrino search with atmospheric neutrino data in Super-Kamiokande

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1. Introduction and Super-Kamiokande(SK)

- ❖ Sterile neutrinos are hypothetical neutrinos that do not interact through the weak interaction and can be searched for through deviations from three-flavor oscillations.
- ❖ Atmospheric neutrinos are a powerful probe of sterile neutrino mixing because they cover a wide range of energies and path lengths, providing sensitivity to a broad range of Δm_{41}^2 .
- ❖ SK is a large water Cherenkov detector located in Japan. The detector is instrumented with about 11,000 photomultiplier tubes.
- ❖ Charged particles produced by neutrino interactions are identified using Cherenkov ring patterns. This particle identification enables SK to separate atmospheric neutrino events into 29 sub-samples.
- ❖ By combining multiple sub-samples, SK can probe several oscillation channels simultaneously and perform a comprehensive search for sterile mixing parameters.



2. Oscillation framework and analysis setup

- ❖ Sterile neutrino oscillations are modeled in the 3+1 framework, which introduces additional mixing angles θ_{14} , θ_{24} , and θ_{34} , CP phases δ_{14} and δ_{24} , and a mass-squared difference Δm_{41}^2 .
- ❖ Oscillation probabilities are calculated using nuSQuIDS[1], including matter effects.
- ❖ In this analysis, the sensitivity is evaluated by scanning $\sin^2 \theta_{24}$, $\sin^2 \theta_{34}$, and Δm_{41}^2 , with $\theta_{14} = \delta_{14} = \delta_{24} = 0$.

4. Sensitivity results

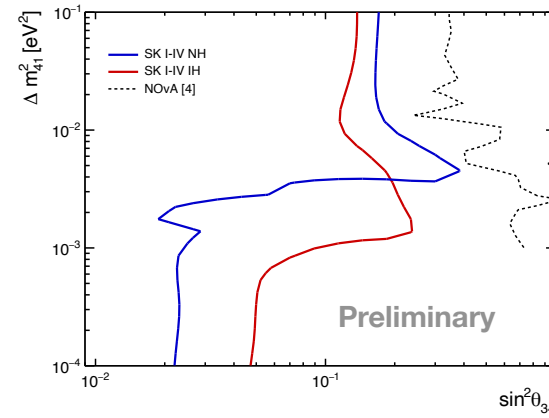
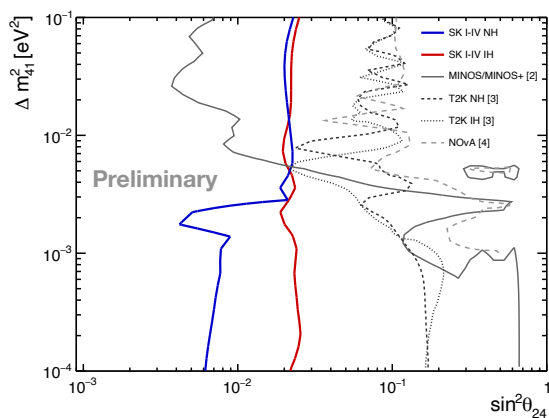
- ❖ The sterile sensitivity is evaluated in the $(\sin^2 \theta_{24}, \Delta m_{41}^2)$ and $(\sin^2 \theta_{34}, \Delta m_{41}^2)$ planes for both Normal and Inverted mass ordering.

Scanned range

- ▶ Δm_{41}^2 ; $10^{-4} \sim 10^{-1}$
- ▶ $\sin^2 \theta_{24}$; $10^{-3} \sim 10^{-1}$
- ▶ $\sin^2 \theta_{34}$; $10^{-2} \sim 1$

- ❖ The lines correspond to the 90% C.L.

- ❖ The sensitivity is particularly strong in the sub-eV region, where matter effects can produce characteristic sterile-mixing signatures in atmospheric neutrino oscillations.



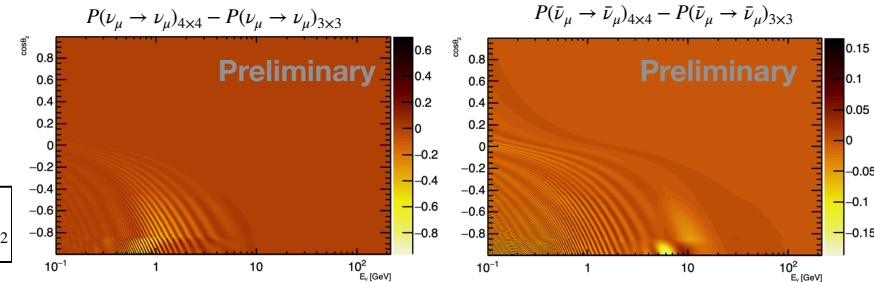
3. Sterile mixing effects in atmospheric neutrino samples

- ❖ Matter effects in the Earth can play an important role in sterile neutrino oscillations.

- ❖ The oscillograms show the probability-level effect for pure ν_μ and $\bar{\nu}_\mu$ survival probabilities at a representative parameter point.

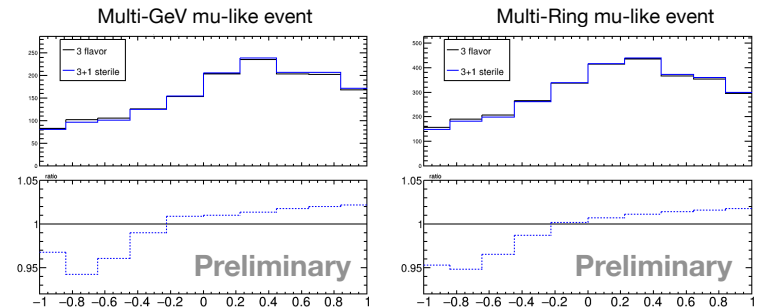
$$\Delta m_{41}^2 = 2 \times 10^{-3}, \text{ NMO for } \Delta m_{51}^2$$

$$\sin^2_{24} = 10^{-2}, \sin^2_{34} = 3.3 \times 10^{-2}$$



- ❖ In reconstructed atmospheric neutrino samples, these structures are smeared by flavor composition, energy resolution, and event classification.

- ❖ Multi-GeV mu-like and Multi-Ring mu-like samples are shown as representative mu-like samples, where the sterile mixing effect can appear as changes in the zenith-angle distributions.



5. Conclusion and prospects

- ❖ SK atmospheric neutrinos are expected to provide strong sensitivity to sterile neutrino mixing in the sub-eV region, especially around and below $\Delta m_{41}^2 \sim 10^{-3} \text{ eV}^2$.
- ❖ Future work includes extending the scan to θ_{14} and adding NC-enhanced samples, since oscillations into sterile neutrinos can reduce the neutral-current event rate. NC-enhanced samples provide a direct probe of sterile neutrino mixing.

Reference

- [1] C. P. C. 277, 108345 (2022) [2] P. R. L. 122, 091803 (2019)
 [3] P. R. D. 99, 071103(R) (2019) [4] P. R. L. 134, 081804 (2025)

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